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Voltage Control in Smart Distribution Network with High Integration of DERs

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A dissertation for the degree of Philosophiae Doctor (PhD) in Electrical Engineering, October 2023

Preface

This thesis is submitted for the degree of Philosophiae Doctor (Ph.D.) in Electrical Engineering at UiT The Arctic University of Norway. The research described herein was conducted at the Arctic Centre for Sustainable Energy (ARC), Faculty of Engineering Science and Technology, Department of Electrical Engineering, under the supervision of Associate Professor Dr. Pawan Sharma, Associate Professor Dr. Charu Sharma, and Associate Professor Dr. Mohammad Amin. The research was carried out during the project period from September 2019 to August 2023.

The thesis is presented as a collection of papers resulting from the research work during the Ph.D. period. However, the thesis is summarized into six chapters. The first chapter consists of an introduction that provides background information about the work related to the main papers included in this thesis. The second chapter presents a brief review of the literature on research work. Then a chapter describing the methodologies related to the implementation of the research work follows. In the fourth chapter, the results obtained during the research are included. In the fifth chapter, the discussion that finds the connectivity between the papers, strengths, weaknesses, contributions, and assumptions considered are described. Finally, the last chapter concludes with the main conclusion.

This work presented here is original and has not been submitted for any other degree at any other university. The thesis contains around 25,400 words, except for the attached paper. Part of this work has been presented in the following publications.

1. Bio-inspired hybrid BFOA-PSO algorithm-based reactive power controller in a standalone wind-diesel power system, International Transaction on Electrical. Energy System., vol. 31, no. 3, p. e12778, Mar. 2021, https://doi.org/10.1002/2050-7038.12778.

2. Optimal Power Flow based Coordinated Reactive and Active Power Control to mitigate voltage violations in Smart Inverter Enriched Distribution Network, International Journal of Green Energy, pp. 1–17, 2023, https://doi.org/10.1080/15435075.2023.2196324.

3. Real-Time Volt-Var Control of Grid Forming Converters in DER-enriched Distribution Network, Frontier in Energy Research (section Smart Grid), no. January, pp. 1–18, 2023, https://doi.org/10.3389/fenrg.2022.1054870.

4. Optimal power flow-based reactive power control in smart distribution network using real-time cyber-physical co-simulation framework, IET Generation, Transmission and Distribution, Feb. 2023, https://doi.org/10.1049/gtd2.12786.

5. Cyber-Physical Co-Simulation Testbed for Real-Time Reactive Power Control in Smart Distribution Network, in 2022 IEEE Innovative Smart Grid Technologies - Asia (ISGT ASIA), 2022, https://doi.org/10.1109/ISGTAsia54193.2022.10003553.

6. Co-Simulation based Optimal Reactive Power Control in Smart Distribution Network, Electrical Engineering, Springer Nature. 2023.

I would like to thank all the respected reviewers, publishers, and readers. My sincere thanks to the thesis assessment committee and the research committee at UiT for providing scientific suggestions and comments during the thesis evaluation. I hope the thesis will provide scientific insight into working in real-time monitoring and control applications in smart distribution networks.

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October 2023

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Nomenclature

AI	Artificial intelligence
API	Application programming interface
AVR	Automatic voltage regulator
BDA	Big data analysis
BFOA	Bacteria foraging optimization algorithm
CPCS	Cyber-physical co-simuation
CPS	Cyber-physical system
DER	Distributed energy resources
DMS	Distribution management system
DN	Distribution networks
DSO	Distribution system operators
FMI	Functional mockup unit
GHG	Green house gas
HIL	Hardware in loop
ICT	Information and communication technology
IED	Intelligent electronic devices
IoT	Internet of things
LV	Low voltage
MEMS	Microgrid energy management system
MGWO	Modified gray wolf optimization
MV	Medium voltage
OLTC	On-load tap changing
OPF	Optimal power flow
PCC	Point of common coupling
PEI	Power electronic interfaces
PMIG	Permanent magnet induction generator
PMU	Phasor measurement unit
PSO	Particle swarm optimization
PV	Photovoltaic
RES	Renewable energy resources
RPC	Reactive power controller
RQ	Research questions
RTDS	Real time digital simulator
SC	Smart converters
SCADA	Supervisory control and data acquistion
SCB	Switched capacitor bank
SDN	Smart distribution network
SG	Synchronous generator
SVR	Step voltage regulator
TSO	Transmission system operators
VRD	Voltage regulating devices
WPP	Wind power plant

Abstract

Global awareness of carbon neutrality, increased energy demand, advancement in control strategies, and a significant reduction in the cost of energy production from renewable energy sources (RES) have encouraged power system operators to incorporate more distributed energy resources (DER) based on RES into the distribution network (DN). With the increasing integration of variable DERs on the distribution network, the distribution network experiences some technical challenges, such as a rise in the voltage in the distribution feeder, rapid voltage fluctuation, and challenges in modelling the distribution network. Additionally, the distribution network also encounters other challenges such as coordination of the protection system, system stability, and various problems of control and management. Moreover, the concern about ancillary services such as spinning reserve, harmonic compensation, and peak savings is also gaining greater attention in DN.

Among several challenges and concerns that distribution system operators (DSOs) face today with the changing energy transition scenario are voltage control issues. This is one of the prominent issues with the high integration of DERs. By implementing appropriate voltage control measures, the voltage profile can be maintained within the desired range, power quality can be enhanced, grid resilience can be increased, energy efficiency (loss minimization) can be achieved, and optimal electrical grid management can be preserved. Moreover, appropriate voltage control also helps to optimize DER integration, improve system performance, and ensure a reliable and sustainable energy supply.

The voltage regulation in the distribution networks is achieved using voltage regulating devices (VRDs). With the increasing integration of DERs into the distribution network, the operation of traditional voltage control techniques continues to be influenced. The reason for this is that the automatic control algorithms in VRDs have not been designed to operate in conjunction with large-scale integration of variable RES. Furthermore, slower response times and mechanical wear and tear in VRDs demand an alternative solution to voltage regulation in DER-enriched DN. Since DERs are integrated into the network using smart converters (SC), appropriate use of SC can be a suitable solution for voltage regulation. As a result, appropriate research for various control and management strategies for the optimal operation of smart converters needs to be investigated. Hence, the thesis aims to investigate the performance of power distribution networks exposed to large-scale integration of DER, propose an advanced control algorithm considering the detailed modelling of the distribution network, and propose a novel cyber-physical co-simulation framework to enhance voltage regulation in DER-enriched smart distribution network. The thesis is presented as a summary of the research findings of the main **Papers A-F** supporting the thesis on voltage control in a smart distribution network with high integration of DERs.

To achieve the main goals, the thesis first aims to address research questions of how such a high integration of DER influences the voltage profile of the distribution network and how smart converters in DERs can be utilized to address voltage violations. For this purpose, the thesis investigates coordinated active and reactive power control in smart converters to mitigate voltage violations. To consider the complex modelling of DER-enriched DN, a data-driven model based on the network information from measurement devices was implemented to formulate the optimal control problem. Secondly, the real-time optimal reactive power control was executed utilizing cyber-physical co-simulation which reproduces grid behaviour and incorporates mutual interactions of voltage controllers with the DN. The investigation was carried out on various IEEE test distribution networks, such as the European LV network and the CIGRE MV network. Finally, the thesis also reports on a new real-time co-simulation framework, which combines distribution network power flow simulations in OpenDSS with Typhoon HIL real-time simulator considering the advantages of algorithms prototyping in a Python environment. In addition, the Typhoon HIL SCADA system was developed to communicate and exchange information on DN and control signals information between OpenDSS and the real-time simulator.

The results of individual studies highlight the importance of voltage control in regulating the voltage profile of the distribution network. The results also highlight how the distribution network can be effectively modelled for optimal operation using the data available from the measurement devices in the distribution network. The optimal setpoints for smart converters also offer the operation of the distribution network with minimum system loss. On the other hand, the real-time optimal control of smart converters using the novel cyber-physical co-simulation framework proposed in the thesis can provide real-time monitoring and control services in the distribution network. The proposed solution regulates the voltage violations caused by fluctuations of DERs and loads in real-time. The suggested

solution offers great simulation and prototyping flexibility and can be used in many real-time control, protection, and monitoring studies, both for wide-area control problems and for individual controller algorithms.

My hope is that the findings of this research can help power system operators, utility companies, researchers, and academics implement the proposed methods to solve the problems associated with the high integration of DERs into the distribution network. Furthermore, the author believes that the thesis will provide scientific insight for working in real-time monitoring and control applications in smart distribution networks.

Acknowledgements

First and foremost, I would like to express my deepest gratitude to my supervisors associate Prof. Dr. Pawan Sharma, Dr. Charu Sharma and Dr. Mohammad Amin. Thank you all for your support and guidance during the past years. You all have been a constant source of inspiration for me. All the time we spent together discussing several innovative ideas was always of great support for me throughout my Ph.D. journey. Moreover, I also would like to acknowledge Professor Terje Gjengedal who initially hired me for the PhD position at UiT and who has been one of my previous co-supervisors. I also would like to express my sincere thanks to Anne Gjerløw and Wenche Svea, who were always there to help with the administrative support at UiT.

Secondly, I am grateful to the Arctic Center for Sustainable Energy (ARC) and Faculty of Engineering Science and Technology at UiT The Arctic University of Norway, Campus Narvik, for providing me with the funding to work with the research objectives presented in this thesis, travel for international conferences, research mobility, and open access publication of the papers. I also would like to acknowledge the Electrical department especially Kjell Birger Hansen (former head of the IVT department), Trond Østrem, and Arild Steen (head of the IVT department) for introducing an interesting perspective to engineering and teaching processes. I am also thankful to all the members of the Electromechanical System Research group at UiT Narvik for the continuous discussion about opportunities and challenges of research in the Arctic region. A sincere acknowledgement to the thesis evaluation committee and the research committee at UiT for providing scientific suggestions and comments during the thesis evaluation.

Thirdly, I would like to express my sincere appreciation to Prof. Francisco Gonzalez-Longatt (Founder DIgEnSys-Lab) who has continuously supported me from the first emails we exchanged for my research stay at the University of South-Eastern Norway. His mentoring, immense power engineering knowledge, and scientific experience have been invaluable during my Ph.D. studies and will be valuable in my future career. In addition, I wish to acknowledge Prof. Jose Luis Rueda (Delft University of Technology) for his continuous support and suggestions. I would also like to thank the technical team of OpenDSS and Typhoon HIL for the technical support provided during my research work.

Next, I am also grateful to my friends Chittaranjan Pradhan (NEVS Sweden), Gioacchino Tricarico (Politecnico di Bari), Luis Santiago Azuara-Grande (Universidad Carlos III de Madrid) and Le Nam Hai Pham (University of South-Eastern Norway) for several fruitful discussions and generous advice. Furthermore, I want to thank my friends at UiT Narvik and all the faculty members of the Electrical Department who have always been there for me in the most stressful periods.

Finally, my heartfelt thanks go to my wonderful wife, Hima, who supported me from the first thought of doing a Ph.D. in Norway. She agreed to travel with me to listen to my daily stories of rejections and acceptances. I also owe my gratitude to my siblings and relatives. They have always believed in me and have encouraged me to have high motivation in life.

I would like to dedicate my Ph.D. thesis to my late father Bhoj Singh Wagle, who always dreamed of me becoming a Ph.D. graduate.

1 Introduction

The Introduction chapter provides a detailed description of the research background, research motivation, problem statement, research questions, research goals and objectives, and research importance.

1.1 Research Background

Global awareness of environmental concerns, economic challenges, increased energy demand, and increased concern about carbon neutrality have encouraged power system operators to incorporate more distributed energy resources (DERs) based on renewable energy sources (RES) into the power system network [1]. DERs are small power generations connected to distribution networks (DN) [2]. The future DN will consist of numerous DERs that form intelligent electrical networks and microgrids based on RESs interacting through power electronics interfaces (PEI). There will be a high deployment of DER in the electricity system to achieve the goal set by the european energy roadmap 2050. This roadmap has set the goal of reducing greenhouse gas (GHG) emissions in developed countries below 80-95 % of the level of 1990 by 2050. **Figure 1** shows the global primary energy by source scenario for 2018 and the projected scenario for 2050. This shows that there will be a massive increase in RES and a decrease in oil and coal in the future. The share of RES, especially photovoltaic (PV) and wind power plant (WPP), is expected to increase from 0.33% and 0.82% to 11.9% and 11.03%, respectively, by 2050 [3].

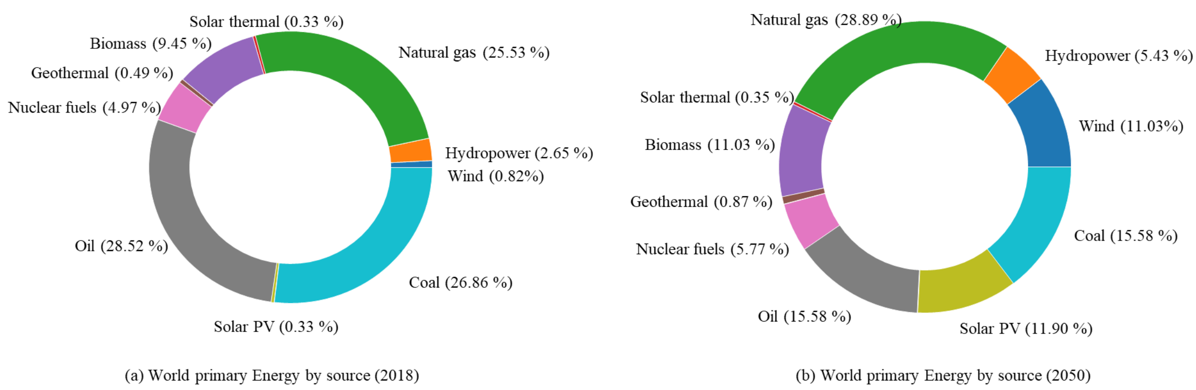


Figure 1: Primary energy in the world by the source of generation [3]

The high integration of DER can enhance the reliability, efficiency, resilience, and diversity of generation in the distribution network [4]. While increased integration of DERs has numerous benefits, it also poses several challenges related to effective control and management, regulatory framework, and stability issues [5]. These challenges need to be carefully addressed to fully realize the benefits of DER integration into distribution networks. Among many technical challenges, voltage control is one of the major ones [7]. A high proportion of DERs in the distribution network introduces intermittent and variable power, leading to more voltage fluctuations. The high amount of DERs can also result in an increase in the terminal voltage of the network during periods of high power generation from DERs and low load consumption. Hence, appropriate voltage controls in DER-rich distribution networks are essential to ensure safe and secure operation of the distribution network.

Voltage control, as an important aspect of the effective operation and control of the distribution network, plays a critical role in maintaining the quality of the electrical supply [6]. Despite the existence of conventional voltage regulating devices (VRDs) in providing voltage control [8], the operation of VRDs in traditional voltage control schemes is highly affected by the high integration of DERs. The reason for this is that automatic control algorithms in conventional VRDs have not been built to operate together with large-scale integration of variable DERs [9]. Their operation is also hindered by slow response times, limited switching capabilities, increased mechanical wear, and elevated switching losses. Ongoing research and development in the field of voltage control continues for improvements in voltage control techniques, making power system networks more resilient and capable of accommodating the evolving landscape of energy supply and demand [10].

As the DERs are integrated into the power network using a power electronics-based converter, more converters will be available in the distribution network. These days such power electronics converters, also called smart converters (SCs) [11] are equipped with modern sensing, monitoring, and communicating units to adjust (either remotely or locally) various parameters to optimize efficiency and power quality. With these additional features, the control of smart converters as suggested by IEEE 1547-2018 [11] has recently gained popularity among distribution system operators (DSOs) [12]. These SCs can be used to handle such voltage problems in the distribution network [13] without additional investment in additional VRDs. These converters also offer a more flexible approach to voltage control.

However, to explore the control and management strategies of these SCs, one of the major problems in applying appropriate control algorithms is modelling of the distribution network. The voltage control problem in the context of distribution networks is a complex process that requires a deep understanding of the dynamics of the power system, control strategies, and emerging technologies [14]. This necessity justifies looking at the viability of modelling and simulation methods for the distribution network [15]. Therefore, in-depth research on modelling distribution networks that can handle the large-scale integration of DERs is also required.

To address the challenges associated with the high integration of DERs in distribution networks in an alternative way, an emerging concept of smart distribution networks (SDNs) [16] has emerged as a pivotal solution to ensure the stability, reliability, and efficiency of SDNs. Furthermore, the concept of digitalization is becoming popular among researchers for effective control and management of the distribution network. For the digitalization of the distribution network, it is critical to develop a comprehensive and implementable platform to test theoretical ideas, computational tools, methodologies, and recent technologies in real-time. Modern distribution network operating conditions require sophisticated technologies to achieve effective real-time monitoring and control using sophisticated hardware and software [17]. Therefore, it is important to evaluate the benefits of adopting such information in the smart operation of a distribution network.

In a smart distribution network to improve the voltage profile, especially in networks that are more likely to experience voltage violations, quick and efficient voltage regulation can help solve several operational and planning challenges. A comprehensive investigation of the contemporary challenges, methodologies, and technologies associated with voltage control is highly required. In addition, a broader scientific discourse on the achievement of resilient, efficient, and sustainable SDNs is necessary through an in-depth analysis of state-of-the-art techniques, practical case studies, and advanced control strategies.

The subsequent chapters will explain a roadmap for the comprehensive study of different voltage control methodologies and architectures in smart distribution networks, addressing some of the pertinent issues such as voltage regulation, loss minimization, the integration of advanced control algorithms, and propose a novel framework for real-time testing in the smart distribution network.

1.2 Research Motivation

The research finds motivation to have a safe, secure, reliable, and sustainable future electric energy system. With the background mentioned in the previous section, higher integration of DERs will resolve future energy demands and motivate us to explore in-depth research about the problems associated with it. Since advanced monitoring and testing of distribution networks in the smart grid paradigm will help DSOs to work more efficiently, the adoption of smart grid features at the distribution level helps achieve reliable operation. With this reliable operation, DSOs can achieve effective control and management to make the system more resilient. In addition, DSOs can coordinate and cooperate with other DSOs to make the operation of the distribution system more safe and secure.

Among several challenges that DSOs face today with the changing energy transition scenario in the distribution network, the voltage control issue is emphasized in this thesis. By implementing appropriate voltage control measures in distribution networks with substantial integration of DERs, the voltage profile can be maintained within the desired range, power quality can be enhanced, grid resilience can be increased, energy efficiency (loss minimization) can be achieved, and optimal electrical grid management can be preserved. Additionally, appropriate voltage control also helps optimize DER integration, improve system performance, and ensure a reliable and sustainable energy supply.

This research also finds motivation in the growing concern about the digitalization of distribution networks in the future. Digitalization of distribution will be essential for autonomous and proactive operation for controlling and monitoring. This means that the modelling of the distribution network should be rethought and reviewed in these changing scenarios. Data-driven distribution network modelling is one of the promising solutions in this regard. Therefore, in this thesis, the three-phase modelling of the unbalanced distribution network using energy meters data is utilized.

Another motivation lies in the fact that real-time testing of control and management actions in distribution networks is essential to handle various types of uncertainty. Cyber-physical co-simulation framework is one of the emerging techniques for implementing real-time testing. Hence, this thesis proposes a novel cyber-physical co-simulation framework to enhance voltage regulation in DER-enriched smart distribution networks. Furthermore, it will also increase the coordination among the DERs in real-time.

My hope is that the findings of this research can be implemented by power system operators, researchers, utilities, and academics to solve one of the prominent problems associated with the high integration of DERs in the distribution network.

1.3 Problem Statement

In a smart distribution network to improve the voltage profile, especially in networks that are more likely to experience voltage violations, quick and efficient voltage regulation can help solve several operational and planning challenges by properly coordinating the controlled devices. As a result, the following research questions (RQs) were identified to specify the research objectives for this thesis.

- **RQ1**: *How do modern distribution networks respond to the large penetration of variable distributed energy supplies in terms of the overall voltage profile and voltage violations?*
- **RQ2**: *How to coordinate between active power curtailment and reactive power assistance from a smart converter to alleviate voltage violations in the DER-enriched smart distribution network? Also, how to select the right control strategies and to arrive at an optimum solution in a distribution network more quickly?*
- **RQ3**: *How to create a framework for real-time testing and validation of different voltage control architectures in the DER-enriched smart distribution network?*

1.4 Research Goals and Objectives

The main research goals of this thesis are to analyze the voltage behavior of the DER-enriched distribution network and to mitigate the voltage violations caused by the high integration of such DERs. Therefore, this research focuses on achieving the following objectives throughout the research period.

- **Objective1**: *To investigate the voltage violations caused by the integration of variable RES-based DER and to identify the role of active and reactive power control strategies to regulate voltage.*
- **Objective2**: *Proposing a novel optimal voltage violation mitigating technique in DER enriched smart distribution network. To identify the right selection and trade-off between different voltage control architectures in a DER-enriched smart distribution network.*
- **Objective3**: *Validating the proposed optimal control method in real-time models of an existing power distribution network with a high penetration of DERs.*
- **Objective4**: *Develop a cyber-physical co-simulation framework to perform real-time simulation studies of various voltage control methodologies in DER-enriched smart distribution networks.*

1.5 Research Importance

Fast and effective voltage control can overcome certain operational and planning issues in distribution networks. Firstly, better voltage control would facilitate the integration of more RES-based power generation into distribution feeders, particularly in networks that are prone to voltage violations. Consequently, this would allow for further enhancement of large-scale DER integration. Secondly, with effective active and reactive power control coordination from smart inverters, the overall power loss in the network can be minimized without additional investment in alternative VRD. Thirdly, real-time tests provide a platform for testing novel concepts and ideas before implementation in the real system. In addition, the cyber-physical co-simulation framework opens multiple horizons for testing optimal control applications in distribution networks in real-time in a faster and more effective way.

Eventually, the research finds application in numerous aspects of control applications in smart distribution networks, in addition to the voltage control technique presented. In particular, the suggested method also suggests co-simulation based optimization for the implementation of optimal control in DER-enriched distribution networks while making use of measurements from energy meters in a realistic manner. The use of the coordination control approach allows the current trend of entirely digital substations, assuming that the future distribution network is equipped with adequate equipment for communication and monitoring [18]. The results of this thesis can be implemented in the control unit at the distribution substation. Lastly, the developed cyber physical co-simulation framework, which was created and used as a real-time testing environment for presented control techniques, has also been intended as a general real-time testing environment for optimal control algorithms. As a result, it can be widely utilized to test and validate cutting-edge concepts and ideas in the smart grid paradigm that requires real-time simulation and validation.

1.6 Overall Thesis Layout

This thesis is a collective summary of the research work contained in six main articles that form the basis of the PhD project. The thesis is divided into six chapters including Introduction, State-of-the-Arts, Methodology, Results and Contribution, Discussions, and Conclusion. Relevant references cited in the main content of this thesis are provided in the References section. The papers supporting the thesis are reproduced in full at the end of this document as part of this thesis. The papers are attached as an Appendix to the Thesis.

Chapter 1 of the thesis gives the basic introduction with the relevant background, the problem statement, the motivation for the research, the goals and objectives of the thesis, and the importance of the research. The introduction is divided into six sections: Research background, Motivation, Problem statement, Research goals and objectives, Research importance, and Overall thesis layout. Background and motivation provide the overall background of the research work and the motivation to explore this research. The problem statement explores the potential research area and formulates fundamental research questions that create the environment for further research. Based on the problem statements and research questions, research goals and objectives are shortlisted to define the specific task of the research. The section on the importance of research highlights the summary of the research in terms of its contribution to the scientific community. Lastly, the overall thesis layout describes the sequencing of the thesis in general.

Chapter 2 provides a recent trend of voltage control in smart distribution networks. This chapter aims to extend the state-of-the-art and recent trends according to the research questions and objectives considered in the thesis. Therefore, this chapter is arranged into three main headings that reflect the main area of consideration. In the first section, a survey of voltage control in a distribution network with a focus on different attributes of different voltage control architectures is presented. Similarly, in the second section, the state-of-the-art and trends of modelling of the distribution network are presented. In the third part, a preview of real-time validation approaches for voltage control in the distribution network is presented.

The methodologies related to the overall formulation of the results in this thesis are presented in **Chapter 3**. A brief presentation of the methodologies applied for the formulation of the papers supporting the thesis is presented in this chapter.

In **Chapter 4** of the thesis, a key outcome of this research of relevance to the research questions is discussed. An overview of the research results is given in connection with the research questions and objectives. Only some of the important results related to research questions and research objectives are presented in this chapter. The list of main papers is presented in **Table 2**. A list of other relevant publications is presented in **Table 3**.

A detailed discussion of the results obtained is presented in **Chapter 5**. The discussion chapter is divided into 9 sections. This section's main goal is to show how the main findings of different papers are connected to present the thesis' general overview. A table showing the link of the papers with the research objectives and the research question is also shown in **Table 6**. In addition, this chapter presents how the research is moving forward by addressing the limitations of one paper and how the research gap is filled in the subsequent paper. Furthermore, this chapter describes various aspects, such as strengths, weaknesses, limitations, assumptions, and implications of the research work. At the end of this chapter, the chapter suggests potential future research directions that could be continued by considering the insights from the presented work.

Finally, **Chapter 6** presents the overall conclusion of the thesis. Conclusions chapter provides a summary of the main research findings.

2 Voltage Control in Smart Distribution Network: State of the arts and trends

A brief review is presented on voltage control in smart distribution networks. The review of the literature presented here is part of the survey supporting the **Papers A-F** forming the thesis. This aims to extend only the state-of-the-art and recent trends on the research questions and objectives considered in the thesis. Therefore, this chapter is not as comprehensive as other review papers on specific topics. The overall chapter is divided into three sections.

In this chapter, three main sections that reflect the main aim of this research work, i.e. attribute of different voltage control architectures, modelling of distribution network, and real-time validation of voltage control in the distribution network, are presented. A comprehensive investigation of the contemporary challenges, methodologies, and technologies associated with voltage control is covered. In addition, a broader scientific discourse on the achievement of resilient, efficient, and sustainable SDNs is conducted through an in-depth analysis of state-of-the-art techniques, practical case studies, and advanced control strategies. In **Section 2.1**, a detailed exploration of previous studies conducted to properly identify different voltage control architectures in the DER-enriched distribution networks is covered. On the other hand, in **Section 2.2** different approaches to modelling the distribution network for optimal control are discussed. Potential challenges, modifications, gaps, and suggestions are highlighted in this section. Similarly, in **Section 2.3**, recent trends and approaches used for real-time validation in the distribution network are presented. A brief description of how and why the system proposed in this thesis is unique compared to the ones in the literature is also presented.

2.1 Voltage Control in Smart Distribution Network with High Integration of DERs

Voltage control in a distribution network is an important aspect in maintaining a secure, stable, and reliable power supply to consumers. Voltage control in the power network regulates voltage within permissible ranges to optimize electrical equipment performance, minimize voltage-related issues, and improve the operating characteristics of electrical energy systems. The power system operators and utilities are responsible for maintaining voltage profiles in the network. For this purpose, they analyze energy supply and demand patterns, monitor voltage profiles, and proactively manage the voltage of the distribution network. The goal is to keep consumer voltage within acceptable levels, minimizing equipment damage, and delivering reliable energy supply.

There are several standards and regulations that recommend the power system operator to maintain the standard voltage profile. These standards are commonly called voltage regulations standards. These standards are based on locations and practices around the world. The Electricity Safety, Quality, and Continuity Regulations (ESQCR) set voltage standards in the UK for a 50 Hz system. This standard defined the permissible voltage limits for the network based on the voltage level of the network [19]. The distribution code and Engineering Recommendation G5/4-1 recommend voltage tolerance limits in the UK, which are generally within $\pm 6\%$ of the nominal voltage. Similarly, voltage regulation in European distribution networks follows the EN50160 standard. The tolerance limits for low-voltage (LV) and medium-voltage (MV) networks in Europe are typically $\pm 10\%$ of the nominal voltage. On the other hand, in the United states, voltage regulation standards and guidelines are set by various organizations such as the North American Electric Reliability Corporation (NERC), the Institute of Electrical and Electronics Engineers (IEEE), and the American National Standard Institute (ANSI). The ANSI C84.1 standard requires power utilities to maintain the customer voltage within the prescribed limits, usually 0.95 and 1.05 pu, as lower and upper limits. Voltage violations can be in the form of undervoltage violations (below the minimum limit) or overvoltage violations (over the maximum limit). Undervoltage violations are especially due to the high power consumption by load and low power generation from DERs. However, overvoltage violations are due to the high power generation from the DER and low power consumption from loads. These standards provide recommendations, but the application of such a standard can vary according to network characteristics, customer needs, and operating conditions.

Currently, voltage control in distribution networks is performed using various voltage regulating devices (VRDs). Most common VRDs are on load tap changing (OLTC) transformers, step voltage regulators (SVRs), switched capacitor banks (SCBs), and switched inductor banks (SIBs) [20]. With the higher integration of variable DERs in the distribution network, the operating characteristic of VRDs is highly affected. Taking into account the greater integration of DER, the distribution network modifies to a completely new paradigm in terms of operation and control [14]. It is difficult to provide prompt voltage control of such devices due to the slower response and limited switching operation [21]. Furthermore, the frequent switching operation of VRD causes mechanical wear and tear, causing an additional financial burden. In addition, it also causes high voltage flicker [22]. There will be increased switching that not only damages the mechanical connection, but also results in increased switching loss [23].

The use of smart converters in DERs in a standalone or in coordination with VRDs can be a suitable option to handle such problems in VRDs [24]. Smart converters (SCs) also have great potential to help DSOs by providing various ancillary services such as spinning reserve, non-spinning reserve, backup supply, harmonic compensation, and network stability [25]. Additionally, the SC might be equipped with several controls that would allow it to react to unique circumstances or coordinate its operation with that of other smart converters in the distribution network.

In the literature, the control of smart converters is utilized in several ways. Active and reactive power control from SC can be utilized for voltage regulation in DER-enriched distribution networks. In some cases, the smart converter is used only to control the reactive power [26]. Reactive power injection or absorption is one way the smart converter can maintain a voltage profile [27, 28]. According to the literature, reactive power control is less effective in the case of low-voltage (LV) networks, as this method increases network losses due to the high $\frac{R}{X}$ ratio of the interconnecting lines between the network [29]. Additionally, the high value of $\frac{R}{X}$ in LV networks limits the effect of reactive power control in LV networks [30]. Another disadvantage of reactive power control of SC as per IEEE 1547-2018 standard is limited capacity and, hence, it might not regulate the voltage within the acceptable range. To provide reactive power support while producing active power, smart converters must be of large size [31]. Therefore, the application of only reactive power control from smart converters may not be feasible when the voltage violations are of significant scale and no other alternative solution for voltage regulation is available.

Currently, in some cases where the integration of DERs is extremely high, controlling the active power of the smart converter is also in practice [32]. The application of the active power control from the smart converter curtails the power production from the DERs. Hence, this method reduces the power production from the DER. Active power curtailment (APC) is considered an effective and efficient method to regulate voltage in LV networks [33] if no other viable alternative is available for voltage regulation or if the power generation from DERs is very high, as defined in the "*IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electrical Power Systems Interfaces*" [11]. This method is considered suitable for regulating voltage violations that are above the prescribed limits. However, the reduction in power generation to regulate voltage may not be a motivating factor in increasing the integration of green energy. Therefore, in-depth research is required to take advantage of the power control capability of smart converters in an optimal way, minimize active power curtailment, and regulate voltage in LV distribution networks [34].

The coordination of smart converter control can be achieved in a centralized, distributed, and local control method [35]. Local voltage control responds quickly to the frequent variation of DER, since it addresses voltage violations based on local measurement [36]. Several control modes, including (i) constant power factor mode, (ii) active power-reactive power mode, (iii) voltage-reactive power mode, and (iv) constant reactive power mode, are frequently employed in the literature [37] as local voltage control. Recent regulation states that the requirement for the grid interfacing converter [11] is to maintain the terminal voltage within a specified standard. Unfortunately, local control lacks coordinated control operation, which reduces the effectiveness of the smart converter. However, by coordinating the converter's controller with the central controller, the centralized control of smart converters may address the voltage violation problem more effectively. However, the centralized control technique requires a huge investment in communication and measurement infrastructure, which may not always be practical in highly sparse radial distribution networks [30]. Furthermore, remote access to internet data can cause security concerns [38], leaving the system open to attack by unethical hackers. However, with the advancement of communication and monitoring infrastructure in smart converers, they can be used in centralized control in a smart distribution network. Using smart converters in centralized control can have several potential advantages and challenges, so it is always good to investigate new research avenues as studied in this thesis. The control of smart converters in the distribution network in centralized mode is shown in **Figure**

2.

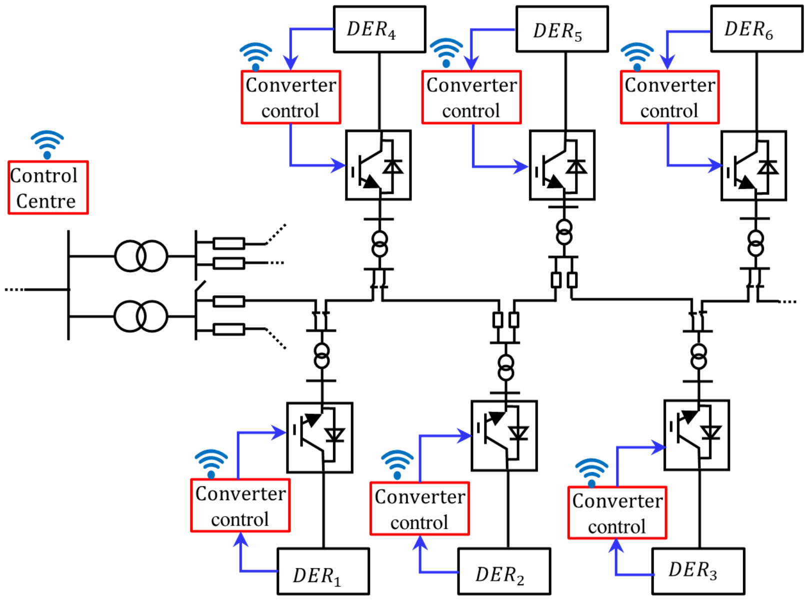


Figure 2: Centralized control in smart converter in distribution network [39]

Smart converters can also be operated in coordination with other VRDs if the distribution network is equipped with such VRDs [40]. Robust optimization to coordinate the OLTC and the smart converter is proposed in [41]. Similarly, in [42] the authors presented a two-stage voltage control architecture in a distribution network. In this work, in the first stage, the controller is designed to act locally based on the information of the node voltage. If the local action is unable to mitigate the voltage violations, then the controller operates in a distributed manner to request additional support from neighbouring controller. Similarly, in [43] a novel control framework is used to coordinate the smart converter with the OLTC to mitigate voltage violations by solving a multi-time-step constrained optimization. In [44] two-time scale multi-objective coordinated control using OLTC, SCB, and smart converter are utilized to regulate the voltage profile in the distribution network. The author in [45] added additional VRD and proposed a double time-scale coordinated voltage control in an active distribution network. In this paper, SVR, SCB, and smart converter are coordinated to maintain the voltage profile of the distribution network. The three-stage incentive-based coordinated operation of OLTC, SCBs, and smart converter is analyzed in [46]. VRDs are operated based on mechanical switching to change the connections that are pre-designed to provide fixed output. Whether in a coordinated operation or in a standalone operation, VRDs are prone to mechanical wear and tear. In the case of remarkably high integration of DERs in the distribution network, optimal operation of smart converters can solve the problem of voltage regulation.

The coordinated operation of smart converters can be achieved in several ways [47]. A voltage sensitivity-based approach for controlling the smart converter is proposed in [48]. In this paper, the voltage sensitivity is computed on the basis of the surface fitting of the data available from the measurement. The optimal setpoints for the operation of the smart converter are calculated on the basis of the voltage sensitivity. Similarly in [49] the model-based voltage control strategy is proposed to regulate voltage violations in the distribution network. In this paper, the voltage control is achieved first using the standard Q-V profile of the smart converter. Later if the voltage violations are not regulated, inter-area coordinated operation of smart converters is proposed to regulate further violations. Similarly, in [50] nodal sensitivity-based control of the smart converter is proposed. This paper highlights that if sufficient monitoring infrastructures are available in the distribution flow-based method is more suitable compared to the sensitivity-based method for voltage regulation.

Furthermore, with the advancement in ICT-based technology in smart converters, optimal power flow-based control is also gaining attention in DER-enriched distribution networks. A complex quadratic program-based OPF to regulate the bus voltage of a distribution network is presented in [51]. Similarly, robust chance constrained OPF-based voltage regulation is proposed in [52]. In [53] the three-phase AC OPF is studied for maximizing renewable energy production by optimizing for the operating characteristics of controllable devices. A new second-order cone programming based on OPF for computing bus voltage angle difference in distribution network is studied in [54]. Three-phase OPF-based control in European medium voltage and low voltage network is studied in [55]. OPF-based control provides a promising result for addressing the voltage control problem in the distribution network. Regardless of the optimization problem formulation, the optimal control of the smart converter can be achieved for several applications in the distribution network. Especially in the DER-enriched distribution network, the control of smart converters can be utilized for both active power and reactive power control.

Apart from investing different attributes of voltage issues in the smart distribution networks. The selection of appropriate modelling approach, and different testing and validation approaches are some of the primary concepts that need to be investigated for implementing suitable voltage control in smart distribution network. Moreover, in practical operation, the output of the DER and the load can vary, affecting the operation of the control strategies [56]. Hence, to tackle the uncertainty due to DERs and Loads, DSOs are moving towards real-time optimal voltage control approaches. In the subsequent sections, brief review of modelling approaches of distribution networks and real-time validation approaches of voltage control in the distribution network are presented.

2.2 Survey on Modelling of Smart Distribution Network for Optimal Voltage Control

With the high integration of variable DERs in the energy system, the conventional presumption of unidirectional power flow and lower terminal voltage at the end of the distribution network are no longer applicable. Due to integration of DERs, a load bus in such grids may transform into a generation bus. And this might create the rise of terminal voltage at the instant of higher generation from DERs and lower power consumptions in loads. Also, changes in power flow result in changes in network's bus voltage [5]. Due to the variation in environmental conditions such as cloud transients and the global irradiance variation [57], the voltage profile of the network is fluctuating in nature. These challenges are of major consideration as they affect the operation of conventional voltage regulatory schemes [58]. To show how the integration of DERs affects the terminal voltage in the distribution network, a simple model with a mathematical model is taken as shown in **Figure 3**.

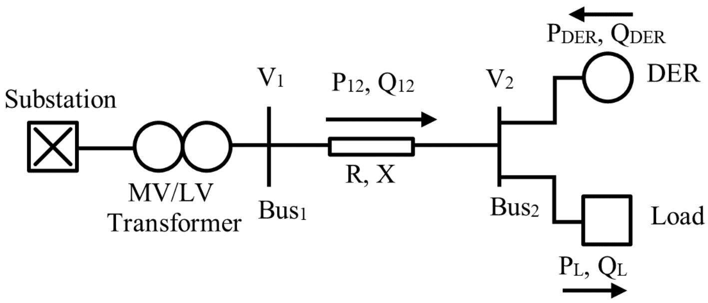


Figure 3: A simplified layout of the distribution network with load and DER

Suppose V is the nominal voltage of the network, V_1 and V_2 are the voltages in Bus_1 and Bus_2. R and X are the resistance and reactance of the line between Bus_1 and Bus_2. And the load with active power P_L and reactive power Q_L is connected at Bus_2. Similarly, the DER with an active and reactive power capacity of P_{DER} and $\pm Q_{DER}$ is also installed at Bus_2. The - sign of Q_{DER} indicates that the reactive power is supplied by the DER and the + sign indicates that it is consumed by the DER. The voltage regulation in this case is given by **Equation 1**. To obtain the voltage at Bus_2, this equation can be rewritten as **Equation 2**.

$$V_1 - V_2 = \frac{R\,(P_L - P_{DER}) + X\,(Q_L \pm Q_{DER})}{V} \tag{1}$$

$$V_2 = V_1 - \frac{R\,(P_L - P_{DER}) + X\,(Q_L \pm Q_{DER})}{V} \tag{2}$$

From **Equation 2**, it can be observed that the voltage at Bus_2 is lower than that at Bus_1 when the power generation from DER is lower than the power consumption from load. However, the voltage might go higher than the voltage at Bus_1, in case of higher power generation from the DER. Also, in case of light load or no-load condition, it can be assumed that $P_L = 0$ and $Q_L = 0$ and then **Equation 2** can be expressed as **Equation 3** which shows the relationship of the injected power of DER in the PCC.

$$V_2 = V_1 + \frac{R\,(P_{DER}) + X\,(\pm\, Q_{DER})}{V} \tag{3}$$

In this mathematical model, the concept to describe the impact of high integration of DER on the voltage profile at the PCC of the distribution network is presented as a simple case. However, realistic distribution networks are exceptionally long and radial in nature serving many customers connected to the network. Unlike transmission networks, distribution networks may also consist of many single-phase loads and generation connection points, which can make the network unbalanced. Therefore, the control or management approaches implemented in transmission networks may not be feasible in distribution networks [59]. One of the major problems in applying the optimal control algorithm in a distribution network is the modelling of the unbalanced distribution network [60]. The accurate and efficient modelling of the distribution network with uncertainties from variable DERs is essential for applying optimal control algorithms in the distribution network. The modelling of the distribution network also depends on the type of application that the research is intended to achieve. For instance, for the stability analysis of the network, dynamic modelling of the network is required [61]. In some cases, stochastic modelling can also be done to incorporate the uncertainties of the components included in the model [62].

Most of the research on optimal control application in a distribution network utilize load flow calculations based on physical modelling techniques. From the physical properties of the network, power flow solutions are solved using the Newton-Raphson method [63] or the fast decoupled method [64]. However, due to unique properties of distribution network such as radial nature, unbalanced operation, multiple number of connection points and interconnecting lines, and non-uniform loading condition, the traditional load flow models may not converge. Furthermore, the high $\frac{R}{X}$ ratio of the distribution network is one of the reasons for the convergence of the optimization problem in the distribution network. The authors in [65] suggested a modified fast-decoupled method to solve the problem of convergence in the network with a high $\frac{R}{X}$ ratio in the distribution network. Some modifications can be made in the traditional modelling method by modifying the Y-bus matrix to achieve reliable convergence [66]. Even with modification in most of the earlier research, the analysis was done for a balanced distribution network. These methods will also still have the problem of convergence with large integration of DERs and unbalanced operation in the network. To consider the realistic distribution network properties, three-phase modelling suitable for both balanced and unbalanced operations must be considered.

Some researchers proposed alternative methods to model the distribution network considering full network properties. In [67] the authors proposed the Backward Forward Sweep (BFS) method to compute the three-phase power flow of the distribution network. However, the convergence of the BFS method is more dependent on the size of the equivalent line impedance and load admittance, which limits the application of the BFS method in a large and unbalanced distribution network. To overcome this challenge of the branch flow method, power injection methods can also be used to approximate the power flow in the network [68]. The authors in [69] proposed the current injection method (CIM) to perform the power flow in the distribution network. Compared to the BFS method, CIM converges faster with fewer iterations even for an unbalanced and heavily loaded network [70].

With the increasing utilization of various measurement devices like energy meters, phasor management units (PMU), intelligent electronics devices (IEDs) in the distribution network, data-driven modelling of distribution network based on the information from these measuring devices is gaining attention. Provided that a significant amount of measurement and monitoring systems are available, data-driven distribution network modelling can be one of the viable solutions in modelling [71,72], Data obtained from energy metres [73], phasor management units (PMU) [74] can be used to accurately model distribution network [75]. With a proper mathematical formulation from the data, the distribution network can be modelled more accurately [76]. In [77], a data-driven approach is proposed to visualize the interactive information of the power system network. The data-driven approach relies on developing algorithms to represent the mathematical characteristics of the distribution network from the derived data. The authors in [78] proposed a data-driven model based on voltage sensitivity to approximate the radial and mesh distribution network using enhanced Z-bus matrix formulation. Various machine learning algorithms are also implemented in the optimal voltage control application in a distribution network [79]. The application of machine learning algorithms removes the barrier of prior knowledge of the complete network information for the modelling of the distribution network.

Even in the case of data-driven modelling of the distribution network, in most cases, the data is processed by a mathematical model describing the network property of the distribution network. Using the network property in the model, more accurate results can be obtained. Among several methods, the current mismatch method based on the current injection model gives a more precise model [80]. In the current injection method, the phase voltage of any terminal can be represented by the active and reactive power injections/absorption from generators/loads at that terminal. Another approach to modelling the distribution network is to use the commercially available distribution network solvers such as OpenDSS, PSCAD, DigSilent Power Factory, CYME-DIST, GridLab-D [81]. This software is developed from time to time so it can replicate the distribution network more precisely.

Table 1 shows the comparison of several commonly available distribution network solvers. To implement the optimal voltage control algorithm in the distribution network, co-simulation based modelling of the distribution network can also be a suitable option [82]. With a detailed mathematical model, the optimization process takes time and, in some cases, convergence may not be achieved. They also require commercial solvers to solve the optimization problem. By co-simulation, the detailed mathematical model of the distribution network can be solved by the distribution network solver. This optimization can be achieved in a short time. Quicker and more precise optimization is required to implement real-time optimal control. However, there are some limitations to this method.

Table 1: Comparison of Basic Features of freely available common distribution network solver [81]

Features	OpenDSS	Grid LAB-D	CYMDIST	PowerWorld Simulator
Power flow analysis for systems with unbalanced loads and Slack bus	YES	YES	NO	NO
Open conductor fault analysis	YES	NO	NO	YES
PV voltage regulation support in power flow	YES	YES	NO	YES
Capacitor bank control based on remote node sensing	YES	YES	NO	NO
Distribution system profiles	YES	NO	YES	YES

2.3 Survey of Real-Time validation of voltage control in smart distribution network

Until now, distribution networks have been considered as a passive termination of the transmission network. The distribution system operator (DSO) only focuses on satisfying the normal operating condition (maintaining voltage and frequency) of the distribution network. However, with increasing integration of variable DERs, the distribution network operates in a different paradigm. The distribution network is no longer passive and incorporates many features of the smart grid that are already implemented in the transmission network. Real-time control, advanced management schemes, and reliable ICT systems are some of the smart grid features that have recently been implemented in the distribution network. Due to this modernization in the operation of distribution networks, distribution networks have now also been called smart distribution networks (SDN) [14].

The transition to SDN requires an extensive use of ICT and an innovative control and automation system. Many automated and intelligent management strategies, such as outage and contingencies management, are supposed to be present in the SDN operation. In SDN, it is also assumed that the DSO can control loads, generators, terminal voltages, and power flows from the control station. The operation of SDN involves numerous fast processing software to ensure that the network not only operates within operating limits, but also operates in an optimal way. The operation in the SDN paradigm makes the distribution network more reliable and secure by increasing the certainty of network states, reducing the contingencies, and increasing the quality of service quality.

Figure 4 shows the typical layout of the smart distribution network. In the SDN framework, the distribution network is equipped with numerous intelligent electronic devices (IEDs) to obtain information about the controllable devices in the network. Information can be exchanged between the distribution management system (DMS) and controllable units. On the other hand, the distribution network can be subdivided into many small controllable units with a microgrid energy management system (MEMS) incorporated to activate communication between the DMS and the MEMS.

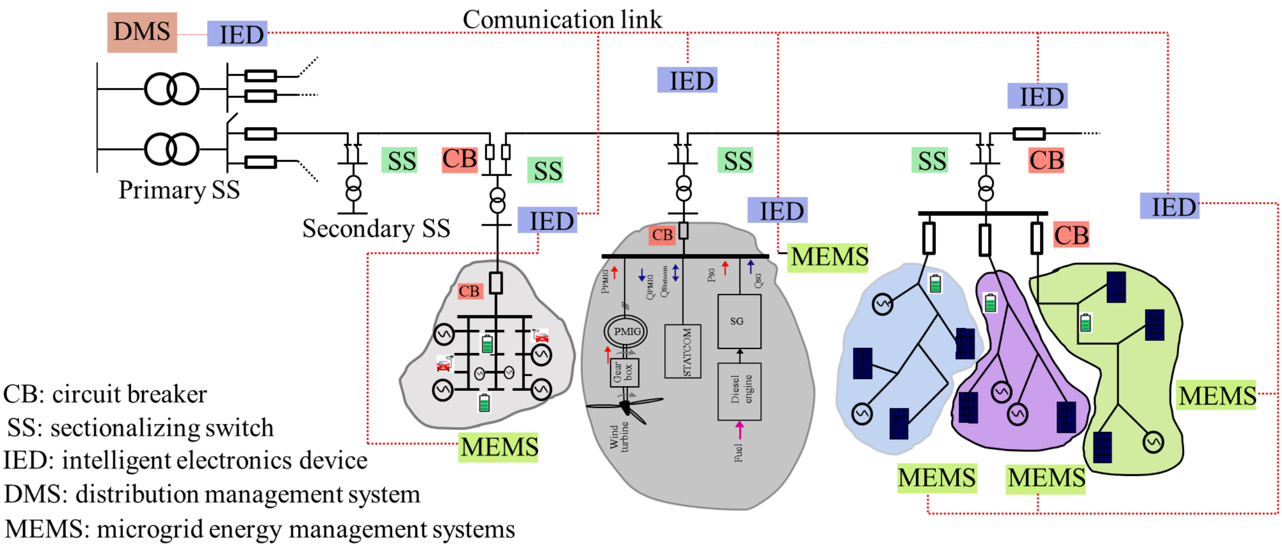


Figure 4: A typical example of a Smart Distribution Network [14].

With the evolving concept of a smart distribution network, real-time control and management strategies are required in future distribution networks. The growing use of smart devices for real-time control and monitoring is accompanied by an increased implementation of the smart grid paradigm in distribution networks. Digitalization and autonomous operation have been extremely changing the operation of several industries due to improvements in innovative information and communication technology (ICT), particularly the revolution in the monitoring and control of power systems [83]. To address the approaching problems in the digitalization of the distribution network, it is critical to develop a comprehensive and implementable platform to test theoretical ideas, computational tools, methodologies, and recent technologies in real-time. Measurements and real-time control applications are expected to become more widespread soon, making voltage control for renewable energy sources an intriguing use for these developments.

Significant advances in cyber-physical systems (CPSs), the Internet of Things (IoT) [84, 85] artificial intelligence (AI) [86], and big data analysis (BDA) [87] are the main driving forces behind this digital transformation. With the advancement of these technologies, it is now possible to continuously gather, manipulate, and interpret real-time data streams in conjunction with high-fidelity models to create a cyber-physical model of complex systems that provides insightful information on their current and anticipated operating conditions [88]. Therefore, through cyber-physical co-simulation (CPCS), a realistic, complete, and adaptable virtual representation of the system is available for real-time monitoring and control. A CPCS allows a system to reflect physical conditions in real-time and offers improved analytics for the system it represents by integrating the physical and cybernetic levels. In all disciplines of academia, research, and business, CPCS is gaining ground [89, 90]. With the help of CPCS, control center operators can respond more quickly to solve operational challenges due to the high integration of RES in real-time. Furthermore, CPCS closes the application gap in control centers [91]. It also provides a novel foundation to increase the flexibility, fidelity, and efficiency of the operation and control of the smart distribution network. The application of CPCS for real-time simulation covers a wide range of applications, as shown in **Figure 5**. The application of CPCS lies within various domains of the power system.

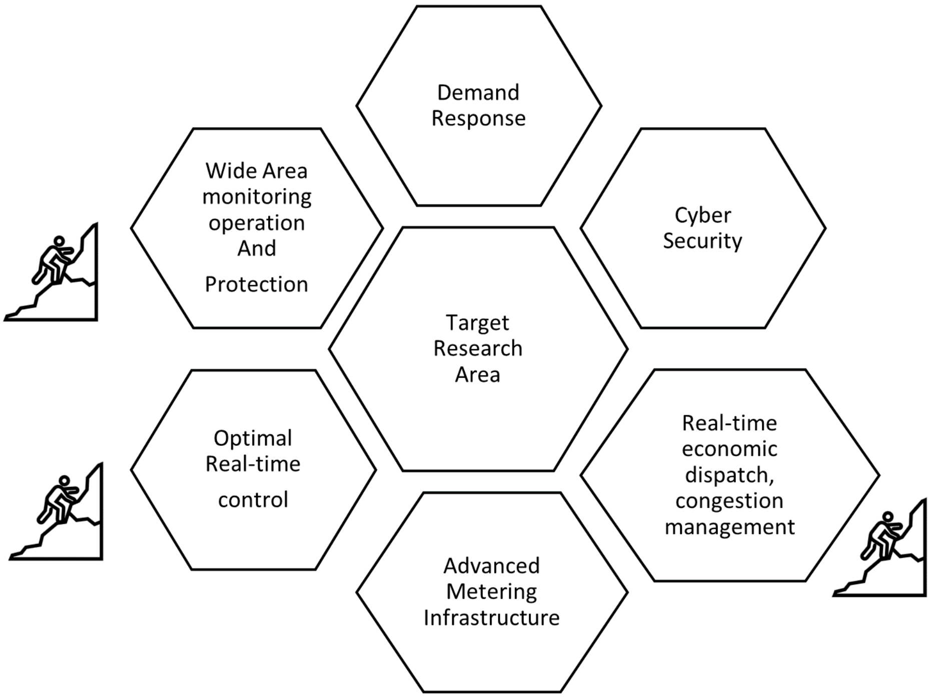


Figure 5: Role of cyber-physical Co-simulation in real-time studies [92]

The simple cyber-physical implementation architecture for the smart paradigm in SDN is shown in **Figure 6**. The purpose of CPCS is to provide effective monitoring, metering, automation, and protection between several layers using a variety of components [93]. CPCS is based on two-way interactions between physical and cybernetic components to boost output, dependability, and efficacy. Through sophisticated communication, a typical CPCS blends a physical system with a cyber system. The physical system must be equipped with an advanced metering infrastructure, such as intelligent electronic devices. To enable secure SDN operation, the physical system should also be equipped with an advanced control and management system capable of rapid communication with the cybernetic layer. For the successful application of CPCS, a realistic operational scenario with high-speed data streams shall be obtained. On the other hand, the cybernetic layer of the CPCS system includes various algorithms and approaches for using the data from measurements to analyze the physical system's states.

Recently, real-time validation of novel ideas and concepts in smart distribution networks is gaining popularity. Based on the purpose of the specific application, real-time validation can be achieved for several aspects of the power system [92]. In [95], a benchmark hardware in-loop test system is performed for dynamic analysis of the distribution network. The paper also highlights the specifications of the framework for information sharing between the TSO and the DSO using a Matlab Simulink model and the OpalRT as the real-time simulator. Similarly, in [96] a holistic test framework using a co-simulation between the open source MOSAIK with functional mockup unit (FMU) is presented to study the multi-dimensional studies in the power system. Likewise, the real-time cyber-physical co-simulation testbed for microgrid control is presented in [97, 98].

Some of the renowned research institutes and heavily funded research projects proposed the framework that is applicable to most of the applications in power systems. While some of the literature focuses on specific purpose application. For example, in [99], real-time validation using a cyber-physical power system is performed to mitigate the potential risk from wide area cyber-attack. A cyber-physical coordinated risk mitigation in a smart grid is studied in [100]. Several other applications of real-time cyber-physical system lie in the modelling of attack mitigation for security vulnerability [101] and cyber-

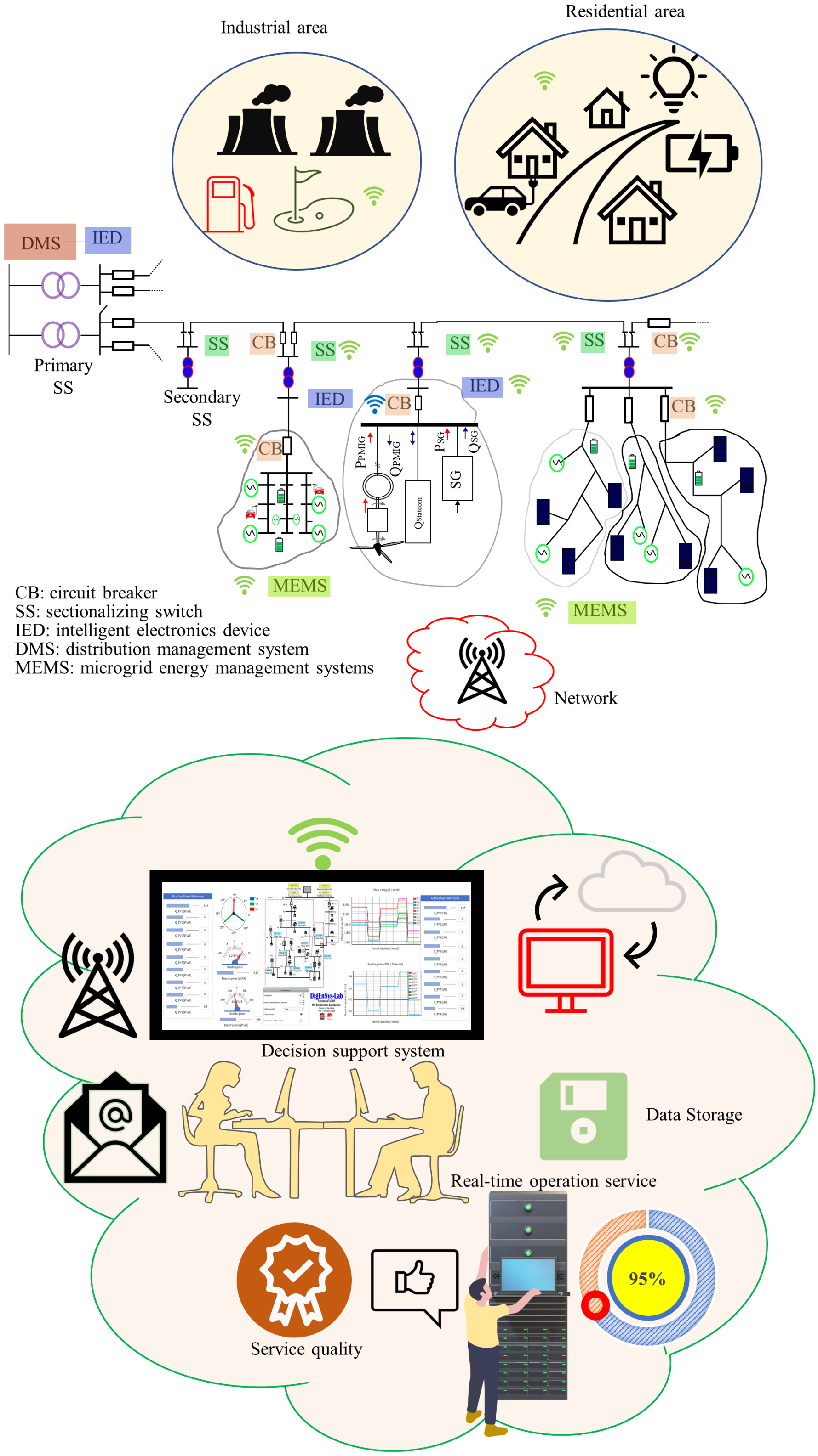


Figure 6: Architecture of Cyber-physical co-simulation framework in SDN [94]

attack detection in distribution network [102]. A significant amount of cyber-physical real-time models focus on cyber-security issues in the distribution network.

Some researchers focus on the other type of real-time application in a smart grid. For instance, in [103], the volt-watt control of the smart inverter in a highly PV penetrated system is studied in real-time. In this study, the control setpoints for smart inverters are obtained offline and the validation was performed on a Typhoon HIL real-time simulator. The real-time experimental verification of several smart grid control functions using a smart converter was carried out in [104]. Optimal cyber defence for frequency deviation mitigation was presented in [105]. A cyber-physical co-simulation testbed for real-time analysis of the frequency response of a distribution network was done in [106].

With the rapid development of real-time validation approaches and methodologies, a framework capable of addressing the upcoming challenges in the smart distribution network is required. The proposed framework should not only test a specific application, but also be able to interact and perform the designed work in an optimal way. The development of the real-time framework also requires real-time coordinated operation among several controllable devices and shall be able to provide flexibility and fidelity to test and validate numbers of smart grid features in the distribution network.

3 Assessment Methodology

After starting the Ph.D., a series of literature studies have been conducted to identify the potential research areas. First, a set of research questions and objectives as defined in the Introduction chapter has been identified. Once the research objectives were identified, detailed modelling of the system under consideration was developed. From the developed model, a simulation analysis was performed to study the impact of high integration of DERs on the voltage profile of the distribution network. Different control algorithms, optimization methods, and network modelling have been done to identify the proper selection and trade-off for optimal voltage control in the distribution network. To further validate the performance of the proposed method, a real-time testing framework has been developed. With the developed real-time testing framework, optimal control algorithms have been tested in the distribution network. First, the real-time Volt-Var control, and then the optimal power flow (OPF)-based control has been tested to resolve the voltage violation problems in real-time. Once the simulation results are obtained, they have been submitted to the related journal and published after peer review. **Figure 7** shows the overall methodology for the implementation of research throughout the Ph.D. project.

In this chapter, a brief presentation of the methodologies applied for the formulation of the main papers supporting the thesis is presented. This has been done to make the reviewers understand the highlights of the methodologies without going through the individual papers attached to this thesis. All the parts of this section are extracted from the papers attached to the thesis. The assumptions considered in the thesis are provided in detail in **Chapter 5**, **Section 5.7**.

3.1 Modelling of Smart Distribution Network for Optimal Voltage Control

In this section, an overview of the various methods of modelling the system for optimal voltage control is described. In **Subsection 3.1.1**, a small isolated microgrid is presented to see how different optimization algorithms will improve the system voltage/reactive power performance to handle unstructured uncertainties. This microgrid analysis is further expanded by considering multiple sources of DERs in a distribution network. The inclusion of these DERs will change the nature of distribution networks, which requires detailed DN modelling. Therefore, **Subsection 3.1.2** describes the modelling methodology of unbalanced three-phase DN. In the third **Subsection 3.1.3**, the distribution network is modelled for optimal control using a co-simulation environment.

3.1.1 Modelling of microgrid for optimal reactive power control

In this subsection, microgrid modelling is presented for optimal reactive power control to minimize voltage violation. First, a microgrid consisting of a wind power plant, a diesel generator, a load, and STATCOM is considered as shown in **Figure 8**. The detailed modelling of the isolated wind-diesel microgrid is considered as proposed in [107]. A permanent magnet induction generator (PMIG) is coupled to the wind turbine due to its ability to provide better voltage regulation compared to the induction generator [107]. Similarly, the diesel engine is coupled to the synchronous generator to form a diesel generator set. PMIG supplies active power but consumes reactive power from the grid. The diesel generator can supply both active and reactive power to the grid. Depending on the fluctuation of the reactive power in the microgrid, the STATCOM absorbs or supplies the reactive power to the grid.

Second, the balance of reactive power between all electrical devices in the microgrid is considered. The reactive power balance in the case of the microgrid considered is given by **Equation 4**.

$$Q_{SG} + Q_{STATCOM} = Q_{PMIG} + Q_L \tag{4}$$

Where, Q_{SG}, $Q_{STATCOM}$, Q_{PMIG}, Q_L are the reactive power of diesel generator, STATCOM, PMIG, and load respectively.

Third, linearized models are convenient for designing the controller and analyzing the system performance for small signal deviation, the microgrid considered in **Figure 8** is modelled according to the small signal modelling of the system. **Figure 9** shows the linearized model of the considered microgrid.

From the linearized model, the deviation in system voltage (ΔV) can be obtained as **Equation 5**.

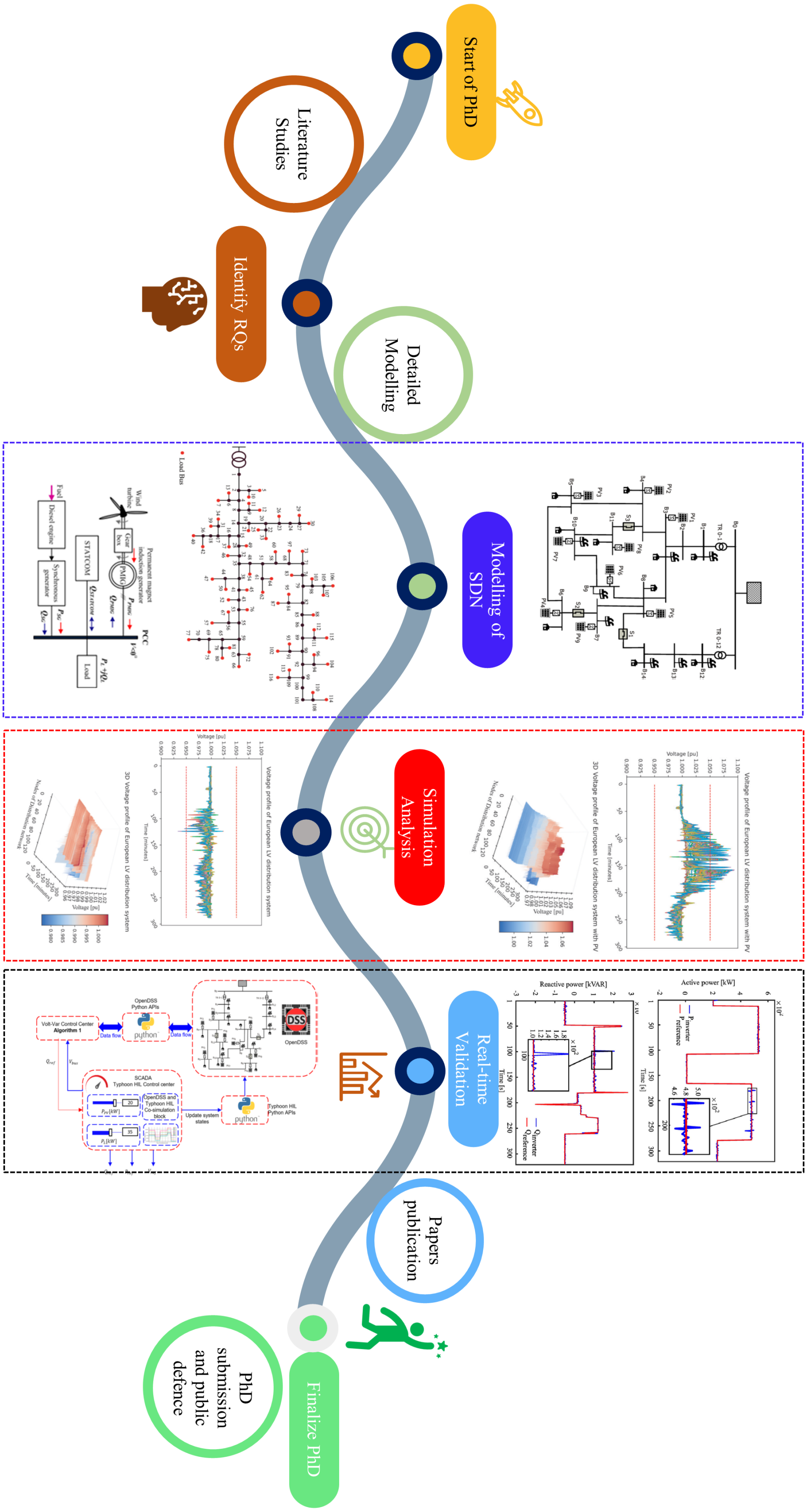


Figure 7: Overall methodology for implementing the research

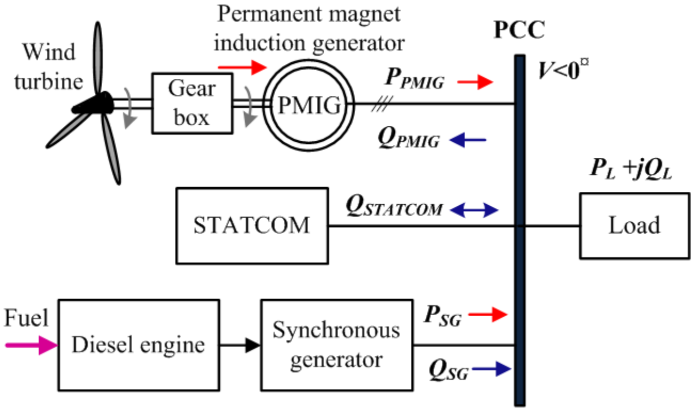


Figure 8: Schematic of isolated wind-diesel microgrid (**Paper A** Figure 1)

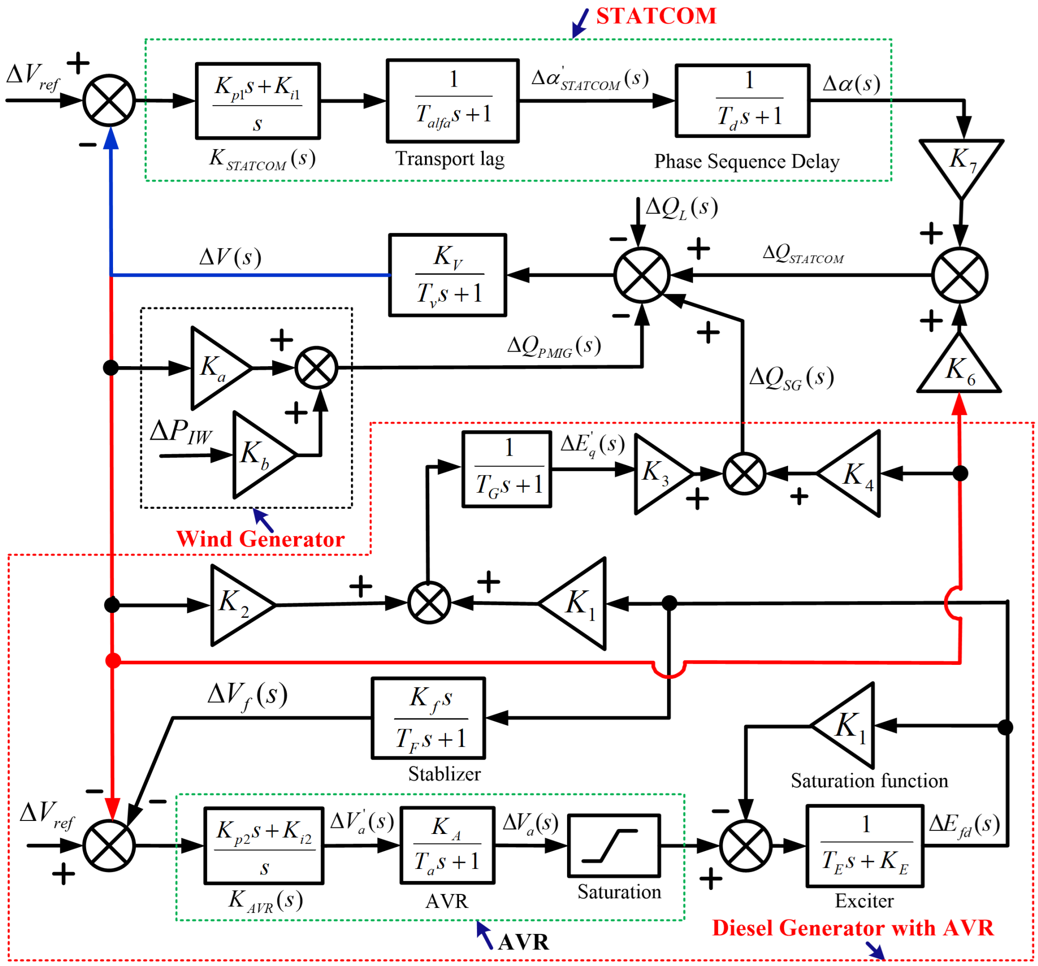


Figure 9: Linearized model of wind-diesel microgrid (**Paper A** Figure 2)

$$\Delta V(s) = \frac{K_V}{1 - sT_v}[V\Delta Q_{SG}(s) + \Delta Q_{STATCOM}(s) - \Delta Q_{PMIG}(s) - \Delta Q_L(s)] \quad (5)$$

Where T_V is the time constant, K_V is the system gain, ΔQ_{SG} is the variation in output reactive power of the diesel generator, $\Delta Q_{STATCOM}$ is the variation in reactive power of STATCOM, ΔQ_L is the change in reactive power of load, ΔQ_{PMIG} is the change in reactive power of PMIG, and ΔV is the change in terminal voltage at the point of common coupling. More detailed mathematical modelling of each of the components can be found in **Paper A** and [107].

Fourth, H_∞ Loop shaping controller is designed to define the objective function to obtain the optimal parameters of K_p and K_I for automatic voltage regulator (AVR) and STATCOM.

Lastly, four different optimization algorithms, namely, the bacterial foraging optimization algorithm (BFOA), particle swarm optimization (PSO), the modified grey wolf optimisation (MGWO), and the hybrid BFOA-PSO, are used to obtain the optimal setpoints of the controller parameters.

3.1.2 Modelling of the distribution network for OPF-based control

In this subsection, modelling of the distribution network for the optimal power flow (OPF) based method is presented to obtain the optimal setpoints from smart converters. First, the distribution network is modelled on OpenDSS. Several components, such as lines, loads, and generators, are placed in the model in OpenDSS. A Python API (Application Programming Interface) of OpenDSS is used to run the model in OpenDSS. Many user-defined functions to extract information from the model's power flow solution are also programmed in Python. Second, from information such as node voltage, power injections, conductance, and susceptance, three-phase modelling of the distribution network using current mismatch is developed. The detailed mathematical formulation of the optimization model can be found in **Paper B**. Third, from the optimization model, the optimal setpoints for smart converters are obtained by solving the optimization problem in PYOMO using the KNITRO solver. **Figure 10** shows the overall methodology for modelling distribution network for OPF-based control.

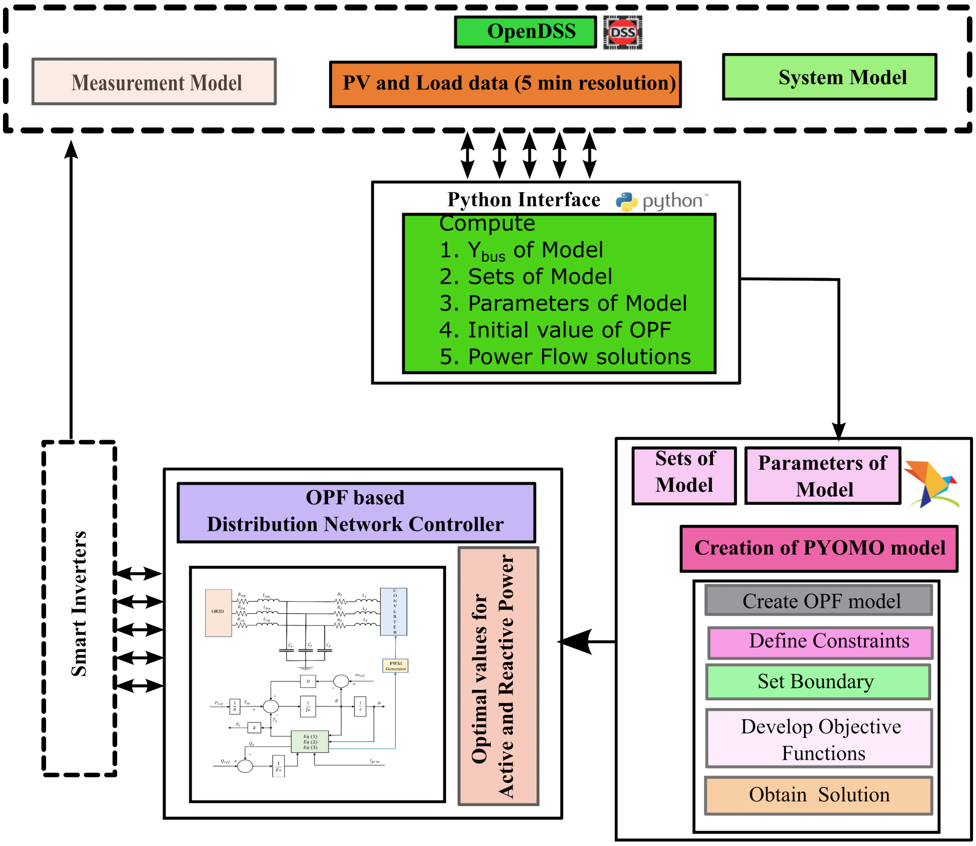


Figure 10: Overall methodology for modelling distribution network for OPF based active and reactive power control in distribution network (**Paper B** Figure 2)

3.1.3 Modelling of the distribution network for Co-simulation based optimization

In this subsection, a methodology for implementing co-simulation based optimization in an SDN is described. **Figure 11** shows the overall block diagram for implementing the cosimulation-based optimization. First, the distribution network is modelled on software specialized for solving distribution power flow. In this case, only OpenDSS and Dig SILENT Power Factory are considered. The load data and the PV generation data are defined in the distribution network in the model. The power flow solutions are solved in the software and the required information for optimization is obtained through co-simulation. By doing this, detailed mathematical modelling in the optimization model can be avoided and more complex power system problems can be solved easily. The data exchange is realized by the Python-based library of the software, to carry out the simulation in engine-mode, defining a co-simulation based optimization in a Python environment. The second step is to define the optimization function. The optimization model includes objective functions, constraints, and a suitable solver to solve the problem. In particular, the optimization problem considered in co-simulation based optimization is non-explicit objective functions which are taken as one of the measured parameters from the co-simulation. For instance, power loss in the network, and voltage deviation are some examples of nonexplicit objective functions. The optimization model is defined in PYGMO. The third step is to analyze the solutions for further analysis. Further analysis can be found in **Paper F**.

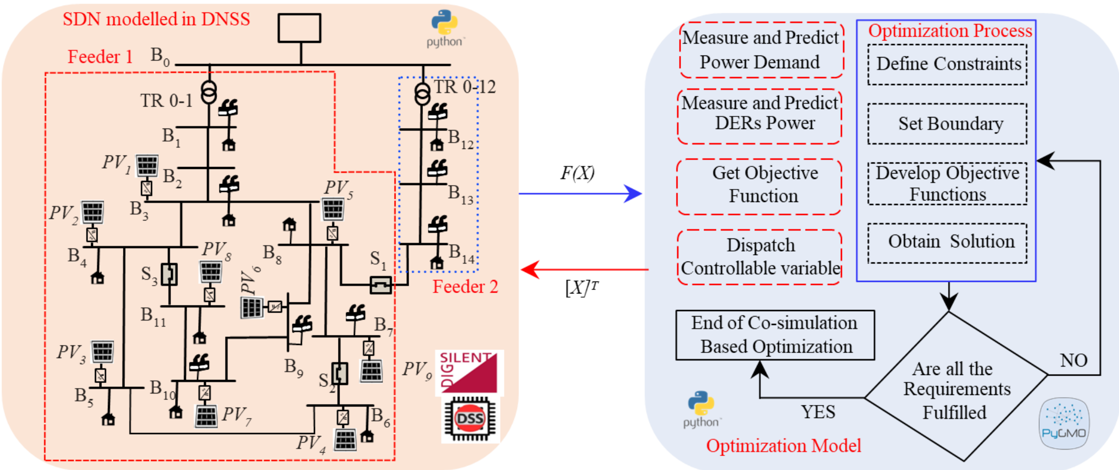


Figure 11: Overall methodology for Co-simulation based optimization in distribution network (**Paper F** Figure 3)

3.2 Real-Time validation of voltage control in smart distribution network

In general, to realize the application in real-time, several essential components are required to monitor and regulate smart distribution networks. In most cases, real-time validation testbeds are made up of two layers: (A) the cybernetic layer and (B) the physical layer. The cybernetic layer includes several components and software for sensing, communicating, and developing the model. The cybernetic layer also includes a set of programmed applications for specific purposes applications. For example, real-time awareness, decision-making algorithms, model validation algorithms, control systems, and SCADA are some of the commonly programmed applications in the cybernetic layer. On the other hand, the physical layer consists of several real or virtual components that are necessary for modelling the test system.

The cybernetic layer and the physical layers are connected either by an ethernet cable or through the equipment following the standard communication protocol. For example, depending on the availability of the measurement devices and the purpose of the application, communication between the physical layer and the cybernetic layer may take place using PMUs, MMS servers, or GOOSE. **Figure 12** shows the general framework for modelling real-time cyber-physical co-simulation testbed. The black and blue blocks represent the cybernetic layer. The red block represents the physical layer. **Paper E** presents a detailed description of the development of a cyber-physical co-simulation framework for reactive power control.

Based on the framework proposed in **Paper C**, two different types of optimal real-time reactive power control in the distribution network are presented. **Paper D**, and **Paper E** were obtained using

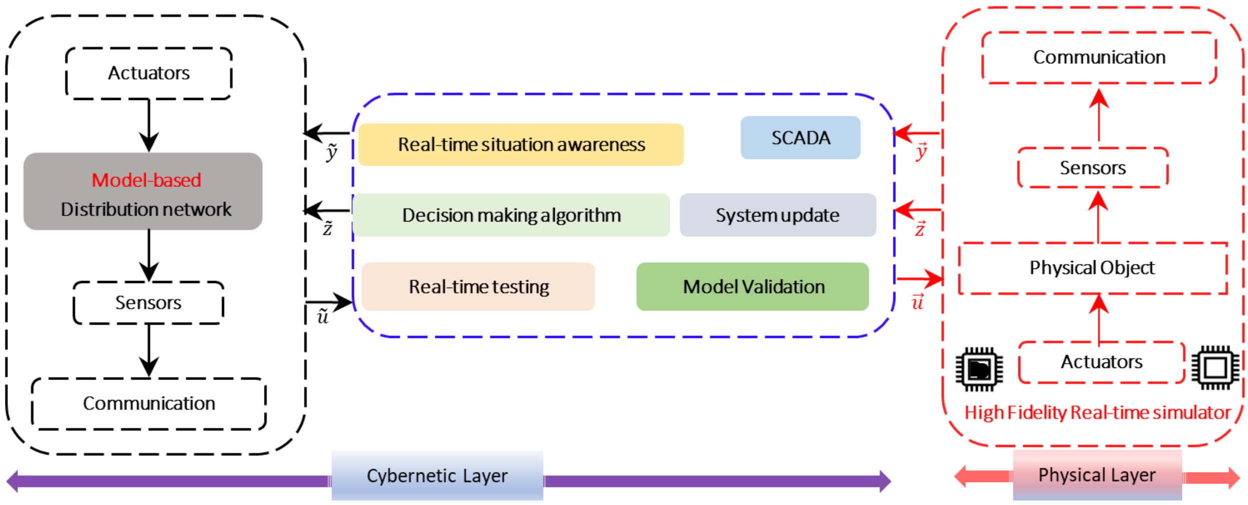


Figure 12: General framework for modelling real-time cyber-physical co-simulation testbed

the framework proposed in **Paper C** with small modification. In both cases, the overall framework for implementing the proposed optimal controller is as shown in **Figure 13**. The cybernetic layer consists of a model-based distribution network, SCADA system, reactive power control center, co-simulation based optimization block. The cybernetic layer also includes graphical interfaces for visualization of the monitored parameters and for creating disturbances in real-time. On the other hand, the physical layer consists of smart converters and the controller designed using the high-fidelity virtual components of the real-time simulator. However, the reactive power control center and co-simulation based optimization block differ in both papers. Detailed implementation of real-time validation can be found in **Paper C** and **Paper D**.

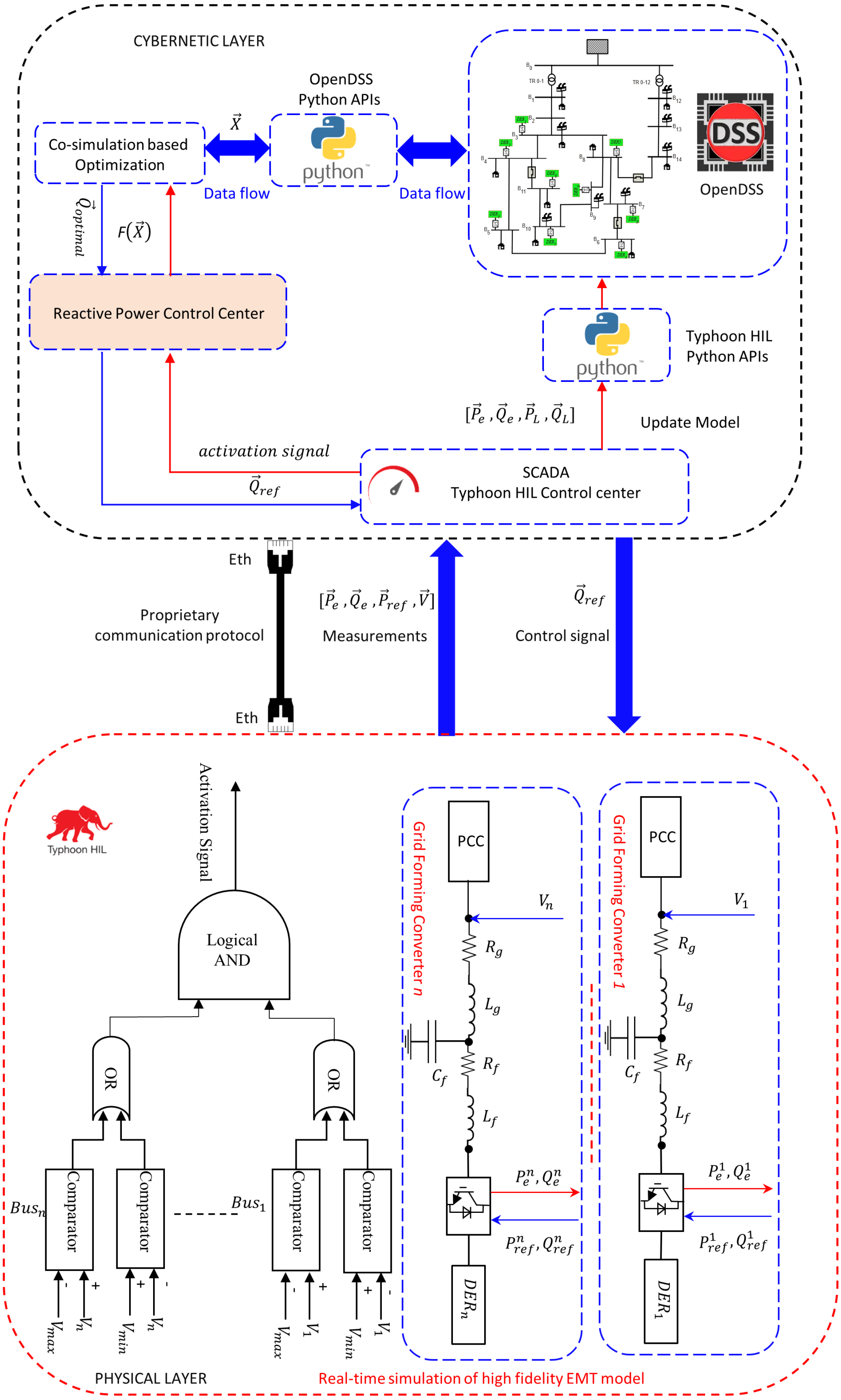


Figure 13: Overall block diagram for optimal power flow based reactive power control in real-time cyber-physical co-simulation framework (**Paper D** Figure 1)

4 Results and Contributions

This chapter highlights the key outcomes of this research in relevance to the research questions identified in this research work. In the first section, the list of main papers supporting the thesis is presented in **Table 2**. Other relevant publications where the candidate was involved are presented in **Table 3**. In **Section 4.3**, an overview of the research results in relation to the research questions and objectives is described. Finally in **Section 4.4** overall contribution of the research work and its relevance to the advancement of the respective scientific field are presented.

4.1 List of Main Papers

A list of the main papers supporting this thesis is presented in **Table 2**. The individual articles are also attached in the Appendix.

Table 2: List of the main papers supporting the thesis

PaperA	**R. Wagle**, P. Sharma, C. Sharma, T. Gjengedal, and C. Pradhan, "Bio-inspired hybrid BFOA-PSO algorithm-based reactive power controller in a standalone wind-diesel power system," Int. Trans. Electr. Energy Syst., vol. 31, no. 3, p. e12778, Mar. 2021 https://doi.org/10.1002/2050-7038.12778	[108]
PaperB	**R. Wagle**, P. Sharma, C. Sharma, and M. Amin, "Optimal Power Flow based Coordinated Reactive and Active Power Control to mitigate voltage violations in Smart Inverter Enriched Distribution Network," Int. J. Green Energy, pp. 1–17, 2023, https://doi.org/10.1080/15435075.2023.2196324 .	[109]
PaperC	**R. Wagle**, P. Sharma, C. Sharma, M. Amin, and F. Gonzalez-Longatt, "Real-Time Volt-Var Control of Grid Forming Converters in DER-enriched Distribution Network," Front. Energy Res., no. January, pp. 1–18, 2023, https://doi.org/10.3389/fenrg.2022.1054870 .	[110]
PaperD	**R. Wagle**, P. Sharma, C. Sharma, M. Amin, J. L. Rueda, and F. Gonzalez-Longatt, "Optimal power flow-based reactive power control in smart distribution network using real-time cyber-physical co-simulation framework," IET Gener. Transm. Distrib., Feb. 2023, https://doi.org/10.1049/gtd2.12786.	[111]
PaperE	**R. Wagle**, G. Tricarico, P. Sharma, C. Sharma, J. L. Rueda, and F. Gonzalez-Longatt, "Cyber-Physical Co-Simulation Testbed for Real-Time Reactive Power Control in Smart Distribution Network," in 2022 IEEE Innovative Smart Grid Technologies - Asia (ISGT ASIA), 2022, https://doi.org/10.1109/ISGTAsia54193.2022.10003553. (Nominated for the best paper award)	[112]
PaperF	**R. Wagle**, H. P. Le Nam, G. Tricarico, P. Sharma, J. L. Rueda, and F. Gonzalez-Longatt, "Co-Simulation based Optimal Reactive Power Control in Smart Distribution Network," Electrical Engineering, Springer Nature.	[113]

4.2 List of other relevant publications

Table 3 shows a list of publications relevant to the research area of the thesis. Some of the publications in this list are part of collaborative work done by the Ph.D. candidate with another researcher. A full list of publications can also be found at https://uit.no/ansatte/person?p_document_id=640537

4.3 An overview of the research results in relation to the research questions and research objectives

To make an overview of the research results clearer, some of the important results related to the research questions and research objectives are presented in the following subsections. All simulation results presented here are taken from the papers. The full papers are attached as part of the thesis.

Table 3: List of other relevant papers not included in the thesis

Paper1	**R. Wagle**, P. Sharma, C. Sharma, and C. Pradhan, "Perturbation and Observer Based Sliding-Mode Controller for Excitation control in Single-Machine Infinite Bus System," 2021 22nd IEEE International Conference on Industrial Technology (ICIT), Valencia, Spain, 2021, pp. 87-92, doi:10.1109/ICIT46573.2021.9453522.	[114]
Paper2	**R. Wagle**, P. Sharma, M. Amin, and F. Gonzalez-Longatt, "Cyber-Physical Co-simulation Framework between Typhon HIL and OpenDSS for Real-Time Applications," in Real-Time Simulation & Hardware-in-the-Loop Testing using Typhoon HIL, 2022.	[115]
Paper3	**R. Wagle**, P. Sharma, C. Sharma, and M. Amin, "Real-time price based optimal energy mix in smart distribution network," in Recent Developments in Electrical and Electronics Engineering, Lecture Notes in Electrical Engineering 979, https://doi.org/10.1007/978-981-19-7993-4_18.	[116]
Paper4	H. P. Le Nam, **R. Wagle**, F. Gonzalez-Longatt, and M N A Montalvo "Non-directional Overcurrent Protection Relay Testing Using Virtual Hardware-in-the-Loop Device," in Real-Time Simulation & Hardware-in-the-Loop Testing using Typhoon HIL, 2022.	[117]
Paper5	G. Tricarico, **R. Wagle**, M. Dicorato, G. Forte, F. Gonzalez-Longatt and J. L. Rueda, "Zonal Day-Ahead Energy Market: A Modified Version of the IEEE 39-bus Test System," 2022 IEEE PES Innovative Smart Grid Technologies - Asia (ISGT Asia), Singapore, Singapore, 2022, pp. 86-90, doi: 10.1109/ISGTAsia54193.2022.10003588.	[118]
Paper6	L. S. Azuara-Grande, F. Gonzalez-Longatt, G. Tricarico, **R. Wagle**, S. Arnaltes and R. Granizo, "Real-Time Implementation of Two Grid-Forming Power Converter Controls to Emulate Synchronous Generators," 2022 IEEE Biennial Congress of Argentina (ARGENCON), San Juan, Argentina, 2022, pp. 1-6, doi: 10.1109/ARGENCON55245.2022.9940076.	[119]
Paper7	G. Tricarico, L. S. Azuara-Grande, **R. Wagle**, M. Dicorato, G. Forte, F. Gonzalez-Longatt and J. L. Rueda, "Security Constrained Unit Commitment and Economic Dispatch applied to the Modified IEEE 39-bus system Case," IECON 2022 – 48th Annual Conference of the IEEE Industrial Electronics Society, Brussels, Belgium, 2022, pp. 1-5, doi: 10.1109/IECON49645.2022.9968474.	[120]
Paper8	**R. Wagle**, H. P. Le Nam, G. Tricarico, P. Sharma, J. L. Rueda, and F. Gonzalez-longatt, "Experiences in a Cyber-Physical Co-Simulation Testbed Development for a Smart-er Distribution Network," in 2023 IEEE Innovative Smart Grid Technologies - Middle East (ISGT ME), 2023.	[121]
Paper9	G. Tricarico, **R. Wagle**, J C Martinez, F. Gonzalez-Longatt M. Dicorato, G. Forte, and J. L. Rueda "A Co-simulation based Optimisation Solution for Smart Converter Reactive Power Control in Active Distribution Grids" 7th I&CPS Industrial and Commercial Power Systems Europe, (Awarded Best Ph.D Poster Award)	[122]
Paper10	H. P. Le Nam, **R. Wagle**, and F. Gonzalez-longatt, "Concise Definition of the Overcurrent Protection System for CIGRE European Medium Voltage Benchmark Network," in 2023 IEEE Innovative Smart Grid Technologies - Middle East (ISGT ME), 2023.	[123]

4.3.1 Research results to study the impact of large integration of variable distributed energy supplies in terms of the overall voltage profile and voltage violations

To show how the modern distribution network responds to the large penetration of variable DERs, an isolated wind-diesel system as shown in **Figure 8** has been considered. As the nature of load-reactive power and wind power depends on consumer behaviour and nature, power consumption and generation are random in nature. To consider this uncertainty, the random disturbance as shown in **Figure 14** has been considered. The controllers are optimized with four different optimization algorithms, namely the hBFOA-PSO, PSO, BFOA, and MGWO algorithms. Once the optimal parameters of the controller were obtained, the test system was simulated to analyze the effect of these uncertainties in the system. The transient response of the different parameters (ΔV, ΔQ_{PMIG}, ΔQ_{SG}, ΔQ_{AVR} and $\Delta Q_{STATCOM}$) was obtained. **Figure 15** shows the dynamic response of the system with the controller optimized by the hBFOA-PSO, MGWO, BFOA, and PSO algorithms. Also, to compare the suitability of the optimization algorithm in finding the optimal solution, an analysis showing the convergence curve has been presented. **Figure 16** shows the convergence curve for obtaining the optimal solutions using different optimization algorithms. Detailed modelling of the system, optimization approaches, and further analysis have been presented in **Paper A**. From the analysis, it has been found that the approach of using a hybrid optimization algorithm plays an effective role in tuning the controllers to enhance the dynamic performance of the power system voltage/reactive power profile. Therefore, this study is an effort to enable the wind-diesel based power system to solve recent environmental and energy crisis issues and offer higher service reliability, increased energy efficiency, and energy independence.

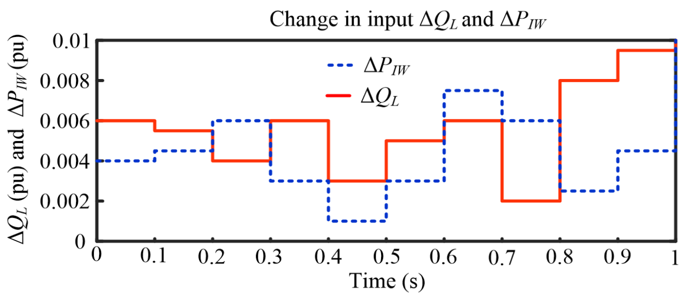


Figure 14: Random changes in ΔQ_L and ΔP_{wind} (**Paper A**, Figure 12)

The impact of DERs on isolated systems and grid-connected systems is of different natures, as the operation in both has its own operational condition and requirements. Therefore, to follow the state-of-the-art in the research, detailed analysis in the case of grid-connected distribution has to be considered.

Two popular distribution networks, the European low voltage (LV) distribution network, and a CIGRE medium voltage (MV) distribution network, have been considered to analyze the impact of high integration of DERs on the distribution network. Several methods and approaches as supported by the state of the arts have been utilized to model the distribution network, perform the analysis, and implement optimal control. A detailed description can also be found in **Paper B**.

Figure 17 depicts the voltage profile on a European LV network without and with PV integration. Without integrating PVs, the voltage profile for the load profile under consideration is approximately within permitted limits. However, voltage violations have been observed in the network with the integration of 100% PVs. To clearly illustrate the voltage profile, a 3D plot of the voltage is also displayed. To show the impact of higher integration, the sizes of the PVs have been modified while doing research.

4.3.2 Research results to coordinate between active power curtailment and reactive power support from a smart converter to alleviate voltage violations in the DER-enriched smart distribution network and to recognize potential trade-offs to choose the right control strategies

As discussed in the literature chapter, active and reactive power control from smart converters can be utilized to mitigate voltage violations in the DER-rich distribution network. However, achieving effective synergy between these two alternatives requires a thorough investigation. Furthermore, the challenge lies in finding the right balance to select the most appropriate control strategies that produce optimal solutions

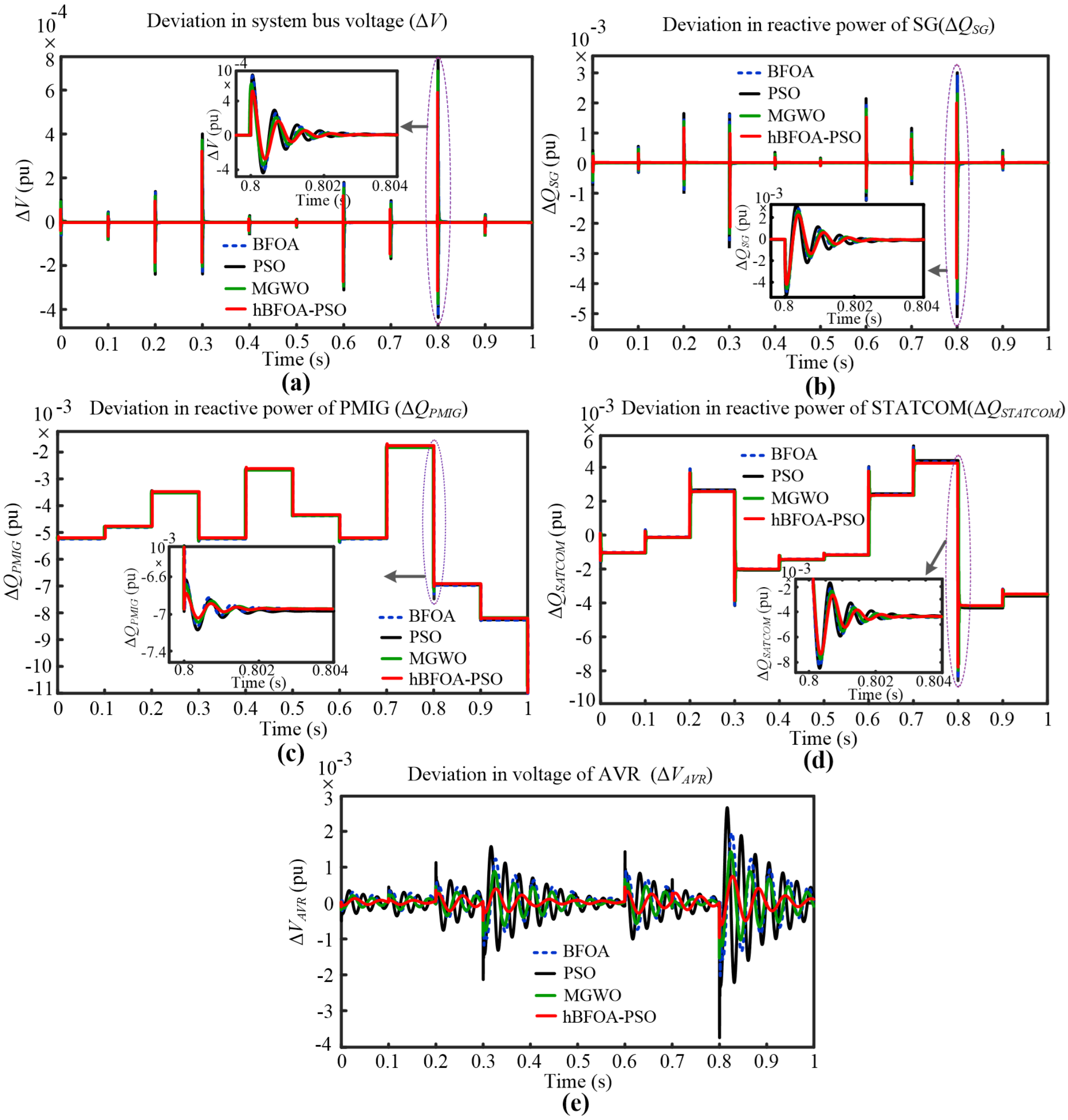


Figure 15: Dynamic response for random changes in ΔQ_L and ΔP_{wind} (**Paper A**, Figure 13)

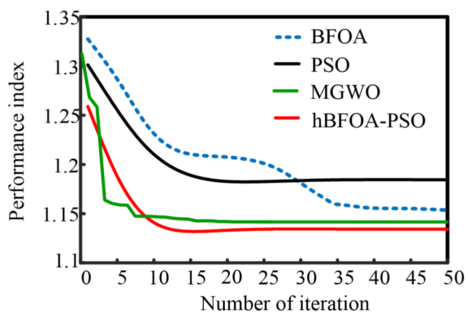
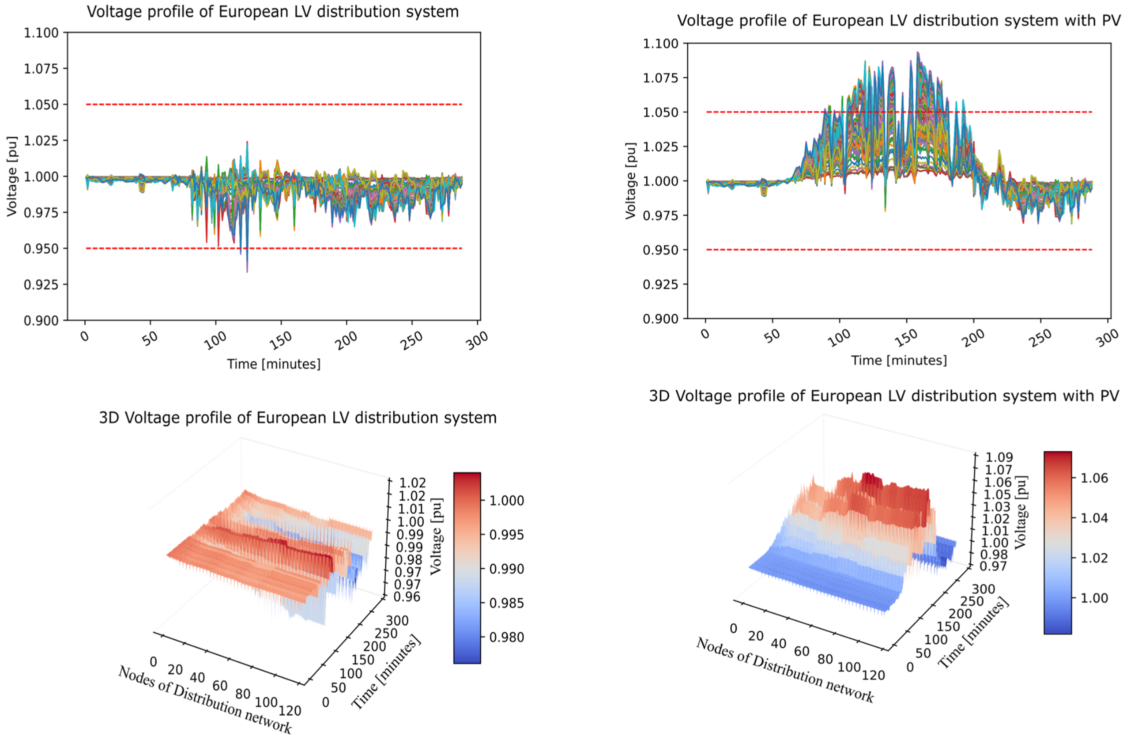


Figure 16: Convergence curve for BFOA, PSO, MGWO and hBFOA-PSO algorithms (**Paper A**, Figure 8)



(a) (b)

Figure 17: Voltage profile of European Low Voltage distribution network (a) without PV (b) with PV (**Paper B**, Figure 7)

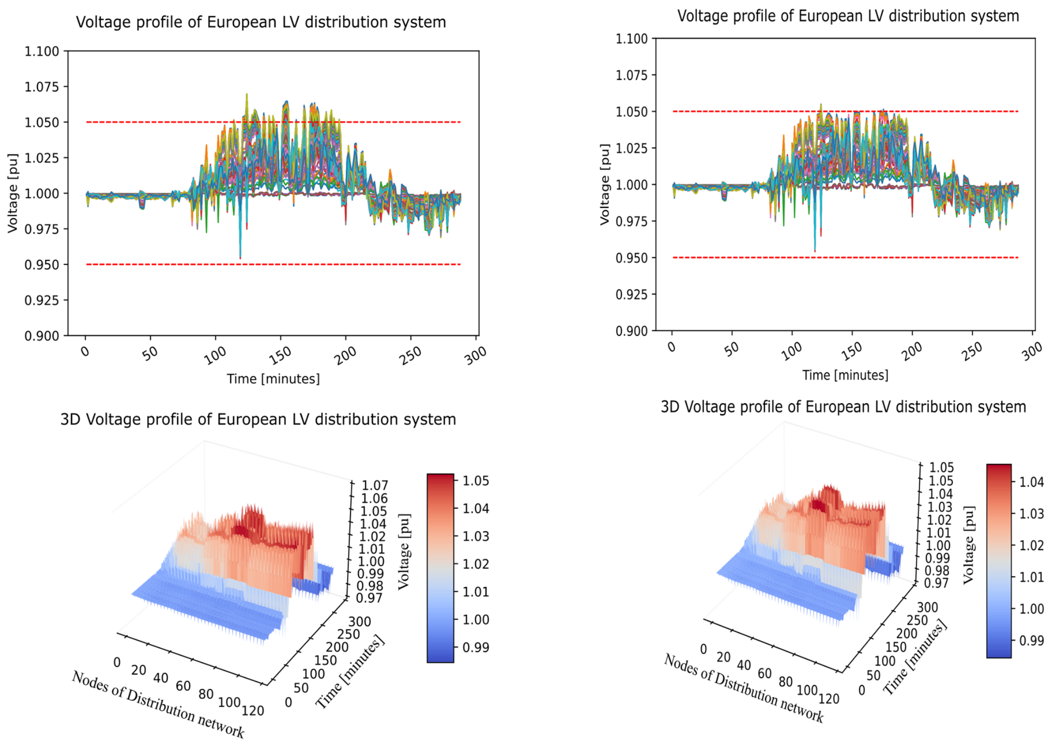
in distribution networks. Several factors come into play, such as the availability of adequate infrastructure for network monitoring, the computational efficiency of the optimization model, and its suitability for real-time validation. Throughout the Ph.D. project, the quest for exploring the most suitable approach is progressing. The following subsection provides information on the analysis conducted during this research effort to address the research gap effectively.

Numerous simulation studies have been undertaken on the European LV and CIGRE medium voltage distribution networks. A detailed account of the assumptions and considerations pertaining to loads and DERs can be found in Paper B. Within this section, only the results that align with the research questions and objectives are presented.

The research has explored four distinct approaches to voltage control through smart converters. These approaches incorporate an Optimal Power Flow (OPF)-based strategy for active and reactive power control, a combined Volt-Var and Volt-Watt control approach, Volt-Var control alone, and Volt-Watt control alone. The objective is to analyze how these various control schemes influence the voltage profile. Furthermore, the research quantifies the amount of active curtailment and reactive power contributions from DERs to facilitate a comprehensive analysis.

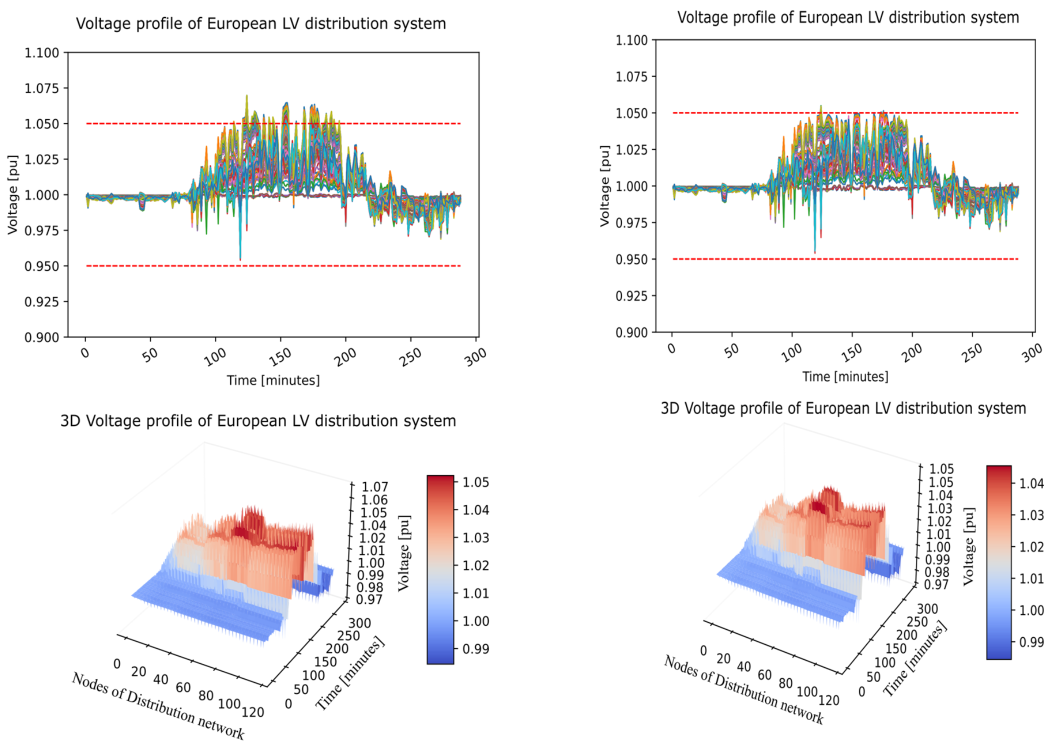
Figure 18 illustrates the voltage profile of the European LV network following the application of Volt-Var control and Volt-Watt control. On analysis, it becomes evident that the Volt-Watt control effectively maintains the voltage profile within the acceptable range. On the contrary, Volt-Var control falls short of fully regulating voltage, primarily because of the constraints associated with smart inverters' capacity to provide reactive power support. However, Volt-Watt control successfully addresses voltage issues by curtailing active power generation, a measure that might not align with the preferences of DER owners. Consequently, a comprehensive study is necessary to coordinate both active power curtailment and reactive power control, especially from an economic perspective.

Figure 19 presents the voltage profile of the distribution network when implementing a combined Volt-Var and Volt-Watt approach based on voltage sensitivity, along with an OPF-based method. This



(a) (b)

Figure 18: Voltage profile of European Low Voltage network (a) with Volt-Var Control (b) with Volt-Watt Control (**Paper B**, Figure 8)



(a) (b)

Figure 19: Voltage profile of European Low Voltage network (a) with combined Volt-Var and Volt-Watt Control (b) with OPF-based control (**Paper B**, Figure 9)

combination effectively regulates the voltage profile in the distribution network to mitigate voltage violations. However, conducting an in-depth analysis to quantify the extent of active power curtailment and reactive power support remains essential.

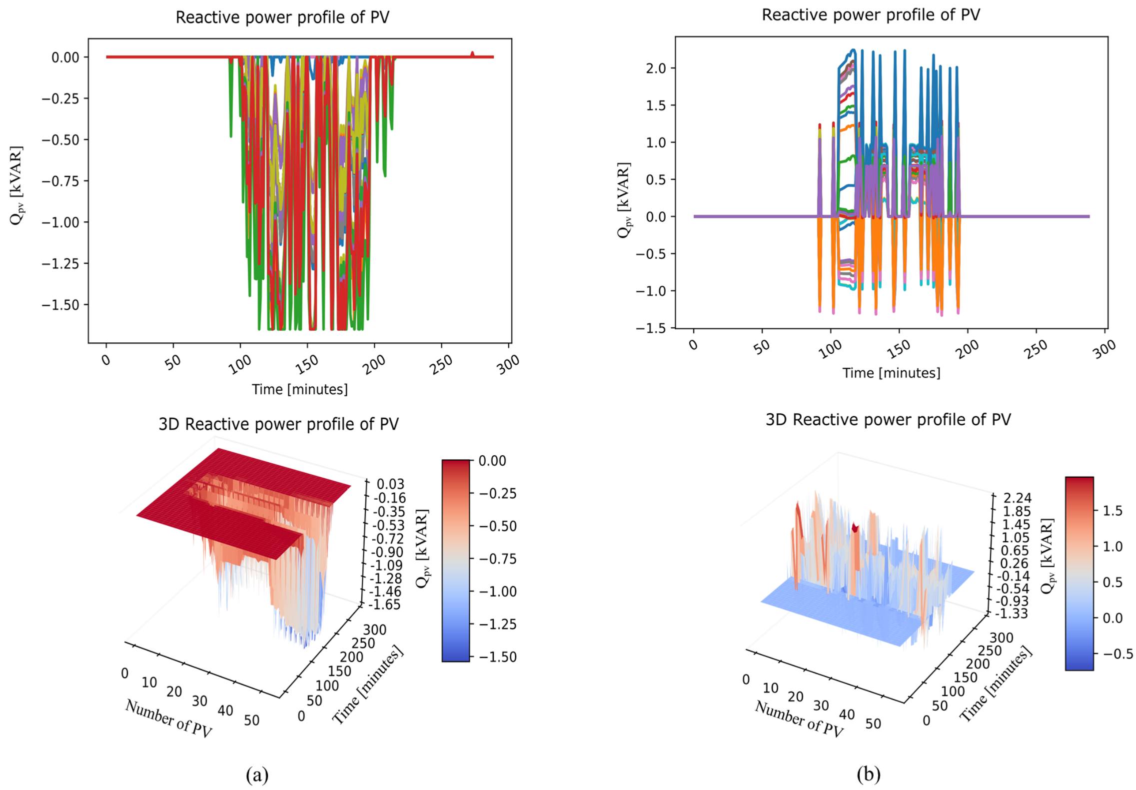


Figure 20: Reactive power profile of PVs on European Low Voltage network (a) with Volt-Var control in PVs (b) OPF-based control in PVs (**Paper B**, Figure 12)

Figure 20 shows the reactive power profile of the PVs installed on the European LV network for Volt-Var control and OPF-based approach. In OPF-based method, the smart converter either absorb or supply the reactive power to minimize the total loss in the network. On contrast, in Volt-Var method reactive power is supplied which might increase the total power loss in the network.

Similarly, **Figure 21** shows the active power profile of the PV after the implementation of Volt-Watt method and OPF-based approach. Since OPF-based approach coordinates the active power curtailment and reactive power support in a coordinated manner, not only in one converter but also among all the converters in the network, the active power curtailment is less in OPF-based method compared to Volt-Watt control only.

In addition, to make a detailed quantitative analysis, a **Table 4** is presented that compares the performance of different voltage control approaches. The performance of individual control approaches for different parameters can provide an in-depth quantitative analysis to trade-off the suitable control approaches that can be implemented in the smart distribution network.

Table 4: Comparision of performance of different voltage control approaches (**PaperB**, Table3)

Comparison index	VVC	VWC	combined VVC and VWC	OPF
Voltage performance index (VPI)	0.17	0.0637	0.0055	0.0285
Total network loss [kW]	1.73	1.89	1.77	1.49
Total PV power [kW]	57.24	57.24	57.24	57.24
Total Active power curtailment [kW]	0.00	44.03	1.73	5.87
Total Reactive power contribution [kVAR]	8.68	0.00	13.76	8.93

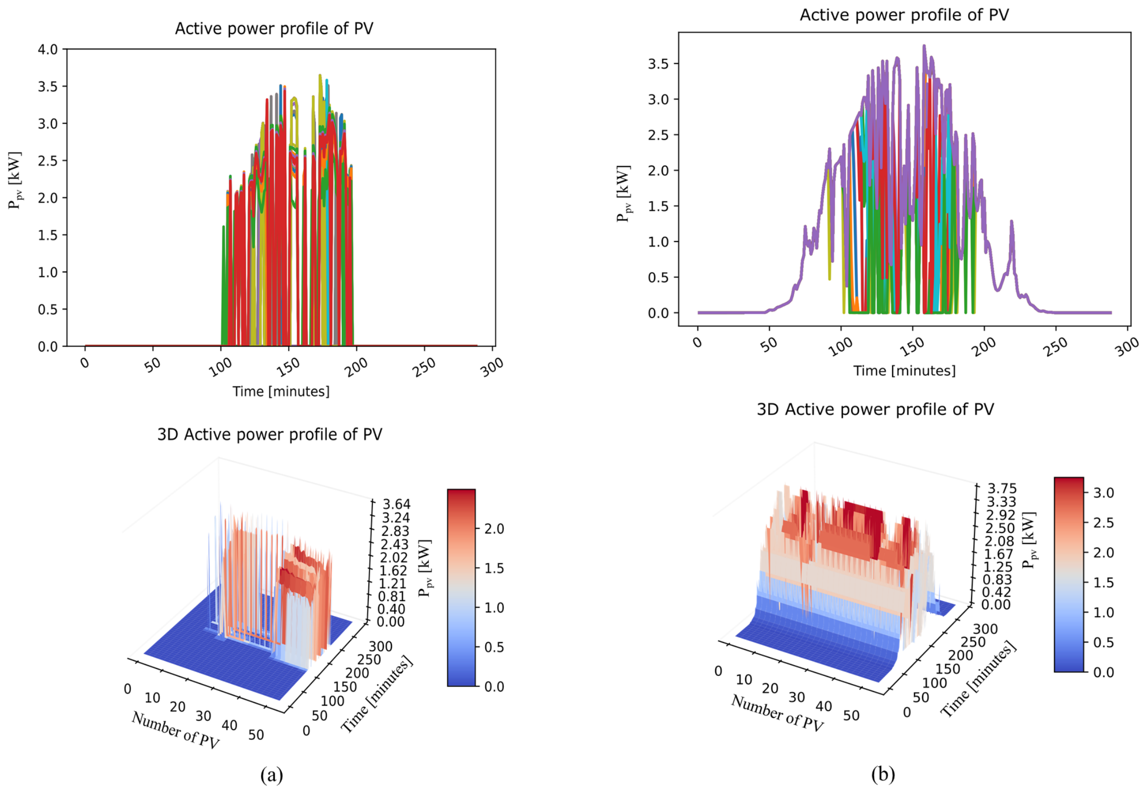


Figure 21: Active power profile of PVs on European Low Voltage network (a) with Volt-Watt control in PVs (b) with OPF-base control in PVs (**Paper B**, Figure 10(a) and Figure 11(a))

Paper F, explored the suitability of co-simulation based optimization approach for optimal voltage control in a distribution network. In this work, a detailed study was performed using different optimization algorithms on models created on different distribution network solvers. The algorithm that was found to give the optimal solution in lower time was consider for real-time optimzation in **Paper D**. This paper also compares the time required to complete the optimization process with the method proposed in **Paper B**. **Table 5** shows the comparison of time required to complete the optimization process with the co-simulation based optimization and detailed modelling based optimization.

Table 5: Comparision of time required for optimization (**Paper F**, Table3)

Optimization method	time [*second*]
Proposed method in **Paper B**	199.87
Proposed method in **Paper F**	117.85

4.3.3 Research results on the development of a framework for real-time validation of different voltage control architecture in the DER-enriched smart distribution network

Establishing a real-time testing and validation framework for a smart distribution network plays a pivotal role in this research. However, creating a comprehensive framework that encompasses all features of the smart grid within a distribution network remains a formidable challenge. Additionally, the time constraints inherent to a PhD project further compound this challenge. Nevertheless, this research has successfully created a framework for testing and deploying real-time optimal reactive power control in smart distribution networks. In this research a cyber-physical co-simulation testbed for real-time reactive power control in the smart distribution network is developed and tested. The framework was developed by integrating Typhoon HIL, OpenDSS, and a user-defined SCADA (Supervisory Control and Data Acquisition) system. The subsection offers a closer look at the framework designed for real-time validation of two different voltage control architectures for DER-rich smart distribution.

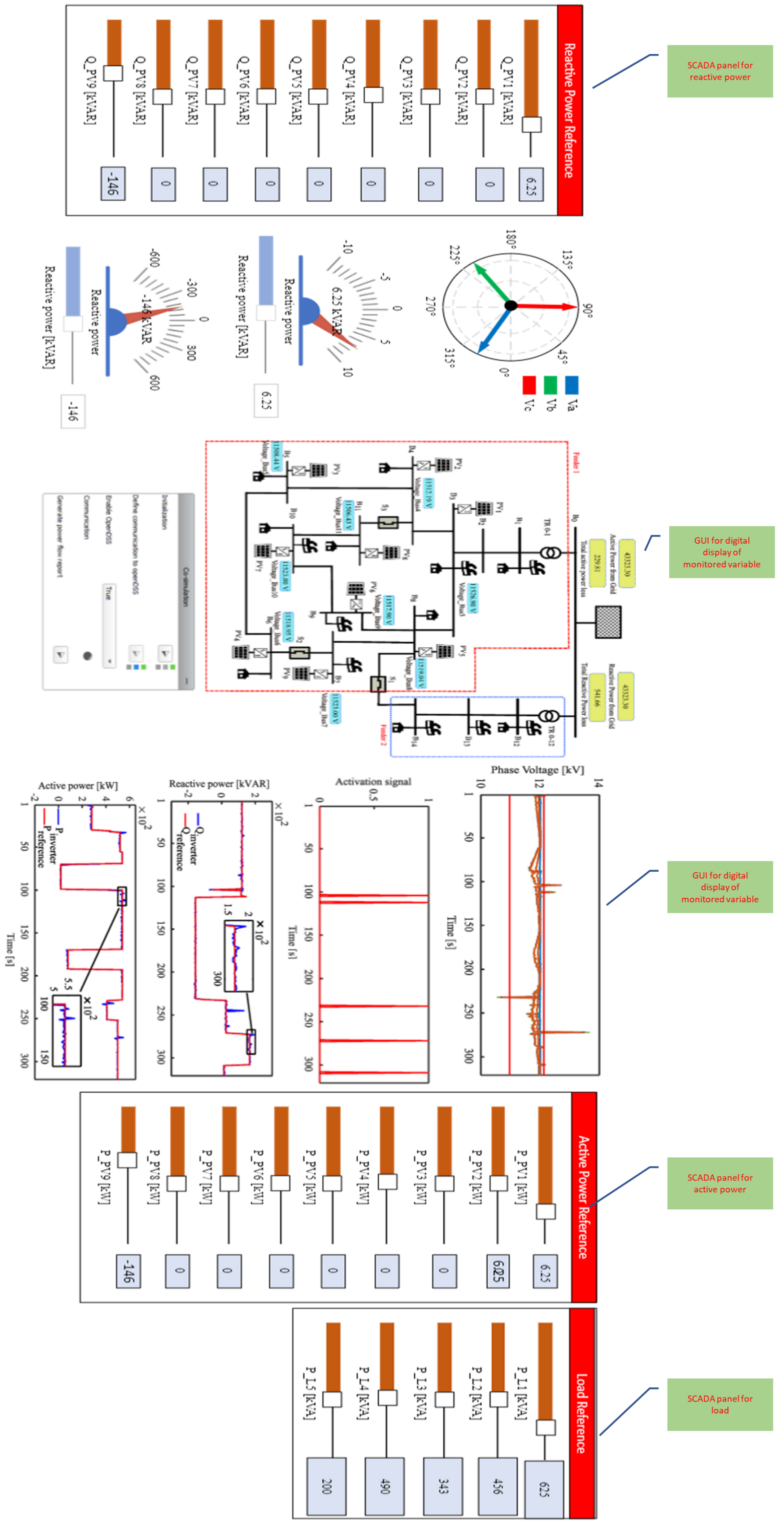


Figure 22: SCADA panel for real-time optimal reactive power control in the smart distribution network [94]

Figure 22 shows the SCADA panel of the framework developed in this research. The developed framework has several monitoring and control units integrated with SCADA. SCADA was developed using the Python-based application programming interface (APIs) for Typhoon HIL and OpenDSS. The use of Python provides flexibility in developing the framework. Integrating with Python-based libraries also offers a wide range of control applications that could be achieved by programming in Python. Furthermore, the integrated graphical user interface in the SCADA panels also allows real-time control and monitoring of the distribution network. More details about the framework and the implementation process can be found in **Paper E**.

In the quest to develop a framework for the real-time validation of different voltage control architectures in the smart distribution network, only two types of real-time voltage control architecture have been analyzed in this research. The framework developed in Paper E has been utilized in further research. **Paper C** and **Paper D** are the research obtained using the same framework. In **Paper C**, real-time Volt-Var control has been implemented. This research work highlights the importance of Volt-Var settings based on voltage sensitivity and emphasizes the role of grid-forming converters in voltage regulation. Volt-Var settings were obtained using the information on the distribution network, and the information was passed to the real-time simulator to obtain the reference reactive power from the controller. With the required reactive power from the converter, voltage violations in the network were mitigated.

Figure 23 shows the reactive power profile of a single converter at a particular node in the distribution network. Using the Volt-Var setting based on the node voltage causes the reactive power to change depending on the voltage at that node. This method requires frequent changes of reactive power setpoints. Due to this frequent change in reactive power setpoints, the reference reactive power setpoints need to be changed dynamically in the real-time simulation. This method only considers the reactive power to regulate the voltage and is not concerned with increasing or decreasing the total loss in the network.

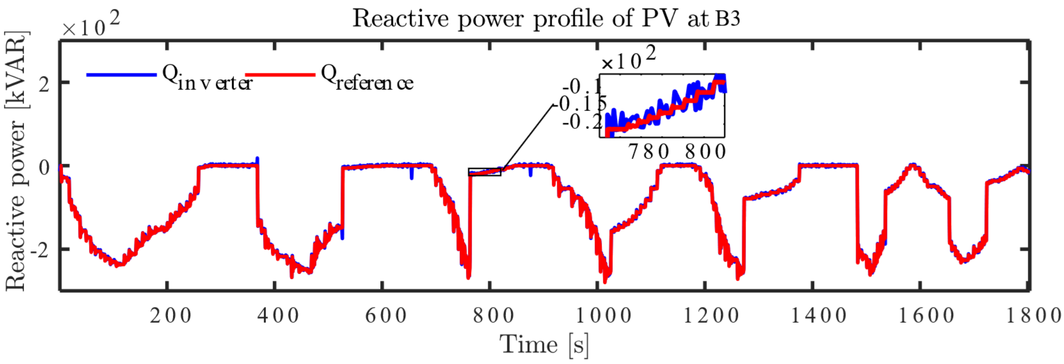


Figure 23: Reactive power profile of PV at Bus3 using real-time Volt-Var Control (**Paper C**, Figure 9(a))

With the OPF-based approach, optimization can be performed for different objectives. In **Paper D**, OPF-based voltage control was performed. **Figure 24** shows the reactive power profile of a converter, where the reference setpoints of reactive power are obtained by using the appropriate co-simulation based optimization obtained from **Paper F**. To limit the number of optimizations in this work, a monitoring system was also developed to detect voltage violations. Once the voltage violations are detected by the monitoring system, the co-simulation based optimization block performs the optimization to find the new set of reactive power set points. Thus, the need for optimization was reduced and implemented only when voltage violations were detected. More simulation results and descriptions can be found in **Paper D**.

Figure 25 shows the comparison of total loss in the distribution network with the implementation of a real-time OPF-based approach and a control based on a fixed power factor. The benefit of using the OPF method is that the network can be operated after fulfilling certain objectives. However, there are some limitations, which are discussed in the next chapter when implementing the OPF-based approach.

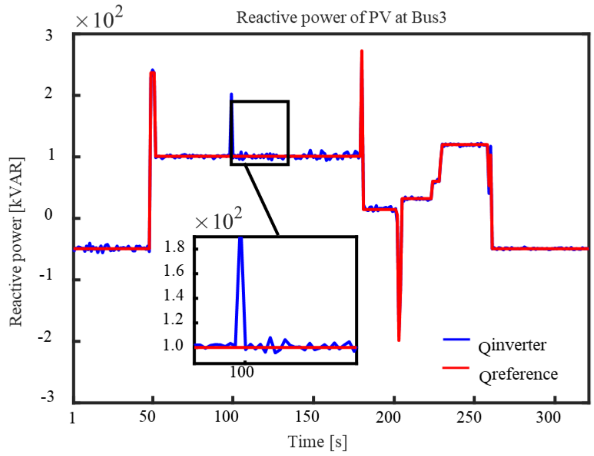


Figure 24: Reactive power profile of PV at Bus3 using OPF-based control (**Paper D**, Figure 12(a))

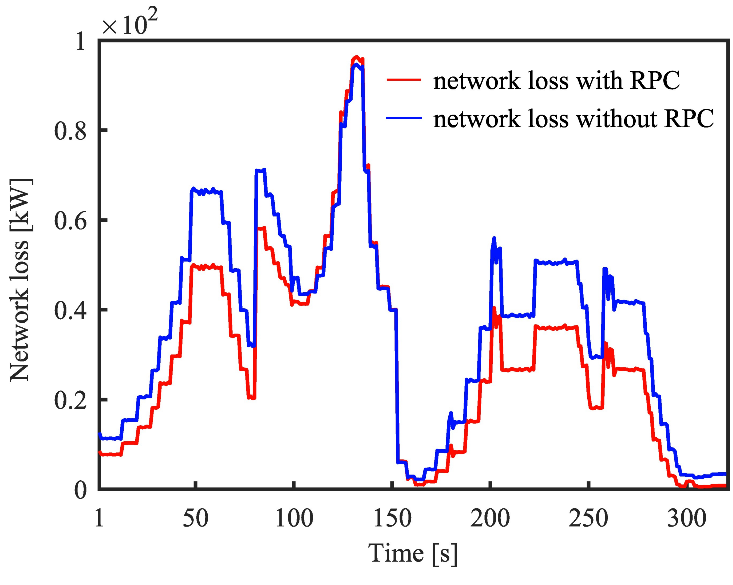


Figure 25: Comparision of total power loss in the CIGRE medium voltage network with real-time OPF based control and fixed power factor based control (**Paper D**, Figure 13

4.4 An overview of the research contribution for the advancement of voltage control in DER-rich smart distribution networks

As the result of this research effort, our goal is that this thesis will serve as a valuable resource, guiding the transition towards a more dynamic and adaptable future energy system in the era of DER dominance. After a comprehensive investigation of voltage control in smart distribution networks with high integration of DER, this thesis will serve as a valuable resource for researchers, engineers, policymakers, and industry stakeholders working toward the realization of efficient, resilient, and sustainable energy systems. An overview of the overall research contributions to the advancement of voltage control in DER-rich smart distribution networks are listed below.

- ➢ Contribution to the proper analysis of the impact of high integration of DERs in smart distribution networks. This research focuses on different aspects while analyzing the impact of high integration of DERs in the distribution network. From the analysis, it was found that suitable modelling techniques should be utilized to analyze the impact efficiently. With the use of a suitable model, a quantitative analysis of the impact can be done. The results obtained from this research can be implemented in either stand-alone microgrids or in grid-connected distribution networks. Furthermore, the research study also suggests several aspects of optimization that can be utilized in the DER-rich distribution network to enhance the reliability and efficiency of the energy system. The main findings from **paper A** can be utilized for enhancing the reliability and efficiency of remote or isolated power systems. Similarly, the detailed analysis performed in **Paper B** can be utilized to identify the appropriate trade-off and selection of the appropriate voltage control architecture in SDN.

- ➢ The main contribution of this research work also lies in the modelling and formulation of optimal voltage control in DER-rich distribution networks. An important part is the formulation of an optimization model using the information of measurement devices installed on the distribution network. Furthermore, a co-simulation based optimization distribution network using commercially or openly available distribution network solvers proposed in this research contributes to the quest for faster optimization required for real-time applications. The quantitative analysis presented in this research helps to coordinate active power curtailment and reactive power control from a smart converter to alleviate voltage violations in the DER-enriched smart distribution network. The in-depth study performed throughout this research work provides a sufficient analysis to recognize the potential trade-offs among the available control methodologies and architectures. Quantitative analysis in **Paper B** helps to assess the effectiveness of different control approaches in the distribution network.

- ➢ Contribution to real-time testing and validation of voltage control applications in smart distribution networks. The research provides a practical solution for real-time voltage control in DER-enriched distribution networks. The most important contribution to the research field is the development of the cyber-physical co-simulation framework for real-time optimal control application. The framework proposed in this research is crucial to test and implement real-time control strategies effectively. The developed real-time validation framework can be applied to real-life distribution networks. The presented work can be applied to any type of network either single-phase or poly-phase, balanced or unbalanced, and radial or mesh networks. In addition, the proposed work can perform real-time studies using a cyber-physical system with a multiple number of controllable devices in the network. The presented work opens a bigger horizon for testing, developing, and validating numerous smart grid paradigms in the distribution network. Hence, this research work expands the multidimensional horizon for real-time monitoring and control.

5 Discussions

In this chapter, the correlation between the articles supporting the thesis, the discussion of the results in each paper, and the strengths, weaknesses, limitations, and assumptions are elaborated in detail. In addition, the implications of the research and future research directions are also suggested in this section. The discussion chapter is subdivided into different sections based on the agendas discussed.

5.1 Relation between the Articles

In this section, an overview of the research results in relation to the research questions and research objectives is presented. The research objectives are answered by the research work in **Paper A-F**. The qualitative relationship between the articles considered in this thesis is shown in **Figure 26**. As illustrated in **Figure 26**, the six main articles that form the basis for this thesis come together to answer the objectives considered in the introduction.

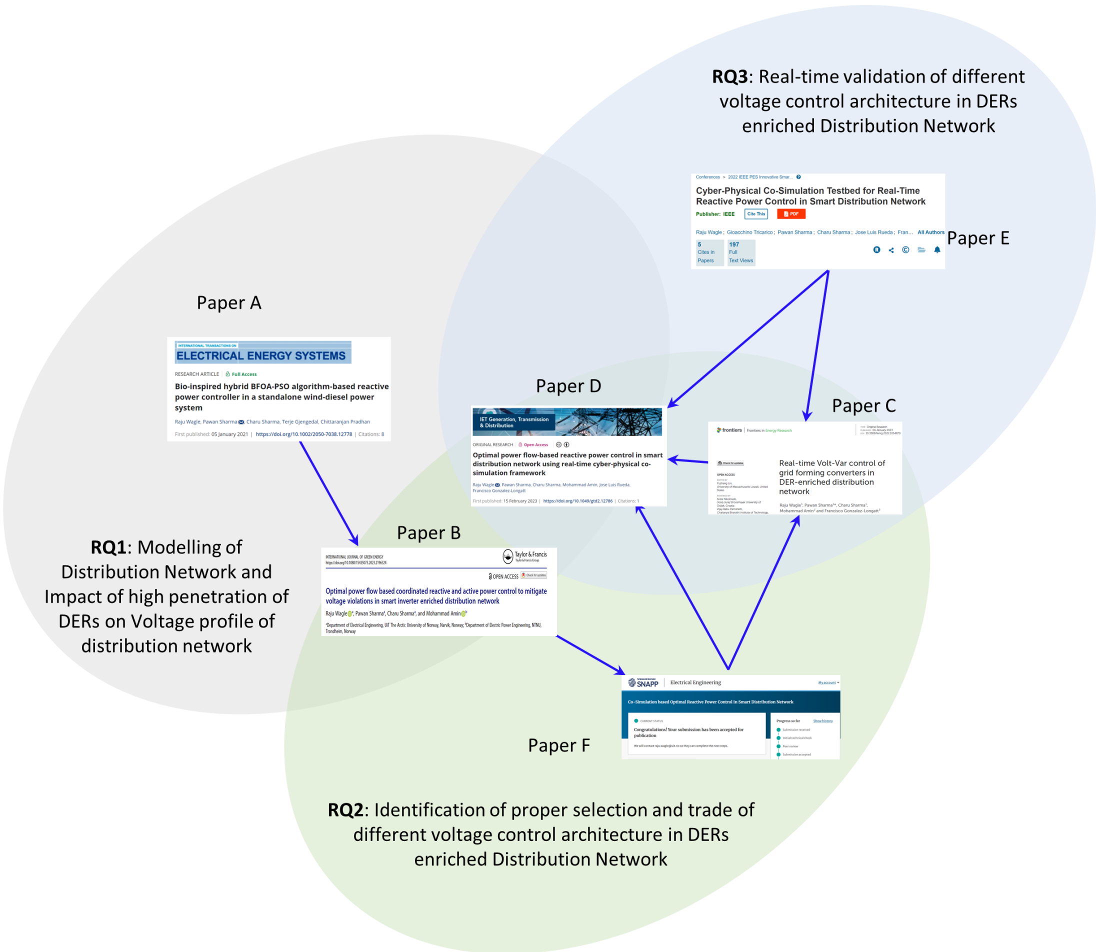


Figure 26: Qualitative relationship between the papers supporting the thesis

The articles supporting the thesis come together to answer the research questions and objectives described in **Section 1.4**. The results that support **RQ1** are presented in **Papers A**, **Paper B**, and **Paper D**. **Paper A** analyzes the impact of optimal reactive power control on the voltage profile in a microgrid. **Paper B** and **Paper D** considered the modelling of the distribution network to investigate the impact of DERs on the voltage profile using a detailed mathematical model and the co-simulation based modelling. **Paper B** on the other hand also identifies the proper selection and tradeoff between the voltage control architecture. The results in **Paper B** also justify the foundation for **RQ2**. Hence, **Paper B** is represented as a common part of **RQ1** and **RQ2**.

The results from **Paper B**, **Paper C**, **Paper D**, and **Paper F** support **RQ2**. In these papers, the selection and implementation of various voltage control architectures and strategies to solve the problem of voltage violations were presented. Similarly, **Paper C**, **Paper D**, and **Paper E** contribute to answering **RQ3**. The framework presented in **Paper C**, **Paper D**, and **Paper E** ware utilized to support **RQ3** for validating real-time optimal power control in DER-enriched distribution networks. Real-time validation of different voltage control architectures was described in those papers. **Paper D** combines results from all the research questions, so is considered as the common of all the **RQs**. **Paper D** model the distribution network, analyze the voltage profile with DER integration, and implements the real-time voltage control.

A detailed connection of the research questions with the research objectives and supporting papers considered in the research work is presented in **Table 6**. The table shows a summary of how individual papers address the research questions to fulfill the objectives.

Table 6: Summary of the research question, research objectives, and the papers

RQ	Research Objectives	Papers
RQ1	**Objective1**: *To investigate the voltage violations caused by the integration of variable RES-based DER and identify the role of active and reactive power control strategies to regulate voltage.*	PaperA PaperB
RQ2	**Objective2**: *Proposing a novel optimal voltage violation mitigating technique in the DER enriched smart distribution network. To identify the right selection and trade-off between different voltage control architectures in a DER-enriched smart distribution network.*	PaperB PaperF
RQ3	**Objective3**: *Validating the proposed optimal control method on real-time models of an existing power distribution network with a high penetration of DERs.* **Objective4**: *Develop a cyber-physical co-simulation framework to perform real-time simulation studies of various voltage control methodologies in DER-enriched smart distribution networks.*	PaperC PaperD PaperE

5.2 Discussion on Results

In **Paper A**, the impact of a dynamic random and fixed step change in the load and reactive power generation from the wind energy source on the voltage at the point of common coupling is studied for the isolated wind-diesel microgrid. Paper A analyzes a microgrid where a detailed mathematical model of the generators, AVR, and STATCOM is considered. Moving from an isolated microgrid case to a distribution network is necessary to analyze the system with high integration studies in the distribution network. For this purpose, a detailed model of the distribution network is necessary. Hence, **Paper B** on the other hand considered a detailed mathematical model of three phase unbalance distribution network. In **Paper B**, two well-known distribution networks, the European low voltage distribution network, and the CIGRE medium voltage distribution network were considered. The current injection method as supported by the explanation in the literature section was used to model the distribution network. Furthermore, coordinated active and reactive power control was implemented on the smart converters. To analyze the impact due to the high penetration of DERs, for the considered analysis, all the load points are also connected to the DER. The optimal power flow-based results were compared with the nodal sensitivity-based approach to show the effectiveness of the approach implemented in the paper. The significance, limitation, and requirement of active and reactive power control of smart converter are highlighted in **Section 2.1**.

In **Paper B**, the trade-off between active power and reactive power control from a smart converter is highlighted. **Paper B** consists of a detailed mathematical model of the distribution network, which when optimized with several operating constraints, makes the optimization process time-consuming. The convergence issue in terms of convergence time and finding optimal solutions in the optimization of a distribution network is another big challenge for real-time applications. To test the optimal control application in real-time, fast, and effective optimization is required. **Paper F** proposed a co-simulation based optimization framework. Some iterative simulation to analyze the convergence issue in terms of convergence time and finding optimal solutions in the optimization of a distribution network is presented in **Paper F**.

Paper E presents the novel framework for real-time optimal reactive power control using cyber-physical co-simulation. **Paper C** and **Paper D** proposed two different methods of optimal control of smart converters in distribution networks. Both papers utilized the modified version of the cyber-physical co-simulation framework developed in **Paper E** for real-time validation of the optimal power control from smart converters. The modification to the framework was basically made in the reactive power control center. For **Paper C**, the reactive power controller (RPC) controls the reactive power using nodal sensitivity-based Volt-Var control. Similarly, in **Paper D**, the RPC controls the reactive power based on real-time OPF. The main finding of the papers was that voltage violations have been mitigated when sudden disturbances occur in the generation or load of the network. Moreover, provided that the distribution network is equipped with the required infrastructure for monitoring and control. **Paper D** provides better regulation with lower network loss in the network. The real-time OPF formulation in **Paper D** was modified from **Paper F**.

5.3 Research Significance to the Scientific field

The appropriate methodologies and architecture for voltage control in smart distribution networks with high integration of DERs are of significant importance in the scientific field. Throughout this research, novel and innovative ideas have been developed, providing a comprehensive framework for various control applications within the smart operation of the distribution network. This study encompasses a wide spectrum of distribution network analysis, ranging from isolated microgrids to interconnected distribution networks. Furthermore, it investigates the impacts of high DER integration in both medium-voltage and low-voltage distribution networks. Additionally, this research proposes methodologies to address voltage related grid vulnerabilities that may arise due to the substantial integration of variable DERs into the distribution network. Several approaches of modelling the distribution network developed in this research open a variety of possibilities to increase the observability of the distribution network.

By implementing the findings of this research, numerous tests and analyses can be performed to assess the impact of high DER integration on the distribution network. Smart converters available in DERs can be utilized to support voltage control, allowing the distribution network to operate with minimal losses. Beyond voltage control, this research suggests a co-simulation-based optimization approach for optimal control in DER-rich distribution networks. The concepts introduced in this research can be applied to digital substations to implement control and management applications in real-world systems. Moreover, the cyber-physical co-simulation framework developed serves as a promising tool for testing numerous smart grid features within smart distribution networks.

In summary, this thesis offers an in-depth exploration of various voltage control methodologies and architectures in smart distribution networks with high integration of DERs, contributing significantly to the pursuit of a more sustainable, reliable, and efficient energy system. It addresses critical challenges related to voltage in the ongoing energy transition, thereby paving the way for the development of a more resilient energy system in the future.

5.4 Strength of the work

There are some notable strengths of the thesis from the perspective of the candidate. Most of the important strengths are as follows.

➢ *Development and application of a consistent and robust approach to model distribution network*

  One important strength of the research work lies in the development and application of a consistent and robust approach to modelling. This approach utilizes the openly available distribution network solver OpenDSS to model the distribution network. Several methods of modelling based on the information provided by the power flow simulation from OpenDSS are considered. In **Paper B**, the current injection-based modeling of the distribution network is performed by utilizing the energy meter data placed at the distribution network. By this approach, the distribution network can be modelled more precisely considering the growing installation of energy meters in the distribution network.

➢ *Development of Cyber-Physical Co-Simulation Framework*

  Another strength of the work is the proposed cyber-physical co-simulation framework. The presented framework is utilized for specific purposes as guided by the objective considered during the research. However, the proposed framework is easily extendible to test numerous smart grid features in the distribution network. For example, the candidate along with other researchers has been working on implementing the proposed testbed for testing protection system coordination in the distribution network (refer to **Paper 4**, **Paper 10** in **Table 3**).

➢ *Application of Real-time optimization*

The application of real-time optimization is considered another strength of the work. The proposed real-time optimization method is applied for only obtaining the optimal setpoints for the smart converters. The authors believe that the same concept can be applied to various smart grid features that require optimization. For instance, the candidate is a part of some external collaborative research (refer to **Paper 5** and **Paper 7** in **Table 3**) where the optimal ancillary services from DERs are developed, and the implication of the real-time optimization is under development.

5.5 Weakness of the Work

Even though, the papers supporting the thesis are published after a thorough peer review process as maintained by the journal to accept only standard articles. The candidate, after a rigorous investigation, believes that there are some weaknesses in the work. Some of the weaknesses in the eye of the candidate are listed below.

➢ *Lack of economic analysis to analyze the economic loss due to active power curtailment and the economic benefit gained by minimizing the power loss*

In the search for an optimal trade-off between various voltage control strategies in the distribution network, the research lacks the economic analysis to further elaborate the economic analysis owing to active power curtailment and reduction in power loss. For instance, in **Paper B**, economic loss due to active power curtailment and the economic benefit of minimizing the power loss in the network might be of interest if a detailed economic analysis is to be analyzed. However, this analysis was out of the scope of this research. Detailed consideration of this economic analysis might open the future research direction for new researchers exploring the same domain of research.

➢ *Maximum number of physical components in Cyber-physical framework*

Another weakness lies in the proposed cyber-physical framework. Even this is due to the limitation of the real-time simulator available in the lab. To test larger systems in real-time, the cybernetic layer of the proposed framework can solve all types of distribution networks. However, the physical layer of the proposed framework is limited by the maximum allowable cores for the single real-time simulator. The candidate believes that this is also one of the weaknesses which can help future researchers to investigate more by applying parallel processing of multiple simulators if available.

➢ *Formulation of optimization problem in co-simulation based optimization*

Even with faster convergence with the co-simulation based optimization which really helps to implement real-time optimization, there are some weaknesses that should be considered prior to implementing the optimization algorithm. For instance, Co-simulation based optimization could be applied to a system where the objective function is a derived function of the computed parameter by the distribution network solver. Some of the computed parameters are for example power loss in the network, voltage deviation, etc.

5.6 Limitation of the work

Several limitations also apply to the work presented. For example, the work does not consider the impact of neutral control in the three-phase modelling of the distribution network in **Paper B**. The power flow in the neutral conductor in the distribution network is significant, especially in the case of a short circuit. However, this work did not consider such a faulty situation, so the output obtained was in normal operating condition. Since the work presented in **Paper B** is based on the information from the model developed in the distribution network solver, by proper modelling of the network in the distribution network solver, the problem can be solved.

During the real-time testing of the work in **Paper C**, **Paper D**, and **Paper E**, only virtual components were utilized. Even though the virtual components of the real-time simulator are designed to replicate the dynamics of the real components, the real-time test would have suffered some technical challenges while working with a real system. However, this is justifiable in the current scenario with limited resources for testing the proposed system. Prototyping of large distribution networks as planned in the presented work is available at only a few research laboratories in the world.

The work is limited to only coordinated control for smart converters. Even though there is some offline research that coordinates the smart converter with other voltage regulating devices, the presented work only considers the coordinated control of the smart converter. Also due to the limitation owing to time and availability of laboratory facilities, the presented work is not compared with an alternative real-time simulator. A detailed comparison of the proposed work with other real-time simulators like Opal RT or RTDS could be done to compare the effectiveness of the proposed cyber-physical co-simulation framework proposed in **Paper E**.

5.7 Assumptions considered in this research work

In order to achieve the goals of the research and produce the papers supporting the thesis, the following assumptions were considered.

➢ *The operation of distribution network in smart grid paradigm*

The main assumption considered in this research is that the distribution network can operate in a smart grid paradigm. This means that the distribution network is equipped with the necessary infrastructure for communication to and from the control station to the controllable devices. This assumption is made to address the possible question that can be raised about the observability of the distribution network.

➢ *Very high integration of DERs in the distribution network*

Another assumption made during the analysis is that DER is integrated highly into the power network. Here, the candidate would like to clarify that high integration is both in terms of size and location. During the analysis in **Paper B**, the DERs are assumed to be placed at all the locations of load connections and the rated capacity of the DERs is so high that they can create voltage violations in the network in the case when the load consumption in the network is low.

➢ *Assumptions considered in the operating condition of the distribution network*

For the sake of simplicity, the operation of the distribution network is assumed to be in a steady state. Further in the analysis, the considered scenarios do not consider abnormal operating conditions like faults or short circuit operations. In the distribution network, the $\frac{R}{X}$ ratio is kept constant as defined in the information of the test network. In **Paper B**, the type of generation from DERs is considered to be PV. In an analysis in **Paper C** and **Paper D**, the output from DERs is changed manually from the SCADA panel of the cyber-physical framework.

➢ *Availability of Research Lab infrastructure*

This assumption is made for the real-time validation of the proposed system. The research work contribution to **Paper C**, **Paper D**, and **Paper E** was done in the research lab where the required infrastructure for real-time testing was available. The candidate assumes that to replicate the presented idea by other researchers, the testing facility, software license, and required system for monitoring and control are available at the lab.

5.8 Implication of the work

The finding of **Paper A** is that by combining different optimization algorithms, a better solution can be achieved. This idea can ignite the door to combine multiple optimization algorithms to get the best solution for optimization problems. In addition, the findings presented in **Paper B** suggest that active power curtailment can be avoided if the power network is robust. To avoid the unnecessary curtailment of power generation and to manage the voltage violations only by reactive power control, upgrading the network can be done. These results have implications for further research on congestion management, network reconfiguration, and other alternative ways to control and manage the effects of higher integration of variable DERs in the distribution network.

The findings of **Paper C** and **Paper D** show that, in addition to operate the distribution with lower network loss, there is a possibility to incorporate the unexpected disturbances both from the generation and loads. The implication of this finding initiates a wider assessment of secure and reliable future energy systems.

5.9 Future works

By the time the candidate is submitting the thesis work, the candidate has foreseen numerous research directions that could open the door for novel scientific research. Three main topics for further research are identified based on the work presented.

Firstly, implementing standard communication protocol in the framework could also develop the foundation for the digital twin-based system for control and monitoring of the distribution network.

Secondly, with the growing installation of ICT-based systems in the distribution network, the distribution network is prone to unethical cyber-attack. The area of cyber-security and network resilience can be explored and incorporated into the framework presented in the thesis.

Lastly, due to the growing integration of converter-based generation in the distribution network, the involvement of such generation in various ancillary services like spinning reserve, non-spinning reserve, backup supply, harmonic compensation, network stability, and energy market regulation can be explored on the proposed cyber-physical co-simulation framework. Real-time ancillary services like real-time reactive power market can be explored in the context of the smart distribution network paradigm on the proposed framework.

6 Conclusions

The scope of the work defined in this thesis is characterized by the research questions and objectives described in the Introduction chapter. The conclusion that can be drawn from the main papers gives an answer to the research question considered in this thesis. This chapter summarises the main contribution of the work presented in **Papers A-F** supporting the thesis in relation to the research questions defined for this work.

- **RQ1**: *How do modern distribution networks respond to the large penetration of variable distributed energy supplies in terms of the overall voltage profile and voltage violations?*

  Variable distributed energy resources (DERs) like PV and wind power are being integrated into distribution networks on a large scale. Dependency on environmental conditions and other reasons make these energy sources variable. High integration of such sources can alter the voltage profile and cause voltage violations in the distribution network. Network operators may use numerous methods and strategies to address these issues: Some of the common methods are discussed below.

  ➢ Application of voltage regulating devices like on load tap changing (OLTC) transformers, step voltage Regulators (SVRs), switched capacitor banks (SCBs), switched inductor banks (SIBs), smart converters (SCs) in DER. These devices compensate for the voltage fluctuations induced by variable DERs and regulate the voltage to avoid voltage violations.

  ➢ Using the optimal operation of the distribution network. For instance, Volt/Var optimization, and Volt/Watt optimization in distribution can be done to regulate the voltage profile. Volt/Var optimization optimizes distribution network voltage and reactive power flow. Voltage and reactive power settings can be adjusted to maintain a consistent voltage profile. Similarly, Volt/Watt optimization regulates network voltage and active power generation to regulate the voltage.

  ➢ Distribution network operators can use advanced planning and forecasting techniques to anticipate the voltage profile in the network. Proper forecasting of either reactive power support or active power curtailment can be done to reduce voltage violations in the network.

  ➢ Real-time Monitoring and Control Systems that monitor voltage levels and detect voltage violations in real-time can be incorporated to prevent voltage violations.

- **RQ2**: *How to coordinate between active power curtailment and reactive power support from a smart converter to mitigate voltage violations in the DER-enriched smart distribution network. Also, How to recognize potential trade-offs to choose the right control strategies and arrive at an optimum solution in a distribution network more quickly.*

  Proper coordination of active power curtailment and reactive power support from a smart converter is decisive to mitigate voltage violations in a DER-enriched smart distribution network. Active power curtailment helps to balance the supply-demand in the system and prevent voltage violations by adjusting the active power generation. By adjusting the reactive power output of the DERs, smart converters can help to regulate voltage and prevent voltage violations. Coordinated control strategies can be developed to ensure effective utilization between active power curtailment and reactive power support. These strategies are designed based on the specific characteristics of the DERs, the distribution system, and the voltage violation scenarios. Advanced control algorithms and optimization techniques can be used for this purpose.

  Paper B provides a fundamental analysis of the coordinated operation of active power curtailment and reactive power support from multiple smart converters to regulate voltage violations. This paper also recognizes the potential trade-offs to choose the appropriate control strategies in order to operate the distribution network optimally. **Paper F** proposed a co-simulation based optimization method to explore the suitable optimization algorithm for real-time application.

- **RQ3**: *How to create a framework for real-time validation of different voltage control architecture in the DER-enriched smart distribution network?*

Creating a real-time simulation framework for control applications in a DER-enriched smart distribution network can be challenging. The methods to create such a framework depend on the objectives and application for which the framework is intended to achieve. Hence, specific goals should be identified prior to developing the framework. The necessary information like characteristics of DERs, network topology, load profiles, DER generation profile, control algorithm, communication infrastructure, and the information about the real-time simulator are important factors to consider beforehand. One of the other important factors is also to identify the appropriate modelling technique for solving power flow analysis or state estimation of the distribution network.

Once the framework is developed, validation and calibration of the developed framework with real-world data or validated test cases is necessary to ensure that the developed framework represents the behaviour of the actual distribution network. The testing can be done by creating several simulation scenarios. These scenarios could range from normal operations to emergency situations. Some realistic scenarios like load fluctuations, DER power variation, and control algorithms can be tested in the framework to check the robustness of the real-time simulation framework.

One of the applications explored in the thesis is real-time monitoring and optimal control of smart converters in DER-enriched distribution to mitigate voltage violations in real-time. **Paper E** proposed a real-time co-simulation based framework for reactive power control in smart distribution networks. **Paper C** and **Paper D** proposed a real-time optimal framework to regulate the voltage violations in real-time. **Paper C** implements the Volt-Var control on the framework developed in **Paper E**. **Paper D** implements OPF-based reactive power control on the same framework.

More generally, I hope that the findings of this research will provide knowledge and motivation for further research in the field of real-time control and monitoring in Smart distribution networks.

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Paper A. Bio-inspired hybrid BFOA-PSO algorithm-based reactive power controller in a standalone wind-diesel power system

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International Transactions on Electrical Energy Systems, 2021, Volume 131, Issue 3, Pages 1-18.

https://doi.org/10.1002/2050-7038.12778

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Authors Contribution:

The conceptualization of the idea to do further research in bio-inspired hybrid BFOA-PSO algorithm based reactive power control in a standalone wind-diesel power system was proposed by Pawan Sharma. The implementation of the methodology, utilization of software, data curation, formal analysis, writing of original draft, validation, and visualization of the paper was done by the **candidate**. All authors contributed essentially to the supervision, review, validation, and proof of the paper.

Received: 5 May 2020 | Revised: 12 October 2020 | Accepted: 21 December 2020

DOI: 10.1002/2050-7038.12778

RESEARCH ARTICLE

WILEY

Bio-inspired hybrid BFOA-PSO algorithm-based reactive power controller in a standalone wind-diesel power system

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Summary

With an increase in the penetration of renewable energy sources such as wind into the power systems, the operation and control of voltage/reactive power have become more complicated and challenging than ever. As a result, the reactive power imbalance between reactive power generation and demand instigates a reduction in system voltage stability. To deal with the aforesaid scenarios, automatic voltage regulator (AVR) and static synchronous compensator (STATCOM) are incorporated to curtail the voltage deviations in a standalone wind-diesel power system. In this article, a hybrid bacterial foraging optimization algorithm-particle swarm optimization (hBFOA-PSO) algorithm is proposed for optimizing the PI controller parameters of AVR and STATCOM to further improve the system voltage/reactive power performance. Additionally, H_∞-loop shaping technique is designed to analyze the performance indexes (ie, robustness and stability) of the presented controller with the aim of handling the unstructured uncertainties from generation and loading situation. In order

List of Symbols and Abbreviations: AGC, automatic generation control; ANN, artificial neural network; AVR, automatic voltage regulator; BFOA, bacteria foraging optimization algorithm; BFOA-PSO, bacteria foraging optimization algorithm and particle swarm optimization; D_v, load voltage characteristics; $\Delta E'_{fd}$, small change in excitation voltage under transient; E_M, electromagnetic energy in the PMIG; FACTS, flexible alternating current transmission systems; G, system open-loop transfer function; GA, genetic algorithm; GWO, Grey wolf optimization; H, system shaped plant transfer function; hBFOA-PSO, hybrid bacteria foraging optimization algorithm and PSO; IG, induction generator; K_A, voltage regulator gain; K_E, exciter gain; K_f, stabilizer gain; K_{I1}, integral gain of the STATCOM; K_{I2}, integral gain of the AVR; K_{p1}, proportional gain constant of the STATCOM; K_{p2}, proportional gain constant of the AVR; K_v, system gain of the AVR; K_α, firing angle gain; LFC, load frequency control; MGWO, modified grey wolf optimization; η_{PMIG}, efficiency of the PMIG; P_{in}, aerodynamic input power of PMIG; P_L, real power load requirement; P_{PMIG}, real power output of the PMIG; P_{SG}, real power output of the synchronous generator; PI, proportional plus integral; PMIG, permanent magnet induction generator; PSO, particle swarm optimization; Q_L, reactive power load requirement; Q_{PMIG}, reactive power output of the PMIG; Q_{SG}, reactive power output of the synchronous generator; $Q_{STATCOM}$, reactive power of the STATCOM; R_1, stator resistance of the PMIG; R'_2, rotor resistance referred to primary side of the PMIG; S, slip of the PMIG; s, frequency parameter in the frequency domain; S_{PMIG}, apparent power of the PMIG; SG, synchronous generator; STATCOM, static synchronous compensator; SVC, static VAR compensator; T_A, voltage regulator time constant; T_d, dead time of the thyristor; T'_{d0}, direct-axis open circuit transient time constant; T_E, exciter time constant; T_F, stabilizer time constant; T_v, system time constant; T_α, delay time of the thyristor; V, system terminal voltage at point of common coupling (PCC); W_1, weighted value of precompensator; W_2, weighted value of postcompensator; WECS, wind energy conversion system; X_1, stator reactance of the PMIG; X'_2, rotor reactance referred to primary side of the PMIG; X'_d, transient state direct-axis reactance of the synchronous generator; X_D, steady-state direct-axis reactance of the synchronous generator; X_M, magnetizing reactance of the PMIG; α, thyristor firing angle; α^0, nominal firing angle of the thyristor; Γ_k, H_∞-norm; γ_k, performance index; ΔE_{fd}, small change/perturbance in the excitation voltage; ΔE_q, small change in armature voltage; ΔM_S, uncertainty in the nominal plant; ΔN_s, uncertainty in the nominal plant; ΔV, small change in the terminal voltage; ΔV_a, small change in AVR output voltage; ΔV_f, small change in exciter feedback voltage; ΔV_{ref}, small change in reference voltage; δ, power angle of the synchronous generator.

to present the efficiency of the proposed controllers, the performance of the hBFOA-PSO controller is compared with the performance of the BFOA, PSO, and modified grey wolf optimization (MGWO)-based PI controllers for the same wind-diesel system. The dynamic responses of the wind-diesel system for different disturbance cases have been investigated in the MATLAB/SIMULINK environment.

KEYWORDS

bacterial foraging optimization algorithm, hybrid BFOA-PSO, PI controller, PSO, wind-diesel standalone power system

1 | INTRODUCTION

1.1 | Motivation and incitement

To cope with the increasing energy demand and environmental concerns around the world, productions of electricity from distributed energy sources like wind energy are gaining attention for a sustainable power production.[1,2] However, the wind-based power systems become more complex and challenging for voltage/reactive power regulation because of the intermittent nature of wind speed especially in isolated areas.[3,4] As a result, the oscillation/disruption experienced by the isolated power system disturbances may extend to wider areas proceeding to power system instability and unreliability. In order to overcome the wind power intermittent problems and to enhance the system reliability, the distributed wind energy resource is usually projected to operate together with diesel generators adding generation capacity at the customer's location for continuous power supply backup in remote communities.[5] On the other hand, flexible AC transmission systems (FACTS) devices like a STATCOM and AVR are utilized in the power systems for continuous and faster reactive power compensation.[6] The performance of a power system depends on the controller structure/topology, designed objective function. Furthermore, performance of power system also depends on the control techniques employed to optimize the controller parameters of the FACTS devices in power system.[1,2] Hence, in this work, optimized reactive power control in an isolated wind-diesel-based power system is analyzed using a hybrid search optimization technique for designing/tuning the proportional plus integral (PI) controller parameters of the STATCOM and AVR.

1.2 | Literature review

During the power system operation, voltage deviation is usually a consequence of power mismatch due to unexpected disturbances, such as sudden load leaping/dropping or generator tripping, etc. In the previous literature, with the aim of augmenting the dynamic voltage/reactive power control performance, the researchers have recommended various control approaches/devices (eg, robust control, FACTS devices, etc.) and/or soft computing algorithms in the wind-based power systems.[6-10] The enhancement of voltage stability in a wind-diesel hybrid power system using STATCOM and PID controller with a derivative filter is observed in Reference 7. The performance of AVR is observed in Reference 8 to ensure stability, robustness, and minimum overshoot by using the optimization process. In References 9 and 10, the coordinated operation of STATCOM and AVR is demonstrated. From this study, it is analyzed that the combined operation of controllers contributes a superior voltage performance in terms of robustness and stabilizing effects. Dynamic reactive power control and adaptive voltage management for a hybrid microgrid consisting of wind and diesel generators using a unified power flow controller (UPFC) are studied in Reference 11.

With respect to the robust control approach, H∞-controllers are more robust against variation in power demand and system uncertainties.[12,13] In Reference 12, H_∞-based multivariable robust control scheme is proposed for regulating the voltage of a standalone microgrid consisting of diesel, PV, and supercapacitor. In Reference 13, H_∞-shaping weighting function is used to synthesize the robustness of the controller. In References 8 and 14, the authors have recommended the H_∞-loop shaping method for designing robust controllers. Seeing the usefulness of the H_∞-controller,

H_∞-loop shaping approach is implemented to obtain the objective function of the studied power system for computing/designing the PI controller parameters.

In practice, proportional (P)/PI/proportional plus integral plus derivative (PID) controllers are mostly used in the industries and power system. In this perspective, the researchers have proposed numerous controller design approaches and formulations to optimize the gains of the controllers to fit the dynamics of the power system.[15] The intelligent optimization techniques like a genetic algorithm (GA),[16] BFOA,[17] fuzzy-GWO,[18] fuzzy-bat algorithm,[9] Jaya algorithm,[19] etc., have been developed and applied to solve different optimization engineering problems such as tune/optimize the system/controller parameters. A comparative study of various soft computing techniques for reactive power compensation for the hybrid power systems is reported in Reference 15. In Reference 16, the authors have implemented the GA to adjust the PI controller parameters of the SVC and AVR for reactive power control. Furthermore, a co-ordinate power management strategy between SVC, AVR, and wind-diesel-based power system for proper power balancing is projected. In Reference 18, the PI controller tuned fuzzy-GWO algorithm is presented in a wind-diesel-based system for improving reactive power performance. A coordinated fuzzy-Bat algorithm is studied for obtaining the optimized parameters for generators and STATCOM in a two-area power with the aim of improving the system voltage performance.[9] In Reference 17, an optimal controller is designed for reactive power control in an isolated wind-diesel-based power system using BFOA, and the effectiveness of the suggested controller is compared with GA and PSO. In 20, the ant-bee colony algorithm and the GWO algorithm are applied separately for automatic reactive power control of isolated wind-diesel hybrid power system. In 21, the authors used MGWO to obtain the optimum parameters of optimal PID-fuzzy-PID controller for load frequency control analysis in a two-area interconnected power system.

Even though numerous intelligent algorithms have been recommended to accomplish the optimal values of the controller/system parameters, they have their own shortcomings.[15] Hence, with the aim of improving search performance (ie, convergence rate and optimized value of controller), the authors have recommended different hybrid algorithms by integrating two intelligent algorithms for reactive power control.[21,22] In Reference 23, the seeker optimization algorithm (SOA) is combined with Takagi-Sugeno (TS)-fuzzy logic controller for controlling reactive power and terminal voltage. In Reference 24, the authors have suggested GA and adaptive neuro-fuzzy inference system (ANFIS) approaches to preserve the optimal performance of STATCOM to control the voltage transients. In regard to the hBFOA-PSO algorithm, it is employed for solving the optimization multimodal and high-dimensional benchmark functions.[25] Furthermore, the hBFOA-PSO is used for tuning the PI controller parameters of the automatic generation control (AGC) in an interconnected two-area power system for enhancing the dynamic load frequency control (LFC) performance.[26] In Reference 22, designing of the PI controller parameters of the static VAR compensator (SVC) is reported in a multimachine system for power system stability enhancement. Since the hBFOA-PSO (ie, consists of BFOA and PSO) algorithm has a better search ability while avoiding the false and premature convergence, the hBFOA-PSO algorithm is implemented in an isolated wind-diesel system for reactive power control, in this article. The hBFOA-PSO algorithm instigates better search performance than the PSO,[27] BFOA,[28] and MGWO[20] algorithms.

1.3 | Contribution and paper organization

In this article, a maiden attempt has been taken to apply hBFOA-PSO algorithm in a standalone wind-diesel-based power system for reactive power control and suppressing the voltage deviations during the system events such as the variations in power demand and wind speed.

The main contributions made by authors in this article:

1. The robustness (ie, performance index) of the proposed controller on voltage deviation owing to fluctuation in reactive power is formulated by using the H_∞-loop shaping approach.
2. The hBFOA-PSO algorithm is implemented for optimizing the PI control parameters of STATCOM and AVR in wind-diesel-based power system for enhancing the system voltage/reactive power performances.
3. The efficacy of the hBFOA-PSO algorithm over BFOA-, PSO-, and MGWO-based algorithms for reactive power control is verified in the same wind-diesel system considering different case studies.

The article is structured as follows: The detailed mathematical modeling of the standalone wind-diesel-based power system is presented in Section 2, whereas the H_∞-controller design approach is illustrated in Section 3. In Section 4, an overview of the bio-inspired hBFOA-PSO algorithm is reported. Simulation results and discussions are observed in Section 5. Finally, the conclusion of the proposed control technique is provided in Section 6.

2 | MODELING OF THE STANDALONE WIND-DIESEL-BASED POWER SYSTEM

2.1 | Wind-diesel-based system

In general, an induction generator (IG) is used as a wind energy conversion system (WECS) in wind power, and the synchronous generator is used in diesel engines set for power generation. Despite several advantages of IG, the consumption of magnetization current for the excitation system results in poor performance in terms of lower voltage regulation, energy efficiency, and power factor.[4] In this context, a permanent magnet induction generator (PMIG) contributes a better voltage regulator/efficiency and power factor comparably to IG in the power system operation and control.[4,5] Hence, in this work, PMIG-based wind integrated diesel generator system is considered for a stable, flexible, and secure power system operation and control. The schematic diagram of the studied isolated wind-diesel-based power system is presented in Figure 1.

In general, the diesel generator set delivers the reactive power, whereas the wind generator and load consumes reactive power as presented in Figure 1 (the power flow direction is indicated by arrow mark). The STATCOM absorbs/supplies the required reactive power in accordance with the system requirements for power balancing between the generations (ie, diesel generator and PMIG) and load.

2.2 | Linearized model of the proposed power system

Linearized/small-signal models are convenient for designing the controller and analyzing the system reactive power/voltage performance of the power system with the variations/deviations in the system parameters, demand/generation, and so on.[16,17] Hence, in this study, a small-signal/linearized model of wind-diesel-based standalone power system with both STATCOM and AVR is considered as presented in Figure 2. The presented small-signal/linearized model in Figure 2 is a generalization functional diagram of the detailed power system model (Figure 1). In this work, the variations in load reactive power (ΔQ_L), wind power (ΔP_{IW}), and voltage reference (ΔV_{ref}) signals are taken as the input variables and changes in system PCC voltage (ΔV) as the output variable in the linearized power system model. The modeling/design system parameters/data of the presented power system are specified in Appendix.

The reactive power and active power balancing equations for the above-mentioned power system (refer Figure 1) under steady-state scenario are expressed as follows:

$$Q_{SG} + Q_{STATCOM} = Q_L + Q_{PMIG} \text{ and } \quad P_{PMIG} + P_{SG} = P_L \tag{1}$$

where, Q_{SG}, $Q_{STATCOM}$, Q_{PMIG}, and Q_L are the reactive power of diesel generator, STATCOM, PMIG, and load, correspondingly. P_{SG}, P_{PMIG}, and P_L are the corresponding active power of diesel generator, PMIG, and load, respectively.

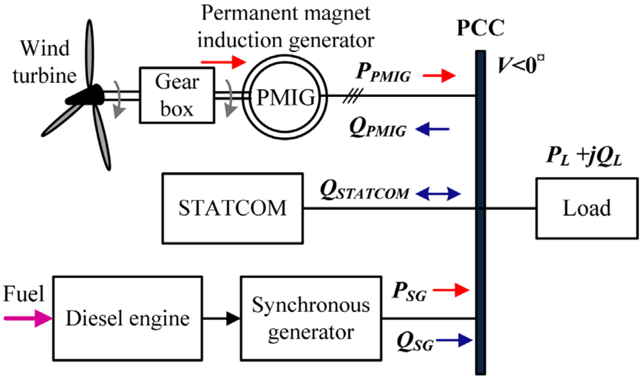


FIGURE 1 Schematic of the standalone wind-diesel power system[29]

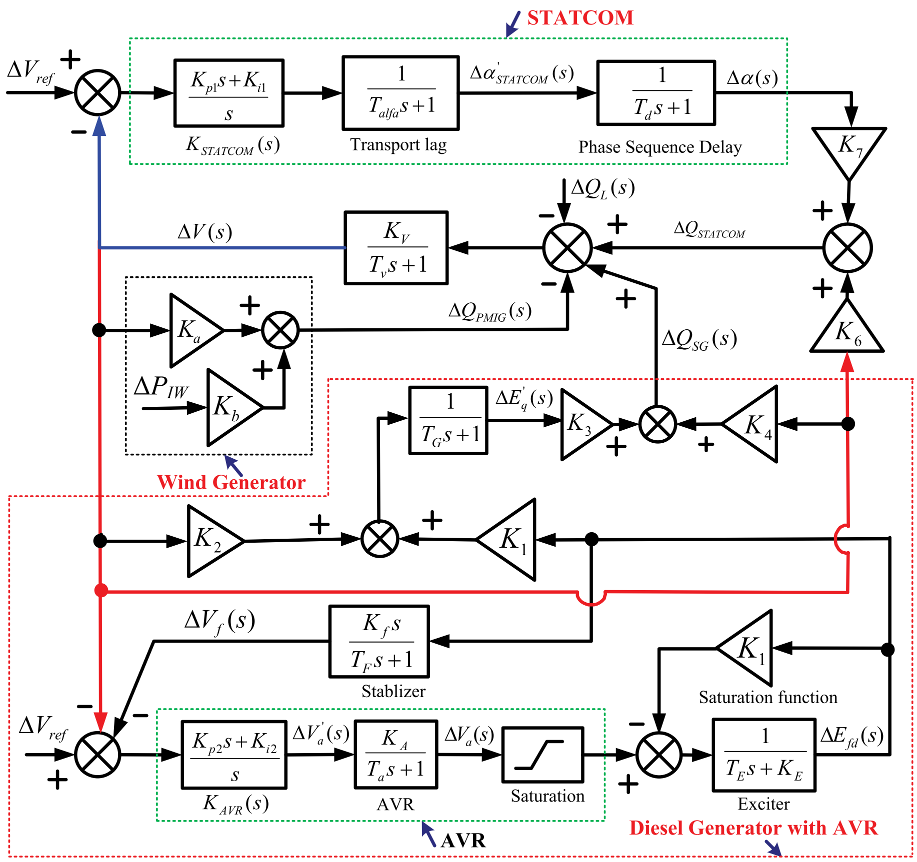
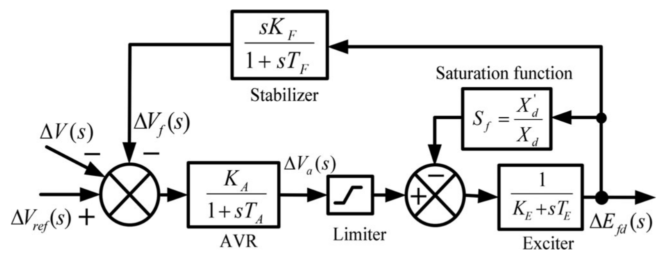


FIGURE 2 Schematic of the linearized wind-diesel-based power system

FIGURE 3 Type-I IEEE excitation control system with $S_F = 0$[30]



By considering a small-deviation (denoted by prefix Δ), the deviation in system voltage (ΔV) is derived w.r.t. the above-mentioned reactive powers as follows (refer Figure 2)[29]:

$$\Delta V(s) = \frac{K_V}{1 + sT_V}[\Delta Q_{SG}(s) + \Delta Q_{STATCOM}(s) - \Delta Q_L(s) - \Delta Q_{PMIG}(s)] \tag{2}$$

where, T_V is the time constant, K_V is the system gain, ΔQ_{SG} is variation in output reactive power of the diesel-based synchronous generator, $\Delta Q_{STATCOM}$ is the variation in reactive power of STATCOM, ΔQ_L is the change in reactive power load requirement, ΔQ_{PMIG} is the change in reactive power of PMIG, and ΔV is the change in system terminal voltage at PCC.

Furthermore, the small-signal model of a type-1 IEEE excitation control system of the diesel generator with AVR is exhibited in Figure 3. In Figure 3, ΔV_{ref} is the reference voltage deviation. Neglecting the saturation function (ie, $S_F = 0$), the transfer functions of the excitation system are presented as follows[30]:

$$\Delta E_{fd}(s) = \frac{1}{K_E + sT_E}\Delta V_a(s) \tag{3}$$

with

$$\Delta V_a(s) = \frac{K_A}{1+sT_A}\left(\Delta V(s) - \frac{K_F}{T_F}\Delta E_{fd}(s) + \Delta V_f(s)\right) \quad \text{and} \quad \Delta V_f(s) = \frac{K_F}{T_F}.\frac{1}{1+sT_F}\Delta E_{fd}(s)$$

where, ΔE_{fd} is the small change in excitation voltage, K_F is the stabilizer time constant, K_E is the excitation gain constant, T_E is the exciter time constant, K_A is the voltage regulator gain, T_A and T_F are the time constant of the voltage regulator and stabilizer, respectively.

Now, the deviation in armature voltage $\{\Delta E'_q(s)\}$ and reactive power of the diesel-powered synchronous generator $\{\Delta Q_{SG}(s)\}$ under transient condition is obtained in terms of the change in flux linkage (ΔE_{fd}) and voltage deviation (ΔV), which are written as follows[30]:

$$\Delta E'_q(s) = \frac{1}{(1+sT_G)}\left[K_1\Delta E_{fd}(s) + K_2\Delta V(s)\right] \tag{4}$$

$$\Delta Q_{SG}(s) = K_3\Delta E'_q(s) + K_4\Delta V(s) = \frac{1}{(1+sT_G)}\left[K_1\Delta E_{fd}(s) + K_2\Delta V(s)\right]K_3 + K_4\Delta V(s) \tag{5}$$

where, $K_1 = X'_d/X_d$; $K_2 = [(X_d - X'_d)\cos\delta]/X'_d$, $T_G = T'_{do}\, X'_d/X_d$, $K_3 = V\cos\delta/X'_d$, and $K_4 = [E'\cos\delta - 2V]/X'_d$, δ is the power angle of the synchronous generator, X'_d is the direct-axis transient reactance of the SG, T'_{do} is the time constant of the direct-axis transient component, and X_d is the steady-state direct-axis reactance of the SG. Similarly, the variation in the reactive power of the wind-powered PMIG $\{\Delta Q_{PMIG}(s)\}$ is expressed as (6). The equivalent circuit diagram of the PMIG is presented in Figure 4. The detailed small-signal modeling of PMIG can be found in Reference 6.

$$\Delta Q_{PMIG}(s) = K_a\Delta P_{IW}(s) + K_b\Delta V(s) \tag{6}$$

with $K_a = \frac{-2X_{eq}R_Y V^2}{\left(R_Y^2 + X_{eq}^2\right)\left\{2R_Y(P_{IW} - P_{coreloss}) + V^2\right\}}$, $K_b = \left[K_{c1} + \frac{V^2}{X_C}\left\{\frac{\left(3aV^2 + 2bV + c\right)}{\left(3X_C{}^3\right)} - \frac{2}{V}\right\}\right]$.

$K_{c1} = \frac{-2X_{eq}V}{R_Y^2 + X_{eq}^2}\left[1 + \frac{2R_Y R_P V^2}{\left(R_Y^2 + X_{eq}^2\right)\left\{2R_Y(P_{IW} - P_{coreloss}) + V^2\right\}}\right]$, $R_Y = R_P + R_{eq}$, and $X_C = (aV^3 + bV^2 + cV + d)^{1/3}$.where, R_{eq} is the equivalent resistance of PMIG, X_{eq} is the equivalent reactance of the PMIG, ΔP_{IW} is the variation in input wind power, R'_2 and X'_2 are the rotor resistance and reactance corresponding to the primary side of the PMIG, X_M is the mutual magnetizing reactance, X_C is the capacitive reactance, and s is the slip of the PMIG. The design variables: a, b, c, and d are the coefficients of the capacitive reactance component in the PMIG. The value of a, b, c, and d is −7.8681, 15.4268, −9.782, and 1.8899, respectively.[29]

Additionally, the STATCOM is employed to produce/receive the required reactive power for maintaining a balanced three-phase sinusoidal voltage.[6] The schematic outline of STATCOM is presented in Figure 5 which is capable of maintaining a balanced three-phase sinusoidal voltage at the fundamental frequency with controllable voltage amplitude and phase angle. The detailed modeling and operation of thyristor-based STATCOM can be found in Reference 6. For a small perturbation, the variation in reactive power of STATCOM $\{\Delta Q_{STATCOM}\}$ is computed as follows[6]:

$$\Delta Q_{STATCOM}(s) = K_6\Delta V(s) + K_7\Delta\alpha(s) \tag{7}$$

with $K_6 = -kV_{dc}B\cos\alpha$ and $K_7 = kV_{dc}VB\,Sin\alpha$.
where, $\Delta\alpha$ is the change in thyristor firing angle, B is the susceptance of the coupling transformer, and kV_{dc} is the magnitude of the fundamental component of the converter output voltage.

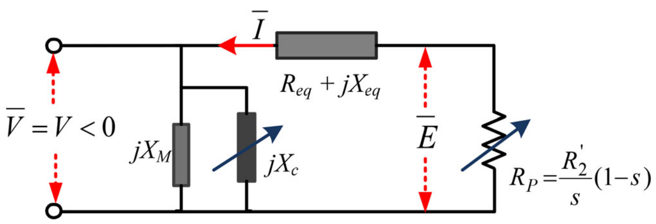


FIGURE 4 Approximate equivalent model of PMIG[6]

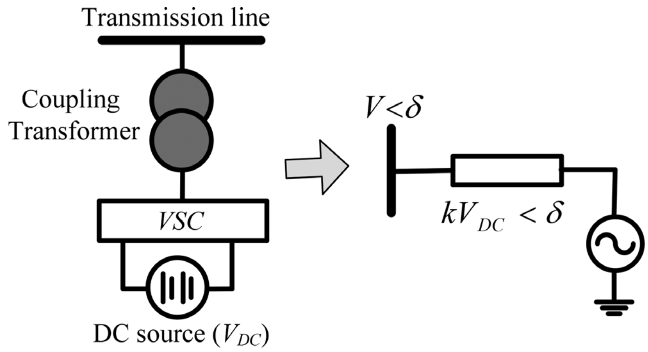


FIGURE 5 STATCOM schematic diagram and equivalent diagram[6]

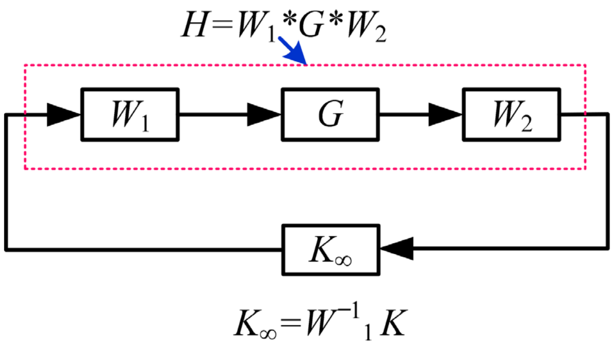


FIGURE 6 H_∞-shaped system controller[31]

3 | H_∞-LOOP SHAPING CONTROLLER DESIGN

From earlier literature studies, it is noticed that the H_∞-controller is a powerful tool to design robust controllers in a nonlinear system with uncertainties in system parameters.[31] It is true that the robustness criteria of a controller are not only the parameter to measure the overall performance of the controllers. However, the system performance parameters like steady-state error, settling time, and under-/overshoot are the important factors to be considered while designing a controller. It is highlighted that fixed structure H_∞-loop shaping technique compensates all these control problems, and the optimization problem is formulated to measure the effectiveness {ie, performance index (γ)} of the designed controller.[31] In this study, STATCOM and AVR are equipped by PI controller, and the optimization problem (ie, objective function) of control parameters are stated by fixed structure H_∞-loop shaping technique for analyzing the robustness of the suggested controller. Furthermore, with the intention of enhancing the reactive power profile of the power system, hybrid BFOA-PSO (hBFOA-PSO) is employed to set the PI control gains of STACOM and AVR. The brief discussion of hBFOA-PSO is presented in Section 4.

The detailed design of the fixed structure robust H_∞-loop shaping controller can be found in Reference 31. The desired shape of open-loop frequency response in the H_∞-loop shaping is obtained by extending the nominal system/plant with precompensator and postcompensator as exhibited in Figure 6. In Figure 6, the shaped plant (H) is derived as $H=W_2GW_1$, where, W_1 and W_2 are the pre- and postcompensator, respectively. G is the transfer function of the plant (in this study, G is derived from the wind-diesel-based power system which is demonstrated in Figure 2), and K_∞ is the controller gain. In this study, the H_∞-norm (γ) is defined as the objective function (J) to tune the PI controller coefficients for improving system performance as expressed in (8). A minimization control assignment is investigated to realize the minimum optimal solution (γ_{min}) of the cost/objective function (ie, Equation (8)). The key objective of the controller is to regulate the reactive power and minimize voltage deviations of the presented power system under load variations or system disturbances.

$$\text{Cost/objective function } (J) = \gamma = \left\| \begin{bmatrix} W_2 \\ W_1^{-1K} \end{bmatrix} \left(W_2 - H(s) W_1^{-1} K(s) \right)^{-1} \begin{bmatrix} W_1^{-1} & H(s) \end{bmatrix} \right\| \quad (8)$$

where, $K = \begin{bmatrix} K_{p1} + \frac{K_{I1}}{s} \\ K_{p2} + \frac{K_{I2}}{s} \end{bmatrix}, W_1 = \begin{bmatrix} 250\frac{s+20}{s+50} & 0 \\ 0 & 150\frac{s+30}{s+40} \end{bmatrix}$ and $W_2 = [\,\mathrm{I}\,]$

$$\text{Subject to}: \begin{matrix} K_{p1,min} \le K_{p1} \le K_{p1,max} \\ K_{p2,min} \le K_{p2} \le K_{p2,max} \\ K_{I1,min} \le K_{I1} \le K_{I1,max} \\ K_{I2,min} \le K_{I2} \le K_{I2,max} \end{matrix} \Longrightarrow \begin{matrix} 1 \le K_{p1} \le 575 \\ 1 \le K_{p2} \le 24000 \\ 0.0001 \le K_{I1} \le 100 \\ 0.0001 \le K_{I2} \le 100 \end{matrix}$$

where, K_{p1} is the proportional gain and K_{I1} is the integral gain of STATCOM and K_{p2} and K_{I2} are the corresponding proportional gain and integral gain of AVR, respectively.

4 | AN OVERVIEW OF BIO-INSPIRED HYBRID BFOA-PSO ALGORITHM

4.1 | Hybrid BFOA-PSO algorithm

PSO is a stochastic search optimization method proposed by Eberhart and Kennedy, stimulated by the social manners of bird or fish schooling/swarming model.[27] In PSO, a direct search method is used to solve optimization problems where each particle adjusts their position in the search space with dynamic self-modified velocity. Established on this schooling/swarming model, the mathematical formulation is designed for upgrading the states (position, velocity) of the particles to obtain the best position/solution.[27]

In addition, the BFOA is a swarm intelligent optimization presented by Dr. Passino. This algorithm is inspired by the foraging (methods of locating, handling, ingesting food) behavior of *E. coli* bacteria in locating their foods and is implemented for dealing with numerous optimization problems. The search mechanism of these bacteria comprises five fundamental steps namely swarming or tumbling, chemotaxis, reproduction, elimination, and dispersal.[28]

With the purpose to enhance the search performance, the hBFOA-PSO algorithm is formulated by using the advantages of the above-mentioned algorithms (ie, the ability of PSO to update its position dynamically on self-modified velocity, elimination, and dispersal performance of BFOA).[25] The hBFOA-PSO algorithm has numerous nested loops in order to improve search performance (ie, achieve the optimal solution and faster convergence).[32] The flowchart of the hBFOA-PSO is exhibited as Figure 7. In this study, the collective performance/parameters of BFOA and PSO algorithms are considered to obtain the hBFOA-PSO algorithm for better-searching ability. In Figure 7, i, j, k, and l are the loop counters for the no. of bacteria (ie, variables/populations), chemotaxis step, reproduction step, and elimination step, respectively. $J(i,j,k,l)$ is the solution/value of the cost function at the ith variable for the kth reproduction step and lth elimination step during the jth iteration. J_{last} is the previously obtained solution/value of the cost function at the ith variable for the kth reproduction stage and lth elimination stage during the jth iteration. To run (ie, to obtain the optimal solution) the algorithms, the value of the BFOA, PSO, and hBFOA-PSO parameters is specified in Table 1. The details of the hBFOA-PSO algorithm can be found in Reference 25.

4.2 | Performance comparison of PSO, BFOA, MGWO, and hybrid BFOA-PSO

In this case study, the efficacy of the hBFOA-PSO algorithm over PSO,[27] BFOA,[28] and MGWO[20] has been verified on executing the objection function (J) of the presented isolated wind-diesel-based power system (Figure 2). GWO is a metaheuristic search optimization algorithm that has been originally introduced by Mirjalili et al.[33] The algorithm is inspired by the hunting behavior of wolves in locating their foods and is used for solving various optimization problems. The details of the GWO algorithm can be obtained in Reference 30. In References 20,21, and 33, the authors have demonstrated that the GWO algorithm has better search performance (eg, faster computational convergence and getting the optimal solution) as compared with other evolutionary algorithms such as PSO, differential evolution (DE), gravitational search algorithm (GSA), etc. Hence, in this work, the search performance of the hBFOA-PSO algorithm is equated with the recently developed MGWO algorithm which is presented in Reference 21. To obtain the optimal solution, the value of the control parameters of the MGWO is taken from Reference 21.

The comparison of convergence curve BFOA, PSO, MGWO, and hBFOA-PSO is displayed in Figure 8, and it shows that the performance indices {ie, achieve the minimal optimal solution of the cost function (J)} against the

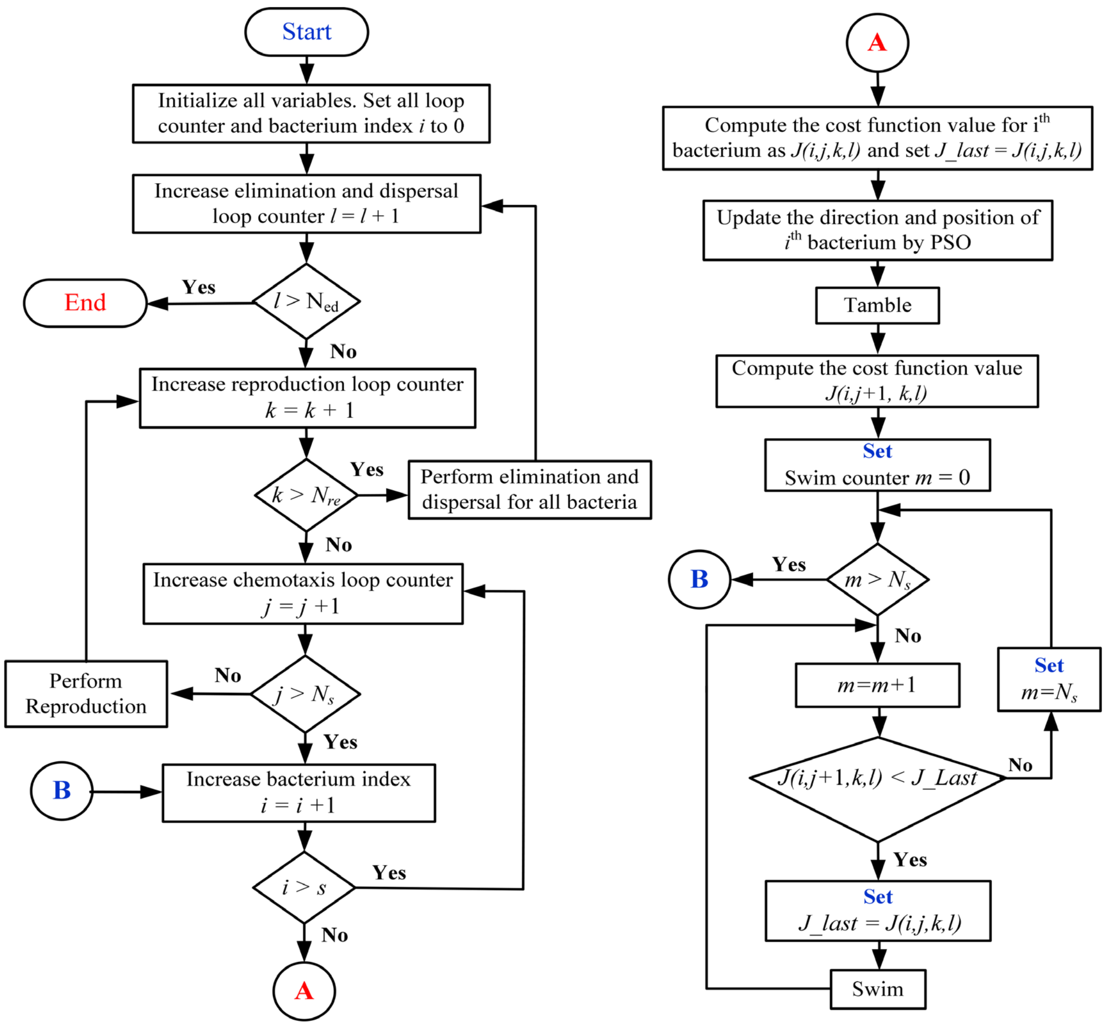


FIGURE 7 Flowchart of the hBFOA-PSO algorithm[25]

TABLE 1 Values of control parameters of the hBFOA-PSO algorithm

Optimization algorithm	Parameters	Value
PSO[25]		
Cognitive parameter	c_1	0.5
Social parameter	c_2	0.5
Average value of momentum or inertia	w	0.5
BFOA[25]	s	50
No. of bacteria or population size	N_C	50
Maximum no. of chemotactic steps or iteration	N_S	4
Length of a swim	N_{re}	2
No. of reproduction steps	N_{ed}	2
No. of elimination-dispersal steps Probability that each bacteria to be eliminated	P_{ed}	0.25

no. of iterations. From Figure 8, it can be investigated that the hBFOA-PSO algorithm reasonably performs a better search performance in terms of optimal solution {ie, performance index (γ_{min}) and faster convergence as compared to PSO, BFOA, and MGWO algorithms. Moreover, it can be observed that all the algorithms achieve their

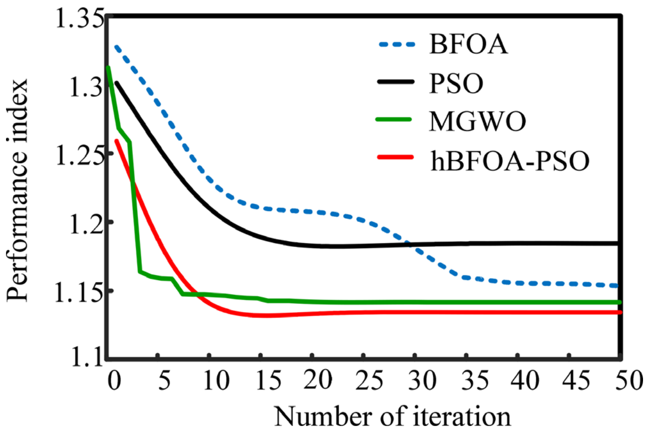


FIGURE 8 Convergence curve for BFOA, PSO, MGWO, and hBFOA-PSO algorithms

TABLE 2 Optimal proportional and integral gains of the PI controller

	STATCOM		AVR	
Optimization algorithm	K_{p1}	K_{I1}	K_{p2}	K_{I2}
PSO	154.5618	13 610.5389	23.8067	36.6399
BFOA	112.4021	22 420.1435	44.5765	49.2008
MGWO	123.0673	24 000	33.1732	100
hBFOA-PSO	132.8909	23 931.1152	13.0948	5.6002

TABLE 3 Comparative Eigen values, settling time of ΔV, and performance index (γ_{min})

Different algorithms	Eigen values 1.0e + 04×	Settling time (t_s) (seconds)	Damping ratio (ξ)	Performance index (γ_{min})
PSO	−6.7822 + 0i −0.0865 + 0i −0.1345 + 1.0746i −0.1345 − 1.0746i −0.0010 + 0.0155i −0.0010 − 0.0155i	0.0031	0.05189	1.1863
BFOA	−6.7543 + 0i −0.0195 + 0i −0.1430 + 0.9945i −0.1430 − 0.9945i −0.0011 + 0.0122i −0.0011 − 0.0122i	0.0030	0.0696	1.1648
MGWO	−6.7443 + 0i −0.0185 + 0i −0.1501 + 0.9361i −0.1501 − 0.9361i −0.0011 + 0.011i −0.0011 − 0.011i	0.0029	0.0871	1.1372
hBFOA-PSO	−6.7377 + 0i −0.0177 + 0i −0.1522 + 0.9154i −0.1522 − 0.9154i −0.0011 + 0.0105i −0.0011 − 0.0105i	**0.0028**	**0.09851**	**1.1358**

minimal objective values (ie, $J_{min} = \gamma_{min}$) for 50 iterations. Hence, for a fair comparison, 50 iterations have been chosen for attaining the minimum value of the cost function and tuning the PI controller gains of STACOM and AVR, in this study. After solving the objective function (J) with considering power system parameters (referring Appendix) and the parameters of the algorithms (referring Table 1), the obtained minimal optimal value (γ_{min}) and the obtained PI controller gains by each algorithm are presented below. The optimal proportional (K_p) and integral (K_i) gains of the PI controllers obtained by PSO, BFOA, MGWO, and the proposed hBFOA-PSO are listed in Table 2.

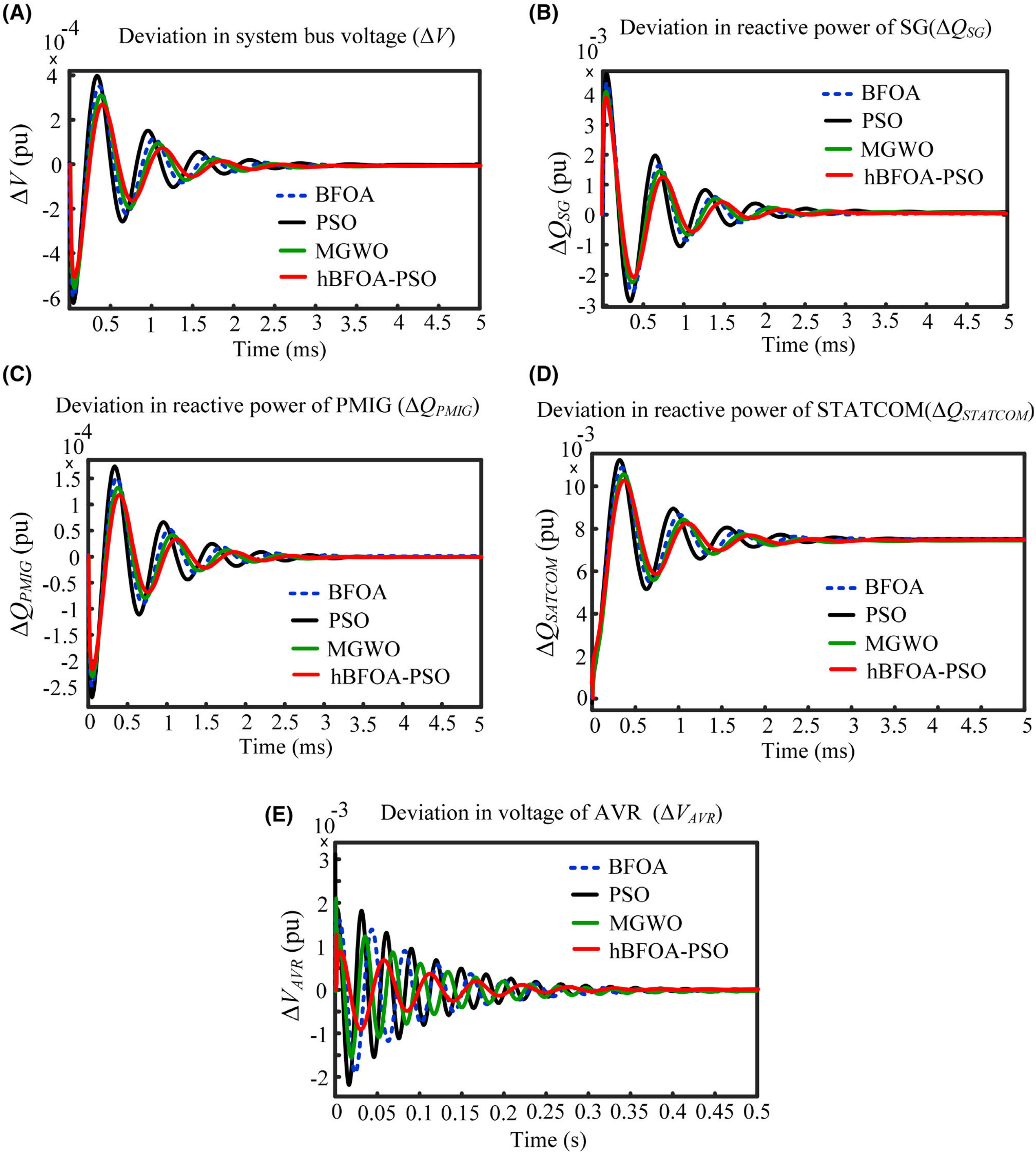


FIGURE 9 Dynamic response for 1% increase in ΔQ_L

TABLE 4 Statistical data/specifications of ΔV for step information

Step info for change in system bus voltage (ΔV)									
Refer Figure 9A	Rise time (s)	Settling time (s)	Settling time min. (s)	Settling time max. (s)	Over shoot	Under shoot	Peak	Peak time (s)
PSO	4.81e-4	3.15e-3	3.015e-3	3.15e-3	4.12e-4	2.95e-4	4.1e-4	4.85e-04
BFOA	4.95e-4	3.05e-3	3.001e-3	3.05e-3	3.72e-4	2.72e-4	3.8e-4	4.95e-04
MGWO	4.98e-4	2.91e-3	2.901e-3	2.98e-3	3.65e-4	2.45e-4	3.6e-4	5.01e-04
hBFOA-PSO	5.01e-4	**2.85e-3**	**2.804e-3**	**2.86e-3**	**3.44e-4**	**2.15e-4**	**3.4e-4**	5.15e-04

5 | SIMULATION RESULTS AND DISCUSSIONS

The time-domain simulation studies are realized using the small-signal linearized model diagram (Figure 2), the objective function (Equation (8)), and the optimized PI controller parameters of STATCOM and AVR (obtained by each algorithm in Section 4.2) by considering different case studies. All simulations and optimization algorithms are implemented in the MATLAB/Simulink power system simulation software. In this work, load reactive power perturbation (ie, ΔQ_L) and change in wind power (ie, ΔP_{IW}) are the input parameters, and voltage deviation (ie, ΔV) is the output parameter. The comparative Eigen values, performance index (γ_{min}), damping ratio (ξ), and settling time (t_s) of the voltage deviation and of the power system for each algorithm are presented in Table 3. Among four different algorithms, the hBFOA-PSO has a higher damping ratio ($\xi = 0.09851$), faster settling time (0.0028 second), and the lowest performance index ($\gamma_{min} = 1.1358$) (represented by bold letters in Table 3) as compared to the BFOA, PSO, and MGWO algorithms. Designing a robust controller with a proper damping ratio indicates that the controller response is sufficient enough to decay the oscillation after disturbance within the desired time frame. The higher the damping ratio slower is the oscillation and reducing the settling time of the system response.[9] From the findings, it can be examined that the hBFOA contributes to superior performance as compared to the BFOA-PSO and MGWO search algorithms.

5.1 | Case I: Step perturbation in load reactive power (ΔQ_L)

For the above-mentioned optimization algorithms, the comparative response of deviation in bus voltage (ΔV) for a 1% step increase in load reactive power (ΔQ_L) at the time (t) = 0 s is displayed in Figure 9 (A). Furthermore, the corresponding dynamic deviations in reactive power of wind-based diesel-powered SG (ΔQ_{SG}), PMIG (ΔQPMIG), STATCOM (ΔQSTACOM) and AVR (ΔQ_{AVR}), in the power system are presented in Figure 9 (B), (C), (D) and (E) respectively. From Figure 9, it can be viewed that the hBFOA-PSO gives a superior dynamic performance (ie, lower oscillations in voltage deviations with faster settling time, rise time, and peak time represented by bold values in Table 4.) relatively than PSO, BFOA, and MGWO. The dynamic statistical data/specifications of ΔV in terms of the settling time, over/undershoot, etc. are described in Table 4. Moreover, the similar observations can be obtained in the ΔQ_{PMIG}, ΔQ_{SG}, ΔQ_{AVR}, and ΔQ_{STACOM} responses for PSO, BFOA, MGWO, and hBFOA-PSO algorithms.

Similarly, the variations in system components such as ΔV, ΔQ_{PMIG}, ΔQ_{SG}, ΔQ_{AVR}, and ΔQ_{STACOM}, for a 5% step increase in load reactive power (Q_L) at $t = 0$ s are shown in Figure 10. The corresponding dynamic deviations in system voltage (ΔV), reactive power of wind-based PMIG (ΔQPMIG), diesel-powered SG (ΔQSG), PMIG (ΔQPMIG), STATCOM (ΔQSTACOM) and AVR (ΔQAVR), and STATCOM (ΔQSTACOM) in the power system are presented in Figure 10 (A), (B), (C), (D) and (E) respectively. From Figure 10, it reveals that the hBFOA-PSO recovers the dynamics of the above-mentioned system components compared than PSO, BFOA, and MGWO algorithms, after system disturbances. Furthermore, from Figures 9 and 10, it can be observed that deviation in system bus voltage is higher for higher the variation in reactive power of the load.

5.2 | Case II: Step perturbation in load reactive power (ΔQ_L) and input wind power (ΔP_{IW})

In this case, a step perturbance in reactive power of load (ie, $\Delta Q_L = 1\%$ increase) and input wind power (ie, $\Delta P_{IW} = 1\%$ increase) occurs simultaneously at $t = 0$ s to present the efficacy of the hBFOA-PSO algorithm. For the above-

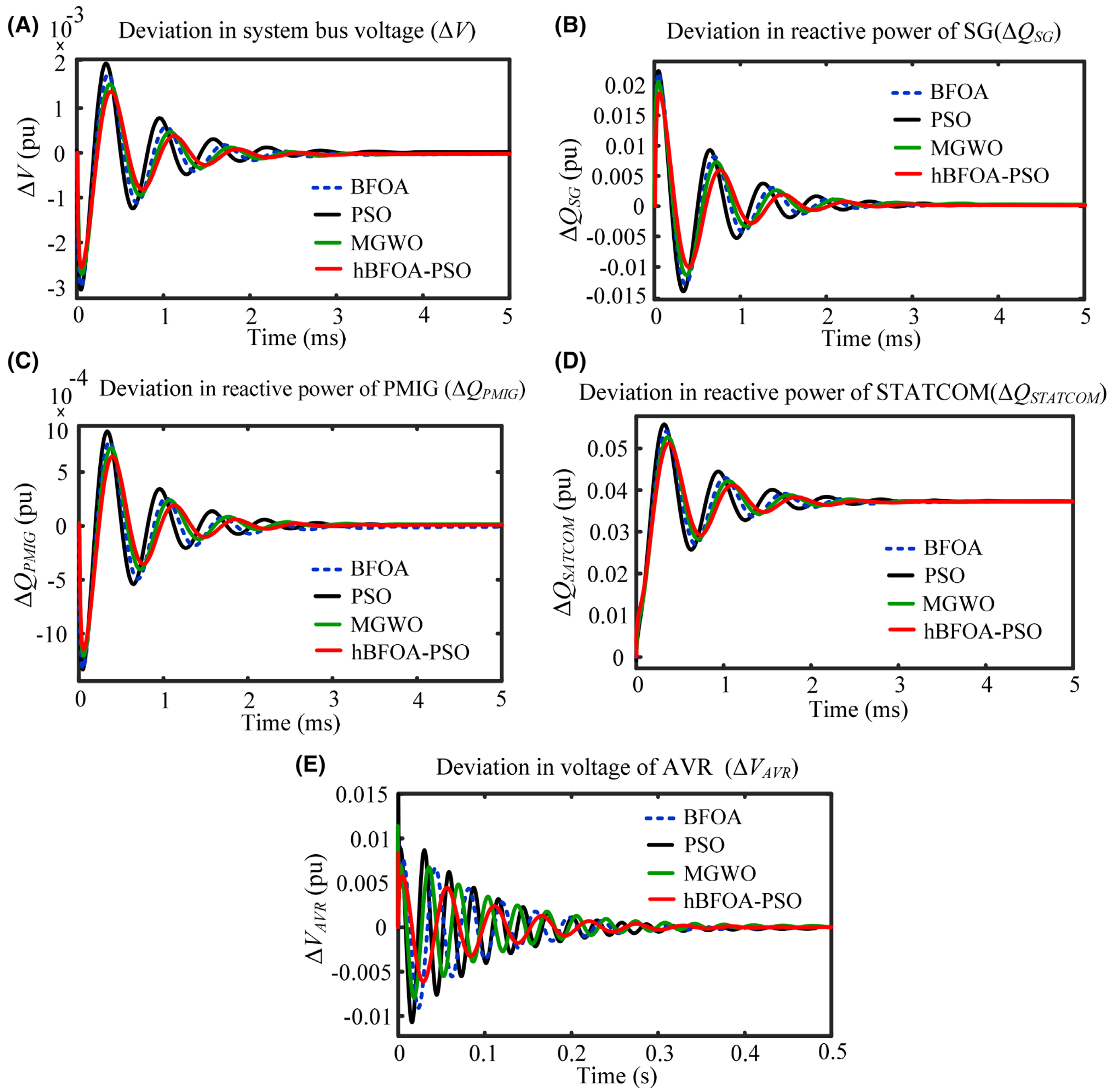


FIGURE 10 Dynamic response for 5% increase in ΔQ_L

mentioned input disturbances, the transient responses of the corresponding dynamic deviations in system voltage (ΔV), reactive power of wind-based PMIG (ΔQPMIG), diesel-powered SG (ΔQSG), PMIG (ΔQPMIG), STATCOM (ΔQSTACOM) and AVR (ΔQAVR), and STATCOM (ΔQSTACOM) in the power system are are displayed in Figure 11 (A), (B), (C), (D) and (E) respectively. Figure 11 represents that the results obtained by the hBFOA-PSO algorithm are improved than MGWO, BFOA, and PSO algorithms.

In practice, the nature of load reactive power and wind power is random in nature which depends on the disturbance at the instant. Hence, in this case, random step change in ΔQ_L and ΔP_{IW} is taken into consideration as in Figure 12 to show the comparative performance of the hBFOA-PSO over PSO, BFOA, and MGWO algorithms. The dynamic responses of ΔV, ΔQ_{PMIG}, ΔQ_{SG}, ΔQ_{AVR}, and ΔQ_{STACOM} are presented in Figure 13 (A), (B), (C), (D) and (E) respectively, for each algorithm. From the findings, it can be noted that the hBFOA-PSO-based reactive power system is more stable and superior than MGWO and when PSO and BFOA algorithms execute individually. It can be established that the hBFOA-PSO is effective for tuning the control gains of the PI controllers in order to enhance the dynamic performance of the power

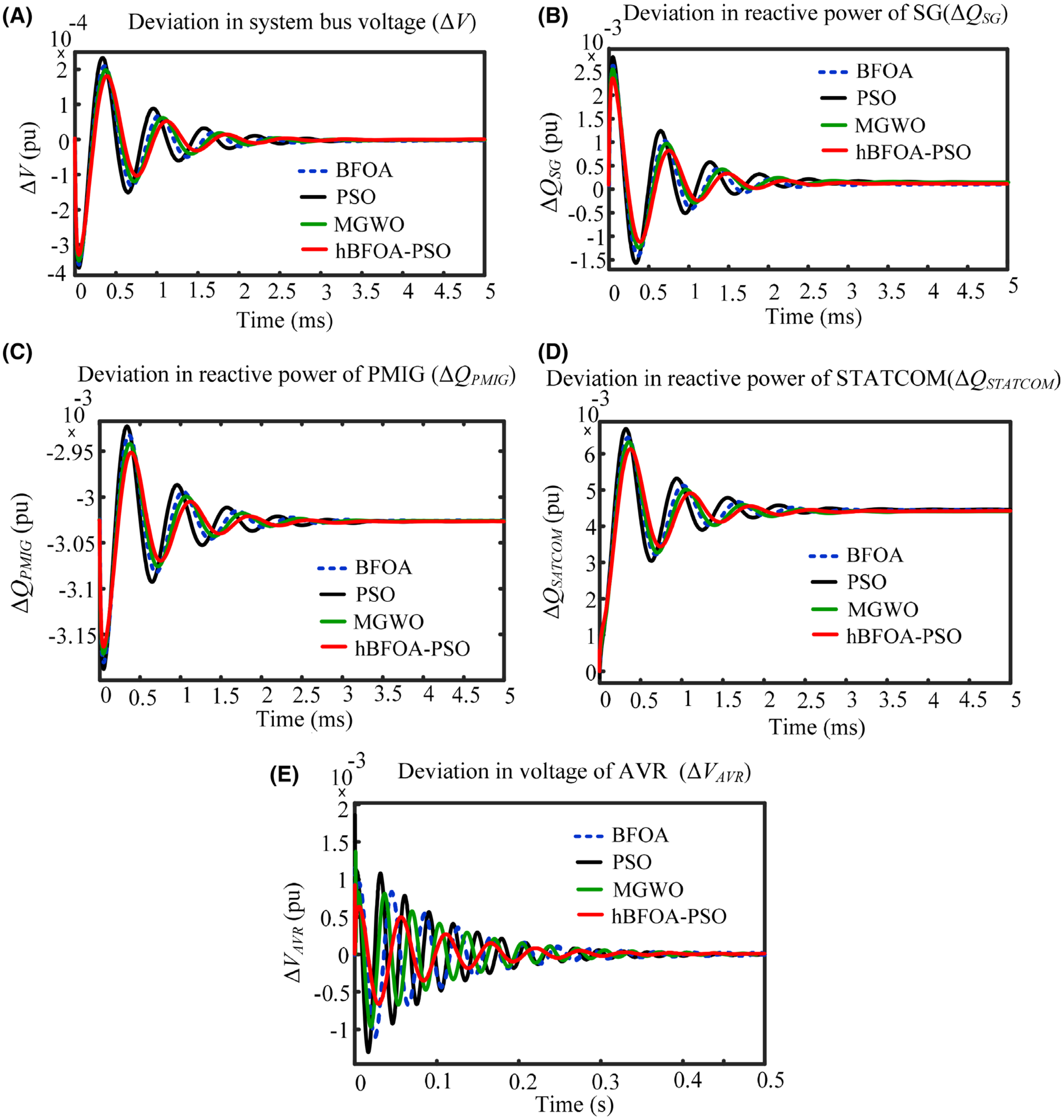


FIGURE 11 Dynamic response of system for 1% increase in ΔQ_L with 1% increase in ΔP_{IW}

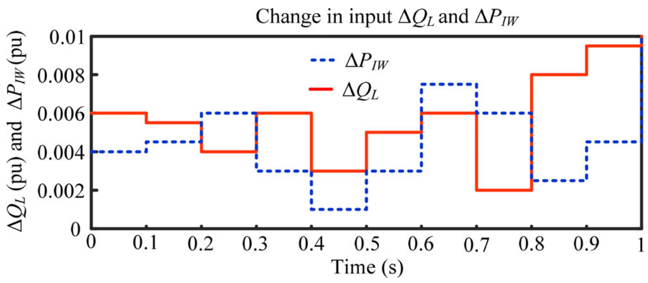


FIGURE 12 Random changes in ΔQ_L and ΔP_{IW}

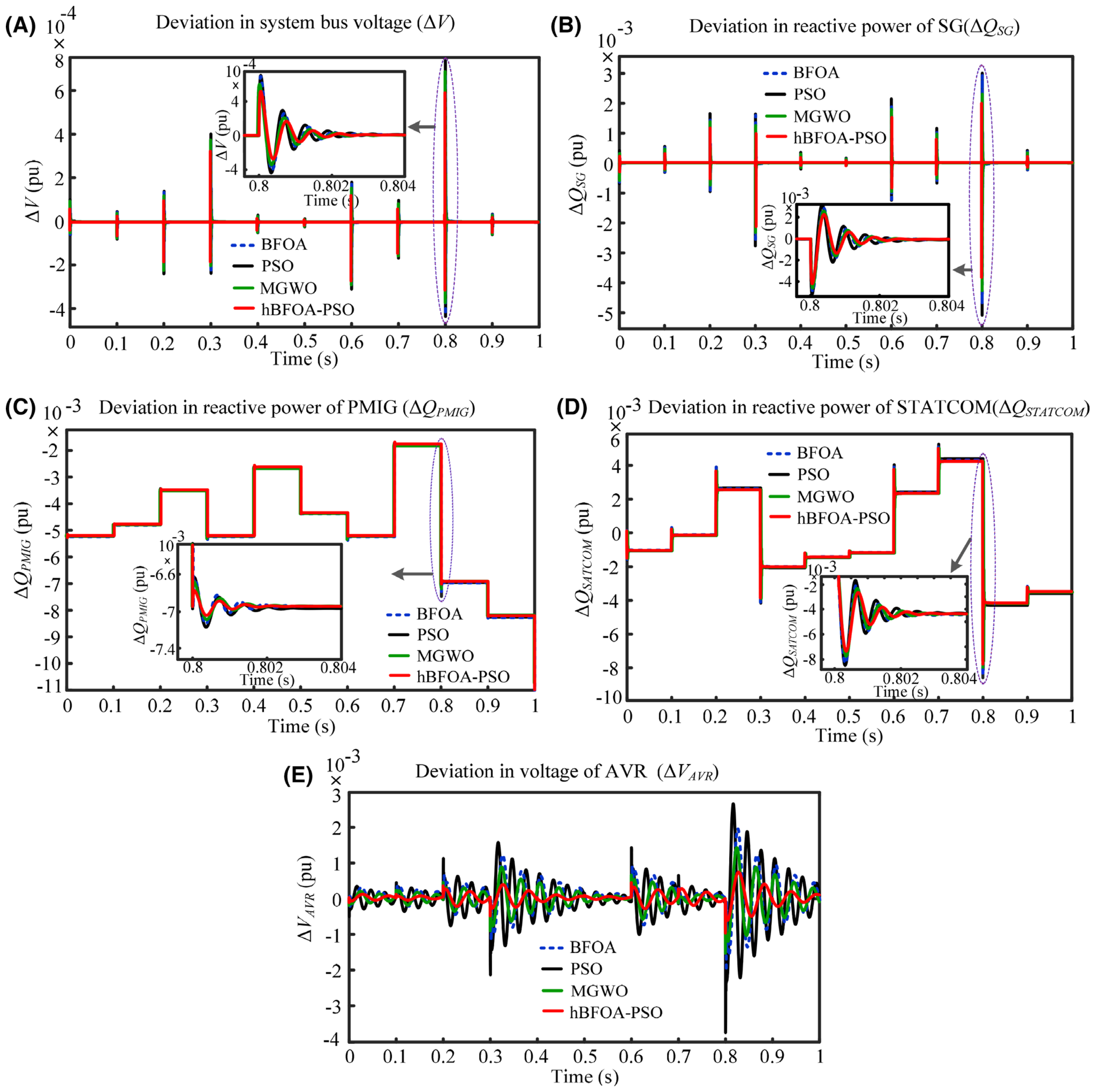


FIGURE 13 Dynamic response for random step variation in ΔQ_L and ΔP_{IW}

system voltage/reactive power profile. Thus, this study is an effort to enable the wind-diesel-based power system to solve the recent environmental and energy crisis issues and offers higher service reliability, increased energy efficiency, and energy independence.

6 | CONCLUSIONS

In this article, the dynamic voltage/reactive power performance of a standalone wind-diesel power system is analyzed by using the hBFOA-PSO optimization technique. The hBFOA-PSO algorithm is used for optimizing the gains of the PI controllers of the AVR and STATCOM in order to improve the voltage stability of the power system and suppress the voltage/reactive power oscillations effectively during the system events such as the variations in power demand and wind speed. The time-domain simulation of the investigated power system model reveals that the hBFOA-PSO algorithm contributes better tuning capability and is relatively robust and stable in comparison to MGWO, BFOA, and PSO algorithms. The H_∞-loop shaping criteria is used for designing and analyzing the robustness (ie, the performance index) of the proposed controller on voltage deviation owing to fluctuation in reactive power. The results indicate that the steady-state performance indices such as a minimum performance index (γ_{min}) and the transient performance indices like settling time, peak time, rise time, and over/undershoots in voltage deviation/reactive power responses are significantly improved for the suggested hBFOA-PSO of the power system.

Though a significant enhancement in the system stability in terms of faster dynamic compensation of voltage and reactive power is achieved with the proposed controller, the hBFOA-PSO may be applied to solve some other engineering optimization problems. Modification of the proposed algorithm and propose of new hybrid optimization algorithms can be studied in future research work.

PEER REVIEW

The peer review history for this article is available at https://publons.com/publon/10.1002/2050-7038.12778.

DATA AVAILABILITY STATEMENT

This manuscript does not contain any data.

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How to cite this article: Wagle R, Sharma P, Sharma C, Gjengedal T, Pradhan C. Bio-inspired hybrid BFOA-PSO algorithm-based reactive power controller in a standalone wind-diesel power system. *Int Trans Electr Energ Syst*. 2021;31:e12778. https://doi.org/10.1002/2050-7038.12778

APPENDIX A

Modeling/design parameters/data of the presented power system

System parameters/data	Value	SI-unit
System load/capacity		
Wind capacity	150	KW
Diesel capacity	150	KW
Load capacity	250	KW
Base power	250	KVA
Synchronous generator		
P_{SG}	0.4	p.u.
Q_{SG}	0.2	p.u.
E_q	1.1136	p.u.
δ	21.05	°
E_q'	0.9603	p.u.
V	1	p.u.
X_d	1	p.u.
X_d'	0.15	p.u.
T_G	5	s
Permanent magnet induction generator		
P_{PMIG}	0.6	p.u.
Q_{PMIG}	0	p.u.
$R_1 + R_2'$	0.19	p.u.
$X_1 + X_2'$	0.59	p.u.
S	−4.0	%
Load		
P_L	1	p.u.
Q_L	0.75	p.u.
Power factor (lag)	0.8	
Reactive power data		
$Q_{STATCOM} + Q_{SG} = Q_{PMIG} + Q_L$	0.739	p.u.
Q_c	0.85	p.u.
A	2.443985	radian
IEEE type-1 excitation system		
K_A	40	
T_A	0.05	s
K_F	0.5	
T_F	0.715	s
K_E	1	
S_F	0	s
T_E	0.55	s
STATCOM data		
T_{alfa}	0.00025	s
T_d	0.00167	s

Paper B. Optimal Power Flow based Coordinated Reactive and Active Power Control to mitigate voltage violations in Smart Inverter Enriched Distribution Network

Raju Wagle, Pawan Sharma, Charu Sharma, and Mohammad Amin

International Journal of Green Energy, 2023, Pages 1-17.

https://doi.org/10.1080/15435075.2023.2196324

The article is published with open-access publication.

Candidate: **Raju Wagle**

Corresponding Author: **Raju Wagle**

Authors Contribution:

The idea to do further research in optimal power flow based coordinated reactive and active power control to mitigate voltage violations in smart inverter enriched distribution network was identified by the candidate. The implementation of the methodology, utilization of software, data curation, formal analysis, writing of original draft, validation, and visualization of the paper was done by the candidate.

All other coauthors are the co-supervisor of Mr. Raju. All co-authors contribute to the review, correction, and proofreading of the manuscript.

International Journal of Green Energy

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/ljge20

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To cite this article: Raju Wagle, Pawan Sharma, Charu Sharma & Mohammad Amin (2023): Optimal power flow based coordinated reactive and active power control to mitigate voltage violations in smart inverter enriched distribution network, International Journal of Green Energy, DOI: 10.1080/15435075.2023.2196324

To link to this article: https://doi.org/10.1080/15435075.2023.2196324

Published online: 30 Mar 2023.

INTERNATIONAL JOURNAL OF GREEN ENERGY
https://doi.org/10.1080/15435075.2023.2196324

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Optimal power flow based coordinated reactive and active power control to mitigate voltage violations in smart inverter enriched distribution network

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ABSTRACT

Voltage violations are the main problem faced in distribution networks (DN) with a higher penetration of inverter-based generations (IBG). Active and reactive power control from smart inverters (SI) can mitigate such violations. Optimal power flow (OPF)-based control provides more accurate operating set points for the coordinated operation of SIs. Therefore, this paper presents a three-phase OPF-based control on SI-enriched unbalanced distribution networks. To consider this, first three-phase model using the current injection model (CIM) is developed. Later, the optimal active and reactive power set points for SIs are obtained by solving a quasi-dynamic optimization problem. The uniqueness of the proposed method is that it regulates the voltage at the affected nodes by obtaining the optimal set points for the smart inverter. The OPF is implemented with a mathematical CIM in Pyomo and solved using the Knitro solver. The proposed method is compared with the sensitivity-based Volt-Var Control (VVC), Volt-Watt Control (VWC), and combined VVC and VWC methods. The effectiveness of the proposed method is verified in a European low-voltage and CIGRE medium-voltage distribution network with 100% penetration. The analysis shows that the OPF-based control optimizes with less network loss and can maintain voltage violations with less reactive power support.

ARTICLE HISTORY
Received 29 August 2022
Accepted 19 March 2023

KEYWORDS
Active power curtailment; Inverter-based generations; Optimal power flow; Reactive power control; Smart inverter enriched distribution network

1. Introduction

The integration of inverter-based generations (IBG) into the low voltage (LV) power distribution network is increasing over time (IEA 2019). With a higher penetration of IBG, distribution networks experience many technical challenges, especially the increase in the voltage of the grid above critical values (Khodayar, Ramin Feizi, and Vafamehr 2019). In particular, voltage violations are an essential problem that needs to be addressed to incorporate a high penetration of IBG. Voltage violations are more noticeable when loads have a low/high power demand and IBG have high/low power generation (Wang, Yan, and Saha 2019). Furthermore, the inherent resistive nature (high R/X) of the LV network makes the voltage increase issue more vulnerable. Single-phase loads in LV networks are initially connected in different phases with the intention of maintaining balance in all phases. But with an increasing number of customers, the LV networks become unbalanced. And this will increase more when the single-phase IBG is connected to the LV networks. The optimal size and location (HassanzadehFard and Jalilian 2018) of such an IBG may solve some of the problems but not all of the challenges. Conventional voltage regulating devices (VRD), such as on-load tap changer transformers (OLTC), step voltage regulators, and switched capacitor/inductor banks may not be reliable solutions in such cases due to their limited capacity and slow operating response (Liu, Canizares, and Huang 2009). And they may not be effective in handling the voltage problem more precisely when the power fluctuation from IBG and loads is high.

One of the appropriate approaches to handling voltage problems in the LV distribution network is the application of active and reactive power control from smart inverters (SI) (Song and Kim 2022). Since SIs are equipped with an advanced communication and monitoring infrastructure, they are considered suitable for control and monitoring applications. Active and reactive power control from SI has its own advantages and challenges. Reactive power control is less effective in the case of LV networks, as this method increases network losses due to the high R/X ratio of the interconnecting lines. Also, the high value of R/X in LV networks limits the effect of reactive power control in LV networks (Nour et al. 2019). Moreover, the amount of reactive power contribution from the SI is limited, and hence it might not regulate the voltage within the acceptable range. Active power curtailment (APC) is considered another effective and efficient method of regulating voltage in LV networks (Nour et al. 2019; Singh and Lather 2020; Tonkoski and Lopes 2011) when power generation is extremely surplus and power curtailment is the only available solution. However, APC is not suitable for those instances where voltages are below the prescribed limits due to the unavailability of power production from IBG. Furthermore, the reduction in power generation to regulate voltage may not be a motivating factor to increase the integration of green energy. Therefore, it is recommended to take advantage of the power control capability of SI in an optimal way, minimize active power curtailment, and regulate voltage in LV distribution networks.

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Controlling the output of active and reactive power from SI can be achieved using various methods (chaudhary and Rizwan 2018). Several studies on local control strategies are considered in the literature (Acosta et al. 2021; Ceylan, Paudyal, and Pisica 2021; Ghosh, Rahman, and Pipattanasomporn 2017; Kim, Song, and Jang 2020; Ku et al. 2015; Li et al. 2020; Molina-García et al. 2017; Nithara and Anand 2021; Wagle et al. 2021; Zhang, Ochoa, and Valverde 2018). Local control strategies are fast and can act with local settings to mitigate voltage problems. In addition, local control operates as an independent entity, so it does not require a huge investment in monitoring and controlling infrastructure. However, the main challenge of the local control technique is the lack of coordinated operation. Additionally, local control techniques suffer from the unequal contribution of SI for voltage regulation. The SI nearest to the substation contributes less, whereas the SI farther away from the substation bears more responsibility. Moreover, local control methods require information about the threshold settings for voltage and power for the controller to become effective. These settings for $Q(V)$, $Q(P)$, and $P(V)$ are defined in the IEEE 1547–2018 standard (IEEE standard 2020). Before implementing the control action, users can set these values based on the type and nature of the network under consideration.

The implementation of centralized methods is one of the solutions to problems related to the coordinated operation of multiple smart inverters (SIs). Since today's SIs are equipped with advanced communication infrastructure, they can be used in centralized control without the additional financial burden of installing a communication system. Additionally, IEEE 1547–2018 requires that all SI have communication capabilities. Therefore, a centralized OPF-based strategy for inverter control may be practical in IBG-enriched distribution networks. When centralized control is implemented, optimal SI operation can be achieved. In (Weckx, Gonzalez, and Driesen 2014), a centralized optimization-based method is proposed to generate linear control functions for local controllers for reactive power control. In (Su, Masoum, and Wolfs 2014), the authors suggested using an OPF-based method to determine the optimal set points of active and reactive power for the inverters. Similarly, in (Zhao et al. 2015), an OPF-based formulation with adaptive weight on the objective function is used to ensure uniform curtailment. Recent studies combine centralized and distributed methodologies. To determine the ideal PV curtailment, the authors in (Ferreira et al. 2013) proposed a local control technique and a linear centralized optimization strategy based on sensitivity. Distributed control was suggested in (Olivier et al. 2016) to methodically regulate the reactive power and reduce the active power. In some recent studies, dynamic optimization is also performed considering dynamic load and PV model (Liu et al. 2022).

Although the OPF-based control approach is not a new field in the optimization of distribution networks. Several attempts have been made to formulate the optimization problem (ali 2019). However, in most of the earlier literature, modeling of the distribution network is given less priority. The mathematical model of the distribution network is done either considering the balanced network or using sensitivity-based modeling. The authors in (Ceylan, Paudyal, and Pisica 2021) proposed a local control strategy based on nodal sensitivity and the OPF-based method to regulate voltage using smart inverter reactive power control. However, the authors consider only the generic formulation of the OPF and solve the optimization problem by co-simulation. In (Ma et al. 2021), worst-case voltage scenarios are presented to reduce voltage fluctuations in distribution networks using centralized voltage control in a generally balanced distribution network. Modeling of the distribution network considering the balance nature and using single-phase modeling may not represent a realistic distribution network. Due to some specific characteristics of distribution networks, such as their radial nature, unbalanced operation, mixed loading models, and the number of nodes and branches, classical load flow models such as Newton-Raphason or Gauss-Seidal may not converge. To cope with such challenges in distribution networks, several three-phase power flow methods are proposed in the literature, such as the backward-forward sweep (BFS) (Bompard et al. 2000) and the current injection method (de Oliveira Alves et al. 2020) for distribution networks. The convergence of the BFS method is correlated with the size of the equivalent line impedance and the load admittance, which limits the application of BFS in a large unbalanced distribution network. Compared to BFS, the current injection method converges faster even for an unbalanced and heavily loaded three-phase network (Tostado-Véliz, Kamel, and Jurado 2021). Furthermore, the current injection method can be implemented with the measurement data of the energy meters installed in the distribution network. To consider this, the authors of (Alabri and Jayaweera 2020) modeling of the three-phase unbalanced distribution network use a current injection model. However, due to the reactive power limits of the smart inverter, controlling only the reactive power of the SI may not fully solve the voltage problems in a highly IBG-penetrated case.

In addition, the SI provides or absorbs reactive power to prevent voltage violations, which can increase network losses. Active power curtailment, although not desirable, may be used in conjunction with reactive power control to overcome the smart inverter's capacity restriction. Proper coordination of the amount of reactive power and active power curtailment is an important factor to consider for optimal control using a smart inverter. Active and reactive power control can be implemented in a coordinated manner when other options are not available to mitigate voltage violations (IEEE standard 2020). The control of active and reactive power is considered in (Bozalakov et al. 2019), but the authors ignore the unpredictability of the PV power supply and load demand. Without considering the variability of generation and load, a realistic situation may not be represented. To the author's best knowledge, active and reactive power control from multiple smart inverters considering unbalanced modeling of the distribution network with the focus on reactive power support from a smart inverter has not been studied in the literature. With increasing concern for reactive power auxiliary services (Tricarico et al. 2022) and real-time control (Wagle et al. 2022) in the distribution network, the analysis performed in this paper is of significant importance in choosing an optimal control approach. Therefore, in this paper, considering realistic data from IBG, load, and a three-phase unbalanced model of the distribution network, reactive and active power control based on OPF from an SI is proposed in an IBG-enriched distribution network. The optimal active and reactive set points for smart inverters are obtained by solving a quasi-dynamic constrained optimal power flow problem. The uniqueness of the proposed method is that it regulates the magnitude of the voltage at the affected nodes by obtaining the optimal set points of active and reactive power from the smart inverter.

Therefore, in this paper, considering the 100% penetration of IBG (at all load buses), an OPF-based coordinated reactive power control and active power curtailment are proposed to mitigate voltage violations in the smart inverter-enriched distribution network. A fair comparison of the proposed method with the standalone Volt-Var Control (VVC), Volt-Var Control (VWC), and combined VVC and VWC-based control is performed. The main contribution of this paper is the formulation of optimal power flow-based reactive and active power control from SI considering modeling a three-phase unbalanced distribution network. The three-phase modeling of the system may represent a realistic distribution network. Therefore, the analysis of this model offers a more convincing analysis. Furthermore, since the use of the reactive power from SI increases network losses, the support of the reactive power from them is an important factor to consider. This paper focuses on the amount of reactive power support and network loss as major factors in evaluating the performance of control approaches. Using the proposed method, the distribution network can run with fewer network losses and keep the voltage profile within the set limits. This study seeks to create an accurate comparison based on the contribution of reactive power between control schemes. This research can help researchers in the reactive power market choose the best method to implement control approaches for smart inverters. The following are the major contributions of the authors in this work.

- An OPF-based approach is proposed to mitigate voltage violations in smart inverter-enriched three-phase unbalanced LV and MV distribution networks. To consider the unbalanced nature of the distribution network, three-phase modeling of the distribution network based on the current injection model is used. When solving the proposed OPF, coordinated set points for reactive power support and active power curtailment are obtained for multiple SIs to mitigate voltage violations.
- The formulation of the optimization model is considered based on the real-time data from the IBGs and the loads. The quasi-dynamic simulation over a period of the day with a 5-min resolution is performed.
- Furthermore, the OPF-based approach is compared with the standalone sensitivity-based Volt-Var Control (VVC), Volt-Watt Control (VWC), and combined VVC and VWC methods. A comparative analysis of the two methods is performed with respect to the voltage performance index, total network loss, total reactive power contribution, and the total amount of active power curtailment to make a fair comparison between the two different approaches.
- The contribution of reactive power support from the smart inverter is computed and analyzed for various control approaches on two highly IBG-penetrated distribution networks. According to the analysis, if the SI is equipped with a communication and monitoring infrastructure, the OPF-based method may be a suitable option to regulate voltage violations.

The remainder of the paper is organized as follows. Section 3 elaborates on the details of voltage control in SDN using local and central control methods. Section 4 describes the overall methodology for obtaining reactive and active power control based on OPF. Section 5 provides a detailed consideration of the test network, the simulation results, and the discussion. Finally, the main conclusions drawn from this paper are provided in the last section.

2. Methods of voltage control in smart inverter

Massive integration of IBG has the potential to alter the operation of power distribution networks so that the substation is no longer the exclusive source of electricity and short circuit capacity. The integration of IBG presents technical challenges, as power production and demand may not match. For example, exceeding the actual power injection more than the power demand may cause the voltage to rise above safe levels. Maintaining the voltage within the allowed range is essential to prevent damage to client appliances. As a result, numerous regulations, regulations, and voltage fluctuation limitations have been implemented. The limitations of voltage fluctuation are $\pm 10\%$ and $\pm 5\%$, respectively, according to EN 50,160 and ANSI C84.1–2011 standards (Nour et al. 2019). The techniques generally used to control the voltage in smart inverters are detailed in the following subsections.

3. Methods of voltage control in smart inverter

Massive integration of IBG has the potential to alter the operation of power distribution networks so that the substation is no longer the exclusive source of electricity and short circuit capacity. The integration of IBG presents technical challenges, as power production and demand may not match. For example, exceeding the actual power injection more than the power demand may cause the voltage to rise above safe levels. Maintaining the voltage within the allowed range is essential to prevent damage to client appliances. As a result, numerous regulations, regulations, and voltage fluctuation limitations have been implemented. The limitations of voltage fluctuation are $\pm$ 10% and $\pm 5\%$, respectively, according to EN 50,160 and ANSI C84.1–2011 standards (Nour et al. 2019). The techniques generally used to control the voltage in smart inverters are detailed in the following subsections.

3.1. Local voltage control methods using smart inverter

Smart Inverters (SI) can supply both inductive and capacitive reactive power to maintain the voltage profile (Srinivasarangan Rangarajan, Sharma, and Sundarabalan 2020) at the point of common coupling. For voltage control applications, the IEEE 1547–2018 standard (IEEE standard 2020) requires the active and reactive power output requirements of SI. According to this standard, SI can supply inductive or capacitive reactive power up to a maximum of 44% of the rated capacity. The application of only reactive power control might not effectively mitigate voltage violations. In addition, reactive power support affects network loss. Active power curtailment is not so desirable, as the owner suffers financially due to curtailment in power production. To effectively manage voltage violations, it is prudent to effectively coordinate reactive power control and active power curtailment. Therefore, in this paper, combined VVC and VWC are considered as a local voltage control method. Furthermore, instead of considering different types of IBG, for simplicity, only PVs are considered. This method is more focused on the operation of the SI and therefore remains independent of the type of IBG considered. Equation (1) (IEEE standard 2020) mathematically represents the combined VVC and VWC. In Equation (1), Q_1, Q_4, v_1, v_2, v_3, v_4 and v_5, are considered fixed quantities in this study and are capacitive 0.44 p.u., inductive 0.44 p.u., 0.92 p.u., 0.98 p.u., 1.02 p.u., 1.035 p.u. and 1.1 p.u. Q_2 and Q_3 are considered 0 p.u. during the normal voltage operation period, which is from 0.98 p.u. to 1.02 p.u., as the controller does not intervene during these periods. P_1 and P_2 are the rated power and the minimum allowable production during active power curtailment. The settings are selected considering the combined effect of the VVC and VWC control. The settings can also be optimally calculated, as in (Lee et al. 2020). For this analysis, all PVs in the network have the same VVC and VWC settings. Figure 1 shows the IEEE standard.

In Algorithm 1, the overall process of the combined operation of the Volt-Var control (VVC) and Volt-Watt control (VWC) modes in an SI is represented. The power flow is executed using OpenDSS and Matlab co-simulation. The bus voltages at the nodes where the IBG is installed are continuously monitored. Depending on the magnitude of the bus voltage, for all SIs in the network, the VVC is first implemented. After the implementation of the VVC, the power flow is executed again, and if the node voltage is not regulated by the application of the VVC, then the VWC is implemented in the SIs connected to the nodes where there are still voltage violations.

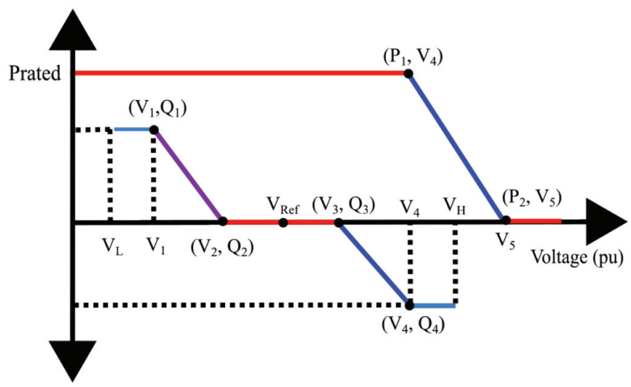


Figure 1. IEEE 1547–2018 standard (ieee standard 2020).

$$(Q,P)(v)=\begin{cases} Q_1, P_{rated} & for\ v \leq v_1 \\ Q_2+\frac{Q_1-Q_2}{v_1-v_2}(v-v_2), P_{rated} & for\ v_1 < v \leq v_2 \\ 0, P_{rated} & for\ v_2 < v \leq v_3 \\ Q_3+\frac{Q_4-Q_3}{v_4-v_3}(v-v_3), P_{rated} & for\ v_3 < v \leq v_4 \\ Q_4, P_2+\frac{P_2-P_1}{v_5-v_4}(v-v_4) & for\ v_4 < v \leq v_5 \\ Q_4, P_2 & for\ v > v_5 \end{cases} \quad (1)$$

Algorithm 1 An algorithm for combined VVC and VWC of a Smart Inverter

Require: $t \geq 0$, $n \geq 0$, $m \geq 0$,$k \geq 0$, $P_k^L(t) \geq 0$, $Q_k^L(t) \geq 0$
Ensure: $t = 0$, $m = 0$, $V_n(0) \geq 0$, $P_m^{PV}(0) \geq 0$, $Q_m^{PV}(0) = 0$
while $t \leq T$ **do Initialization**
  while$m \leq n-1$ **do Implement VVC**
    if $V_m(t) > v_2$ & $V_m(t) \leq v_3$ **then**
      $Q_m^{PV}(t) = 0$
      $P_m^{PV}(t) = P_{rated}$
    else if $V_m(t) \leq v_1$ **then**
      $Q_m^{PV}(t) = Q_1$
      $P_m^{PV}(t) = P_{rated}$
    else if $V_m(t) > v_1$ & $V_m(t) \leq v_2$ **then**
      $Q_m^{PV}(t) = Q_2 + \frac{Q_1-Q_2}{v_1-v_2}(v-v_2)$
      $P_m^{PV}(t) = P_{rated}$
    else if $V_m(t) > v_3$ & $V_m(t) \leq v_4$ **then**
      $Q_m^{PV}(t) = Q_3 + \frac{Q_4-Q_3}{v_4-v_3}(v-v_3)$
      $P_m^{PV}(t) = P_{rated}$
    else if$V_m(t) > v_4$ **then**
      $Q_m^{PV}(t) = Q_4$
      $P_m^{PV}(t) = P_{rated}$
    end if
  end while
set P **and** Q **and Run power flow**
Obtain voltage after VVC
  while $m \leq n-1$ **Implement VWC**
    if $V_m(t) > v_4$ & $V_m(t) \leq v_5$ **then**
      $P_m^{PV}(t) = P_2 + \frac{P_2-P_1}{v_5-v_4}(v-v_4)$
    else if $V_m(t) > v_5$ **then**
      $P_m^{PV}(t) = P_2$
    end if
  end while
set P **and** Q **and Run power flow**
Compute voltage after VWC
end while

3.2. Centralized voltage control methods in smart inverter

In a centralized control, the set points required for active power and reactive power are sent from a central controller. Reactive power support and active power curtailment to prevent voltage violations or to limit voltage within a certain voltage band are produced by optimal power flow solutions in centralized control. This optimization may be carried out by a centralized controller (Maharjan, Khambadkone, and Peng 2021) or by intelligent smart inverters that communicate with each other in a distributed manner (Wagle et al. 2023).

Reactive power can only be delivered in a certain quantity. The portion of the inverter capacity reserved for reactive power may not be sufficient to maintain the voltage at acceptable levels during substantial active power generation. Moreover, the impact of the reactive power is constrained by the large R/X values in LV networks. Therefore, active power curtailment is necessary to avoid exceeding the upper voltage limit. Methods to reduce active power are suggested in (Kashani, Mobarrez, and Bhattacharya 2017; Noh et al. 2019). The owner of the IBG suffers directly from this curtailment since less power will be produced. Therefore, it is wise to use the available reactive power as efficiently as possible and to reduce the active power curtailment. This can be achieved by an OPF-based centralized controller using the penalty factor in the objective function. The process of achieving OPF-based reactive and active power control from the smart inverter is explained in Section 4

4. Overall methodology of OPF based reactive and active power control from smart inverter

Figure 2 shows the overall method for optimal reactive and active power control from a smart inverter. The distribution network is first modeled in OpenDSS (EPRI 2007). Simulations collect power flow solutions based on test data defined in Section 5, network information (such as Y_{bus}, I, V), and sets and parameters of the optimization model. The optimization model consists of a number of user-defined functions that collect and process measurement data (obtained from energy meters installed on the test network) that are required for optimization. Pyomo is used to create a mathematical model based on the information obtained, as described in Sections 4.1 and 4.2. This work is inspired by (Rigoni and Keane 2019), which creates an open-source tool for optimal co-simulation between OpenDSS and Python. In reality, the reactive and active power of each instance obtained from the optimization is fed to the SIs, thereby completing the cycle of the overall process. However, in this work, the optimization model computes the optimal reactive and active power required to maintain the voltage profile. All monitored parameters are calculated from the mathematical model developed in this study. The simulation is performed in a time step of 5 min. The optimization process is carried out for a period of one day. A detailed description of the distribution network modeling and the formulation of the optimization model is described in the following subsections.

4.1. Modeling of 3 phase unbalanced network

The formulation of a mathematical model of a three-phase unbalanced distribution network plays an important role in obtaining optimal voltage control (Rigoni and Keane 2020). In the power system, load flow problems are solved using the Newton-Raphson method or the fast decoupled method new-(Monticelli, García, and Saavedra 1990). However, due to some specific characteristics of distribution networks, such as their radial nature, unbalanced operation, mixed loading models, and the number of nodes and branches, the classical load flow

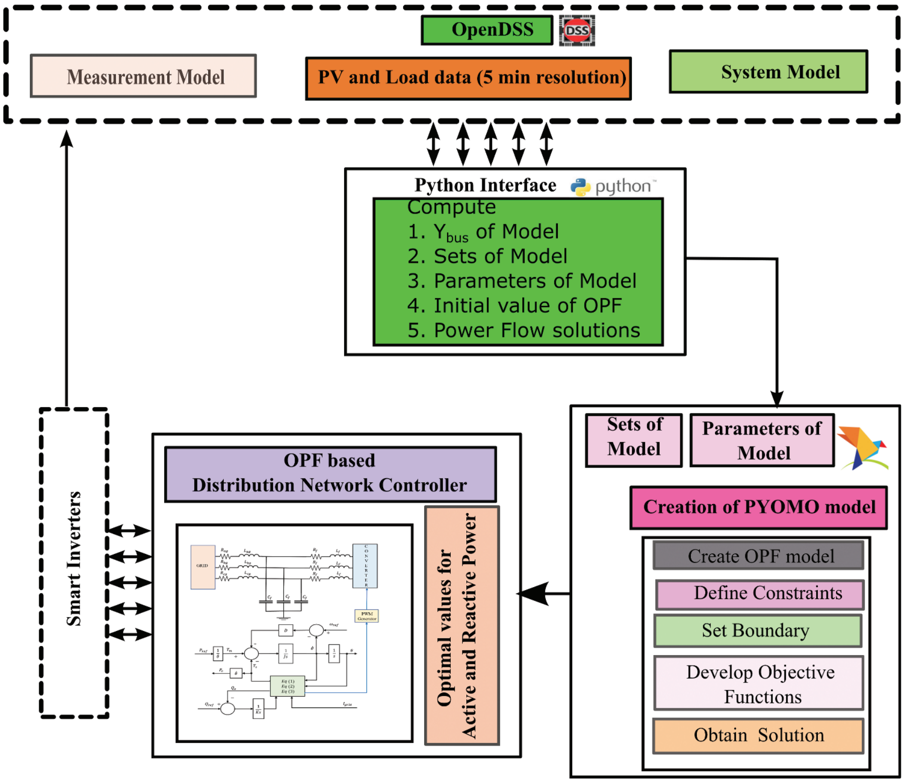


Figure 2. Overall block diagram to perform the OPF-based reactive and active power control in Smart Inverter.

models may not converge. To address the challenges in distribution networks, several three-phase power flow methods, such as the backward-forward sweep (BFS) (Bompard et al. 2000) and the current injection method (de Oliveira Alves et al. 2020) for distribution networks, are proposed in the literature. The convergence of the BFS method is correlated with the size of the equivalent line impedance and the load admittance, which limits the application of BFS in a large unbalanced distribution network. Compared to BFS, the current injection method converges faster even for an unbalanced and heavily loaded three-phase network (Tostado-Véliz, Kamel, and Jurado 2021). In this paper, the current mismatch method obtained from the current injection model is used to mathematically formulate the model. To simplify the modeling, neutral cables are explicitly neglected in this analysis. Nodal voltage phasors are represented in terms of active and reactive power injections/absorption from generators/loads by the current mismatch equations.

Figure (3) shows the simple layout to calculate the power injections considered in this paper. The loads and IBG are placed according to the planning and optimal locations in the distribution network as active and reactive power injections. Based on the loads and the generation of power from IBG obtained from the energy meters, the specified active and reactive power is calculated. The specified active and reactive power injections into the network with respect to the IBG connected to a bus m and the load connected to a particular bus k in phase s and at time t is given by Equation (2) and (3).

$$\left(P_k^s(t)\right)_{specified} = \begin{cases} \left(P_m^s(t)\right)_{generation} - \left(P_k^s(t)\right)_L & for\ m = k \\ -\left(P_k^s(t)\right)_L & for\ m = 0 \end{cases} \tag{2}$$

$$\left(Q_k^s(t)\right)_{specified} = \begin{cases} \left(Q_m^s(t)\right)_{generation} - \left(Q_k^s(t)\right)_L & for\ m = k \\ -\left(Q_k^s(t)\right)_L & for\ m = 0 \end{cases} \tag{3}$$

where, $P_m^s(t)_{generation}$ is active power generation on the bus m for phase k and at time t, $Q_m^s(t)_{generation}$ is reactive power generation on the bus m for phase k and at time t, $P_k^s(t)_L$,$Q_k^s(t)_L$ are active and reactive load demands on the bus k for phase s and at time t.

The specified active and reactive power injections are related to the voltage phasors and the specified current injections. From Equation (4) and (5), real and imaginary parts of the specified current can be calculated.

$$\left(P_k^s(t)\right)_{specified} = \Re\left(V_k^s(t)\right) \times \Re\left(I_k^s(t)\right)_{specified} + \Im\left(V_k^s(t)\right) \times \Im\left(I_k^s(t)\right)_{specified} \tag{4}$$

$$\left(Q_k^s(t)\right)_{specified} = \Im\left(V_k^s(t)\right) \times \Re\left(I_k^s(t)\right)_{specified} - \Re\left(V_k^s(t)\right) \times \Im\left(I_k^s(t)\right)_{specified} \tag{5}$$

where, $\left(P_k^s(t)\right)_{specified}$ is specified as active power injection in the bus k for phase s at time t. $\left(Q_k^s(t)\right)_{specified}$ is specified for reactive power injection in bus k for phase s at time t. $\Re\left(I_k^s(t)\right)_{specified}$ is Real part of specified current injection in bus k for phase s at time t. $\Im\left(I_k^s(t)\right)_{specified}$ is Imaginary part of specified current injection on bus k for phase s at time t, $V_k^s(t)$ is the voltage phasor of bus k for phase s at time t.

The calculated current depends on the property of the network and the nodal voltage of the network. From the calculated voltage and the network property, the calculated current can be calculated using Equation (6) and (7). The real and imaginary parts of the calculated current injections on the bus k for phase s and at time t are given in Equation (6) and (7).

$$\Re\left(I_k^s(t)\right)_{calculated} = \sum_{i\in\Omega}\sum_{a\in\rho}\left[G_{k,i}^{s,a}\Re(V_i^a(t) - B_{k,i}^{s,a}\Im(V_i^a(t)\right] \tag{6}$$

$$\Im\left(I_k^s(t)\right)_{calculated} = \sum_{i\varepsilon\Omega}\sum_{a\in\rho}\left[G_{k,i}^{s,a}\Im(V_i^a(t) + B_{k,i}^{s,a}\Re(V_i^a(t)\right] \tag{7}$$

where Ω is the set of network buses and ρ is the set of all phases $\{a, b, c\}$. $\Re\left(I_k^s(t)\right)_{calculated}$ and $\Im\left(I_k^s(t)\right)_{calculated}$ are the real and imaginary parts of the calculated current injections on the bus k for phase s and at time t. $\Re(V_i^a(t)$ and $\Im(V_i^a(t)$ are the real and imaginary parts of the voltage phasors at node i

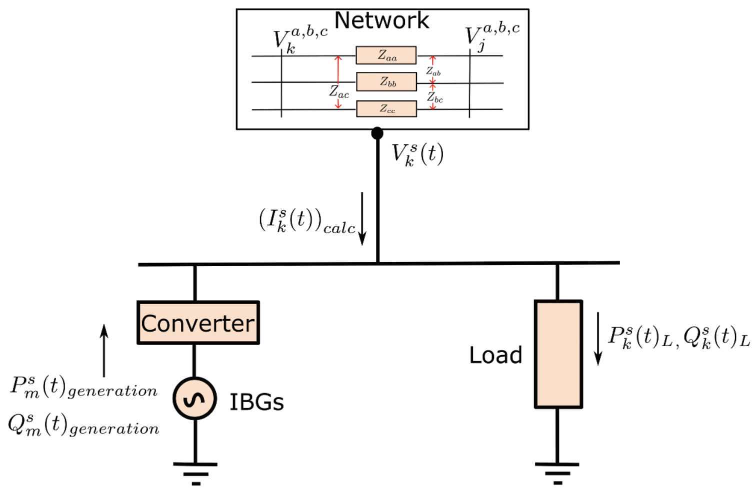


Figure 3. Current injection model.

and phase a at time t. $G_{k,i}^{s,a}$ and $B_{k,i}^{s,a}$ are the conductance and susceptance between node k and i for phases s and a.

The difference between the calculated current and the specified current is considered the mismatch current. Equation (8) is the mismatch current at bus k for phase s and at time t.

$$\Delta I_k^s(t) = \left(I_k^s(t)\right)_{calculated} - \left(I_k^s(t)\right)_{specified} \tag{8}$$

where, $\left(I_k^s(t)\right)_{calculated}$ and $\left(I_k^s(t)\right)_{specified}$ are the calculated and specified current injections in the bus k for phase s and at time t.

4.2. Formulation of optimization model

A multistep control is proposed within a finite time horizon. It is assumed that the predicted values are capable of anticipating uncertainties in the IBG and loads along the time horizon. From these predicted values, the optimization model calculates the decision variables (reactive power and active power curtailment of the smart inverter in this case) to regulate SI in the network to overcome voltage violations and optimally utilize reactive power and active power curtailment (Weckx et al., 2014). The complex power output of the smart inverter is limited by the nominal apparent power rating of the inverter $\left|S_i^{Nom}\right|$ given by Equation (9)

$$(P_j^{IBG}(t) - P_j^{Pcurt}(t))^2 + (Q_j^{IBG}(t))^2 = (\left|S_j^{Nom}(t)\right|)^2 \tag{9}$$

where $P_j^{IBG}(t)$ is the power of the smart inverter connected to node j, $P_j^{Pcurt}(t)$ is the curtailed power of the smart inverter connected to node j, $Q_j^{IBG}(t)$ is the reactive power produced/absorbed by the IBG at node j.

The smart inverter cannot curtail power more than the power produced by the IBG. Therefore, the power restriction can be between 0 and the power produced at that instant. This adds to the constraint given by Equation (10)

$$0 \leq P_j^{Pcurt}(t) \leq P_j^{IBG}(t) \tag{10}$$

As it can be assumed that the inverter operates at a certain power factor at a particular instant in time, this also introduces a constraint that relates reactive power and active power production from PV as given by Equation (11)

$$Q_j^{IBG}(t) \leq \alpha(P_j^{IBG}(t) - P_j^{Pcurt}(t)) \tag{11}$$

In Equation (11), α is constant, which limits the ratio between the reactive and active power of the PV inverter. Smart inverters have a reactive power limitation. This limitation is given by Equation (12) where κ is the limiting value of the reactive power of the smart inverter considered in this paper.κ is taken as 0.44 pu in this case.

$$\kappa \leq Q_j^{IBG}(t) \leq \kappa \tag{12}$$

As the objective is to limit the voltages in the network, the maximum limit (V^{max}) and the minimum voltage limit (V^{min}) are set as one of the constraints, as shown in Equation (13).

$$V^{min} \leq V_i^a(t) \leq V^{max} \tag{13}$$

The objective of the proposed method is to regulate voltage violations by coordinating reactive power control and active power curtailment by a smart inverter. The objective of the controllers is also to curtail as little active power as possible. The unnecessary use of reactive power could result in higher losses. To avoid unnecessary use of reactive power, a small penalty factor for reactive power is added to the objective function. To ensure that active power curtailment dominates the penalty factor for reactive power, a penalty factor $w = 0.01$ is included. The ultimate optimization challenge is described by Equation (14).

$$\begin{aligned} \underset{Q_i^{IBG}(t), P_i^{Pcurt}(t)}{\text{minimize}} \quad & \sum_{t=1}^{T} \sum_{i=1}^{m} \left[w\left(Q_i^{IBG}(t)\right)^2 + (1-w)\left(P_i^{Pcurt}(t)\right) \right] \\ \text{subject to} \quad & (9-13) \end{aligned} \tag{14}$$

where T is the overall simulation time period. T includes a day with a 5-minute time interval.

5. Simulation results and analysis

5.1. Test system

The proposed methodology is implemented in a European low voltage distribution network (LVDN) (European 2022) and a CIGRE medium voltage (MV) distribution network (Cigre 2014). This system is well known and represents a number of common distribution networks (Schneider et al. 2018). The original European LVDN has 906 nodes (including the substation node) and 905 branches. Among the 906 nodes, 55 nodes are used to connect different sizes of single-phase loads. To solve the optimization problem of the original European LVDN on a daily basis with a 5-minute time resolution, there will be 288 instances. The simulation is performed on an Intel (R) Core (TM) i5-8265 U CPU 1.8 GHz processor with 8 GB RAM, 64-bit operating system. The optimization process takes a significant time for convergence, and hence a reduced ordered European LVDN is considered in this analysis. The reduced ordered network operates under full load conditions without loss of critical network information, as studied in (Khan and Hayes 2022). In this way, optimization can be achieved faster. Reduced/modified European LVDN is shown in Figure (4). The reduced network has 117 nodes (including a substation transformer) and 116 lines. The number of loads is considered the same as in the original LVDN. The summary of network information is shown in Table 1. The load data are taken from (European 2022; Schneider et al. 2018). Data for reduced European LVDN are available in IEEE Data Port (Khan and Hayes 2022).

In this paper, PVs (PV) is considered an inverter-based generation (IBG). The power produced by each PV is considered to vary in nature throughout the day, as shown in Figure (5). PV data is taken from(LV network models, 2014), which are processed for a 5-minute resolution and randomly scaled (multiplied by 2.5) to create intentional voltage violations in the network. Scaling is done to consider a case of very high PV penetration, which results in voltage violations. Therefore, 3.5 kW PVs are considered to be placed on all load buses in the

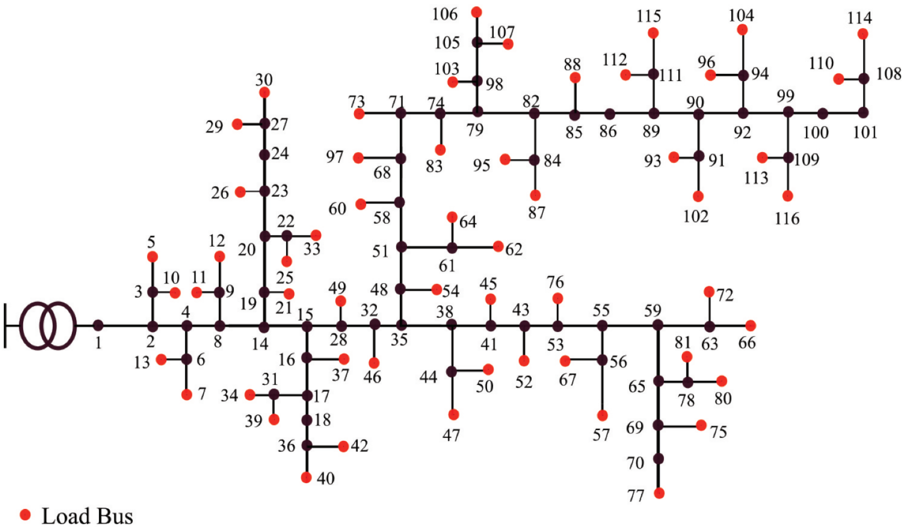


Figure 4. Simplified European Low Voltage Test System (Khan and Hayes, 2022).

Table 1. European LV Test System.

Network Type	No. of Nodes	No. of Branch	No. of Loads
Original Network	906	905	55
Simplified Network	117	116	55

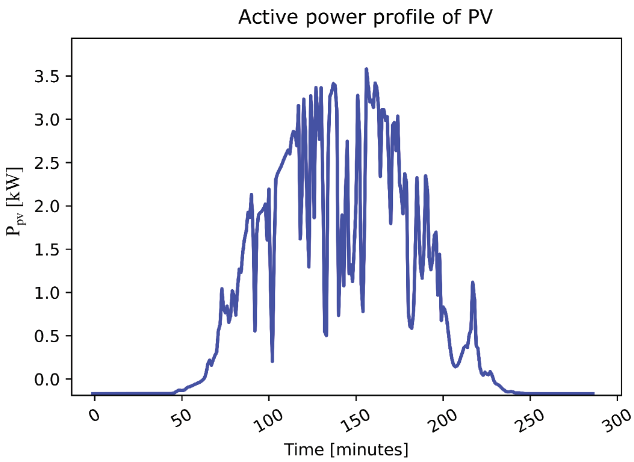


Figure 5. Active power profile of PV for a day at 5 mins resolution (LVnetwork 2017).

network. Mitigating voltage violations resulting from the penetration of PV is the main scope of the study. In this analysis, it is assumed that all installed PVs follow the same profile throughout the day.

Similarly, in this study, the original CIGRE MV network is considered. However, to consider the study with very high penetration, all load buses are connected with inverter-based generations (IBG). The network property of the original network is considered the same. The size of the loads and IBG is calculated using the hosting capacity calculation performed in a separate study. The power profile of the PV system is considered the same, but the scaling factor of all PV systems in the network is considered the same and is equal to 300 kW. Furthermore, to consider the daily load profile of the loads, the load shape shown in Figure (6) is considered. This load shape is obtained by resampling the data for a winter of (Porsinger et al. 2017). By resampling the data, 5 min resolution data are created to fit the load profile for the OPF. For simplicity, the same load shape is considered for all loads. However, the load ratings are considered as given in Table 2. In the original test network, the network consists of residential and commercial loads, but in this study, the cumulative residential and commercial load is considered.

5.2. Simulation of European LV distribution network with VVC, VWC, combined VVC and VWC method, and OPF-based control in smart inverter

For the OPF-based method, the optimization is developed in Pyomo and is solved using the Knitro solver. optimization results are processed to obtain the required observation variable. In the case of combined VVC and VWC, the simulation is first performed using Matlab and OpenDSS co-simulation. The control algorithm is programmed in a Matlab script. From the simulation, the output profiles for voltage, active power, reactive power, and active power curtailment are obtained for both cases. To see the effect of PV in the network, the simulation is performed without considering the penetration of PV and then considering the integration of PV. Later, control methods are implemented to obtain the desired output responses. The control methods are implemented separately; one for the combined VVC and VWC methods and another for the OPF-based method.

Figure (7) is the voltage profile without and with PV integration on a European LV network. For the load profile considered, the voltage profile is almost within the allowable limits without the integration of PVs. However, with the integration of 100% PVs, voltage violations are observed in the network. 3D plot for the voltage is also shown to provide a clear visualization of the voltage profile.

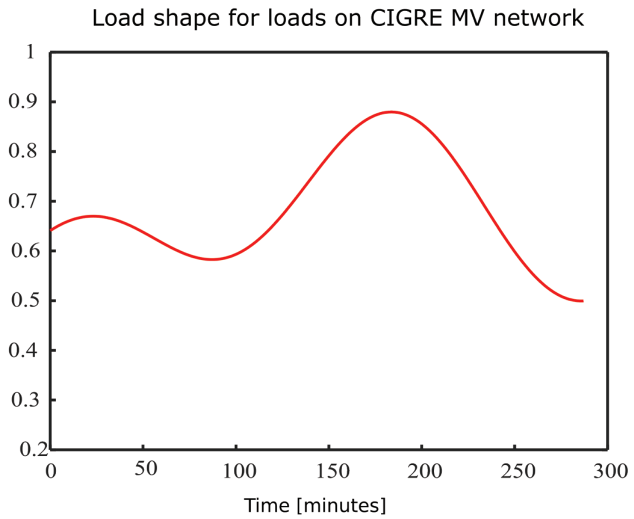


Figure 6. Load shape of loads on CIGRE MV network at 5 mins resolution (LVnetwork 2017).

Table 2. CIGRE MV distribution network benchmark application: Load parameters.

Node	S_{max} (kVA)	power factor
Bus1	20400	0.98
Bus3	550	0.97
Bus4	445	0.97
Bus5	750	0.97
Bus6	565	0.97
Bus7	90	0.95
Bus8	605	0.97
Bus9	675	0.85
Bus10	570	0.97
Bus11	340	0.97
Bus12	20580	0.98
Bus13	40	0.97
Bus14	605	0.97

Figure (8) is the 2D and 3D plots for the voltage profile of the network with VVC and VWC based on sensitivity. From the figure, it is observed that the voltage profile is properly maintained by applying the VWC method. However, in VVC, the voltage is not maintained. This could be due to the capacity limitation of the smart inverter to support the reactive power. Therefore, in the case of extremely high power generation, where no other option is available to regulate the voltage, active and reactive power control from the smart inverter can be an option. However, to optimize the network operation, the OPF-based method or the combined VVC and VWC methods can be implemented.

Figure (9) is the 2D and 3D plots for the voltage profile of the network with the OPF-based method and the combined VVC and VWC method. In the figure, it is observed that the voltage profile is properly maintained by applying the combined VVC and VWC method. But in the OPF-based method, the voltage is just above the upper limit boundary. This could be due to a small penalty factory introduced in reactive power in the objective function to prevent unnecessary use of the reactive power.

Figure (10) is the 2D and 3D plots for active power and reactive power profiles with the application of VWC and VWC. Active and reactive power from the smart inverters is obtained after the standalone VWC and VVC are implemented. Since in standalone VWC, no reactive power support is provided and in standalone VVC no active power is curtailed, the outputs for them are not presented here.

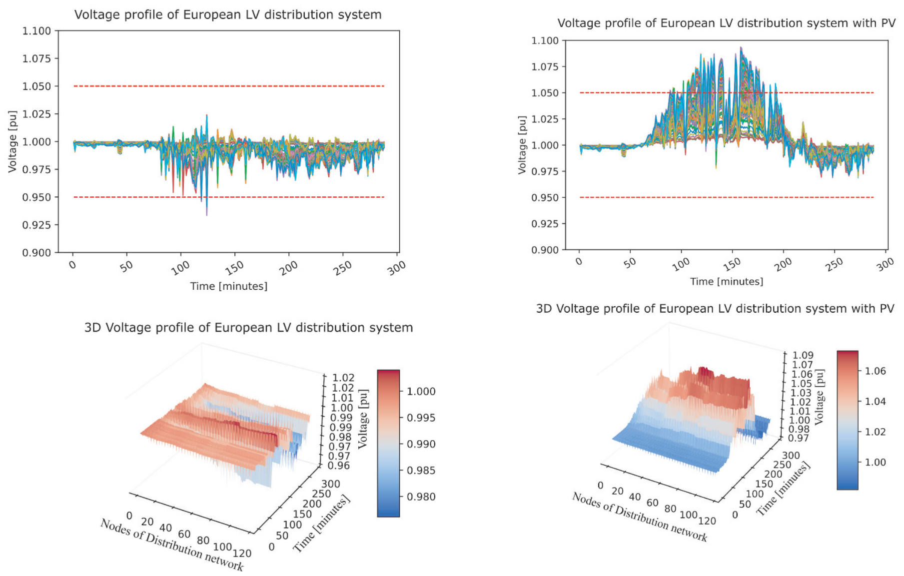
Figure (11) shows the active power profile in 2D and 3D after the implementation of the combined VVC and VWC method and the OPF-based method. The active power profile after the application of the control is obtained by subtracting the active power curtailment from the power produced. Because less active power is curtailed in the case of a combined VVC and VWC, the active power profile of the combined VVC and VWC has a nature similar to that of the power produced by PVs. Less power curtailment is observed in the combined VVC and VWC, as the voltage is first regulated by the VVC prior to the implementation of the VWC. However, in OPF-based methods, active power curtailment is achieved on the basis of optimization. The active power profile depends on the active power curtailment.

Similarly, Figure (12) shows the 2D and 3D profiles of the reactive power, respectively. Reactive power profiles are obtained from the application of the OPF-based method and the combined VVC and VWC method. In this study, the positive reactive power is considered to be a capacitive reactive power support and the negative reactive power is considered to be inductive. Voltage violations below the prescribed limit are supported by capacitive reactive power, whereas voltage violations above the prescribed limit are supported by inductive reactive power. Since in combined VVC and VWC, the reactive power support is implemented first, the smart inverter provides a greater amount of reactive power support to regulate voltage violations. In the OPF-based method, proper coordination results in lower reactive power support. With the OPF-based method, the reactive and active power of the smart inverter is controlled in a coordinated manner. A less reactive power contribution is observed to maintain the voltage profile.

Figure (13) shows the 2D and 3D profiles of the active power curtailment of smart inverters using two control approaches. In the case of combined VVC and VWC, the active power curtailment is implemented only if there are voltage violations even after the application of reactive power control. In the case of the OPF-based method, the active power curtailment is one of the optimization variables obtained from the optimization.

5.3. Simulation of CIGRE MV distribution network with sensitivity-based VVC and OPF-based control in smart inverter

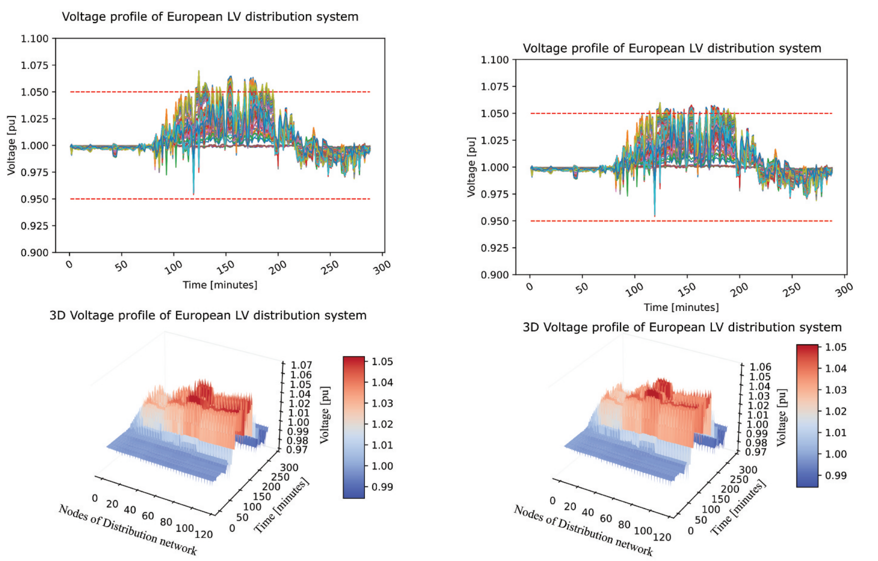
Analysis has been done for the combined VVC and VWC on the CIGRE medium voltage network. However, the results obtained for combined VVC and VWC, show that only reactive power control (VVC) can mitigate the voltage violations due to the robustness of the CIGRE network, and active power curtailment is not required. To present comparable results, the network needs significant modifications. Therefore, the simulation results related to the power curtailment are not included



(a) voltage profile of European LV test system without PV

(b) Voltage profile of European LV test system with PV

Figure 7. Voltage profile of European LV test system without PV and with PV penetration.



(a) Voltage profile of European LV test system with VVC control in smart inverter

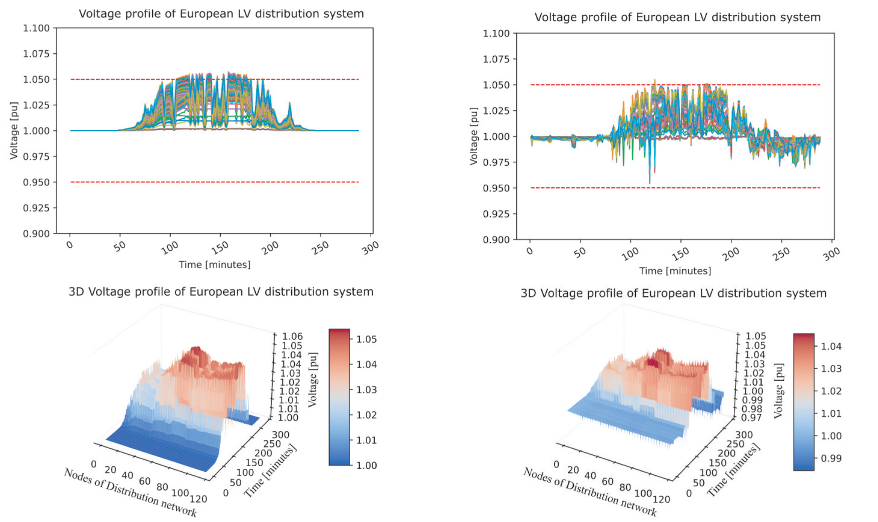
(b) voltage profile of European LV test system with VWC control in smart inverter

Figure 8. Voltage profile of European LV test system with VVC and VWC control in smart inverter.

in this paper. For this purpose, the optimization model for OPF-based control is developed using the same methodology implemented for the European LV test system. However, a small modification is made to remove the effect of active power curtailment in the formulation of the optimization problem. Similarly, sensitivity-based Volt-Var control (VVC) is achieved in a similar way. The results related to reactive power control are presented in the paper as shown in Figure (14). These figures show that the voltage profile can be managed by applying only reactive power control.

Figure (14) is the 2D and 3D plots for the voltage profile for the CIGRE MV network without and with PV. For the load profile considered, the voltage profile without PVs in the network is within the allowed limit. However, after the integration of PVs into the network, the voltage profile changes and some voltage violations are observed in the network.

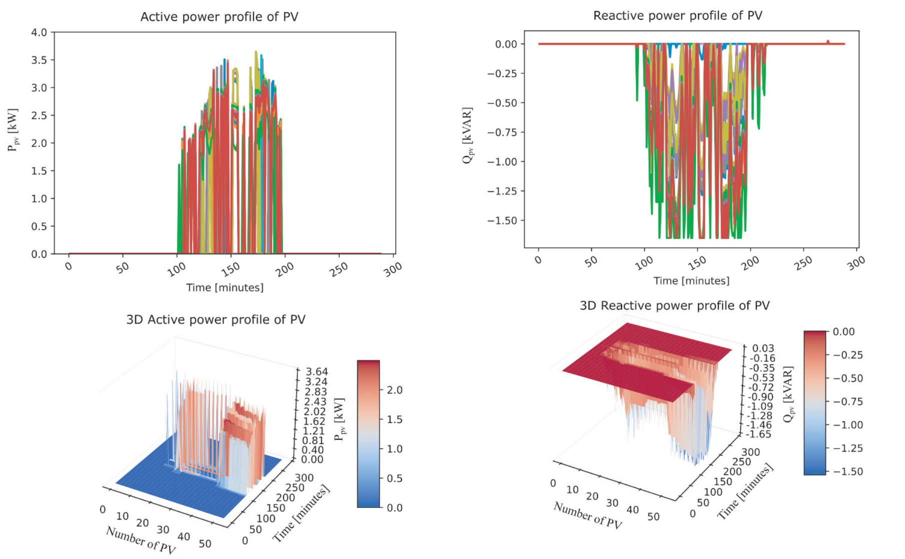
Similarly, Figure (15) is the 2D and 3D plots for the voltage profile for the CIGRE MV network with OPF-based reactive power control and VVC based on sensitivity. From



(a) voltage profile of European LV test system with OPF-based reactive and active power control in Smart Inverter

(b) voltage profile of European LV test system with combined VVC and VWC control in Smart Inverter

Figure 9. Voltage profile of European LV test system with OPF-based and combined VVC and VWC-based control in smart inverter.



(a) Active power profile of PV with VWC in Smart Inverters on a European LV distribution network

(b) voltage profile of European LV test system with VWC control in smart inverter

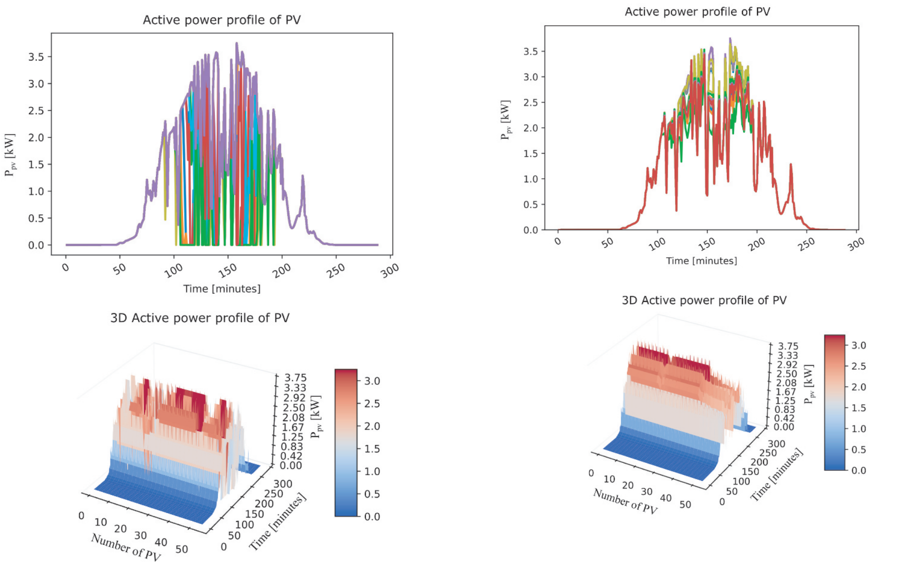
Figure 10. Active power and reactive power profile of PVs with VWC and VVC respectively.

the figure, it is observed that the voltage profile is properly maintained in both cases. However, in the OPF-based method, the voltage profile is compensated for so that less reactive power support is utilized.

To show the effectiveness of the OPF-based method and the sensitivity-based method in terms of the contribution of reactive power, 2D and 3D plots for reactive power supports for both methods are presented in Figure (16). In the case of the OPF-based method, a lesser contribution of reactive power is observed to maintain the voltage profile.

5.4. Comparison of OPF-based control approach with sensitivity-based VVC, VWC, and, combined VVC and VWC

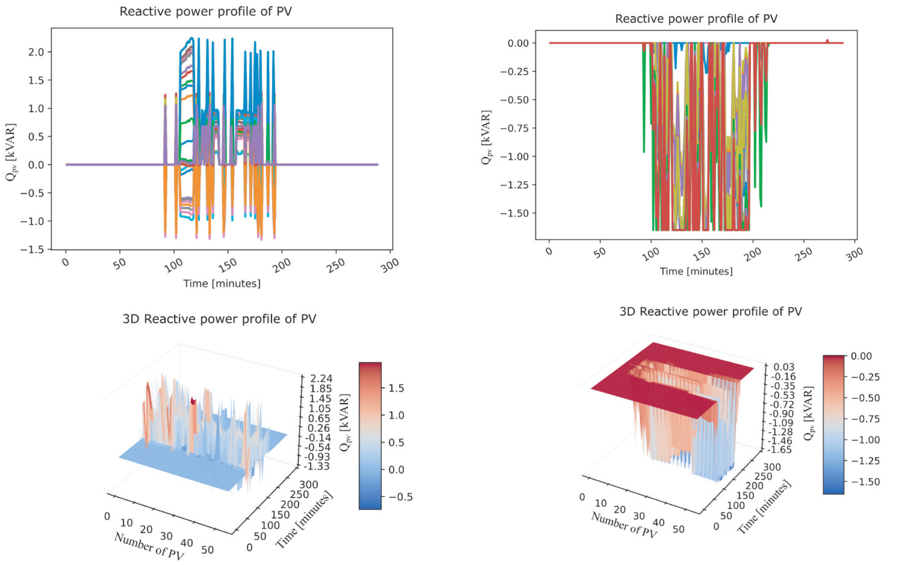
To compare the effectiveness of various control methodologies, performance indices such as the voltage performance index, total power loss, total contribution of reactive power,



(a) Active power profile of PV with OPF-based control in Smart Inverter on a European LV distribution network

(b) Active power profile of PV with combined VVC and VWC in Smart Inverter on a European LV distribution network

Figure 11. Active power profile of PVs with opf-based control and combined VVC and VWC in smart inverter on a European LV distribution network.



(a) Reactive power profile of PV with OPF based reactive and active power control in Smart Inverter on a European LV distribution network

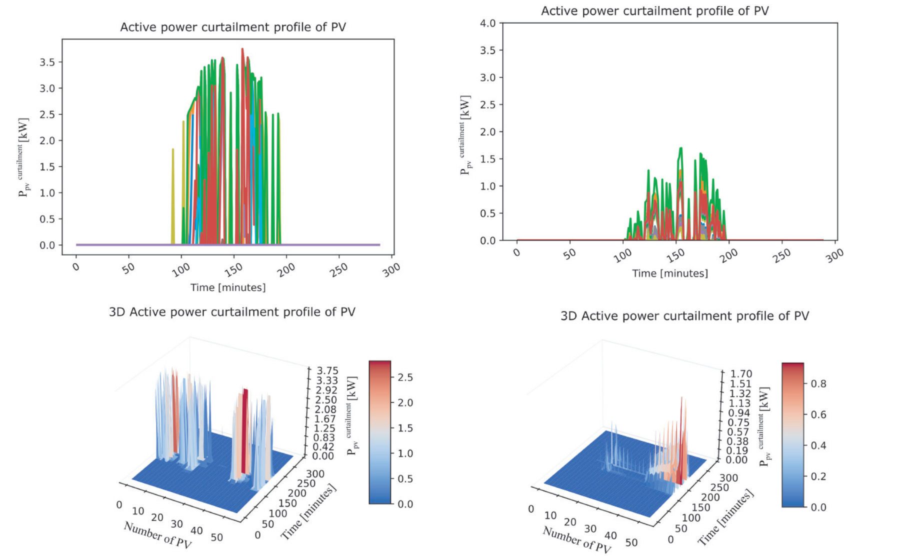
(b) Reactive power profile of PV with combined VVC and VWC in Smart Inverter on a European LV distribution network

Figure 12. Reactive power profile of PVs with opf-based control and combined VVC and VWC in smart inverter on a European LV distribution network.

and total curtailment of active power are used. Detailed explanations of each comparison index are explained in the following way.

• Voltage performance index (VPI): The voltage performance index (VPI) is defined by the sum of the difference in voltages in phase s of bus k at time t and the maximum allowable upper limit V_{max} (1.05 p.u. in this case). Mathematically, VPI is given by Eq. (15)

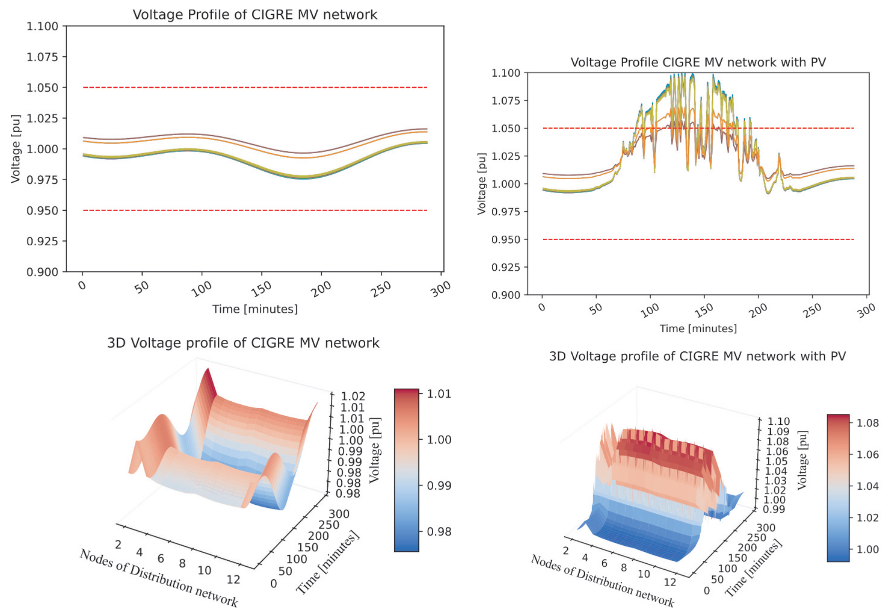
$$VPI = \sum_{k \in N_{bus}, s \in (a,b,c), t \in T} (V_k^s(t) - V_{max}) \tag{15}$$



(a) Active power curtailment profile of PV with OPF-based reactive and active power control in Smart Inverter on a European LV distribution network

(b) Active power curtailment profile of PV with combined VVC and VWC in Smart Inverter on a European LV distribution network

Figure 13. Active power curtailment profile of PVs with opf-based control and combined VVC and VWC in smart inverter on a European LV distribution network.



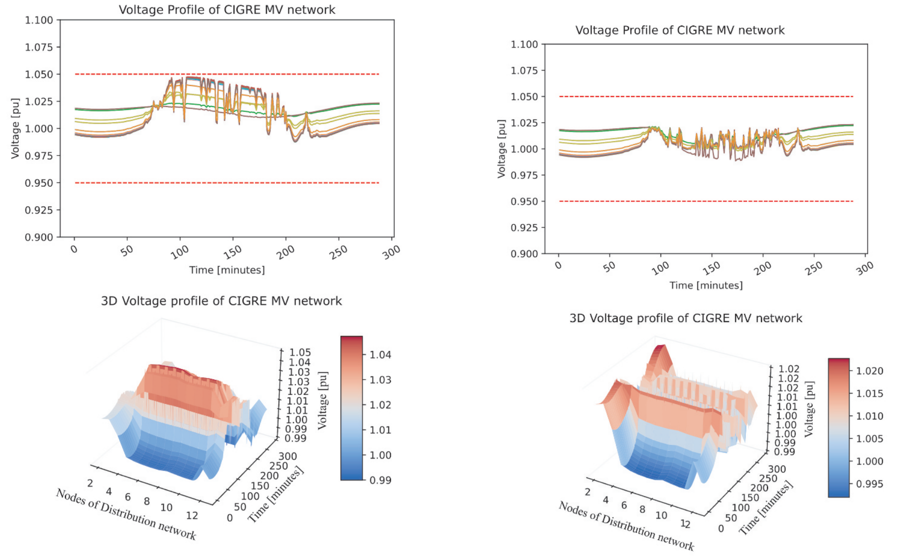
(a) voltage profile of CIGRE MV distribution network without PV

(b) Voltage profile of CIGRE MV distribution network with PV

Figure 14. Voltage profile of CIGRE MV distribution network without PV and with PV penetration.

The lower value indicates that only a few voltage instances have violated the upper limit. Therefore, the lower the VPI index, the better the controller performance. Among the control approaches considered, the combined VVC and VWC have a better performance in terms of VPI. The higher value of the VPI in the case of the OPF-based method is due to a small penalty factor introduced in the reactive power in the objective function to prevent the unnecessary application of the reactive power.

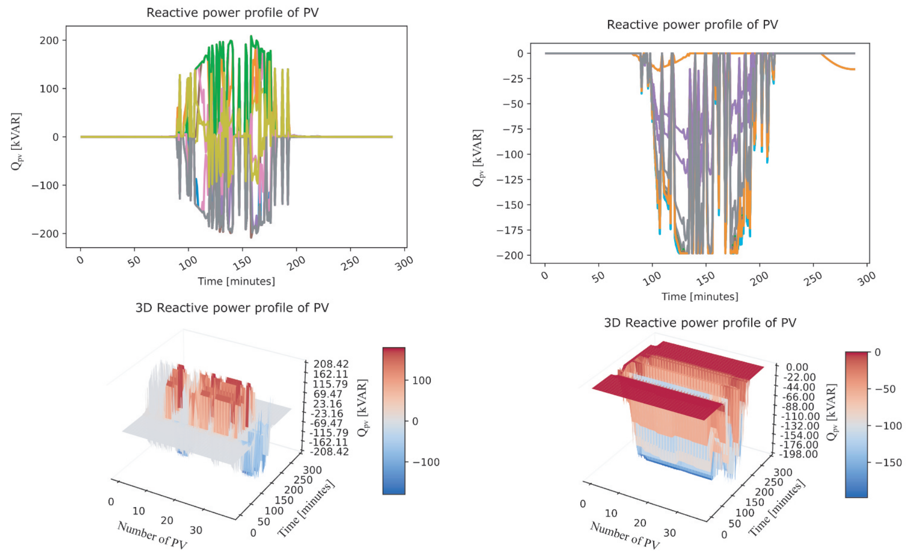
- Total power loss: The total power loss in the network is obtained from the optimization and the co-simulation. Having a lower network loss is beneficial for the distribution system



(a) voltage profile of CIGRE MV distribution network with OPF-based reactive power control in Smart Inverter

(b) voltage profile of CIGRE MV distribution network with sensitivity based VVC in Smart Inverter

Figure 15. Voltage profile of CIGRE MV distribution network with OPF-based and VVC control in smart inverters.



(a) Reactive power profile of PV with OPF based reactive power control in Smart Inverter on CIGRE MV distribution network

(b) Reactive power profile of PV with sensitivity based VVC in Smart Inverter on CIGRE MV distribution network

Figure 16. Reactive power profile of PVs in CIGRE MV distribution network with OPF based and VVC control in smart inverters.

operator. On the other hand, a lower network loss also indicates that a lower current is flowing through the line. In cases where the network is marginally loaded, lowering the current flow can increase the capacity of the network to accommodate additional loads. The OPF-based method utilizes the reactive and active power in an optimal way so that total power loss is observed while using the OPF-based controller. In terms of total power loss, the OPF-based method is considered suitable to compare with the sensitivity-based VVC, VWC, and the combined VVC and VWC method.

- Active power curtailment: Another important performance index considered is active power curtailment (APC). APC is the amount of active power that is cut out to mitigate voltage violations. Although APC is not

Table 3. Comparison of the performance of the OPF-based method with the combined VVC and VWC method in the European LV distribution network.

Comparison index	VVC	VWC	combined VVC and VWC	OPF
Voltage performance index (VPI)	0.17	0.0637	0.0055	0.0285
Total network loss [kW]	1.73	1.89	1.77	1.49
Total PV power [kW]	57.24	57.24	57.24	57.24
Total Active power curtailment [kW]	0.00	44.03	1.73	5.87
Total Reactive power contribution [kVAR]	8.68	0.00	13.76	8.93

a desirable option as this method reduces the power production of PVs, this can be an option when other regulating solutions are not available. The lower the active power curtailment, the better the controller performance. The APC is calculated from the sum of active power curtailed from the smart inverter in each instance. A more active power curtailment is observed while using VWC and no APC in VVC. In combined VVC and VWC, active power curtailment is implemented only after the application of VVC, so fewer APCs are observed. However, among the approaches considered, the OPF-based method provides a less active power curtailment.

• Reactive power support: To avoid voltage violations, smart inverters can provide or absorb reactive power. In the case of a distribution network (high R/X), when the smart inverter provides reactive power to resolve voltage violations, there will be an increase in network losses. Therefore, it is crucial to identify the reactive power support from the smart inverter. Furthermore, with increasing concern for the reactive power market, the amount of reactive power support from the smart inverter is a significant index for comparison. The total contribution of reactive power is computed by taking the absolute value of the reactive power obtained to discard the effect of positive (capacitive) and negative (inductive) reactive power support in this study. Since in the OPF-based method, the active power curtailment and the reactive power support are optimally obtained, the smart inverter provides a combination of inductive and capacitive reactive power support in the OPF-based method. Reactive power support is not provided by the VWC method. However, in the case of the VVC and combined VVC and VWC methods, inductive reactive power support is provided, which will increase network loss.

The summary of the comparison of the different performance index for the methods considered is shown in Table 3. Table 3 shows that the combined VVC and VWC methods provide better voltage performance and less active power curtailment. However, in this method, more network loss and more reactive power compensation are observed. Similarly, in the case of the OPF-based method, less network loss and less reactive power contribution are observed. In terms of reactive power support and total network loss, the OPF-based method is considered better than the combined VVC and VWC.

Similarly, the comparative analysis of various performance indices for the CIGRE MV network is presented in Table 4. From Table 4, it can be seen that the OPF-based method is more suitable than VVC based on sensitivity in terms of lower network loss and reactive power support.

Table 4. Comparison of the performance of the OPF-based method with sensitivity-based VVC method on CIGRE MV distribution network.

Comparison index	VVC	OPF
Voltage performance index (VPI)	0.00	0.00082
Total network loss [kW]	164.99	73.28
Total PV power [kW]	4870.89	4870.89
Total Reactive power contribution [kVAR]	1408.09	1248.02

6. Conclusions

An OPF-based control to mitigate the voltage violations due to the high penetration of inverter-based generation in a smart inverter-enriched unbalanced distribution network is considered in this paper. The optimal set points for reactive power and active power curtailment to mitigate voltage violations are obtained using an optimization model developed in this study. This paper also compares the proposed method with the Volt-Var (VVC), Volt-Watt (VWC), and combined VVC and VWC methods. The main focus of the comparative study is to identify the amount of reactive power support from various approaches and to determine the possible impact on overall network loss and other performance indices. A fair comparison is made in terms of voltage performance index, active power loss, active power curtailment, and reactive power contribution from Smart inverters in a reduced European LV distribution network and CIGRE MV distribution network. The simulation demonstrates that various approaches may effectively address voltage violation issues. However, voltage violations are resolved through a combined VVC and VWC method with a lower voltage performance index (VPI) and less active power curtailment. A higher active power curtailment is observed with VWC only. The lower active power curtailment in combined VVC and VWC is due to the application of active power curtailment after the implementation of the possible reactive power support from the smart inverter. However, combined VVC and VWC produce a greater system loss in the network and a greater contribution of reactive power support from the smart inverter. On the other hand, the OPF-based method optimally utilizes reactive power support and active power curtailment, providing lower network loss and less reactive power support from smart inverters. In this paper, the contribution of reactive power support for various control strategies is considered a key differentiating factor when considering the type of suitable control approach. The authors believe that the analysis presented here is significant when there is growing concern about the ancillary reactive power service in the distribution network. OPF-based methods may be a good choice in the context of the growing economic concern about the reactive power of smart inverters and the advancement of smart inverters with intelligent monitoring and communication infrastructures.

The coordination of reactive and active power curtailment of smart inverters is the focus of this analysis. However, the application of other voltage-regulating devices in coordination with the smart inverter is left for future research. This method is modeled using real-time data sets obtained from energy meters installed on the distribution network. The proposed method can be more suitable for implementing a real-time control application, as they include real-time measurements to create the optimization model for obtaining the optimal set points. Real-time application of the proposed method is planned as future work.

Acknowledgements

The authors are very grateful to the Arctic Centre for Sustainable Energy (ARC) (project number 740108), UiT The Arctic University of Norway, Norway, for providing an environment for this research.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This research did not receive external funding. The APC was funded by UIT The Arctic University of Norway.

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Data availability statement

The data that support the findings of this study in European LV network are openly available in at https://ieee-dataport.org/open-access/paper-reduced-electrically-equivalent-model-ieee-european-low-voltage-test-feeder http://doi.org/10.21227/0d2n-j565. The data that support the findings of this study in Cigre network are openly available in at https://cmte.ieee.org/pes-testfeeders/resources/. Derived data supporting the findings of this study are available from the corresponding author R.Wagle on request.

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Paper C. Real-Time Volt-Var Control of Grid Forming Converters in DER-enriched Distribution Network

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Frontiers in Energy Research, 2023, Pages 1-18.

https://doi.org/10.3389/fenrg.2022.1054870

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Authors Contribution:

The conceptualization of the idea to do further research on real-time volt var control was obtained by the candidate. Moreover, the implementation of the methodology, utilization of software, development of the real-time system, data curation, formal analysis, writing of the original draft, validation, and visualization of the paper was done by the candidate.

The development of the proposed real-time cyber-physical co-simulation framework and the application of grid forming converter was generated during the research exchange of the candidate at DigEnSys-Lab and with numerous technical meetings and discussions with Professor Francisco. The concept of offline Volt-Var control in the converter was generated from previous Paper B. The cyber-physical co-simulation framework utilized in this work is developed in Paper E.

All co-authors contributed essentially to the supervision, review, validation, and proof of the paper.

frontiers | Frontiers in Energy Research

TYPE Original Research
PUBLISHED 06 January 2023
DOI 10.3389/fenrg.2022.1054870

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Real-time Volt-Var control of grid forming converters in DER-enriched distribution network

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SPECIALTY SECTION
This article was submitted to Smart Grids, a section of the journal Frontiers in Energy Research

RECEIVED 27 September 2022
ACCEPTED 21 December 2022
PUBLISHED 06 January 2023

CITATION
Wagle R, Sharma P, Sharma C, Amin M and Gonzalez-Longatt F (2023), Real-time Volt-Var control of grid forming converters in DER-enriched distribution network. *Front. Energy Res.* 10:1054870.
doi: 10.3389/fenrg.2022.1054870

The growing installation of distributed energy resources (DERs) in a distribution network (DN) poses substantial issues related to voltage regulation. Due to constrained switching operation and slower response time, traditional voltage regulation devices cannot handle current voltage-related challenges. One alternative to solve these problems is to use smart converters to control the reactive power to regulate the voltage. Volt-Var control (VVC) is one of the simplest approaches for controlling the reactive power from smart converters. Among several converters, grid forming converters (GFCs) are more suitable in DER-enriched distribution networks. Since DER-enriched distribution networks have a higher fluctuation in voltage profile, real-time control is advantageous. Therefore, this work presents an advanced real-time reactive power control for handling voltage violations in a DN using GFC. The uniqueness of this method is that it controls the voltage magnitude of affected nodes by dispatching reactive power from smart converters in real-time. By running cyber-physical co-simulation (CPCS) between the Typhoon HIL 604 and OpenDSS, the Volt-Var control can be done in real time. The grid-forming converter is modelled in Typhoon HIL 604, which acts as a physical layer of the proposed cyber-physical system for real-time VVC. A CIGRE medium voltage distribution network is designed in OpenDSS and serves as one of the parts of the cyber layer. The CPCS between Typhoon HIL and OpenDSS and the control algorithm are both done by a programme written in Python. The execution of the control algorithm is performed in real time using the Supervisory Control and Data Acquisition (SCADA) developed in this study. The real-time simulation shows that the proposed real-time VVC is capable of handling voltage violations in real time in DER-enriched distribution networks.

KEYWORDS

cyber-physical co-simulation, distribution network (DN), real-time control (RTC), grid forming converters, Typhoon HIL

1 Introduction

1.1 Motivation and incitement

To meet the target set by the European Energy Roadmap 2050 (Langsdorf, 2011), there will be a significant deployment of renewable energy resources (RES) based on distributed energy resources (DER) in the electrical system. By 2050, the proportions of wind and solar energy in the world's energy mix are expected to increase from 0.33% to 0.82%, respectively, to 11.9% and 11.03% (DNV GL, 2020). Due to the significant intermittency and dependence on the environmental condition of RESs, the continuous growth of the integration of such resources into power systems alters the operating conditions of both electricity transmission and distribution networks. This will have a significant impact on the existing control, management, and operation of the power system (Chen et al., 2020). In fact, the high penetration of variable RES increases the uncertainty of the state of the system, increases the risk of contingencies (Liu et al., 2022), and lowers the overall quality of the service (Bollen et al., 2017). Furthermore, the appearance of bidirectional power flows, reverse power flows, and terminal voltage rises (Anastasiadis et al., 2019) creates additional challenges to the control and management of distribution networks.

In addition, the digitalization of the distribution network is an emerging concern for effective control and management of the distribution network. The growing use of smart devices for real-time control and monitoring is accompanied by an increased implementation of the smart grid paradigm in distribution networks. Furthermore, the operation of the distribution system requires a more robust and adequate monitoring and control infrastructure as a result of the growing integration of converter-based renewable energy sources with cutting-edge ICT (information and communication technology). To address the approaching problems in the digitalization of the distribution network, it is critical to develop a comprehensive and implementable platform to test theoretical ideas, computational tools, methodologies, and new technologies in real time.

1.2 Literature review

Among many technical challenges due to the high integration of DER, voltage violation is a critical issue that must be solved to accommodate the high penetration of DER (Wang et al., 2019). Additionally, the voltage violation problem is more sensitive because of the inherently resistive (high R/X) character of the distribution network. Due to limited capacity and poor operational response, conventional voltage-regulating devices (VRDs), such as load tap changing (OLTC) transformers, step voltage regulators, and switched capacitors/industry banks, could not be viable options in such situations (Liu et al., 2009). They may not handle the voltage issue more accurately when DER power generation and load fluctuations are large. With the advancement in smart converter technology, smart converter reactive power regulation is one of the best methods to deal with voltage problems in distribution networks.

There are various approaches for controlling the reactive power in the scientific literature (Ku et al., 2015; Ghosh et al., 2016; Mahmud and Zahedi, 2016; Molina-García et al., 2016; Zhang et al., 2017; Kim et al., 2020; Li et al., 2020; Ceylan et al., 2021; Wagle et al., 2021). In most studies, reactive power control is achieved in centralised, distributed, and decentralised forms. The key problem with the centralised technique is the lack of communication and monitoring infrastructure in the distribution network. The distributed method incorporates both the concept of centralised control and the local control method in a coordinated fashion to implement the control action. This method somehow tries to coordinate the operation between the local control and the centralised control in a two-level control structure (Tang et al., 2020). In the distributed control method, the centralised controller operates at a larger time step and the local controller acts at a smaller time step. On the other hand, the decentralised/local method uses local measurement, and, based on that, the optimal settings for the reactive dispatch are estimated. Due to the fast-responding nature of local controllers, local control based on real-time applications is gaining attraction among researchers. Moreover, local control methods require information about threshold settings for voltage and power for the controller to become more effective. These settings for $Q(V)$, $Q(P)$, and $P(V)$ are defined in the Amendment to IEEE Std 1547-2018 (2020). However, users can specify these values on the basis of the type and nature of the network under consideration before implementing the control action.

It is not a new field of study to use smart converters for reactive power control. In the past, much research has been done in the literature to implement Volt-Var control using the smart converter. A droop-based reactive power (Q) absorption approach was studied by (Ghosh et al. (2016); Molina-García et al. (2016) introduced piece-wise linear droops to regulate the voltage using a smart inverter (Mokhtari et al., 2013). used Droop-based active power curtailment as well as empirical $Q(P)$rules to reduce reactive power at the same time. The absorption of reactive power and the reduction of active power of photovoltaics were coordinated using the sensitivity V/P and V/Q by Ku et al. (2015). A nodal sensitivity-based approach is implemented in a distribution network to produce the best voltage performance index by Ceylan et al. (2021). However, this research does not consider real-time validation and proposes solutions as anticipated offline solutions to the problem. Due to the rapid increase in the integration of DER in the distribution network, the future distribution network is subject to significant voltage fluctuations (Guo and Shi, 2020). Therefore, researchers in the distribution system should consider switching from conventional offline mode to real-time mode. Moreover, with higher integration of DERs, conventional generators alone may not maintain the stability of the system due to lack of spinning reserve. Grid forming converters (GFC) are suitable to provide virtual inertia to maintain the system dynamics (Hu et al., 2022). Hence, this paper proposes a novel implementation of real-time Volt-Var Control (VVC) on GFC on a cyber-physical co-simulation (CPCS) framework developed in this study.

CPCS is one of the effective techniques for solving this complexity (Mihal et al., 2022). There is ongoing research on CPCS in a variety of industries, including the automotive, military, building science, and energy. As a consequence, several cosimulation systems are already available, each with a variety of features and degrees of use (van der Meer et al., 2017). The cyber-physical framework can be implemented to study the effects of cyber attacks and their mitigation techniques (Dai and Shi, 2020; Zhang et al., 2022a). Furthermore, Cyber-physical systems can also be implemented for long-term risk mitigation studies (Dai et al., 2019; Zhang et al., 2022b), security vulnerability analysis (Gao and Shi, 2020), optimal cyber defence strategy planning (Hou et al., 2020). Even though cyber-physical co-simulation is expanding, a number of issues remain, particularly as a framework for modelling the distribution network is under development. The importance of co-simulation in achieving the best reactive power regulation is emphasised in (Acosta et al., 2021). CPCS frameworks combine digital and cybernetic systems with physical systems to improve the monitoring and management of the physical system (Venkataramanan et al., 2016). proposes a real-time cyber-physical test bed for microgrid control, where the power system network is constructed in RSCAD and real-time co-simulation is performed using the real-time digital simulator (RTDS). In Cao et al. (2019) a real-time simulation test bed is also suggested that runs between OpalRT and Matlab Simulink. In this paper, the microgrid control algorithm and the impact of cyber incidents on microgrid performance are tested using a test bed. However, the modelling of distribution networks is limited to Matlab user only, which may not be a suitable system to model large distribution networks. The communication network was created using OPNET and the Real-Time Laboratory (RT-LAB) is studied by Wang et al. (2021). Sun et al. (2015) offers a detailed analysis of the real-time co-simulation testbed.

Furthermore, the existing literature provides information on microgrids or small distribution networks for CPCS. Most CPCS frameworks in comparable domain listed in the literature (Cintuglu et al., 2016) place more emphasis on power system models that are typically balanced in operation. However, the distribution network differs from the power system network in many factors, such as unbalanced operation, network topology, multiple load points, and many more. The distribution network solver taken into consideration in the co-simulation should be able to solve all forms of distribution networks (either single-phase or three-phase, balanced or unbalanced) in order to assess a realistic distribution network. Also, to solve the realistic distribution network, real-time operation for distribution networks must also be reliable and quick. OpenDSS is a highly potent technology developed specifically to address the distribution network problem (Gao et al., 2017). A general framework for co-simulation between OpenDSS and Typhoon HIL is presented in Wagle et al. (2022), however, in this paper only a basic implementation without detailed modelling of the controller is presented.

1.3 Contribution and paper organization

To the authors' best knowledge, the proposed CPCS framework between Typhoon HIL and OpenDSS for real-time Volt-Var control is the first of its kind. The proposed system can be applied to any kind of distribution network, either balanced or unbalanced, single-phase or three-phase. Therefore, the goal of this effort is to provide a CPCS framework that will be used to execute a real-time simulation between Typhoon HIL and OpenDSS together with the implementation of a real-time Volt-Var control on a proposed CPCS framework. In this context, the contributions of this work are as follows.

1) In this study, a cyber-physical co-simulation framework for real-time Volt-Var control in grid forming converters (GFC) is developed. The proposed framework is implemented using real-time co-simulation between the distribution network solver OpenDSS and Typhoon HIL. The GFC controller is designed in the Typhoon HIL real-time simulator and the active and reactive power output obtained from the GFC is fed to the distribution network in OpenDSS during the real-time simulation to obtain the voltage profile of the network.
2) In this study, real-time Volt-Var control is proposed in a distribution network to mitigate the uncertain voltage violations of the network. The voltage regulation due to real-time variation in DER generation and load is achieved by the proposed real-time Volt-Var controller in DER enriched distribution network.
3) Real-time simulation studies are performed to show the efficacy of the proposed real-time Volt-Var controller in handling the real-time disturbances from DERs and loads.

The rest of this article is organised as follows. **Section 2** details the Volt-Var control methods used in this work. **Section 3** describes the detailed modelling of GFC. **Section 4** explains the overall methodology implemented for real-time Volt-Var control. The system under consideration, test

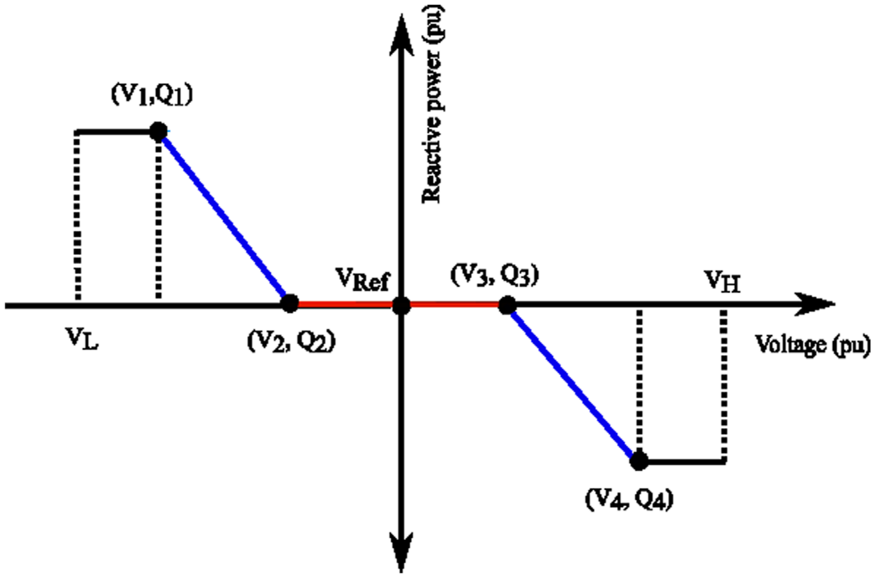

FIGURE 1
IEEE standard 1547-2018 V-Var Mode (pho, 2020).

data and simulation studies is presented in **Section 5**. The main conclusions drawn from this article are provided in **Section 6**.

2 Volt-Var control

The voltage of the distribution network must adhere to standards to ensure proper operation of the network. Under typical operating circumstances, the voltage restrictions are derived from the power quality criteria, which are based on the EN 50160 standard (Standard et al., 2007) in Europe. According to the standard, the steady-state voltage limits, under normal operating conditions, excluding voltage interruptions, during each period of 1 week, shall be 95% of the mean RMS values of the supply voltage for 10 min within the range of ±10%. However, some networks can have reduced criteria to ±5%. To maintain the voltage profile (Kabiri et al., 2014) at the point of common coupling, converters can deliver both inductive and capacitive reactive power. The IEEE1547-2018 standard (pho, 2020) specifies the reactive power output requirements for voltage control applications using smart converters. According to IEEE1547-2018, DER units can provide inductive or capacitive reactive power up to 44% of the total rated capacity.

The reactive power required for the smart converter is given by Eq. **1**. In Eq. **1**, Q_1, Q_4, v_1, v_2, v_3, v_4, are considered fixed quantities in this study and are capacitive 0.44 pu, inductive 0.44, 0.92, 0.98, 1.02, and 1.08 pu, as shown in **Figure 1**. Q_2 and Q_3 are considered 0 pu during the normal voltage operation period, which is from 0.98 to 1.02 pu, as the controller does not intervene during those periods. For this analysis, it is assumed that all DERs in the network have the same Volt-Var settings.

$$Q(v) = \begin{cases} Q_1 & for\ v \le v_1 \\ Q_2 + \dfrac{Q_1 - Q_2}{v_1 - v_2}(v - v_2) & for\ v_1 < v \le v_2 \\ 0, & for\ v_2 < v \le v_3 \\ Q_3 + \dfrac{Q_4 - Q_3}{v_4 - v_3}(v - v_3) & for\ v_3 < v \le v_4 \\ Q_4 & for\ v_4 < v \le v_5 \end{cases} \quad (1)$$

In order to realise the reactive power control in smart converters, the fundamental concept of the power capability curve of the power converter needs to be precise. **Figure 2** shows the capability curve and the relationship of converter size with the reactive power.

In **algorithm 1**, the overall process of Volt-Var control (VVC) mode in a converter is represented. For all converters in the network, Volt-Var is implemented at the same time. To bring the system under similar consideration, the Volt-Var settings for all converters are considered the same. In **algorithm 1**, n is the total number of buses. m is the total number of buses with DER integration. k is the total number of load buses. The active and reactive power consumption of the load on the bus k at a particular moment in the simulation time t is represented by $P_k^L(t)$ and $Q_k^L(t)$. Similarly, $P_m^{DER}(t)$ and $Q_m^{DER}(t)$ represent the active and reactive power of DER on the bus m at the simulation instant t. The values of the active power and reactive power of the loads and the active power generation of the DERs are taken from the measurement data. This initialisation process is performed using the Typhoon HIL signal processing toolchain and is programmed in Python. After retrieving the required signals, the loads and active power generation of DERs are changed in the distribution system model in OpenDSS by co-simulation between the Typhoon HIL and OpenDSS. With the assigned values, the power flow in the distribution network is calculated using co-simulation. After successful completion of the power flow, the required information (voltage of the bus) is extracted. From the information available from the extracted data, Volt-Var is implemented on each DER in the network. The implication of Volt-Var control is that it provides the required reactive power for the DER to mitigate voltage violations. The VVC is implemented in all converters to obtain the reactive power reference. The reactive power reference is then sent to the controller in the real-time simulator. The process is repeated until the user manually stops the simulation. The general methodology that describes the real-time Volt-Var control and the detailed process of exchanging the required information is explained in Section 4.

The block diagram representation of the real-time VVC is presented in Figure 3. Typhoon HIL control centre, the Volt-Var control centre, and the Typhoon HIL and OpenDSS co-simulation are the main components for obtaining the real-time Volt-Var control using the propsed method. The Typhoon HIL control centre consists of various Python-based programmes to execute the co-simulation between the OpenDSS and the real-time simulator. The control centre also communicates with the Volt-Var control centre using the Python-based programme. The Volt-Var control centre communicates with OpenDSS to implement Algorithm 1 from the information obtained from the Typhoon HIL control centre and OpenDSS.

Require: $t \geq 0$, $n \geq 0, m \geq 0, k \geq 0$, $P_k^L(t) \geq 0$, $Q_k^L(t) \geq 0$
Ensure: $t = 0, m = 0$, $V_n(0) \geq 0$, $P_m^{DER}(0) \geq 0$, $Q_m^{DER}(0) = 0$

while True **do**
Initialisation
Run power flow with initial values using cyber-physical co-simulation
Get the measurement signals for monitoring the voltage profile
  while $m \leq n-1$ **do Implement VVC**
  if $V_m(t) > v_2$ and $V_m(t) \leq v_3$ **then**
  $Q_m^{DER}(t) = 0$
  else if $V_m(t) \leq v_1$ **then**
  $Q_m^{DER}(t) = Q_1$
  else if $V_m(t) > v_1$ and $V_m(t) \leq v_2$ **then**
  $Q_m^{DER}(t) = Q_2 + \frac{Q_1 - Q_2}{v_1 - v_2}(v - v_2)$
  else if $V_m(t) > v_3$ and $V_m(t) \leq v_4$ **then**
  $Q_m^{DER}(t) = Q_3 + \frac{Q_4 - Q_3}{v_4 - v_3}(v - v_3)$
  else if $V_m(t) > v_4$ **then**
  $Q_m^{DER}(t) = Q_4$
  end if
  end while
Set P and Q reference to the converters in physical system
Run power flow using cyber-physical co-simulation
Obtain voltage after VVC
  $t = t + 1$
end while

Algorithm 1. An algorithm for real-time Volt-Var control.

3 Detailed modelling of grid forming converters

DERs like wind power plants and solar photovoltaics, are not directly connected to the grid (Wen et al., 2022). Generally, converters are used to connect them to the grid. An appropriate control design is an important aspect to connect the DERs efficiently. The control algorithms are anticipated to establish active power and reactive power from the DERs based on the scope of interconnection. The literature has several control measures that have been suggested (Ansari et al., 2021). The degree of integration of RESs into the network should also be taken into account when choosing the appropriate control mechanisms. Synchronous generators in the network can manage unstable power dynamics when there are fewer DERS interconnected. However, these generators are not able to manage such system dynamics and maintain system stability in converter-dominated systems, as converter-based DERs lack damping or spinning inertia (Van Wesenbeeck et al., 2009). Researchers are becoming more interested in the idea of virtual synchronous machines (VSMs) (Zhong and Weiss, 2010) as a potential solution to this problem. Physically, VSMs are power electronics converters that can provide the grid with virtual inertia and damping (Azuara-Grande et al., 2022). This work uses the grid-forming synchronverter (Zhong and Weiss, 2010; Zhong, 2016) created as a voltage source for real-time reactive power regulation. The grid forming converter has the ability to maintain angle and voltage at the coupling point. Are therefore thought to be appropriate for DER-enriched distribution networks Awal et al. (2020).

Control of the synchronverter to regulate active and reactive power is governed by a mathematical model of the synchronous generator (Zhong et al., 2015). As the main focus of this paper is to implement the real-time control using the developed CPCS framework, this paper implements the control similar to (Zhong et al., 2015). Assume that the stator windings are placed in slots around the uniform air gap in a synchronous

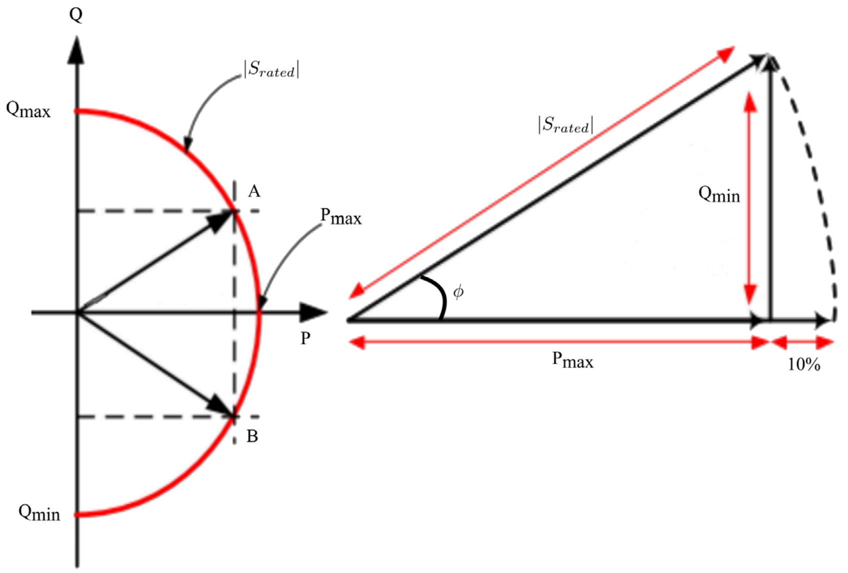

FIGURE 2
Power capability curve of smart converter (Kabiri et al., 2014).

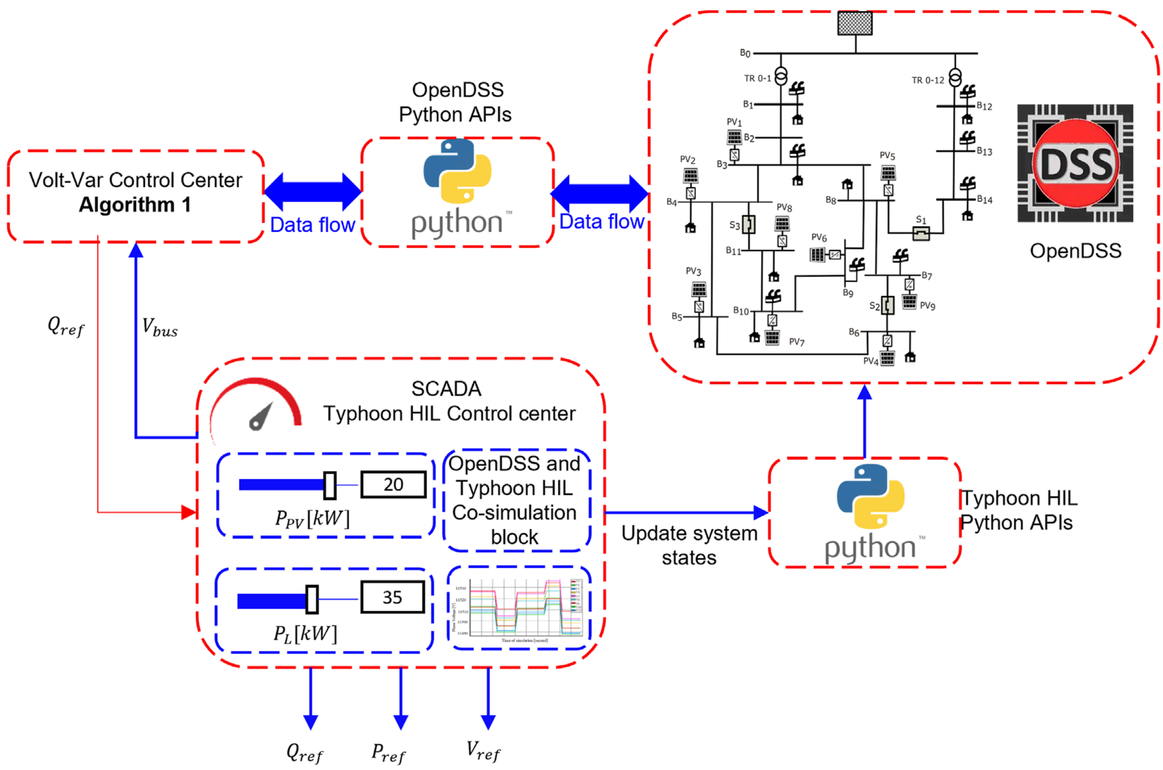

FIGURE 3
Co-simulation between OpenDSS and Typhoon HIL for real-time Volt-Var control.

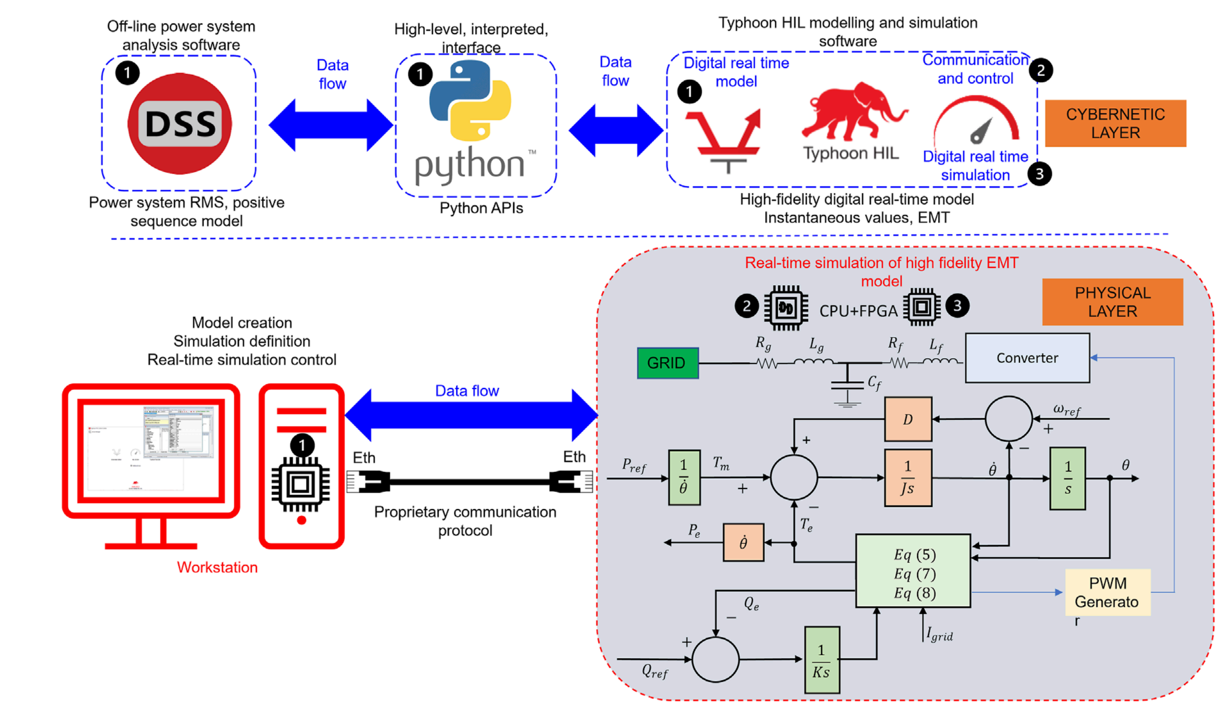

FIGURE 4
Overall methodology of proposed real-time Volt-Var control using cyber-physical co-simulation framework.

generator and that the stator winding has a self-inductance of L, mutual inductance of M, and resistance R_s characterise the stator winding. The electromagnetic flux (Φ) produced by the stator winding and the current (i) flowing through the winding can be represented by Eq. 2.

$$\Phi = \begin{bmatrix} \Phi_a \\ \Phi_b \\ \Phi_c \end{bmatrix}, I = \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{2}$$

The phase shift between the phases differs by $\frac{2\pi}{3}$. So, the phase shift vector $\tilde{cos}\theta$ and $\tilde{sin}\theta$ is represented by Eq. 3. θ is the rotor angle corresponding to phase a.

$$\tilde{cos}\theta = \begin{bmatrix} cos\theta \\ cos\left(\theta - \frac{2\pi}{3}\right) \\ cos\left(\theta - \frac{4\pi}{3}\right) \end{bmatrix}$$
$$\tilde{sin}\theta = \begin{bmatrix} sin\theta \\ sin\left(\theta - \frac{2\pi}{3}\right) \\ sin\left(\theta - \frac{4\pi}{3}\right) \end{bmatrix} \tag{3}$$

The phase terminal voltage $\vec{v} = [v_a \quad v_b \quad v_c]^T$ of the generator is given by the Kirchhoff voltage law and can be represented by Eq. 4

$$\vec{v} = \vec{e} - R_s\vec{I_f} - L_s\frac{d\vec{I_f}}{dt} \tag{4}$$

where, $L_s = L + M$ and $\vec{e} = [e_a \quad e_b \quad e_c]^T$ is the back emf. The back emf is given by Eq. 5.

$$e = M_f\vec{I_f}\frac{d\theta}{dt}\tilde{sin}\theta - M_f\frac{d\vec{I_f}}{dt}\tilde{cos}\theta \tag{5}$$

The relative location of the electrical rotor axis and the magnetic field axis in a synchronous generator is fixed under normal operating conditions. However, any disturbance causes the rotor to decelerate or accelerate, reducing or increasing the rotor angle θ. The swing equation (Grainger and Stevenson, 1994) describes a relative motion of the rotor for synchronously rotating air gap. The swing equation is given by Eq. 6.

$$\frac{d^2\theta}{d^2t} = \frac{1}{J}\left[T_m - T_e - D\frac{d\theta}{dt}\right] \tag{6}$$

Where J is the moment of inertia of all the rotating parts, D is the damping factor, T_m is the mechanical torque, and T_e is the electromagnetic torque. The electromagnetic torque is given by Eq. 7.

$$T_e = M_f \vec{I}_f \langle \vec{I}, \tilde{sin\theta} \rangle \tag{7}$$

where $\langle \cdot, \cdot \rangle$ denotes the inner product in $\mathbb{R}^3$. The converter's active and reactive power is obtained using Eq. 8.

$$\begin{aligned} P_e &= \frac{d\theta}{dt} M_f \vec{I}_f \langle \vec{I}, \tilde{sin\theta} \rangle \\ Q_e &= -\frac{d\theta}{dt} M_f \vec{I}_f \langle \vec{I}, \tilde{cos\theta} \rangle \end{aligned} \tag{8}$$

The controller block diagram is placed within the overall methodology block diagram 4. Inside the block diagram, the controller is represented by the mathematical model described above. The controller takes P_{ref} and Q_{ref} as input and provides P_e and Q_e as electrical outputs. $\boldsymbol{I}$ is the current that flows into the grid from the synchronverter. $\boldsymbol{I}$ is given by Eq. (2). P_{ref} and Q_{ref} are obtained from the controlling and monitoring system developed in SCADA of the proposed cyber-physical testbed for real-time Volt-Var control. P_e and Q_e are sent back to the converters in the distribution network through the SCADA. A detailed description of the signal flow to and from the controller is described in **Section 4**.

4 Proposed real-time Volt-Var control

For monitoring and controlling the distribution networks, a number of crucial components are needed to implement the real-time application (Borlase, 2017). One of the most fundamental needs is a tool to calculate three-phase unbalanced power flow. Other factors include the control system and its implications for supervisory control and data acquisition (SCADA). Remotely controlled equipment infrastructure, improved real-time metering, and communication infrastructure are also essential. Some of the requirements are developed in the cybernetic layer and some of them in the physical layer. The cyber-physical co-simulation (CPCS) framework for real-time Volt-Var control is made up of two layers 1) the cybernetic layer and 2) the physical layer. The cybernetic layer consists of monitoring and controlling components, software to interface with the physical layer, and software to communicate with the distribution system simulator (OpenDSS in this instance). For simplicity, all the software of the cybernetic layer is executed on the host PC. All controllable hardware, both virtual and actual, is part of the physical layer.

The cybernetic layer is the central core of the CPCS framework for real-time Volt-Var control. The host PC contains the cybernetic layer. Additionally, the host PC has the software required to administer and model the real-time digital simulator. The main purpose of the proposed CPCS framework for Volt-Var control is to simulate an entire distribution network and implement real-time Volt-Var control. As a result, the proposed CPCS framework is equipped with measuring and monitoring devices to obtain the necessary parameters, such as voltage magnitudes in the network. To create variation in DER generation and load demand in real-time, different sliders are placed in SCADA. The change in SCADA is represented in the distribution network by a signal processing system designed within the programme. After the co-simulation, the network experiences a change in the operating condition. With a change in the network operating condition, the SCADA monitoring system triggers the Volt-Var controller to obtain the reactive power references for the GFC. The voltage profile resulting after the application of Volt-Var Control can be observed in real-time. A monitoring and control system created in Typhoon HIL SCADA may be used to dynamically adjust the active power production and loads. A graphical user interface (GUI) is the monitoring and control system of a CPCS framework for real-time Volt-Var Control, and it enables real-time visualisation and control of the simulation. The GUI is specifically designed to show the signals produced by the measurement devices linked to the test system during real-time simulation. The GUI also shows the current condition of the bus voltages visually or digitally. This study uses the Typhoon HIL SCADA system to construct the GUI. Using the Python API, the HIL SCADA communicates with both the cybernetic and physical layers. The true simulation happens at the physical layer. The physical layer in this investigation was HIL 604 from Typhoon HIL Inc. The HIL 604 has eight processing cores, two digital I/O channels, and two analogue I/O channels. It also has two Advanced RISC Machine (ARM) cores.

The general process of implementing the real-time Volt-Var control is shown in **Figure 4**. Firstly, the test distribution system is modelled in OpenDSS. DERs are placed on the distribution network in the OpenDSS model. The OpenDSS modules are executed *via* Python API. A Python programme is written inside the Typhoon HIL SCADAIL to interface with OpenDSS. In a Typhoon HIL schematic editor, the grid-forming converter is modelled according to the mathematical model as described in **Section 3**. The communication interface between the SCADA and the Typhoon HIL real-time simulator is developed using signal processing components available in Typhoon HIL and the Python API of Typhoon HIL. The SCADA system continuously monitors the node voltage of the network and, using the information of the voltage, the Volt-Var controller is designed in the cyber layer. The detailed algorithm for the Volt-Var control for all connected GFCs is presented in **Section 2**. The reference active and reactive power after the application of the Volt-Var controller is then sent to the GFC. The GFC controller is designed in such a way as to track the reference active and

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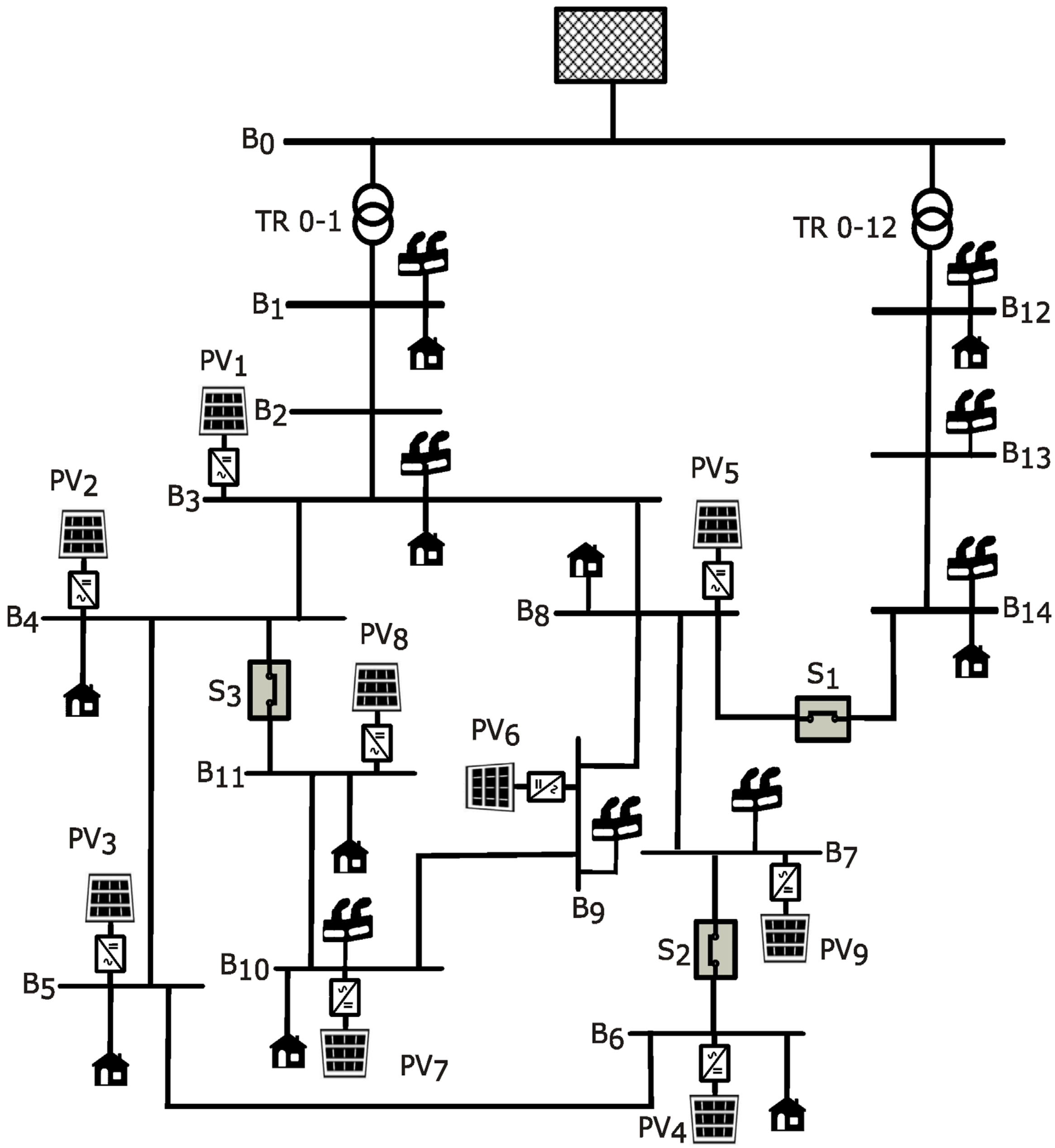

FIGURE 5
Layout of CIGRE network with loads and DERs (Barsali et al., 2014).

reactive power. The electrical power output of the GFC is then fed to the distribution system. The model can interact with the SCADA and the Typhoon HIL real-time simulator using the signal processing blocks developed in the Typhoon HIL SCADA. The SCADA also consists of a Python programme to get the signals from OpenDSS, process the signal, and display them in real-time. SCADA is equipped with different sliders (to change the load and generation) to send the real-time signal to the OpenDSS. The signals exchanged between the cyber and physical layers are P_{ref}, Q_{ref}, P_e, Q_e, V_{grid}. The exchange of information is done with the help of the signal processing block available in the typhoon HIL and a programme written in Python. The real-time simulation is executed at a fixed time step (1.00 s), which is the maximum allowable execution time of Typhoon HIL. After each time step, the process is repeated until the user stops the simulation.

TABLE 1 MV distribution network benchmark application: parameters of PV units (Barsali et al., 2014).

Node	Type of DER	$P_{max}(kW)$
B3	PV	690
B4	PV	690
B5	PV	680
B6	PV	680
B7	PV	740
B8	PV	740
B9	PV	740
B10	PV	740
B11	PV	740

TABLE 2 MV distribution network benchmark application: Parameters of residential load.

Node	$S_{max}(kVA)$	*powerfactor*
B1	74	0.98
B3	264	0.97
B4	812	0.97
B5	895	0.97
B6	532	0.97
B8	760	0.97
B10	653	0.97
B11	315	0.97
B12	14173	0.98
B14	199	0.97

TABLE 3 MV distribution network benchmark application: Parameters of commercial load.

Node	$S_{max}(kVA)$	*powerfactor*
B1	20.70	0.95
B3	1.30	0.85
B7	0.40	0.85
B9	3.30	0.85
B10	0.40	0.85
B12	25.20	0.95
B13	0.20	0.85
B14	1.90	0.85

TABLE 4 Parameters of controller of grid forming converter (Zhong et al., 2015).

Parameter	Value	Units
Moment of inertia (J)	0.1	kg/m^2
Mechanical friction (D)	1	Nms
Reactive power droop (K_v)	0.0001	—
Grid frequency (ω)	314	$rad/$sec
Filter resistance (R)	0.1	Ω
Filter inductance (L)	10.1859	mH
Filter capacitance (C)	24	μF
$M_f i_f$ of synchronous generator	0.5	Vs

5 Real-time simulation studies

This section demonstrates the proposed real-time simulation analysis of the proposed real-time Volt-Var control. The study was performed in the Digital Energy Systems Laboratory (DIgEnSys-Lab). The DIgEnSys-Lab features physical equipment for real-time monitoring and control (for more information, see https://fglongattlab.fglongatt.org). The following subsections go through each component of the simulation research. In this research, Typhoon HIL 604, OpenDSS and Python are used for cyber-physical co-simulation (CPCS) for real-time Volt-Var control.

5.1 Test system

European MV distribution network can be used for DER integration studies (Acosta et al., 2021). Therefore, in this study, the European MV distribution network developed by the CIGRE Task Force C6.04 in "Benchmark Systems for Network Integration of Renewable and Distribution Energy Resources" (Barsali et al., 2014) is considered. The network is symmetric and balanced. The test system is shown in Figure 5. The network can be operated in radial or meshed topology by turning on or off the switches S1, S2, and S3. However, in this analysis, all switches are considered closed. To study the effectiveness of real-time Volt-Var control in GFC in this case and to represent the dominance of GFC, the wind power plant on bus B7 considered in the original study is replaced by a DER source. In this study, PVs are considered as DERs.

Table 1 shows the PV ratings considered in this study. In this study, the size of the photovoltaics and the load are modified according to the hosting capacity and the calculation of the spare load capacity performed for the same distribution network. For simplicity, constant impedance loads are considered in this analysis. The main aim of this study is to incorporate the proposed cyber-physical co-simulation framework for control application, even though constant power loads have destabilising effects on volt-volt control methods, the effect is not considered in this study. Tables 2, 3 are the values

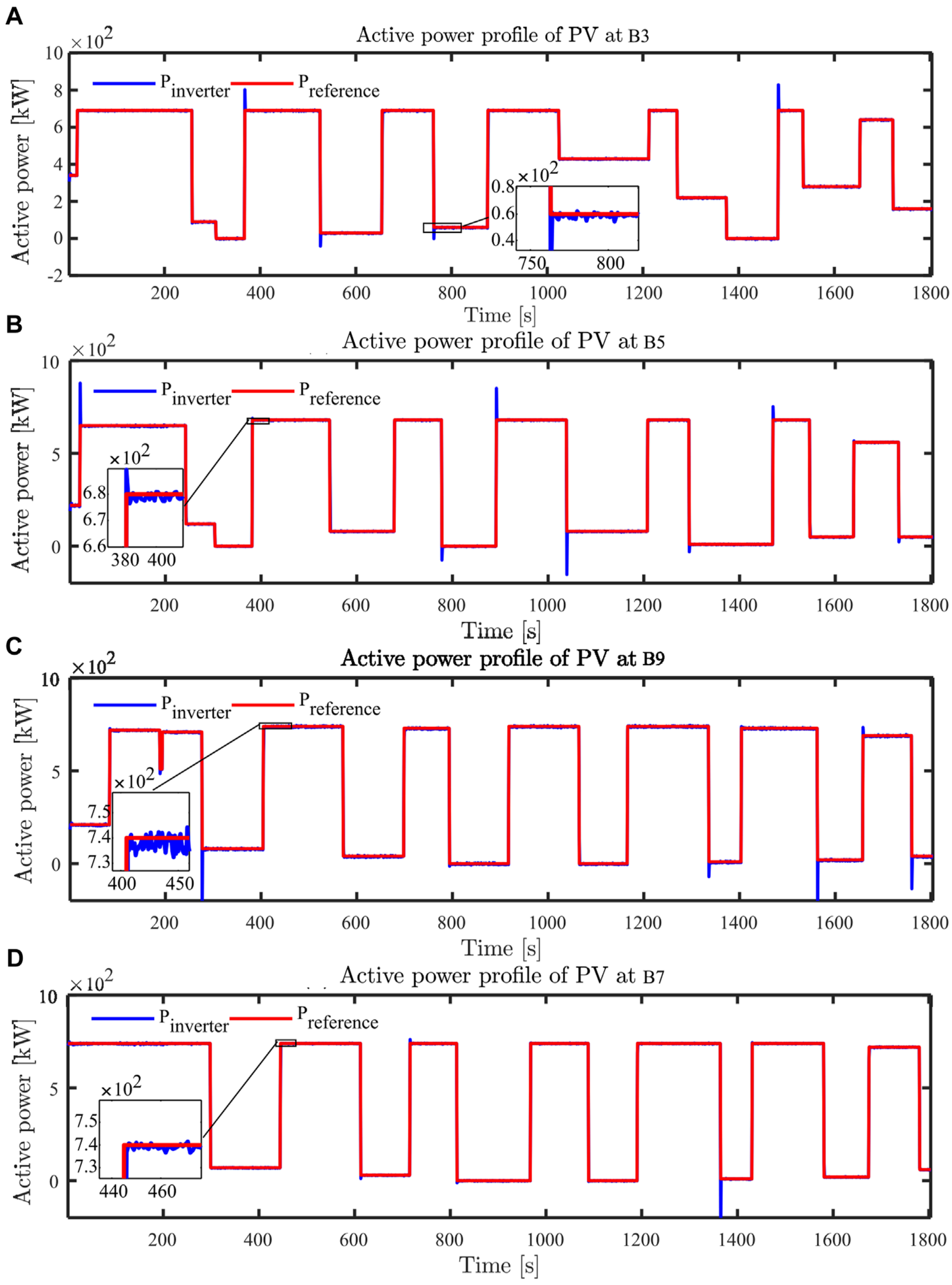

FIGURE 6
Active power profile of PV at **(A)** B3, **(B)** B5, **(C)** B9, and **(D)** B7.

of residential and commercial loads considered in this study. Network information is taken as in the original CIGRE test network.

The controller parameters considered in this study are given in Table 4.

5.2 Real-time simulation results and discussion

A case study is considered to check the effectiveness of the proposed real-time Volt-Var Control (VVC) in the distribution

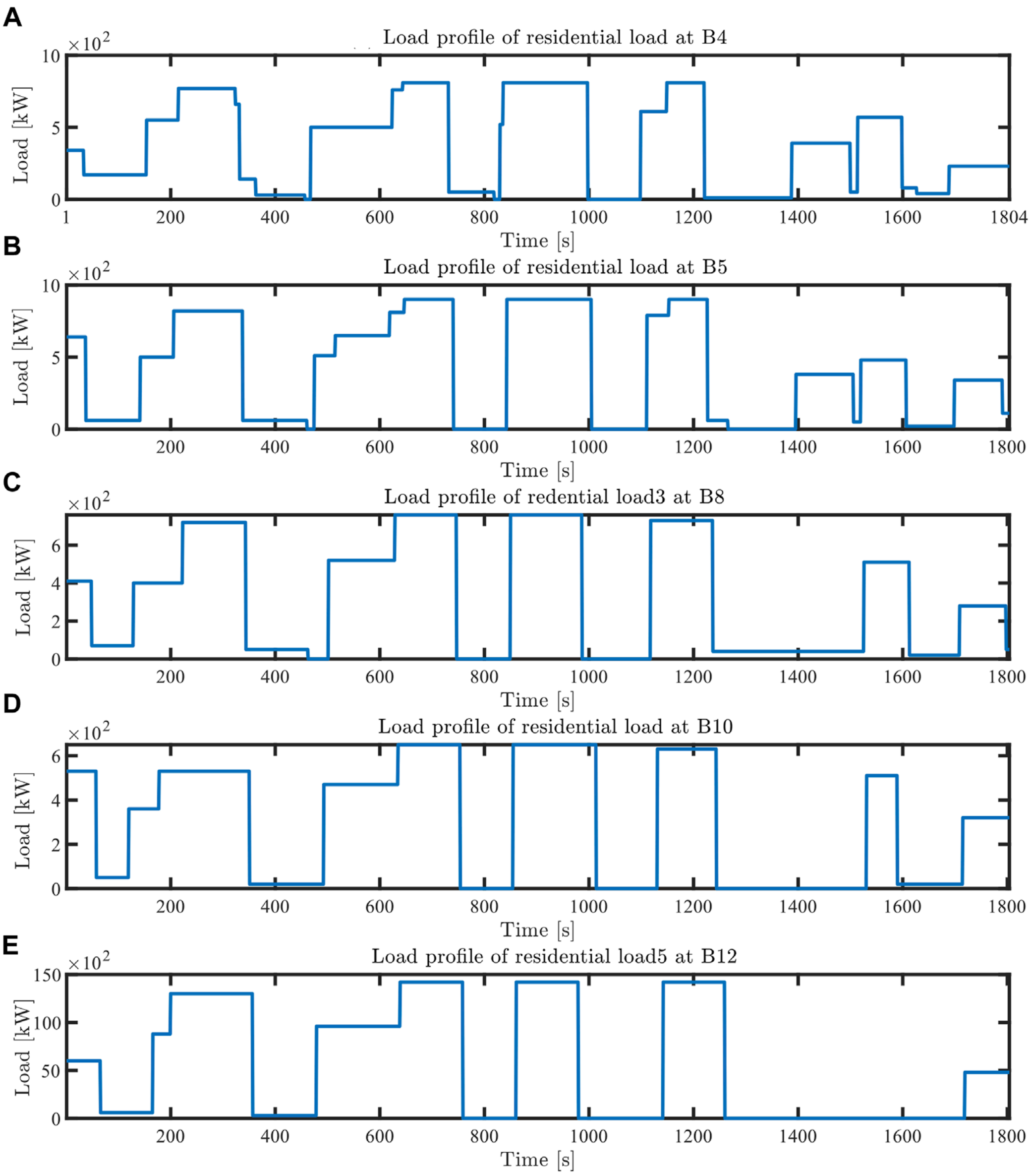

FIGURE 7
Load profile of residential load at **(A)** B4, **(B)** B5, **(C)** B8, **(D)** B10, and **(E)** B12.

network. In this case study, active power generation from PVs and some residential loads is dynamically changed during the real-time simulation of the SCADA panel developed in this study. The power from PV and the load can be changed in real time by changing the value of the slider widget in THIL SCADA, developed for this specific purpose. The real-time simulation is executed at an execution time of 1.00 s. The proposed VVC and all signal processing are completed within the time frame of each iteration.

The change in active power from the PVs and the loads from the SCADA modify the operating condition of the distribution network by CPCS between OpenDSS and Typhoon HIL. The loads and active power of PV are randomly changed during the real-time simulation in this study. These values are stored in a database during a real-time simulation. After each execution time, the corresponding voltage profile of the distribution network is monitored through the monitoring system developed using advanced model-based system engineering tool chains of Typhoon HIL. Inside a Typhoon HIL, a Python-based programme activates the VVC and provides the reactive power references to manage uncertain voltage violations. This reactive power reference is passed to the grid-forming converter

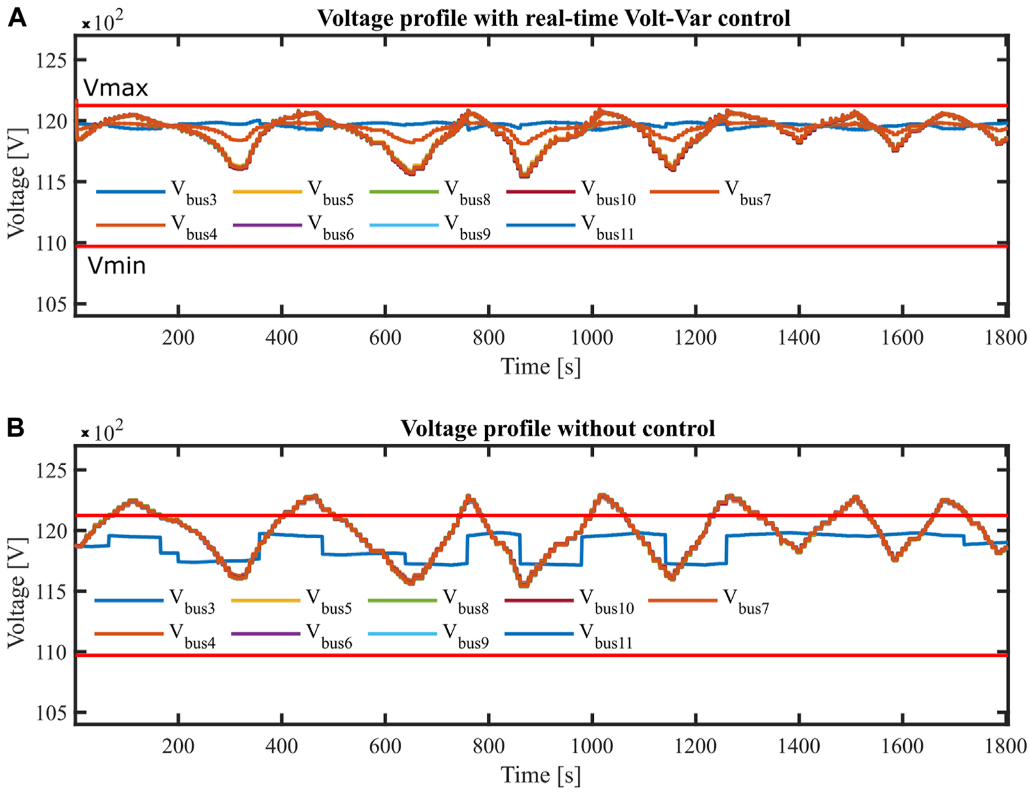

FIGURE 8
Voltage profile comparison of the CIGRE network **(A)** with real-time Volt-Var control in PV **(B)** with fixed power factor in PV.

TABLE 5 Computational analysis of proposed CPCS.

Name of component	Number of components	Percentage of available resources
Standard processing core utilization	1 out of 3	33%
Signal generator utilization	12 out of 12	100%
Matrix memory utilization	—	0.5%
Simulation step time	1μs	—
Scaled discretization step	1μs	—
Time slot utilization of core	—	66.25%
Time slot utilization of other functional units	—	42.5%
Signal processing IO variables utilization	24 out of 4194304	0.00057%
Signal processing Probes utilization	51 out of 1024	4.98%
Total utilization of the internal memory	54 out of 254 kB	21.24%

modelled inside the real-time simulator. The active and reactive power output of the converter is fed back to PV in the distribution network. This process is repeated until the end of the simulation. To consider the limitations of the Typhoon HIL configuration available in the laboratory, only four smart converters are designed in Typhoon HIL. For the rest of the PV in the network, the active power reference and the reactive power reference are fed directly to the PV in the distribution network. The real implementation of the power converters developed in THIL are PV1, PV3, PV6, and PV9 connected to B3, B5, B9, and B7, respectively. However, the active power reference is changed for all the PVs connected to the network to change the system's dynamics. Figure 6 shows the active power reference and the active power generated by the converter. Active power

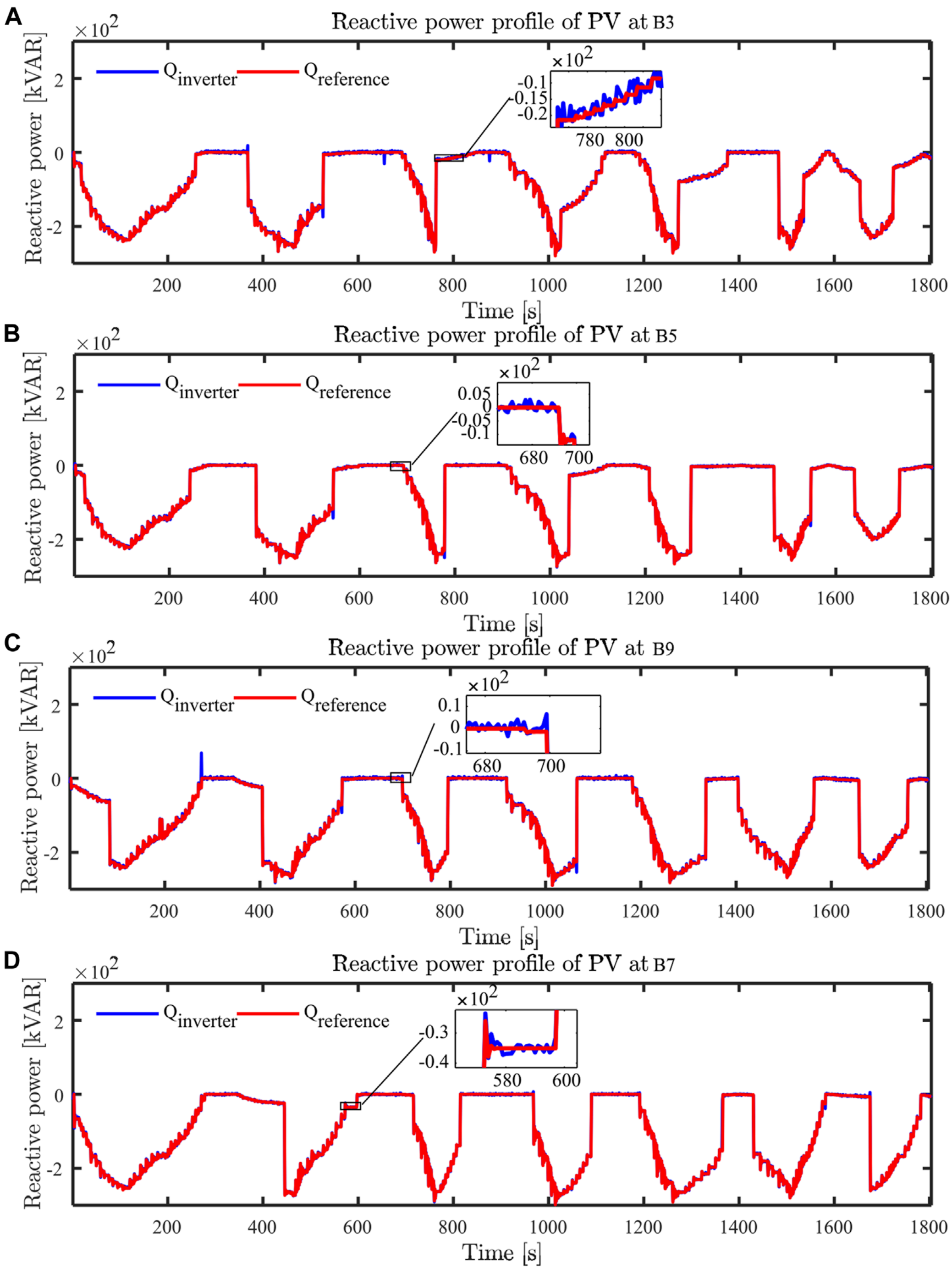

FIGURE 9
Reactive power profile of PV at **(A)** B3, **(B)** B5, **(C)** B9, and **(D)** B7.

references are obtained by randomly changing the sliders in SCADA.

Similarly, to make the real-time simulation more realistic, some of the residential loads in the distribution network are dynamically changed. Residential loads in B4, B5, B8, B10, and B12 are only changed in this study, and the rest of the loads are considered constant. However, it is possible to change all loads during a real-time simulation. The change in loads is exchanged with the distribution network model by a similar process as explained for the change in the active power reference of PVs.

The load profile of residential loads in B4, B5, B8, B10, and B12 is shown in **Figure 7**. The load profile is obtained by changing the values randomly in real-time from the SCADA.

The distribution network experiences changes in the voltage profile of the network with the change in the active power of the PVs and loads. In **Figure 8B**, it is observed that there are some instances where voltage violations are observed. This voltage profile is obtained by offline co-simulation with the values stored during real-time simulation to make a comparative analysis.

However, during real-time Volt-Var control, as soon as voltage violations are observed in the network, the real-time Volt-Var controller dispatches the required reactive power to mitigate these voltage violations. With this reactive power from the converter, voltage violations are supposed to be mitigated. The voltage profile obtained during the real-time simulation is depicted in **Figure 8A**. It is observed that there are no voltage violations during the real-time simulation. This analysis shows the effectiveness of the real-time Volt-Var controller to mitigate voltage violations. The real-time Volt-Var controller is able to mitigate voltage violation issues that were observed with the same PV and load profile on the network.

The reference reactive power and the output reactive power from the PV1, PV3, PV6, and PV9 converters are shown in **Figure 9**. Reactive power references are sent from the real-time Volt-Var controller based on the voltage of the network at that instant. The GFC controller tracks the reactive power reference. This electrical power is fed to the PV in the distribution network. According to the standard, the positive reactive power is considered as a capacitive reactive power support and the negative reactive power as inductive. Voltage violations below the prescribed limit are supported by capacitive reactive power, while voltage violations above the prescribed limit are supported by inductive reactive power. The reactive power reference profile is obtained from the Volt-Var setting as described in **Section 2**.

5.3 Computational analysis

The computational efficiency of the cyber-physical co-simulation framework is highly dependent on the executable model in the physical layer. This also differs according to the application of the cyber-physical system. The authors in (Tzanis et al., 2018) analyse the computational part of the real-time transient behaviour of a single full-bridge inverter with FPGA hardware resources in a cyber-physical system of a modern distribution grid. Only a few component analyses are presented, for example, the number of logical function blocks (33% of available resources), the number of input output blocks (29% of available resources), the number of digital signal processing blocks (4% of available resources), and a computational time of 0.126 μS. The detailed description of the computational analysis also differs from that of the real-time simulator considered for the developed CPCS. **Table 5** shows the detailed computational analysis of the proposed CPCS.

6 Discussion and conclusion

In this study, a fundamental framework for real-time Volt-Var control is designed in a DER-enriched distribution network to address voltage violations caused by increased penetration of DERs. This study also shows how effectively the suggested framework for real-time cyber-physical co-simulation (CPCS) can handle voltage violations in DER-enriched distribution networks. The suggested method is more adaptable for implementation on any sort of distribution network since the distribution network was modelled on an open source distribution network solver called OpenDSS. The controller for the grid-forming converter modelled in Typhoon HIL tracks the active power reference from the SCADA and the reactive power reference from the Volt Var controller. Reactive power references are computed in real-time by the Volt Var controller to mitigate voltage violations. In the Typhoon HIL, an SCADA is created to perform CPCS and real-time Volt Var control. Taking into account the alteration in the generation profiles of DERs and the consumption profiles of loads, a scenario of voltage violations was developed. The effectiveness of the real-time VVC suggested to mitigate voltage violations is shown by real-time simulations. This study broadens the multidimensional horizon for real-time simulation studies on a CPCS between Typhoon HIL and OpenDSS. The framework developed in this study can be implemented on any type of distribution network, whether single-phase or multi-phase, balanced or unbalanced.

The model-based system engineering tool chains of Typhoon HIL are used in this work to process signals and exchange information between the cyber and physical layers. However, the application of C37.118 or IEC61850 communication protocol is left for future work.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

RW, PS, and FG-L contributed to the conception and design of the study. RW and FG-L developed the methodology and software validation. RW performed the simulation studies. RW wrote the first draft of the manuscript. PS, CS, MA, and FG-L review the manuscript. All authors contributed to the revision of the manuscript, read and approved the submitted version.

Acknowledgments

The authors are very grateful to the Arctic Centre for Sustainable Energy (ARC) (project number 740108), The Arctic University of Norway, Norway, for providing an opportunity for Raju to visit and work at DIgEnSys-Lab. The authors thank UiT The Arctic University of Norway for covering the publishing cost. The authors also acknowledge the technical support provided by the Typhoon HIL and OpenDSS teams.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationship that could be construed as a potential conflict of interest.

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Nomenclature

Abbreviations

DER Distributed energy resources

RES Renewable Energy Sources

DN Distribution Networks

GFC Grid Forming Converters

DSO Distribution System Operators

PV Photovoltaics

VRD Voltage regulating devices

OLTC On-load Tap Changing

VVC Volt-Var Control

LV Low voltage

CPCS Cyber-physical co-simulation

J Moment of inertia

D Mechanical friction

k_v Reactive power droop

ω Grid frequency in rad/sec

$V_k(t)$ Voltage phasor of bus k at time t

$P_m^{DER}(t)$ Active power generation of DER at bus m at time t

$Q_m^{DER}(t)$ Reactive power generation of DER at bus m at time t

$P_k^L(t)$ Active load demand of bus k at time t

$Q_k^L(t)$ Reactive load demand of bus k at time t

n Notation for bus

k Notation for load bus

m Notation for bus with DER integration

t Simulation time instant

Paper D. Optimal power flow-based reactive power control in smart distribution network using real-time cyber-physical co-simulation framework.

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IET Generation, Transmission and Distribution, 2023, Pages 1-14.

https://doi.org/10.1049/gtd2.12786

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Authors Contribution:

The implementation of the methodology, utilization of software, data curation, formal analysis, writing original draft, validation, and visualization of the paper was done by the **candidate**.

The conceptualization of the idea to do further research and development of the proposed optimal power flow-based reactive power control in a smart distribution network using real-time cyber-physical co-simulation framework was generated by the **candidate** during the research exchange at DIgEnSys-Lab. The framework for realizing cyber-physical co-simulation is developed in Paper E. The tradeoff in real-time optimization is identified in Paper F. Resources, real-time results and application was developed by the **candidate**.

All co-authors contributed essentially to the supervision, review, validation, and proof of the paper.

Received: 21 October 2022 | Revised: 6 December 2022 | Accepted: 1 February 2023

IET Generation, Transmission & Distribution

DOI: 10.1049/gtd2.12786

The Institution of Engineering and Technology WILEY

ORIGINAL RESEARCH

Optimal power flow-based reactive power control in smart distribution network using real-time cyber-physical co-simulation framework

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Abstract

Future distribution networks (DN) are subject to rapid load changes and high penetration of variable distributed energy resources (DER). Due to this, the DN operators face several operational challenges, especially voltage violations. Optimal power flow (OPF)-based reactive power control (RPC) from the smart converter (SC) is one of the viable solutions to address such violations. However, sufficient communication and monitoring infrastructures are not available for OPF-based RPC. With the development of the latest information communication technology in SC, cyber-physical co-simulation (CPCS) has been extensively used for real-time monitoring and control. Moreover, deploying OPF-based RPC using CPCS considering the controller design of SC for a realistic DN is still a big challenge. Hence, this paper aims to mitigate voltage violations by using OPF-based RPC in a real-time CPCS framework with multiple SCs in a realistic DN. The OPF-based RPC is achieved by performing the CPCS framework developed in this study. The CIGRE medium-voltage DN is considered as a test system. Real-time optimization and signal processing are achieved by Python-based programs using a model-based toolchain of a real-time DN solver and simulator. Real-time simulation studies showed that the proposed method is capable of handling uncertain voltage violations in real time.

1 | INTRODUCTION

Global awareness of carbon neutrality, increased energy demand, technological advancement in control strategies, and significant cost reduction have encouraged power system operators to incorporate more renewable energy-based distributed energy resources (DER) into the distribution network (DN) [1]. To run the DN with higher observability, controllability, and flexibility, the DNs are transitioning from conventional architecture to smart architecture [2]. DNs are now operated in the smart grid paradigm and hence are also renamed smart distribution networks (SDNs). In smart architecture, SDNs are equipped with smart meters, smart converters (SC) [3], intelligent electronic devices (IED), and advanced communication infrastructure. For smart operation, SDN requires a more resilient, robust, and high-speed control and management system [4].

SDN poses many technical challenges with the high integration of DER and recent modernization in network operation [5, 6]. One significant challenge in SDN is maintaining an efficient and robust regulation of fluctuating node voltages [7, 8]. Generally, the DERs are connected to the SDN using SCs. The use of SCs as a quick response solution to regulate voltage using RPC can be a suitable choice [9, 10]. Furthermore, with the advancement of SC technology, most SCs have powerful communication and monitoring equipment [11]. Therefore, they can meet the requirement for smart operation in SDN without additional investments [12].

Reactive power control (RPC) of SCs can be achieved in several ways [13]. Provided adequate communication, control, and monitoring infrastructure is available, optimal power flow (OPF)-based RPC is one of the most suitable solutions [14]. Optimal RPC and SDN management strategies should also consider moving away from traditional offline approaches and shifting towards real-time solutions to make the system more reliable, fast, and precise [15]. Although many researchers [16, 17] contribute to the development of autonomous systems to improve interaction, resiliency, effectiveness, and reliability, little attention is paid to real-time implementation. So far, only some smart grid functionalities have been developed and prototypically evaluated [18]. With a large number of controllable devices and complex network properties, the implementation in SDN is a complex process [19]. Cyber-physical co-simulation (CPCS) is one of the options to implement real-time implementation in SDN [20].

The use of cyber-physical real-time co-simulation that illustrates the complex behaviour of SDNs has gained attention in recent years [21]. The development of cyber-physical real-time co-simulation depends on the task for which they are designed [22]. The technical literature related to CPCS for SDN reviewed so far focuses mainly on cyber security, cyber theft detection [23], and false data detection [24]. Similarly, some of them use the cyber-physical real-time test only in a small system, for example a single converter system [25], without taking into account the dynamics of the DN. Only a few studies have focused on using the cyber-physical system for real-time RPC. For example, in [26], a distribution grid model was developed, implemented and simulated using OPAL-RT for dynamic performance evaluations in the real-time simulator (RTS). Similarly, in [27], three-phase electromechanical models for grid-following and grid-forming inverters were implemented in a three-phase DN. However, these articles do not consider the optimal OPF-based RPC in their studies. In [28], an attempt is proposed to realize real-time volt-watt control in a smart inverter considering voltage deviation as an objective function. However, this method incorporates offline optimization to obtain the optimal set points for smart inverters. Comprehensive studies of smart grid control functions are proposed on globally available power system networks using a RTS in [29]. The OPF is also implemented to obtain the optimal setpoints for SCs. But modelling of the converters and their real-time control is not implemented.

Considering the real-time operation of SDN for optimal RPC using the cyber-physical system, multiple converters, and the complex network property of SDN need to be considered. In addition, to operate the SDN optimally, real-time optimization is also another key factor that cannot be neglected. This paper presents a novel attempt to incorporate existing gaps as discussed above. Therefore, this paper proposes an OPF-based optimal RPC in SDN using CPCS. This paper uses the CPCS frameworks with multiple SCs, the converter controller, and the three-phase unbalanced DN to represent the realistic scenario of SDN. Furthermore, real-time optimization is also implemented in the paper to operate the SDN optimally. Therefore, the contribution made in this paper opens the multidimensional horizon for optimal real-time control and monitoring studies in SDN. In this paper, the focus is given on real-time OPF-based RPC, but the CPCS framework developed during this study can also be utilized for many other DER integration studies in SDN. This paper proposes and validates the OPF-based RPC in SDN using CPCS. The main contributions made by the authors in this paper are listed below.

1. Develop a framework for an optimal OPF-based RPC using CPCS. The proposed framework is developed using real-time co-simulation between the distribution network solver (DNS) and RTS.
2. Design a controller for SCs in the physical layer (PL) of the cyber-physical framework and create a suitable monitoring and signal processing system to communicate with the optimal RPC centre. In addition, the proposed CPCS framework requires only a little information to update the system states of the designed controller and the SDN.
3. Develop a co-simulation-based optimization framework for obtaining the optimal reactive power setpoints to mitigate the voltage violations in the SDN. The performance of the co-simulation-based optimization is compared with several approaches before selecting the suitable algorithm and DNS.
4. The efficacy of the proposed OPF-based RPC using a real-time CPCS framework is validated by different scenarios of voltage violations created by changing the generation of power from DER and load consumption in real time. The proposed method can handle voltage violations using multiple SCs in the SDN.

The remainder of the paper is organized as follows. Section 2 covers the general method for real-time RPC using CPCS. The mathematical formulation of OPF-based RPC and co-simulation-based optimization is explained in Section 3. Similarly, the modelling of the SC is described in Section 4. The real-time simulation results and discussions are highlighted in Section 5. Finally, the last section concludes the main contribution and suggests future research directions. Further, test data information is included in Appendices.

2 | PROPOSED METHODOLOGY FOR OPF-BASED RPC IN SDN USING CYBER-PHYSICAL CO-SIMULATION

An overall method to implement the proposed OPF-based RPC in the SDN using CPCS is shown in Figure 1. Optimal RPC requires several important components for modelling, monitoring, controlling, and optimizing [2]. To achieve the general goals, two main components are necessary [30]. The first is the cybernetic layer (CL), which has major subcomponents like DNS, the Supervisory Control and Data Acquisition (SCADA) system, and the OPF-based RPC centre. The CL consists of tools and software to perform communication between the components within the CL and the PL. The CL is housed on the host PC that has related proprietary software and applications to manage the real-time digital simulator (RTS). The CL also has a user-defined SCADA panel, an OPF-based control centre, and a distribution system simulator. Furthermore, signal process-

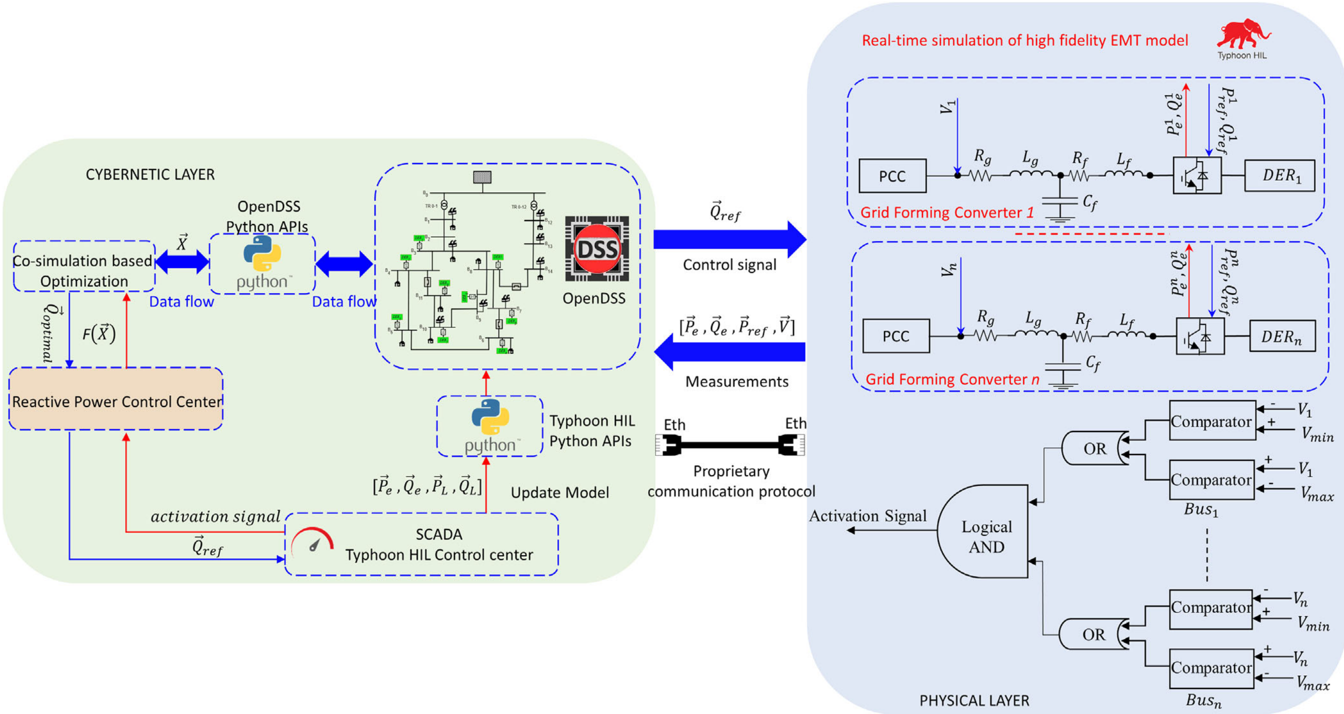

FIGURE 1 Overall method for OPF-based optimal RPC in SDN using proposed real-time cyber-physical co-simulation framework. OPF, optimal power flow; RPC, reactive power control; SDN, smart distribution network.

ing components and Python-based application programming interfaces (APIs) are present in the CL to operate in coordination with the model-based system engineering toolchain of DNS and RTS. The proposed CL also performs the OPF-based optimization as described in Section 3 to obtain the optimal reactive power set points for SCs. The CL also includes various graphical user interfaces (GUI) to interact with the PL and graphical displays to show the real-time output profile of the SDN. The PL is the other part where the real-time simulation of the SCs takes place. In PL, SCs with the controller as explained in Section 4 are designed. The monitoring system with signal processing components to detect the voltage violations is also present in the PL.

The active power references $\vec{P}_{ref}$ are created using the SCADA system in the CL. $\vec{Q}_{ref}$ is the optimal reactive power setpoints obtained from the OPF-based RPC centre. These $\vec{Q}_{ref}$ are sent from CL to PL using ethernet communication between CL and PL. The voltage reference on the nodes of the test system $\vec{V}$ is also exchanged to keep the same voltage profile of the point of common coupling (PCC) in both layers. The SC tracks the active power reference and the reactive power reference and provides the electrical power outputs $\vec{P}_e$ and $\vec{Q}_e$. In the PL, the activation signal generator block is also created. The OPF-based optimization is activated based on the activation signal obtained from the PL. A combination of logical *OR* and *AND* is utilized so that the activation signal is activated when voltage violations occur in the network. The control logic for a comparator used in the activation signal generator block is given by Equation (1). $|V_{IN}|$ is the bus voltage of the network and $|V_{REF}|$ is the reference voltage that can be according to the voltage regulation standard considered in the analysis. $|V_{OUT}|$ is the signal output of the comparator. Once the CL receives the information from the PL, the SCADA updates the system parameters of the SDN in the CL. The detailed methodology for running co-simulation between SCADA and the DNS in CL is presented in [31]

$$|V_{OUT}| = \begin{cases} 1, & |V_{IN}| > |V_{REF}| \\ 0, & |V_{IN}| < |V_{REF}| \\ \textit{no change}, & |V_{IN}| = |V_{REF}| \end{cases} \quad (1)$$

The PL and CL are designed in the RTS and Typhoon hardware in loop (HIL) control centre of the RTS, respectively. The CL and the PL are connected using a proprietary Typhoon HIL communication protocol using an ethernet cable. $\vec{P}_e, \vec{Q}_e, \vec{P}_{ref}, \vec{Q}_{ref}, \vec{V}$ are the signals that are exchanged between the cybernetic and the PL to achieve the proposed real-time CPCS. Since OpenDSS is a powerful DNS [32] and Typhoon HIL is the latest technology for real-time applications [33]. In this paper, OpenDSS is considered as DNS and Typhoon HIL real-time simulator is RTS. The overall process is repeated until the user stops the user.

3 | OPTIMAL RPC IN SMART DISTRIBUTION NETWORK

The SC injects or absorbs reactive power to adjust the voltage profile of the SDN [34]. The absorption or injection of reactive power has a considerable impact on power loss, as the R/X of the line in the DN is high. R is the resistance and X is the reactance of the interconnecting lines. Therefore, when reactive power is required, the impact of network power loss should be considered. This makes the RPC an optimization problem. There are various approaches to optimal control of reactive power in the scientific literature [35]. Most research shows that RPC can be decentralized, distributed, and centralized. The decentralized technique uses local measurements to determine the optimal settings for reactive power dispatch. On the other hand, the distributed method coordinates between the local controller and the central controller. The centralized method is an OPF-based method. OPF can be implemented in DNs with significant integration of DERs.

To implement the OPF-based method in the DN, the DN is typically modelled using the LinDistFlow equations [36] or sensitivity-based modelling [37] in the literature. All network features may not be represented by the linearized version of the DN. Further, the extensive mathematical model of the DN and convergence concerns are additional hurdles in real-time optimization of DNs. Modelling the network in the distribution system simulator and optimizing it through co-simulation [38] is one way to avoid explicit mathematical modelling of the SDN in the optimization model. This method also eliminates convergence concerns because the complicated power flow equations are solved in the co-simulation. This technique can also solve any form of network, whether balanced or unbalanced, radial or mesh, and single-phase or poly-phase. Hence, this paper presents co-simulation-based optimization to grab the advantages of co-simulation-based optimization in real-time applications.

To optimize the SDN using co-simulation. First, the model is built using DNS inside the host PC. The load and generation data from the DERs are defined in DNS. During co-simulation-based optimization, the DNS solves the load flow solutions. The optimization model is built separately using Python-based DNS APIs. Data exchange is implemented in Python so that the simulation runs in engine mode. The optimization model involves objective functions, constraints, and a suitable solver. In particular, the objective function considered in this co-simulation-based optimization is an explicit objective function obtained from co-simulation. In this paper, the objective function $F(\vec{x}, \vec{u})$ is formulated by using the exterior penalty function (EPF) method [39]. The arbitrary penalty function is used to transform constrained problems into unconstrained problems. The EPF is used to incorporate bus voltages ($\forall i = 1, 2, \ldots, N_{bus}$) constraints in the objective function and change it to an unconstrained objective function. N_{bus} is the number of buses in the test system. The objective function $F(\vec{x}, \vec{u})$ in Equation (2) is the linear combination of $f(\vec{x})$ and the penalty function $g(\vec{x}, \vec{u})$.

$$\min_{\vec{x}} F(\vec{x}, \vec{u}) = f(\vec{x}) + g(\vec{x}, \vec{u}) \tag{2}$$

The main aim is to find the reactive power setpoints for the DERs. The controllable variable $\vec{x}$ in Equation (3) is the vector of the reactive power from N_{DER} number of SCs available in the SDN.

$$\vec{x} = [Q_{DER_1} \cdots Q_{DER_j} \cdots Q_{DER_N}]^T \tag{3}$$

The reactive power output of DER is limited by its maximum apparent power and active power. Mathematically, Equation (4) is the available reactive power (Q_{DER_j}) from the SC of size (S_{DER_j}) that produces the active power of (P_{DER_j})

$$QDER_j \leq \pm\sqrt{|SDER_j|^2 - PDER_j^2}\ \forall j = 1, \ldots, N_{DER} \tag{4}$$

Furthermore, according to the IEEE 1547–2018 standard [40], the reactive power of SCs is limited, adding one more constraint to the optimization model as given by Equation (5).

$$-K\ SDER_j \leq QDER_j \leq K \times SDER_j \tag{5}$$

where K = scaling factor for reactive power limit and $j = 1, \ldots, N_{DER}$. The function $f(\vec{x})$ considered in this study is an explicit function obtained from the co-simulation and is given by Equation (6).

$$f(\vec{x}) = P_{loss}(\vec{x}) \tag{6}$$

The second part of the objective function is defined as an arbitrary penalty function $g(\vec{x}, \vec{u})$. The voltage limit for voltage is taken as (V^{min}, V^{max}). Many standards define the permissible voltage limits in the DN. In this scenario, however, the voltage limit is within (V^{min}) and (V^{max}). The penalty function is defined as Equation (7) [39].

$$g(\vec{x}, \vec{u}) = K_p \left[\sum_{j=1}^{N_{bus}} M_j(\vec{x})\right] \tag{7}$$

where K_p is the penalty multiplier, an extremely high value that makes the objective function extremely high when the voltage violation occurs during the optimization process. In this paper, the penalty multiplier is taken with fixed value and is considered as K_p. The penalization functions $M_j(\vec{x})$ are defined by Equation (8)

$$M_j(\vec{x}) = \begin{cases} 0, & V_j^{min} \leq |V_j| \leq V_j^{max} \\ 1, & otherwise \end{cases} \quad \forall j = 1, 2, \ldots N_{bus} \tag{8}$$

Equation (2) is the objective function of the problem and Equations (4) and (5) are the constraints for optimization.

The developed optimization model is solved using differential evolution (DE) algorithm. The flow chart of DE algorithm [41] is shown in Figure 2. Since DE is a population-based optimization algorithm, population size, and other parameters such as strategy, mutation, recombination index, seed, polish, tolerance, number of workers, and maximum iteration are

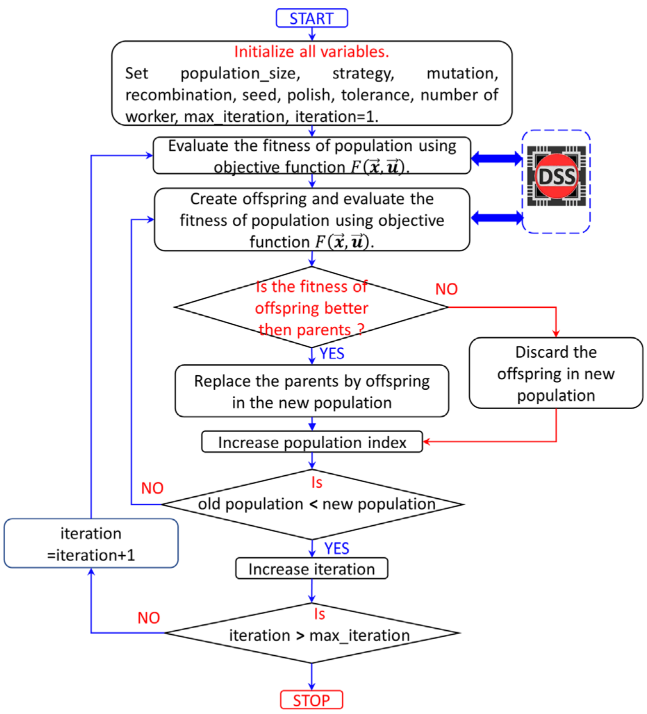

FIGURE 2 Flow chart for the differential evolution optimization algorithm [42]. maxiter = 1000, popsize = 15, tol = 0.01, mutation = (0.5, 1), recombination = 0.7, seed = None, callback = None, disp = False, polish = True, atol = 0, updating = immediate, workers = 1, x0 = None.

initialized in the initial phase. Once initialization is complete, the fitness function of the population is calculated using the objective function. From the population, offspring are generated, and the fitness functions for the offspring are also computed. If the fitness of the offspring is better than that of the parents, then the parent population is replaced by the offspring to find the best match. This process is repeated for all the populations until the maximum iteration is reached. The following parameters were considered for the DE algorithm. Strategy = best1bin,

4 | DETAILED MODELLING OF SMART CONVERTER

The power generated by renewable energy-based DERs, such as wind power plants and solar PV, fluctuates in nature or is different in nature (AC or DC), so its powers are not directly connected to the grid. In most cases, power electronics converters (PECs) are used. The PECs can be controlled and optimized to obtain regulated power output from the converters. Depending on the objective, the control algorithms are expected to set active power and reactive power set points for the converters. Many control strategies have been proposed in the literature [43]. Additionally, one of the deciding factors when selecting the appropriate control strategies is to consider the level of integration of DERs in the network. When a smaller number of DERs are present in the network, synchronous generators (SGs) in the network can handle uncertain power dynamics. However, with increasing integration of DER, SGs will no longer be able to handle such system dynamics and maintain the system stability [44]. As converter-based DERs do not have spinning inertia or damping, the power system becomes more susceptible to instability [45]. The concept of virtual synchronous machines (VSM) [25] is gaining popularity among researchers to solve this problem. VSMs are physically PECs but synchronous machines mathematically. VSMs can supply virtual inertia and damping to the grid [46]. The synchronverter is one of the popular types of VSM [32]. So, in this paper, the synchronverter developed in [33] as a voltage source converter is used for real-time RPC.

The control of the synchronverters to regulate active and reactive power is governed by a mathematical model of the SG [49]. Assume that the stator windings are positioned in slots around the uniform air gap in a SC and that the stator winding has a self-inductance of L, mutual inductances of M, and resistances R_s characterize the stator winding. The electromagnetic flux ($\vec{\Phi}$) produced by the stator winding and the current ($\vec{I}$) flowing though winding can be represented by the equation Equation (9) [49]

$$\vec{\Phi} = \begin{bmatrix} \Phi_a \\ \Phi_b \\ \Phi_c \end{bmatrix}, \vec{I} = \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{9}$$

The phase shift between the phases differs by $\frac{2\pi}{3}$. So, the phase shift vectors $\widetilde{cos}\theta$ and $\widetilde{sin}\theta$ are represented by Equation (10) [49]. θ_a is the rotor angle corresponding to phase a of VSM. For all three phases $\vec{\theta} = [\ \theta_a\ \theta_b\ \theta_c\ ]^T$

$$\begin{aligned} \widetilde{cos}\theta &= \begin{bmatrix} cos\theta_a \\ cos\theta_b \\ cos\theta_c \end{bmatrix} = \begin{bmatrix} cos\theta_a \\ cos\left(\theta_a - \frac{2\pi}{3}\right) \\ cos\left(\theta_a - \frac{4\pi}{3}\right) \end{bmatrix} \\ \widetilde{sin}\theta &= \begin{bmatrix} sin\theta_a \\ sin\theta_b \\ sin\theta_c \end{bmatrix} = \begin{bmatrix} sin\theta_a \\ sin\left(\theta_a - \frac{2\pi}{3}\right) \\ sin\left(\theta_a - \frac{4\pi}{3}\right) \end{bmatrix} \end{aligned} \tag{10}$$

The phase terminal voltage $\vec{v} = [\ v_a\ v_b\ v_c\ ]^T$ of the generator is given by Kirchhoff's voltage law and can be represented by Equation (11) [49].

$$\vec{v} = \vec{e} - [R_s]\ \vec{I} - [L_s]\ \frac{d\vec{I}}{dt} \tag{11}$$

where $L_s = L + M$ and $\vec{e} = [\ e_a\ e_b\ e_c\ ]^T$ is the back emf. The back emf is given by Equation (13) [49] and $[R_s]$ and $[L_s]$ are given by Equation (12).

$$[R_s] = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix}$$
$$[L_s] = \begin{bmatrix} L_s & 0 & 0 \\ 0 & L_s & 0 \\ 0 & 0 & L_s \end{bmatrix} \tag{12}$$

$$\vec{e} = M_f\, I_f \dot{\theta} \widetilde{sin}\theta - M_f \frac{dI_f}{dt} \widetilde{cos}\theta \tag{13}$$

The relative location of the rotor axis and the magnetic field axis in a SG is fixed under normal operating conditions. However, any disturbance causes the rotor to decelerate or accelerate, reducing or increasing the rotor angle $\vec{\theta}$. The swing equation describes the relative motion of the rotor for a synchronously rotating air gap. The swing equation is given by Equation (14) [50].

$$\ddot{\theta} = \frac{1}{J}\left(T_m - T_e - D\dot{\theta}\right) \tag{14}$$

where J is the moment of inertia of the rotating parts, D is the damping factor, T_m is the vector of mechanical torque, and T_e is electromagnetic torque of VSM. The electromagnetic torque is given by Equation (15) [50].

$$T_e = M_f I_f \langle \vec{I}, \widetilde{sin}\theta \rangle \tag{15}$$

where $\langle , \rangle$ denotes the inner product in $\mathbb{R}^3$.

The active and reactive power output of the SCs is obtained using Equation (16) [50].

$$P_e = \dot{\theta} M_f I_f \langle \vec{I}, \widetilde{sin}\theta \rangle$$
$$Q_e = -\dot{\theta} M_f I_f \langle \vec{I}, \widetilde{cos}\theta \rangle \tag{16}$$

The detailed design of the controller is more dependent on the application of the converter in the power system. This research aims to implement real-time RPC in the DN with a greater focus on network dynamics. Hence, this analysis does not consider a rotor-side controller (for maximum power tracking) to maintain the DC link voltage. Instead, for simplicity, a constant DC link voltage is considered. Only the grid-side controller to regulate active and reactive power is considered.

The overall block diagram for controlling active and reactive power using a synchronverter is explained in Figure 1. The $\vec{P}_{ref}$ and $\vec{Q}_{ref}$ are sent to the controller developed in the RTS schematic. The $\vec{P}_{ref}$ and $\vec{Q}_{ref}$ are the active power reference and reactive power reference for all the DERs in the SDN.

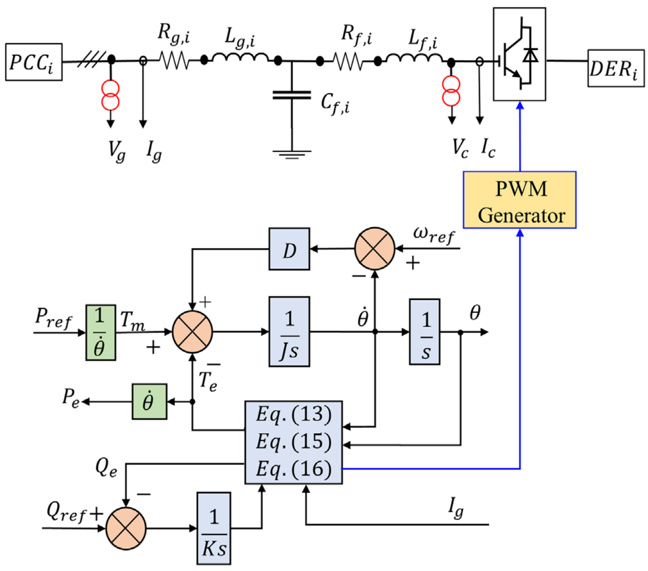

FIGURE 3 The control block diagram of the synchronverter [48].

$\vec{P}_{ref}$ and $\vec{Q}_{ref}$ for all the converters are considered as respectively in Equation (17)

$$\vec{P}_{ref} = [P_{ref},\, DER_1 \cdots P_{ref},\, DER_j \cdots P_{ref},\, DER_N]$$
$$\vec{Q}_{ref} = [Q_{ref},\, DER_1 \cdots Q_{ref},\, DER_j \cdots Q_{ref},\, DER_N] \tag{17}$$

The $\vec{Q}_{ref}$ are the reactive power obtained from the CL. Since the optimization is activated only when there is an activation signal, for other instances the $\vec{Q}_{ref}$ are kept the same as those values obtained from the previous optimization. The $\vec{Q}_{ref}$ are updated after the activation signal is triggered. Considering the losses in the controller and transformer system, the active power input to the converter $\vec{P}_{ref}$ is considered only 90%. So, the active power output $\vec{P}_e$ of the designed controller tracks $0.9\vec{P}_{ref}$. I_f is the vector of current flowing from the PCC of multiple inverters. ω_{ref} is the angular frequency which is a fixed value (314 rad/s for a 50 Hz system) in this study. The reference voltage reference of the grid $\vec{v}$ is set according to the voltage of the bus (where the SCs are connected) obtained from a real-time simulation. Equation (16) are the mathematical equations to obtain $\vec{P}_e$ and $\vec{Q}_e$. For multiple converters, $\vec{P}_e$ and $\vec{Q}_e$ are the active power and reactive power of all the converters and are given by Equation (18).

$$\vec{P}_e = [P_e,\, DER_1 \cdots P_e,\, DER_j \cdots P_e,\, DER_N]$$
$$\vec{Q}_e = [Q_e,\, DER_1 \cdots Q_e,\, DER_j \cdots Q_e,\, DER_N] \tag{18}$$

Figure 3 is the block diagram notation of Equations (8)–(16). The controller parameters considered in this study are given in Appendix 1. For simplicity, for this analysis, all the controllers are supposed to have the same parameters. Parameters are taken as proposed in [49].

5 | RESULTS AND DISCUSSIONS

This section illustrates the application of the proposed OPF-based optimal reactive power using CPCS. The research was carried out at the

Digital Energy Systems Laboratory (DIgEnSys-Lab). The DIgEnSys-Lab has physical equipment for real-time monitoring and control (https://fglongattlab.fglongatt.org). Typhoon HIL (HIL 604) is used as a RTS. Eight CPU cores, two digital I/O channels, and two analogue I/O channels are included in the HIL 604. Two advanced RISC machine (ARM) cores are also included. OpenDSS is considered as a DNS. The SDN is modelled in DNS, and the Python-based API is utilized to run the DNS in engine mode. Optimization is performed using a DE algorithm in SciPy [42]. A separate comparative study is performed to find the optimal optimization algorithm.

5.1 | Test system

In this paper, the CIGRE medium voltage (MV) DN is considered. The test system consists of two typical feeders at 20 kV, 50 Hz, and three-phase feeders 1 and 2. The feeder can be operated in radial or meshed topology by turning ON or OFF switch S1, S2, and S3. However, in this analysis, all switches are considered closed. Figure 4 shows an overview of the test system with GUI obtained during the real-time simulation. DERs are installed at the same location as suggested by the CIGRE benchmark. The size of DERs and loads is modified on the basis of sensitivity analysis. Appendix 2 and Appendix 3 are the rated size of the DERs and the load considered in this study.

5.2 | Sensitivity analysis of the test system

Before implementing the proposed method, a series of simulation studies were carried out. First, to observe the voltage profile of the network with the change in generation of power from DERs and loads, a sensitivity analysis is

performed. To perform the sensitivity analysis, a Monte Carlo simulation is done to obtain the voltage profile of the network random change in the generation of power from DERs and loads. Figures 5 and 6 are the voltage profiles of the monitored buses due to the change in power generation from DERs and loads at B_4, B_5, B_8, B_9, and B_{10} respectively. From the sensitivity analysis, it is observed that voltage violations can occur if the power generation from DERs is beyond some limits. Similarly, with the change in load, voltage violations occur if the loads are below and above certain limits.

5.3 | Simulation results without proposed method

First, simulation studies are performed without considering the proposed method. For this purpose, the load and generation profiles of the DERs are the same value as that considered for the real-time simulation studies. These values were stored using data loggers during the real-time simulation. Figure 7 is the voltage of the test system without implementing the proposed method. The V_{max} and V_{min} are are the upper and lower limits of the permissible phase voltage which is 5% above and below the rated phase voltage ($\frac{20}{\sqrt{3}}$ kV) of the test network. Voltage violations are observed when the proposed method is not implemented.

5.4 | Simulation with the proposed method

To verify the effectiveness of the proposed method, intentional voltage violations are created in the test system by changing the active power generation of the DERs and the loads at some buses. The power of the DERs and the loads can be changed in real time by changing the sliders in SCADA developed for this specific purpose. In this analysis, all DERs and only five loads at buses B_4, B_5, B_8, B_9, and $B_{10}$are changed in real time. The load is varied so that the voltage profile of the network varies above the prescribed limit. Figure 8 shows the load profile created during the real-time simulation. To plot all loads in the same figure, the load L_5 at B_{10} is scaled down by 10 times. The power generation from all DERs is changed during the real-time simulation.

The HIL OpenDSS co-simulation block continuously performs the load flow at each execution interval. The corresponding voltage profile is monitored through the monitoring system. When the voltage of any bus in the network exceeds the prescribed limit of 5% of the nominal phase voltage. The optimization block is activated as soon as the monitoring system senses some voltage violations; then the monitoring system makes the activation signal high. The activation signal for this case is shown in Figure 9. When the activation system is high, the OPF-based RPC centre activates the real-time co-simulation-based optimization block to perform the optimization. After completing optimization, first, the RPC centre exchanges the information with the SCADA. Later, SCADA updates the system states in the DN. At last, the CL sends the reactive power reference to the SC in the PL. The controller of the SCs tracks the electrical active and reactive power to the optimal reference value obtained from the CL. The electrical output from the SCs is fed to the DERs in the CL. SCADA updates the

model in DNS with values obtained from the PL. This process is repeated until the end of the simulation. The voltage profile of the DN using the proposed methodology is shown in Figure 10. In the figure, the voltage profile of only the node with DER integration is presented to make a clear visualization. The voltage profiles are within the prescribed limit.

Considering the limitation of the available RTS configuration in the lab, only four SCs are designed in RTS. For the rest of the DERs in the network, the active power reference and optimized reactive power are fed directly to the SDN. The physical converters developed in RTS are DER_1, DER_3, DER_6, and DER_9 connected to the buses at B_3, B_5, B_9, and B_7 respectively. However, the active power reference is changed for all DERs

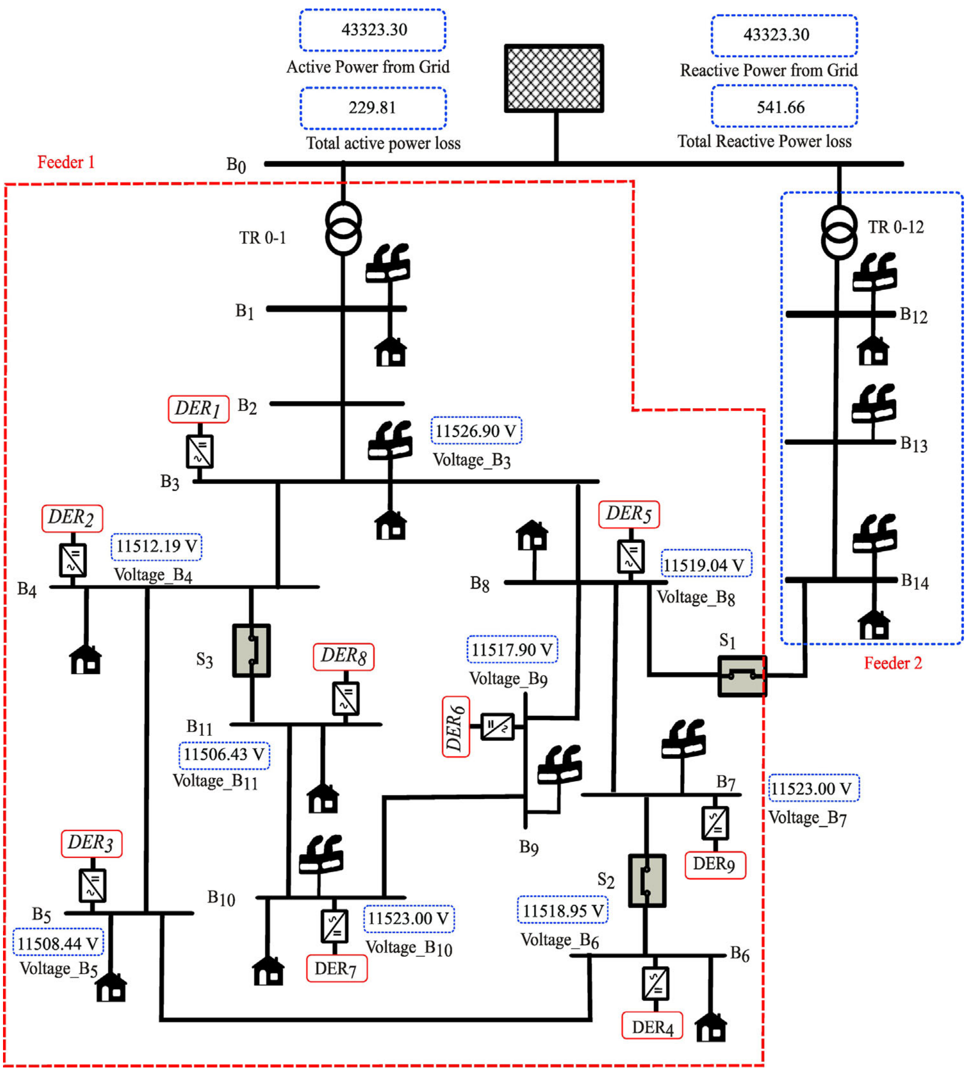

FIGURE 4 Modified layout of the CIGRE MV network with loads and DERs with GUI implemented in SCADA of the proposed CPCS [51]. CPCS, cyber-physical co-simulation; DERs, distributed energy resources; GUI, graphical user interfaces; MV, medium voltage; SCADA, supervisory control and data acquisition.

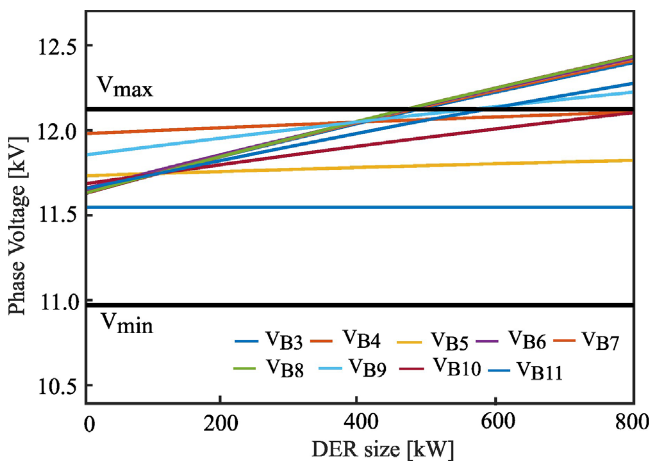

FIGURE 5 Voltage profile of the CIGRE MV network with change in size of all the DERs considered in this study. DERs, distributed energy resources; MV, medium voltage.

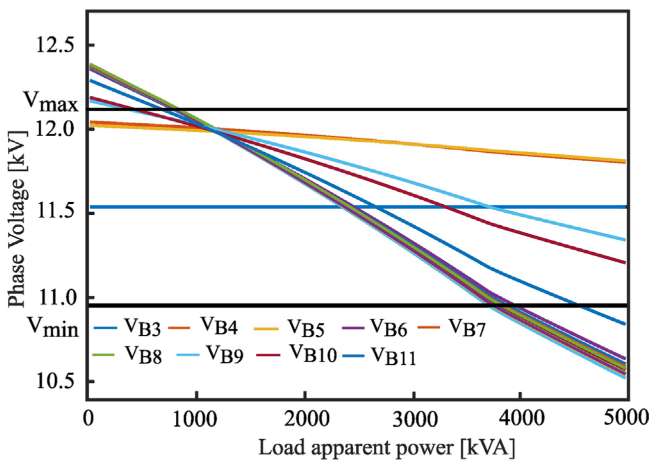

FIGURE 6 Voltage profile of the CIGRE MV network with change in load at B_4, B_5, B_8, B_9, and B_{10}. MV, medium voltage.

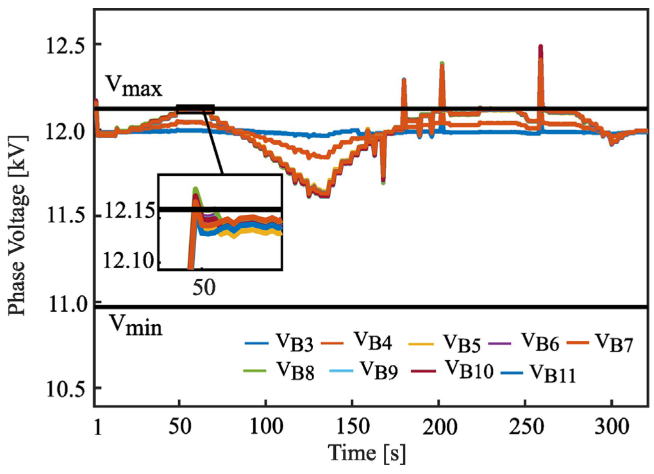

FIGURE 7 Voltage profile of the test system with the change in active power generations of DERs. This is obtained by simulation offline on the same test system without implementing the OPF-based RPC. DERs, distributed energy resources; OPF, optimal power flow; RPC, reactive power control.

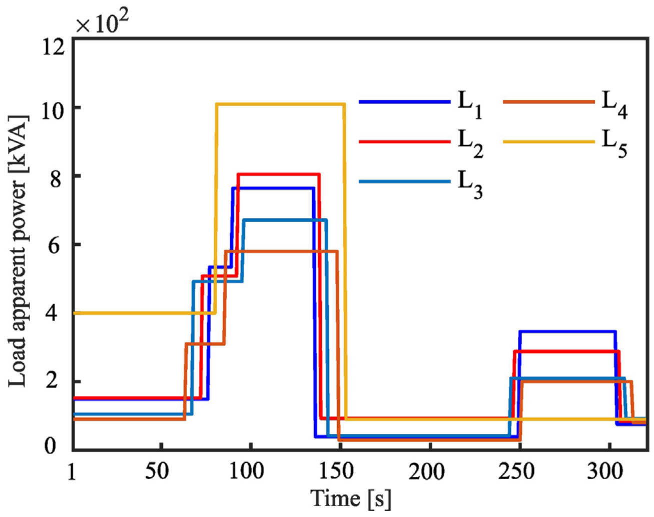

FIGURE 8 Load profile of the loads changed from SCADA in the cybernetic layer at B_4, B_5, B_8, B_9, and B_{10}. The load at B_4 is L_1, at B_5 is L_2, B_8 is L_3, B_9 is L_4, and at B_{10} is L_5. SCADA, supervisory control and data acquisition.

connected in the network to change the real-time dynamics of the test system. Figure 11 shows the active power reference and the active power generated by the SCs.

During real-time simulation, to mitigate voltage violations, the proposed system performs real-time optimization to set the optimal reactive power references for each converter, as shown in Figure 12. These reactive power references are sent to the converters in the PL. The converter generates the reactive power to match the reference. With the reactive power generated by the converter, voltage violations were mitigated in the network.

Table 1 shows the computational performance of the proposed real-time system. From the table, it is observed that the proposed method can operate with a simulation time of 1×10^{-6} (s), total utilization of internal memory of 24.38% and

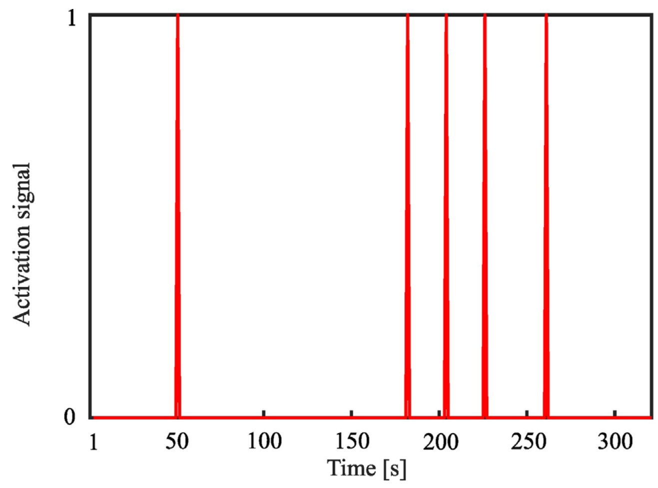

FIGURE 9 Activation signal from the monitoring system in the instances of voltage violations due to a change in the active power generation from DERs in real time. DER, distributed energy resources.

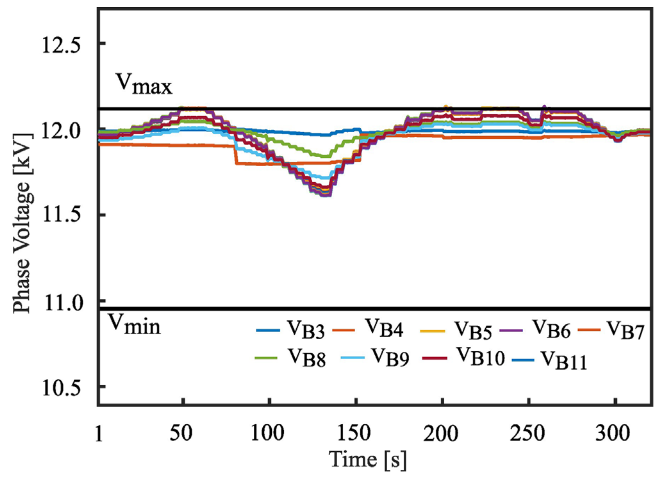

FIGURE 10 Voltage profile of the test system with proposed OPF-based RPC using cyber-physical co-simulation. OPF, optimal power flow; RPC, reactive power control.

TABLE 1 Computational performance of the proposed CPCS

Name of component	Number of utilized components	Utilized percentage
Standard processing core utilization	1 out of 3	33.33%
Signal generator utilization	12 out of 12	100%
Matrix memory utilization	–	0.50%
Simulation step time	1×10^{-6} (s)	–
Time slot utilization of core	–	62.25%
Signal processing IO variables utilization	38 out of 4,194,304	–
Signal processing probes utilization	52 out of 1024	5.07%
Total utilization of the internal memory	62 out of 254 kB	24.38%

CPCS, cyber-physical co-simulation.

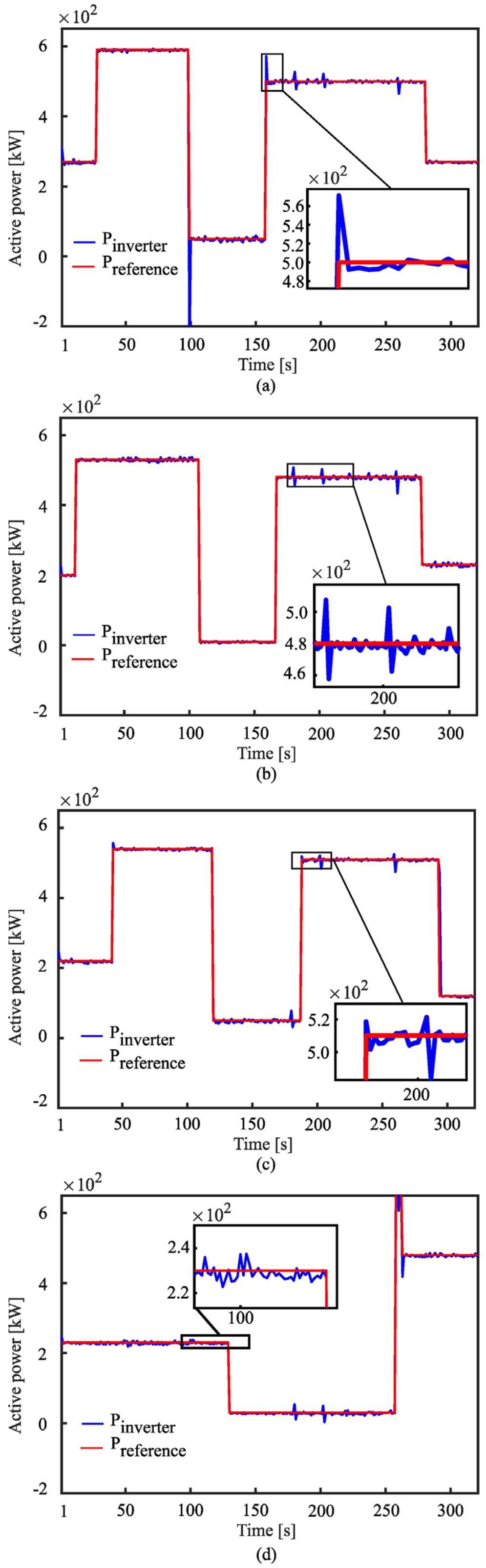

FIGURE 11 Active power references changed from SCADA in the cybernetic layer and electrical power output from smart converters obtained from the physical layer (a) DER_1 at B_3, (b) DER_3 at B_5, (c) DER_6 at B_9, and (d) DER_9 at B_7. DER, distributed energy resources; SCADA, supervisory control and data acquisition.

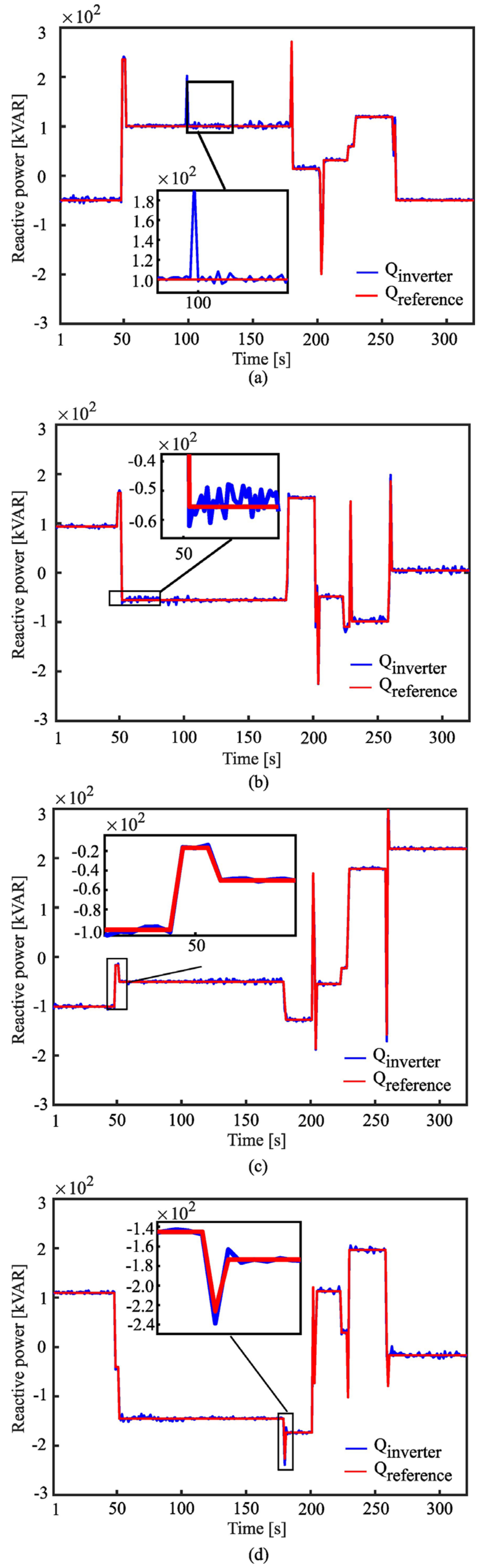

FIGURE 12 Reactive power references obtained from the OPF-based RPC centre and reactive power output from smart converters obtained from the physical layer (a) DER_1 at B_3, (b) DER_3 at B_5, (c) DER_6 at B_9, and (d) DER_9 at B_7. DER, distributed energy resources; OPF, optimal power flow; RPC, reactive power control.

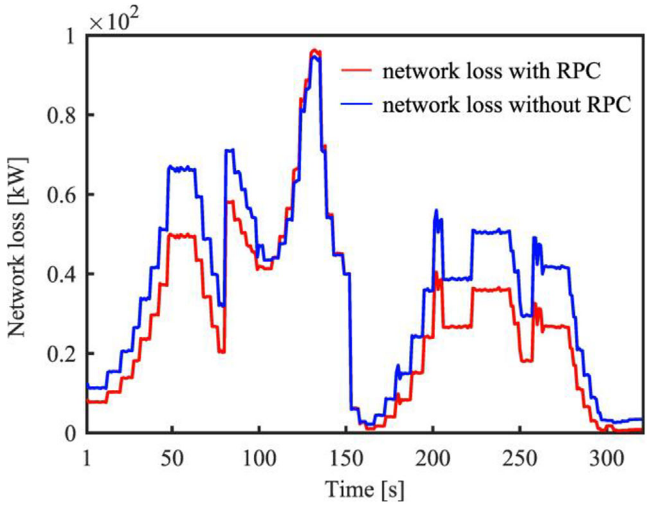

FIGURE 13 Comparison of the total system loss of the CIGRE MV network with the proposed real-time OPF-based reactive power control and without reactive power control. MV, medium voltage; OPF, optimal power flow.

by utilizing only 5.07% of available signal processing probes. All these performance parameters suggest that the proposed method is fast and computationally simple.

5.5 | Comparison of total system loss

The absorption or injection of reactive power has a considerable impact on total system loss in the DN. A comparison of system loss in the network with and without the proposed method is presented in Figure 13. The system loss is computed considering the same DER generation profiles, and the same load profiles considered for real-time studies. Since the optimization process obtains the optimal reactive power setpoints to reduce system loss, the network experiences lower losses with the proposed method. From the figure, it is also observed that the system loss over a period change in the network depends on the size of DER generation profile, size of load profile, and the reactive power support from the DERs.

6 | CONCLUSION AND OUTLOOK

With the advancement of SC information and communication capability, the use of SCs in real-time monitoring and control of the DN is increasing. Deployment of CPCS for real-time control and monitoring of realistic distribution with multiple controllable devices is still a big challenge. This research expands the multidimensional horizon for real-time control and monitoring studies. This research proposes a novel way of regulating the reactive power of SCs in SDNs using OPF-based optimal RPC on a proposed real-time CPCS framework. Real-time simulation studies show that the voltage profile of the DN can be regulated using the proposed methodology. This approach is simple and can be implemented on any type of network: single-phase or multiphase, balanced or unbalanced, and radial or mesh. The proposed framework is also capable of performing real-time CPCS studies with multiple numbers of controllable devices in the network.

The proposed CPCS framework can be implemented in several ways to test, develop, and validate the smart grid paradigm in the DN. Investigation with more advanced features of the smart grid is planned in the future.

NOMENCLATURE

$\vec{P}_e$	active power outputs of N_{DER} number of SC
$\vec{P}_{ref}$	active power references of N_{DER} number of VSM
$\vec{Q}_e$	reactive power outputs of N_{DER} number of SC
$\vec{Q}_{ref}$	reactive power references of N_{DER} number of SC
$\lvert V_{IN}\rvert$	input bus voltage of the network to comparator
$\lvert V_{OUT}\rvert$	signal output of the comparator
$\lvert V_{REF}\rvert$	reference bus voltage for the comparator
K_p	penalty multiplier (1000)
K_v	reactive power droops of VSM
N_{DER}	number of DERs in the SDN
N_{bus}	number of buses on the SDN
P_{DER_j}	active power of DER at node j
Q_{DER_j}	reactive power of DER at node j
S_{DER_j}	apparent power of DER at node j
T_e	electromagnetic torques of VSM
T_m	mechanical torques of VSM
V_j^{min}	lower limit of voltage at node j
$\vec{v}$	voltage at the nodes of the test system
v_j^{max}	upper limit of voltage at node j
ω_{ref}	reference angular speed (rad/s)
AND	logical AND
API	application programming interface
CL	cybernetic layer
CPCS	cyber-physical co-simulation
DE	differential evolution
DER	distributed energy resources
DN	distribution network
DNS	distribution network solver
HIL	hardware in loop
IED	intelligent electronics devices
MV	medium voltage
OPF	optimal power flow
OR	logical OR
PCC	point of common coupling
PEC	power electronics converter
PL	physical layer
R	resistance of the interconnecting lines
RPC	reactive power control
RTS	real-time simulator
SC	smart converters
SCADA	supervisory control and data acquisition
SDN	smart distribution network
SG	synchronous generator
VSM	virtual synchronous machine
X	reactance of the interconnecting lines

D damping constant of VSM
J moment of Inertia of VSM
K scaling factor for reactive power limit

AUTHOR CONTRIBUTIONS

Raju Wagle: conceptualization, data curation, formal analysis, methodology, software, validation, visualization, writing original draft, writing review edition. Pawan Sharma: conceptualization, supervision, validation, writing review edition. Charu Sharma: supervision, writing review edition. Mohammad Amin: supervision, writing review edition. Jose Luis Rueda: supervision, writing review edition. Francisco Gonzalez-Longatt: conceptualization, methodology, resources, software, supervision, validation, writing review edition. All authors read and approved the final manuscript.

ACKNOWLEDGEMENTS

The authors are incredibly grateful to the Arctic Centre for Sustainable Energy (ARC) (project number 740108), UiT The Arctic University of Norway, Norway, for providing an opportunity for Mr. Raju to visit and work in DIgEnSys-Lab. The authors also thank UiT for covering the article processing charge to make the paper fully open access. The authors also acknowledge the technical support provided by OpenDSS and Typhoon HIL.

CONFLICT OF INTERESTS STATEMENT

The authors declare that they have no competing interests.

DATA AVAILABILITY STATEMENT

The essential data are attached in the paper. All other source codes, executables, sample datasets, and documents are available on request from the corresponding author.

FUNDING INFORMATION

This research did not receive external funding. The publication charges for this article have been funded by a grant from the publication fund of UiT The Arctic University of Norway.

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How to cite this article: Wagle, R., Sharma, P., Sharma, C., Amin, M., Rueda, J.L., Gonzalez-Longatt, F.: Optimal power flow-based reactive power control in smart distribution network using real-time cyber-physical co-simulation framework. IET Gener. Transm. Distrib. 1–14 (2023). https://doi.org/10.1049/gtd2.12786

APPENDIX

Appendix A

Parameters of the synchronverter [49]

Parameters	Value	Unit
Moment of inertia (J)	0.1	(kg/m^2)
Mechanical friction (D)	1	(N m s)
Reactive power droop (K_v)	0.0001	–
Angular speed (ω)	314	(rad/s)
Filter resistance (R)	0.1	Ω
Filter inductance (L)	10.1859	(mH)
Filter capacitance (C)	24	(μF)
$M_f \vec{I}_f$	$\begin{bmatrix} 0.5 & 0 & 0 \\ 0 & 0.5 & 0 \\ 0 & 0 & 0.5 \end{bmatrix}$	(V s)

Appendix B

Rating of the DERs considered in this study

Name of DER	Rating of DERs	
	P (kW)	Q (kVAr)
DER_1	690.00	303.00
DER_1	690.00	303.00
DER_1	680.00	300.00
DER_1	680.00	300.00
DER_1	740.00	325.00
DER_1	740.00	325.00
DER_1	740.00	325.00
DER_1	740.00	325.00
DER_1	740.00	325.00

Appendix C

Rating of residential and commercial loads considered in this study. These load profiles were taken at 19:00 [34]

Bus	Apparent power, S [kVA]		Power factor	
	Residential	Industrial	Residential	Industrial
B_1	74.00	20.70	0.98	0.95
B_2	—	—	—	—
B_3	264.00	1.30	0.97	0.85
B_4	812.20	—	0.97	—
B_5	894.70	—	0.97	—
B_6	532.40	—	0.97	—
B_7	—	0.40	—	0.85
B_8	760.40	—	0.97	—
B_9	—	3.30	—	0.85
B_{10}	653.90	0.40	0.97	0.85
B_{11}	315.00	—	0.97	—
B_{12}	14172.90	25.50	0.98	0.95
B_{13}	—	0.20	—	0.85
B_{14}	199.20	1.90	0.97	0.85

Paper E. Cyber-Physical Co-Simulation Testbed for Real-Time Reactive Power Control in Smart Distribution Network

Raju Wagle, Gioacchino Tricarico, Pawan Sharma, Charu Sharma, Jose Luis Rueda, and Francisco Gonzalez-Longatt

2022 IEEE PES Innovative Smart Grid Technologies - Asia (ISGT Asia), 2022

DOI: 10.1109/ISGTAsia54193.2022.10003553

The paper is attached with the consent from the publisher.

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Authors Contribution:

The implementation of the methodology, utilization of software, data curation, formal analysis, validation, and visualization of the paper was done by the **candidate**.

The conceptualization of the idea to do further research and development of the proposed real-time cyber-physical co-simulation framework was generated by the **candidate** and Professor Francisco. The **candidate** contributed to the development and testing of the real-time framework. The **candidate** and Gioacchino wrote the first draft of the paper.

All authors contributed essentially to the supervision, review, validation, and proof of the paper.

Paper F. Co-simulation based Optimal Reactive Power Control in Smart Distribution Network

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Electrical Engineering, Springer Nature (accepted manuscript), 2023, Pages 1-26.

The article will be published with open-access publication.

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<u>**Authors Contribution**</u>:

The implementation of the methodology, utilization of software, data curation, formal analysis, writing original draft, validation, and visualization of the paper was done by the **candidate**.

The conceptualization of the idea to do further research, and development of the proposed co-simulation based optimal reactive power control in a smart distribution network was generated by the **candidate** and Professor Francisco. The **candidate** performed the co-simulation based on using OpenDSS. Le and Gioacchino performed the co-simulation based optimization using DigSilent Power Factory. The original draft, data processing, and formal analysis were done by the **candidate**.

All authors contributed essentially to the supervision, review, validation, and proof of the paper.

Co-Simulation based Optimal Reactive Power Control in Smart Distribution Network

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Abstract

The increasing integration of distributed energy resources (DERs) such as photovoltaic (PV) systems into distribution networks introduces intermittent and variable power, leading to high voltage fluctuations. High PV integration can also result in increased terminal voltage of the network during periods of high PV generation and low load consumption. These problems can be solved by optimal utilization of the reactive power capability of a smart inverter. However, solving the optimization problem using a detailed mathematical model of the distribution network may be time-consuming. Due to this, the optimization process may not be fast enough to incorporate this rapid fluctuation when implemented in real-time optimization. To address these issues, this paper proposes a co-simulation based optimization approach for optimal reactive power control in smart inverters. By utilizing co-simulation, the need for detailed mathematical modelling of the power flow equation of the distribution network in the optimization model is eliminated, thereby enabling faster optimization. This paper compares three optimization algorithms (Improved Harmony Search, Simplicial Homology Global Optimization, and Differential Evolution) using models developed in OpenDSS and DigSilent PowerFactory. The results demonstrate the suitability of the proposed co-simulation-based optimization for obtaining optimal setpoints for reactive power control, minimizing total power loss in distribution networks with high PV integration. This research paper contributes to efficient and practical solutions for modelling optimal control problems in future distribution networks.

Keywords: Co-simulation, Smart distribution networks, Smart inverters, Optimal Reactive power control

Acronyms

BFS	Backward forward sweep
CIM	Current injection method
DE	Differential equation
DER	Distributed energy resources
DNSS	Distribution network specialized software
DSO	Distribution system operators
IED	Intelligent electronic devices
IHS	Improved harmony search
MV	Medium voltage
NLP	Non linear programming
OLTC	On-load tap changing
OPF	Optimal power flow
PCC	Point of common coupling
PMU	Phasor measurement unit
PV	PhotoVoltaic
p.u.	per unit
RES	Renewable energy resources
SCB	Static capacitor bank
SDN	Smart distribution network
SHGO	Simplicial homology global optimization
SIB	Static inductor bank
SVR	Static voltage regulators

List of Symbols

V	Nominal voltage of the distribution network
V_1	Voltage at Bus_1
V_2	Voltage at Bus_2
P_L	Active power of load
Q_L	Reactive power of load
P_{PV}	Active power generation from PV
Q_{PV}	Reactive power capacity from PV
P_{loss}	Active power loss in the network
x	Vector of the reactive power from PV
N_{pv}	Number of PV available in the distribution network
P_{PV_j}	Active power generation of j^{th} PV
Q_{PV_j}	Reactive power capacity of j^{th} PV
S_{PV_j}	Rating of j^{th} PV
V_i^{min}	lower permissible voltage limit
V_i^{max}	upper permissible voltage limit
N_{bus}	Total number of buses in the distribution network

1 Introduction

1.1 Motivation and Incitement

To promote the use of green energy, renewable energy resources (RES) such as photovoltaic(PV) systems, wind turbines, and fuel cells are highly integrated into the distribution network [1, 2]. With the advancement in PV technology and cost reduction, the integration of photovoltaic systems is expected to increase in the distribution network [3]. This increased integration of PV in the distribution network presents additional technical challenges, as discussed in [4–6]. The energy obtained from PV is highly intermittent, uncertain, and variable in nature. The higher integration of PV creates several problems, particularly an increase in terminal voltage and voltage fluctuations [7, 8]. PVs are integrated into the distribution network using power electronics devices, and their control can provide fast and reliable operation. Therefore, the application of these interfaces has been suggested as a quick-responding solution to regulate voltage [9–11].

Although various control strategies have been proposed [12] to overcome the challenges resulting from the high integration of PVs, the optimal control of smart inverters in smart distribution networks (SDN) can be one of the alternatives to address these challenges [13]. Optimal control of smart inverters in SDN can be solved by optimization. Formulating and solving the optimization problem using a detailed distribution network modelling might be challenging [14]. The optimization process with detailed mathematical modelling of SDN may encounter some problems, such as slow convergence or no convergence at all [15]. Furthermore, the need for faster optimization techniques is more pressing with the growing concern of implementing real-time control applications among distribution system operators (DSOs) [16]. Hence, this paper is intended to explore the applicability of co-simulation based optimization approach for optimal reactive power control from smart inverters in SDN.

1.2 Literature Review

Currently, the voltage in distribution networks is regulated through voltage regulating devices (VRDs) such as On-load tap changing (OLTC) transformers, static voltage regulators (SVR), static capacitor banks (SCB), and static inductor banks (SIB) [17]. However, with the rapid transition in the distribution network, the operating condition of VRD is altered [18], which requires frequent switching operations to regulate the rapidly fluctuating voltage. Providing prompt voltage control from such devices is difficult due to slower response and limited switching operation [19]. Also, the frequent switching operation of VRDs causes mechanical wear and tear, causing an additional financial burden. In addition, it also causes high voltage flicker and increased switching loss [20]. Therefore, the reactive power control of smart inverters, as suggested by IEEE 1547-2018[21], is recently gaining attraction among DSOs [22, 23].

There are various approaches to control the reactive power in the scientific literature [24, 25]. In most studies, reactive power control is achieved in centralized, decentralized, or distributed methods. The decentralized method uses local measurement, and, on the basis of that, the optimal settings for reactive dispatch are estimated. However, the decentralized method lacks proper coordination between the controller and the central controller. The centralized method provides optimal reactive power setpoints by solving optimal power flow in the distribution network. The key problem with the centralized technique is the lack of communication and monitoring infrastructure in the distribution network. However, as smart inverter technology advances, most smart inverters now have powerful communication and monitoring equipment [26]. Therefore, a centralized control mechanism based on optimal power flow (OPF) can be used in distribution networks with substantial integration of photovoltaics [27]. Some researchers incorporate centralized and local control and propose them as distributed control. Regardless of the optimal control approach, the most important factor is the modelling of the distribution network for optimization.

One of the main problems in applying the optimal control algorithm in a distribution network is modelling an unbalanced distribution network [28]. Accurate and efficient modelling of the distribution network with uncertainties from variable DERs is essential for applying optimal control algorithms in the distribution network. In most cases, the distribution networks are exceptionally long and radial in nature and serve many customers connected to the network. Unlike transmission networks, distribution networks can also consist of many single-phase loads and generation connection points, which can cause the network to be unbalanced. Therefore, the optimal control approaches implemented in transmission networks may not be feasible in distribution networks [29].

Most of the research on the optimal control application in a distribution network utilizes load flow calculations based on physical modelling techniques. From the physical properties of the network, power flow solutions are solved using the Newton-Raphson method [30] or the fast decoupled method [31] or LinDistflow equations [32] or sensitivity-based modelling [26]. However, due to the unique properties of the distribution network such as radial nature, unbalanced operation, multiple numbers of connection points and interconnecting lines, and nonuniform loading conditions, the traditional load flow models may not converge. The use of these modelling methods rarely produces better results for distribution systems [33]. In addition, the high R/X ratio of the distribution network is another problem for the convergence of the optimization model in the distribution network. The authors of [34] suggested a modified fast decoupled method to solve the problem of convergence in the network with a high R/X ratio in the distribution network. Some modifications have been made to the traditional modelling method by modifying the Y-bus matrix to achieve reliable convergence [33]. Even with modifications to most of the earlier research, the analysis has been done for a balanced distribution network. These methods will also still have the problem of convergence with large integration of DERs and unbalanced operation in the network.

Some researchers proposed alternative methods to model the distribution network considering all properties of the network. In [35] the authors proposed the Backward Forward Sweep (BFS) method to compute the three-phase power flow of the distribution network. However, the convergence of the BFS method is more dependent on the size of the equivalent line impedance and load admittance, which limits the application of the BFS method in a large and unbalanced distribution network. To overcome this challenge of the branch flow method, power injection methods can also be used to approximate the power flow in the network [36]. The authors in [37] proposed the current injection method (CIM) to perform the power flow in the distribution network. Compared to the BFS method, CIM converges faster with fewer iterations even for an unbalanced and heavily loaded network [38].

With the increasing utilization of various measurement devices such as energy meters, phasor measurement units (PMUs), and intelligent electronics devices (IEDs) in the distribution network, data-driven modelling of the distribution networks based on the information from these measuring devices is gaining attention. With a proper mathematical formulation of the data, the distribution network can be modeled more accurately [39]. The authors in [40] proposed a data-driven model based on voltage sensitivity to approximate the radial and mesh distribution network using the enhanced formulation of the Z-bus matrix. Various machine learning algorithms are also implemented in the optimal voltage control application in a distribution network [41]. The application of machine learning algorithms removes the barrier of prior knowledge of the complete information of the network for modelling. Even in the case of data-driven modelling, in most cases, the data are processed by a mathematical model that describes the network property of the distribution network. Among several methods, the current mismatch method based on the current injection model gives a more precise model [42]. In the current injection method, the phase voltage of any terminal can be represented by the active and reactive power injections/absorption from generators/loads at that terminal.

Even with a detailed mathematical model of the distribution network, the optimization process takes time and, in some cases, convergence may not be achieved. They also require commercial solvers to solve the optimization problem. Another approach to avoid detailed mathematical modelling of the SDN in the optimization model is to model the network in the distribution system simulator and optimize them using co-simulation [43]. By co-simulation, the detailed mathematical model of the distribution network can be solved by the distribution network solver, and the optimization can be achieved in a short time. This method also reduces the convergence issues as the complicated power flow equations are solved in the co-simulation. Also, any type of network, either balanced or unbalanced, radial or mesh, and single-phase or polyphase, can be solved by this method. Several commercially available distribution network solvers such as OpenDSS, PSCAD, DigSilent Power Factory, CYME-DIST, GridLab-D to model the distribution network[44]. To implement the optimal voltage control algorithm in the distribution network, co-simulation based modelling of the distribution network can also be a suitable option [45].

1.3 Scopes and Contributions

In practical operation, DER outputs and loads may vary from the forecasted, affecting the operation of control strategies [46]. To incorporate the uncertainties of DER and load, as a result, DSOs are moving away from the traditional offline approach and switching to real-time mode. The availability of smart devices in smart inverters also allows real-time control and monitoring without further investment in communication and monitoring infrastructure. To implement real-time optimal control, the need to solve the optimization problem in short instants of time is demanding [27].

Hence, considering the fact that co-simulation based optimization can give quicker and more precise solutions to optimization, this paper proposes a co-simulation based optimal reactive power control method in SDN. The main contributions made by the authors in this article are:

1. The smart inverter injects or absorbs reactive power to adjust the voltage [47]. The absorption or injection of reactive power has a considerable impact on power loss since the R/X of the line in the distribution system is high. Therefore, when reactive power is deployed, the impact of network power loss should be considered. As a result, this scientific study formulates, analyses, and presents the optimal reactive power control based on co-simulation to minimize the power loss in the distribution network.
2. A comparison of three different optimization algorithms for models developed in two different distribution network simulators is carried out to propose a co-simulation based optimal reactive power control using PV inverter.
3. To show the efficacy of the proposed co-simulation-based optimal reactive power control for computing optimal reactive power setpoints for the smart inverter, a time series analysis with variable PV power generation is presented.

1.4 Paper Organization

The remainder of the paper is presented as described here. Section 2 describes a mathematical model to show the impact of reactive power on the voltage profile of the distribution network and highlights the importance of reactive power control of the inverter in maintaining the voltage profile. Section 3 presents the formulation of the proposed co-simulation model for optimal control. The general methodology to implement optimization using the proposed method is presented in Section 4. The simulated results and discussion of the results obtained are shown in Section 5. Finally, the last section highlights the main contributions of the article and suggests future research directions.

2 Impact of high integration of PVs in the distribution network

With the high integration of PV in the distribution network, the conventional presumption of unidirectional power flow and lower terminal voltage at the end of the distribution network is no longer applicable. As PV is installed at the point of common coupling (PCC), a load bus in such a network may become a generation bus. And this could create an increase in the terminal voltage at the time of higher RES generation and lower power consumption in loads. To understand the effect of PV at the PCC, a simple model with a mathematical model is taken as shown in **Fig.** 1.

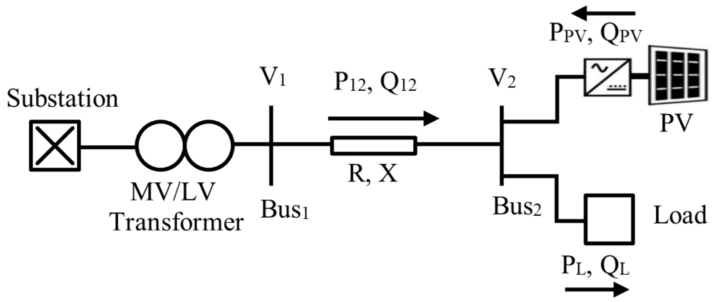

Fig. 1 A simplified layout of the distribution network with load and PV

Suppose V is the nominal voltage of the network, V_1 and V_2 are the voltages in Bus_1 and Bus_2. R and X are the resistance and reactance of the line between Bus_1 and Bus_2. And the load with active power P_L and reactive power Q_L is connected at Bus_2. Similarly, the PV with an active and reactive power capacity of P_{PV} and $\pm Q_{PV}$ is also installed at Bus_2. The - sign of Q_{PV} indicates that the reactive power is supplied by the PV and the + sign indicates that it is consumed by the PV. The voltage regulation in this case is given by **Equation** 1 [48]. To obtain the voltage at Bus_2, this equation can be rewritten as **Equation** 2.

$$V_1 - V_2 = \frac{R\left(P_L - P_{PV}\right) + X\left(Q_L \pm Q_{PV}\right)}{V} \tag{1}$$

$$V_2 = V_1 - \frac{R\left(P_L - P_{PV}\right) + X\left(Q_L \pm Q_{PV}\right)}{V} \tag{2}$$

From **Equation** 2, it can be observed that the voltage at Bus_2 is lower than that at Bus_1 when the power generation from PV is lower than the power consumption from the load. However, the voltage might go higher than the voltage at Bus_1, in case of higher power generation from the PV.

In case of a light load or no-load condition, it can be assumed that $P_L = 0$ and $Q_L = 0$ and then **Equation** 2 can be expressed as **Equation** 3 which shows the relationship of the injected power from PV at the PCC.

$$V_2 = V_1 + \frac{R\,(P_{PV}) + X\,(\pm\, Q_{PV})}{V} \tag{3}$$

From **Equation** 3, it can be seen that the terminal voltage in the PCC can be regulated by controlling the active and reactive power output from the PV. Furthermore, the ability of the smart inverter to supply and consume reactive power might be useful in regulating the voltage in both ways, increasing or decreasing, depending on the requirement.

In this section, the impact of PV on the voltage profile at the PCC of the distribution network is presented as a simple case. However, in realistic distribution networks where single-phase loads and generation are connected, the effect of the DERs and load on each phase can be varied. But this can be analyzed with appropriate modelling of the distribution network.

3 Formulation of Optimization model for Co-Simulation based Optimal Reactive Power Control in SDN

Normally, the optimization model includes objective functions, constraints, and a suitable solver to solve the optimization problem. Depending on the purpose of optimization in the distribution network, a detailed mathematical model to solve the power flow equations in the networks are also required. These equations are defined as constraints in the optimization model. In most cases, solving these power flow equations, especially for three-phase unbalance power flow equations, is time-consuming. However, in the formulation of co-simulation based optimization model for a distribution network, the detailed mathematical model for solving power flow equations in the distribution network need not be modelled. Power flow equations are solved in distribution network-specified software (DNSS). DNSS can solve the power flow equations more precisely and efficiently. This may result in faster convergence of such an optimization model. Moreover, co-simulation based optimization is applied in a case where the objective function is a derived function of the computed parameters (for example, power loss in the network, voltage deviation, etc.) in DNSS. The most powerful behavior of co-simulation based optimization is the modelling flexibility: it allows one to define objective functions and constraints using the parameters obtained from DNSS. These parameters can be easily assessed using user-defined functions. The optimization model is also capable to interact with the DNSS. Moreover, the co-simulation based optimization model allows us to further modify the parameters of the distribution network to modify the constraints, controllable variables, and other required parameters in the optimization model. The optimization model is created separately using python-based libraries of DNSS.

In this section, the formulation of the optimization model for optimal reactive power control in the distribution network is discussed. From **Equation** 3 in Section 2, it can be seen that the change in reactive power from PV can change the voltage level at the PCC. In a distribution network with high integration of PVs, the voltage level at all buses in the network can be regulated with the optimal amount of reactive power from PV. Once the voltage profile in the network is improved, the current flow in the lines between the two buses can be minimized. Lowering the current flow can result in lower power loss in the network. Therefore, finding the optimal amount of reactive power is of great importance in minimizing power loss in the network. For this purpose, the minimization of power loss (P_{loss}) in the network is considered the main objective function. Reactive power from PV inverters is considered a controllable variable. The objective function $F(x)$ is given by **Equation 4**.

$$\min_{x} F(x) = P_{loss}(x) \tag{4}$$

Where controllable variable x is the vector of the reactive power from N_{pv} number of smart inverters available in the SDN.

$$x = \left[Q_{PV_1}, \ldots, Q_{PV_j}, \ldots, Q_{PV_{N_{pv}}}\right]^T \tag{5}$$

Its power capability curve limits the reactive power limits of the smart inverter. **Fig.** 2 shows the PV capability curve.

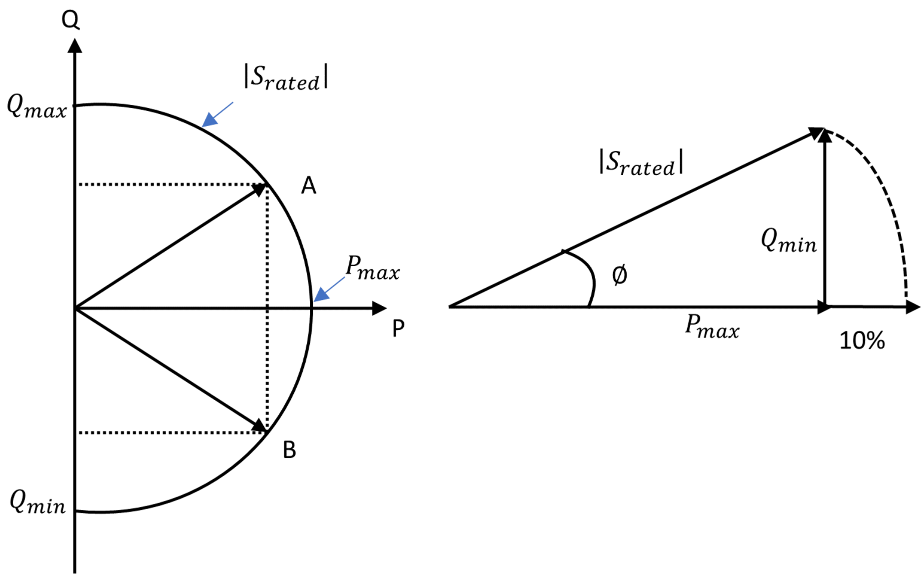

Fig. 2 PV capability curve for inverter size and reactive power capability [49]

Each PV's reactive power output is limited by its maximum apparent power and the active power it generates. Mathematically, **Equation** 6 [50] is the reactive power available (Q_{PV_j}) from the smart inverter of size (S_{PV_j}) that produces the active power of (P_{PV_j}).

$$Q_{PV_j} \leq \pm\sqrt{\left|S_{PV_j}\right|^2 \; - \; P^2_{PV_j}} \qquad \forall j = 1, \ldots, N_{pv} \tag{6}$$

In addition, according to the IEEE 1547-2018 standard, the reactive power of smart inverters can be limited to ±44% of the rated capacity. The optimization model has one more constraint given by **Equation** 7 [21] .

$$-k \times S_{PV_j} \leq Q_{PV_j} \leq k \times S_{PV_j} \tag{7}$$

in which $k = 0.44$ pu and $j = 1, \ldots, N_{pv}$. The optimization model also includes a voltage constraint. Many standards define the permissible voltage limits in the distribution network. In this scenario, however, the voltage limit is within 0.95 pu $\left(V_i^{min}\right)$ and 1.05 pu (V_i^{max}). As a result, the voltage constraint used in this analysis is **Equation** 8. where N_{bus} is the total number of buses in the SDN.

$$V_i^{min} \leq \; V_i \leq v_i^{max} \qquad \forall \; i \; = \; 1, 2, \ldots N_{bus} \tag{8}$$

Equation 4 is the objective function of the problem, and **Equations** 6, 7, and 8 are the optimization constraints considered in this study.

4 Proposed Methodology for Co-Simulation based Optimal Reactive Power Control in SDN

Once the optimization model is developed (as described in Section 3, the next step is the implementation of the proposed methodology. For this purpose, the distribution network is first developed on a distribution network specialized software (DNSS) using all the properties (like line parameters, interconnections, etc.) of the network. The loads and the PVs are placed in the DNSS. The DNSS solves the power flow in the distribution network, so the detailed model for solving the power flow equations of the distribution network in the optimization model can be neglected. Various parameters required in the optimization model can be obtained from DSSS using user-defined functions. Data exchange is carried out by those user-defined functions. Most DNSS have Python-based libraries to run the simulation in engine mode. These user-defined functions also allow us to modify the parameters of the distribution network. This is how the proposed co-simulation based optimization model coordinates between the DNSS and the optimization model.

A methodology for co-simulation based optimization in an SDN is described in this section. **Fig.** 3 depicts the overall block diagram to complete the optimization process. The objectives functions, constraints, and controllable variables are defined in the previous section. In this work, the x vector of the controllable variable, $F(x)$ is the objective function. Once optimization is started, the optimization model sends the controllable variables to the DNSS. DNSS returns the objective function to the optimization model. The optimization model then checks if the returned objective

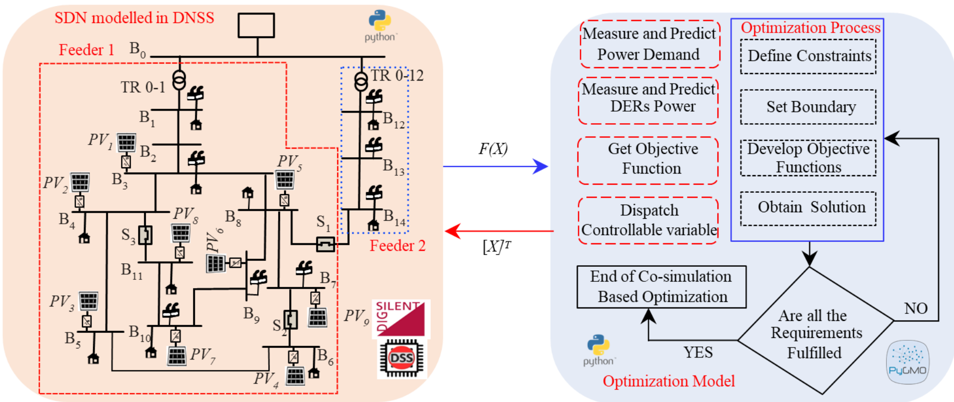

Fig. 3 Overall block diagram of optimal reactive power control based on cosimulation

function is meeting all the optimization requirements. If the requirements are not met, the process continues until the termination condition is reached. In this analysis, population-based optimization algorithms are used. Therefore, the optimization model continues to perform the same process until all the conditions are met. The optimization model then provides the one which gives the best solutions from different iterations.

To provide a clear understanding of the implementation of the optimization algorithm, an example of the differential evolution algorithm is shown in **Fig.** 4. Since DE uses a population-based optimization technique, other factors include strategy, mutation, and recombination index, as well as population size. In the initial stage, the parameters seed, polish, tolerance, number of workers, and maximum iteration are initialized. The population's fitness function is determined using the goal function when initialization is complete. The offspring are produced from the population and the fitness functions of the offspring are also calculated. In order to discover the best match, the parents' population is replaced by the children if their fitness is higher than that of the parents. All populations go through this process again and again until the maximum number of iterations is reached. A similar algorithm can be implemented for other optimization algorithms. The fundamental difference while implementing the other algorithm is that the initialization parameters for specific algorithms need to be fixed.

5 Results and Discussion

This section presents the simulation results obtained by the proposed method. OpenDSS and DIgSILENT PowerFactory are used as DNSS. Python-based defined functions are utilized to perform the co-simulation based optimization and develop the optimization model. This section is divided into three subsections to describe the test system, simulation results, and the discussion on the results.

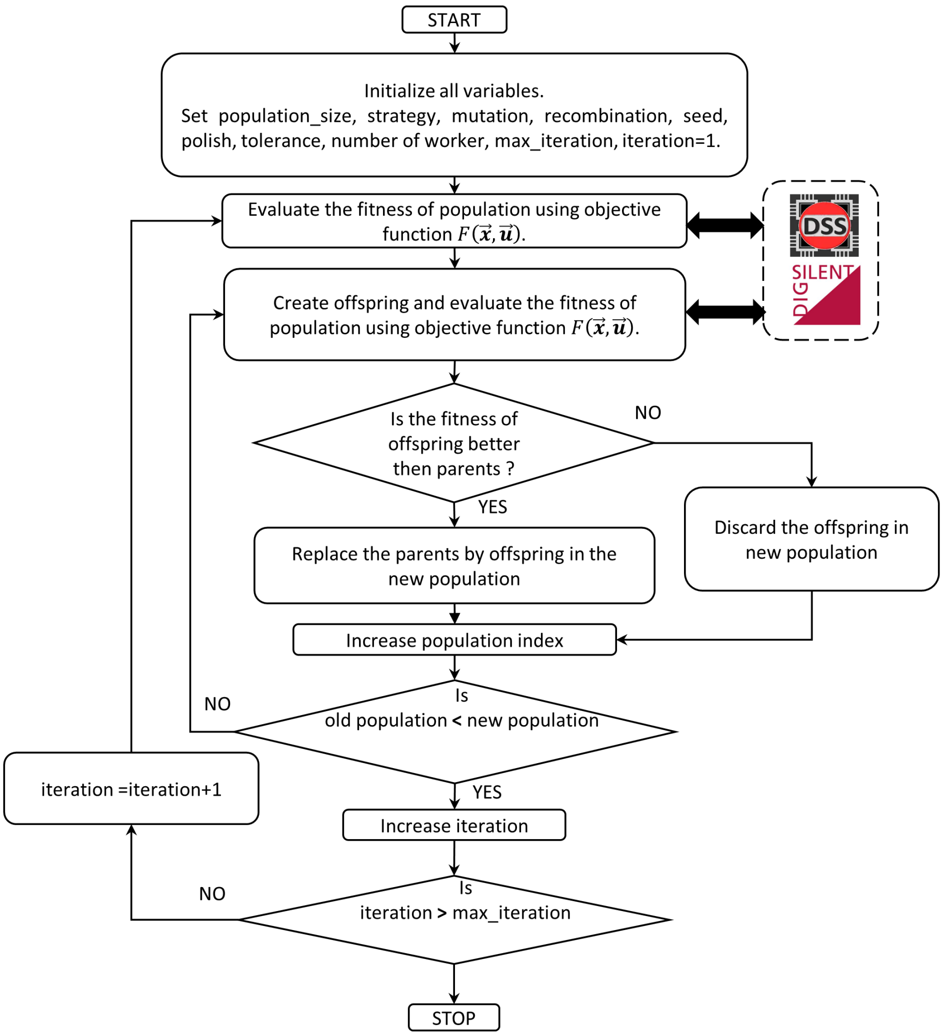

Fig. 4 Flow chart for the differential evolution optimisation algorithm [51]

5.1 Test System

MV distribution feeders can be used in DER integration studies [52]. In this investigation, the CIGRE medium voltage distribution network established by the CIGRE Task Force C6.04 is used. The network is symmetric and balanced. However, the proposed methodology can be implemented in all types of distribution network studies. The test system consists of two conventional 20kV, 50 Hz three-phase feeders named feeder 1 and feeder 2. The feeder can be operated in a radial or meshed topology by turning on or off the switches S1, S2, and S3. In this analysis, all switches are assumed to be closed. The detail about the rating of the PV and load utilized in this analysis are shown in **Tables** 4, 5, and 6

To optimize the test system, three different optimization algorithms are considered, namely improved harmony search algorithm (IHS) [53], simplicial homology global optimization (SHGO) [54], and differential evolution (DE) [55]. In this analysis, the following parameters are considered for different optimization algorithms. For IHS, the following parameters were considered. The number of generations = 100, rate of choosing from memory = 0.9, minimum pitch adjustment = 0.35, maximum pitch adjustment = 0.99, minimum distance bandwidth =1e-5, and maximum distance bandwidth = 1. Similarly, for the DE algorithm, the following parameters were considered. strategy=best1bin, maxiter=1000, popsize=15, tol=0.01, mutation=(0.5, 1), recombination=0.7, seed=None, callback=None, disp=False, polish=True, , atol=0, updating=immediate, workers=1, x0=None. The sampling method for SHGO was considered to be simplicial.

5.2 Simulation Results

First, the distribution network is simulated separately before optimization by setting the fixed power factor on the smart inverter. In this mode of operation, the power loss in the network is calculated. Later, the developed optimization model is used to obtain the optimal set points of reactive power. To perform a comparative analysis of different optimization algorithms, three different optimization algorithms are used to solve the optimization problem. The time required to obtain the optimal solution is taken as one of the metrics to compare the optimization results. For iterative optimization analysis, the frequency of obtaining the optimal solution and the frequency of finding the optimal solution is considered as the comparison matrices. The nature of individual optimization algorithms is different. IHS tackles multiobjective (unconstrained), constrained (single-objective), mixed-integer, and stochastic problems in Pygmo. On the other hand, SHGO is used for global optimization and is suitable for achieving global optimality in general-purpose NLP and black-box optimization problems. Differential evolution is stochastic in nature and does not use gradient methods to find the global minimum of a multivariate function. These algorithms are chosen for their unique diversity and applicability in this paper.

To create diversity in the analysis, three different types of simulation studies are considered. First, optimization is performed for a single optimization. Then to make a precise conclusion of the comparison of different optimization algorithms, iterative optimization (for 100 iterations) considering the same operating condition as considered in the first case is performed. To see the effect when PV power generation is varied, a time series analysis is also implemented for one of the algorithms.

5.2.1 Single Optimization analysis for comparative analysis of different optimization algorithm

To check the performance of the individual algorithms in the proposed optimized model, first, the three algorithms are implemented separately. After completion of each optimization, the optimal setpoints for the reactive power are obtained for all PVs.

Table 1 shows the comparison of the optimization variable, the optimized value, and the execution time.

Table 1 Comparison of the optimization algorithm in OpenDSS and DigSilent PowerFactory

	IHS		SHGO		DE	
Q_{PV}	OpenDSS	PF	OpenDSS	PF	OpenDSS	PF
PV_1 $[kVAR]$	7.647	6.417	8.999	9	6.617	5.495
PV_2 $[kVAR]$	7.322	0.798	9	9	5.099	5.511
PV_3 $[kVAR]$	0.580	13,202	13.500	13.5	12.571	12.549
PV_4 $[kVAR]$	9.670	7,345	13.499	13.5	11.079	11.032
PV_5 $[kVAR]$	11.972	1.044	13.5	13.5	8.837	12.861
PV_6 $[kVAR]$	3,638	9.725	13.5	13.5	10.859	9.994
PV_7 $[kVAR]$	14.244	15.716	18	18	16.314	13.104
PV_8 $[kVAR]$	2.211	1.422	4.5	4.5	0.986	1.530
PV_9 $[kVAR]$	667.482	669.758	674.451	675	665.031	674.930
P_{loss} $[kW]$	107.85	109.95	107.383	109.68	107.60	109.78
$Time$ $[second]$	1.19	9.53	18,59	22.00	0.036	0.84

5.2.2 Iterative Optimization analysis for comparative analysis of different optimization algorithm

From simulation studies performed for a single iteration, among three different algorithms, SHGO provides the better optimized value; however, the optimization takes longer to converge. Since SHGO is a global optimization algorithm, it provides the same optimized value for several optimizations. However, the execution time and the output of the optimized variable may differ for different scenarios. Therefore, multiple iterations are only considered for two algorithms, DE and IHS.

To make a precise comparison, the optimization is simulated for both algorithms 100 times. The histogram and the box plot of the optimal values (that is, optimal reactive power setpoints for PV) obtained for 100 simulations are shown in **Fig.** 5.

A similar analysis is performed to assess the total time needed to complete the optimization process. The histogram plot and the box plot for the execution time derived from 100 simulations are shown in **Fig.** 6.

5.2.3 Time series co-simulation based optimization for Optimal reactive power control in SDN

To support the analysis with different scenarios, in this subsection, the variation in PV power generation is considered. For this purpose, the intermittent nature of PV is considered. The nature of the PV profile is taken from[13]. The individual PV ratings are then computed by multiplying the PV profile with the PV rating connected to the distribution network. In this analysis, it is assumed that all installed PVs follow the same profile throughout the day. However, the total power production from each PV throughout the day depends on the PV rating of that individual PV. **Fig.** 7 shows the PV power profile of the day with a resolution of 5 min.

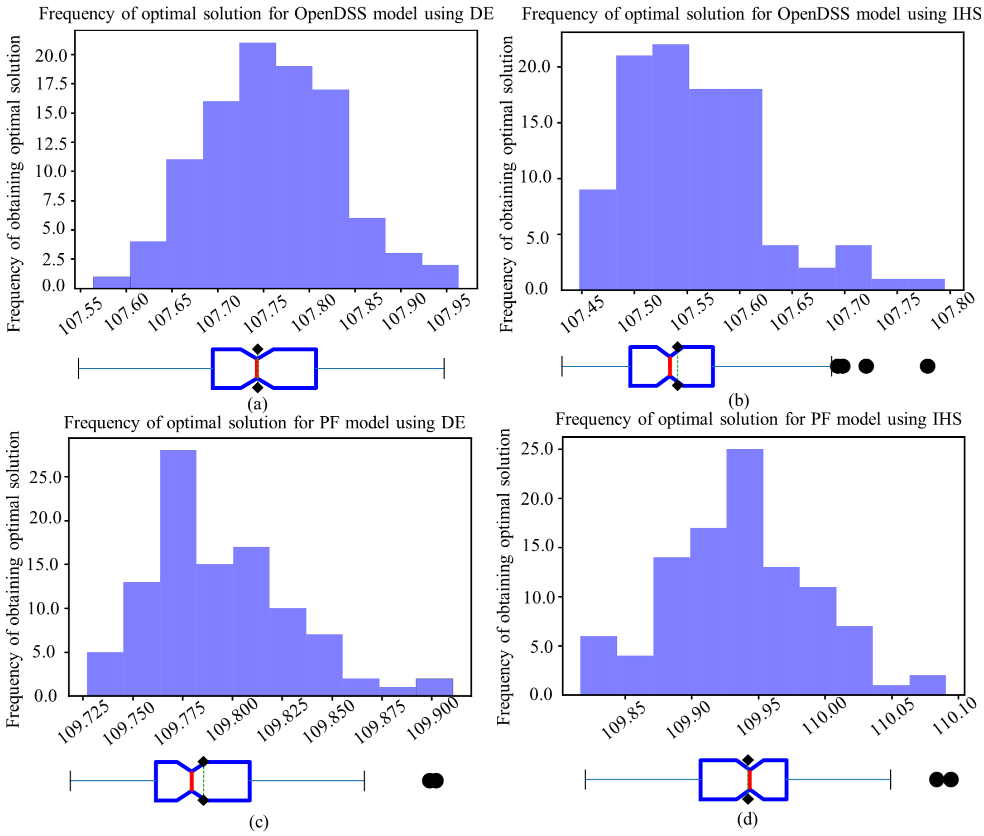

Fig. 5 Histogram and box plot for optimal values for 100 simulations of (a) DE in OpenDSS (b) IHS in OpenDSS (c) DE in PowerFactory and (d) IHS in PowerFactory

After completion of the optimization using the proposed method, the optimal set-points of reactive power will be achieved for all PVs. **Figures** 8 and 9 show the reactive power profile obtained for PV_1 and PV_8. Similarly, the reactive power profiles of all other PVs are obtained but are not shown here.

5.3 Discussion on Simulation Results

The proposed methodology is implemented in the CIGRE MV distribution network using three different optimization algorithms. On the basis of the simulation results, the discussion is also divided into three subsections. First, the analysis for single optimization is discussed. Later, iterative optimization is discussed. Finally, in the last subsection, the discussion of the finding of the proposed method on time series co-simulation based optimization is presented. A comparison in terms of the time required to obtain optimal solutions is also presented.

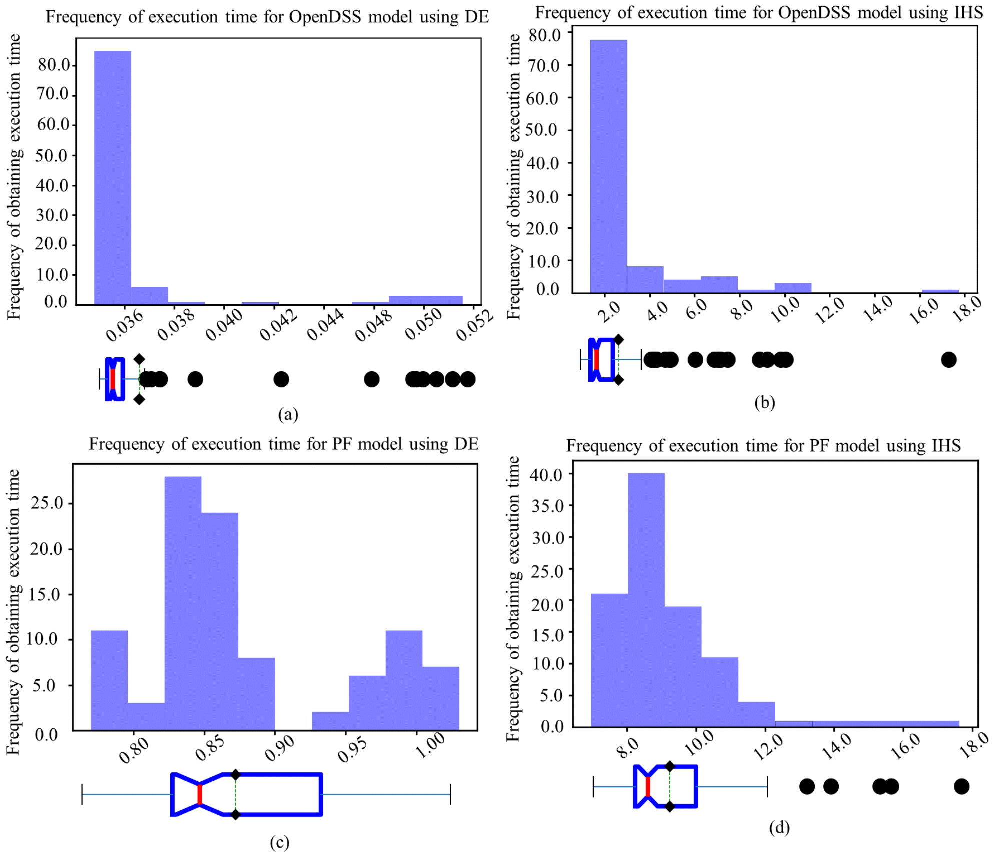

Fig. 6 Histogram and box plot for optimal values for 100 simulations of (a) DE in OpenDSS, (b) IHS in OpenDSS, (c) DE in PowerFactory and (d) IHS in PowerFactory

5.3.1 Discussion on single Optimization analysis

When the distribution network was operated with a constant power factor (without optimization) of PV, the total active power loss in the system was found to be 117.16 kW. On the other hand, the total active power loss in the network with the implementation of the proposed method is lower. With optimal setpoints for the PV inverter, the power loss in the network is reduced. **Table** 2 shows the comparison of active power loss in the distribution network with fixed power factor and with optimal setpoints of reactive power for PV inverters.

5.3.2 Discussion on iterative Optimization analysis

From the iterative optimization studies (for 100 iterations) performed between the models created in OpenDSS and PowerFactory, convergence was found to be faster in the case of a model designed in OpenDSS. For obtaining a better optimal solution,

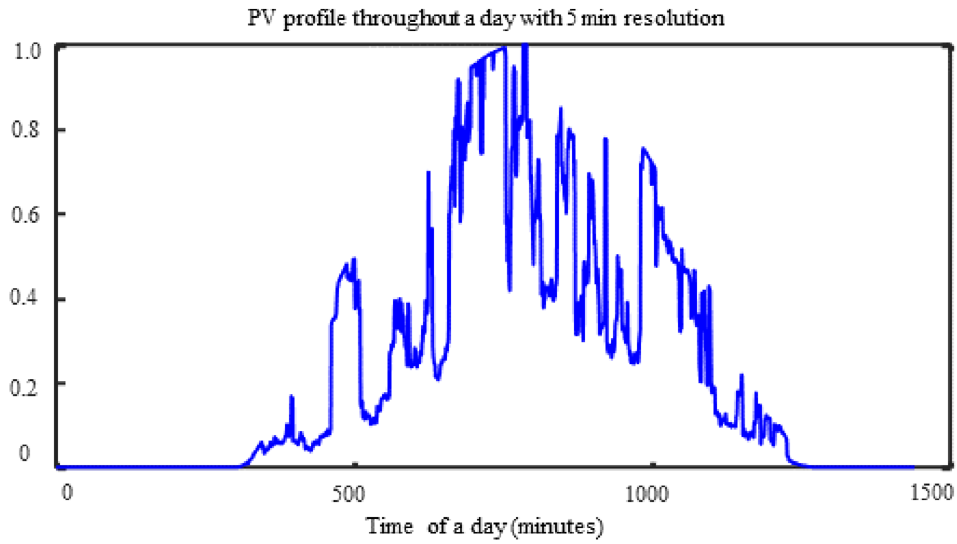

Fig. 7 PV power profile throughout the day with 5 min resolution

Table 2 Comparision of power loss in the network with fixed power factor and with optimal setpoints of reactive power for PV inverter

Optimization method	Power loss $[kW]$
Fixed power factor	117.16
DE	107.85
SHGO	107.383
IHS	109.78

the DE algorithm modelled in OpenDSS is more suitable. On the other hand, the DE solves the optimization problem in a short time.

From the iterative analysis, it is observed that for the model developed in OpenDSS, the probability of obtaining the optimal value (i.e. power loss) of 107.60 kW and 107.85 kW using DE and IHS is 32 % and 27 %, respectively. However, the optimal values do not deviate much from the mean value in this case. The mean values are taken as the values obtained from a single optimization in the previous subsection. Similarly, for the model developed in Power Factory, 36%, and 29% are the probability of obtaining optimal values of 109.95 and 109.78 using IHS and DE, respectively.

Similarly, the probability of attaining an optimal solution in 0.036 seconds and 1.19 seconds using DE and IHS for the OpenDSS model was found to be 80% and 91%, respectively. Similarly, for the Power Factory model, the probability of reaching ideal values in 0.84 seconds and 9.53 seconds using DE and IHS, respectively, is 40% and

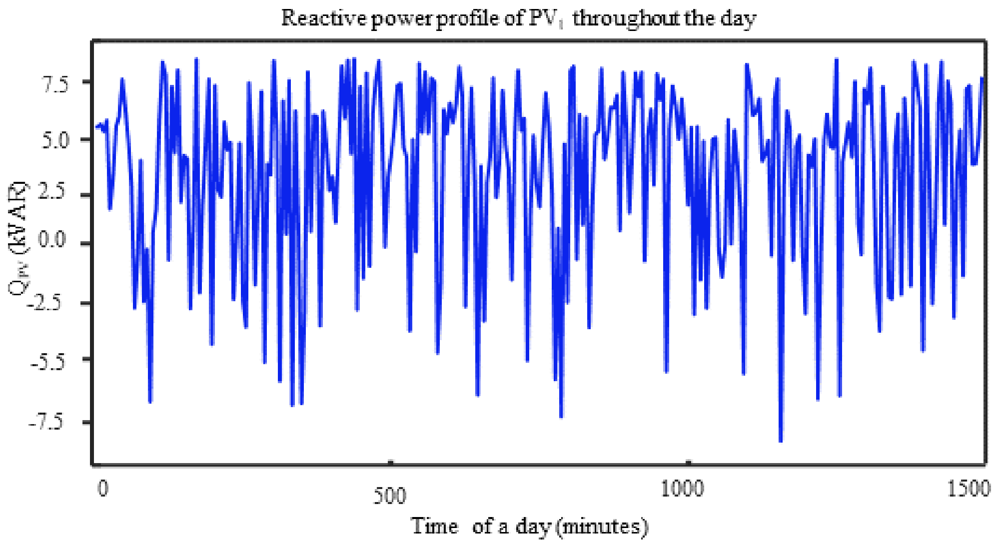

Fig. 8 Optimal Reactive power profile of PV1 throughout the day

30%. In this case, the average time is the value obtained from a single optimization in the previous subsection.

5.3.3 Discussion on time series co-simulation based optimization

From time series co-simulation based optimization using the proposed method, the reactive power setpoints of all PVs installed in the considered test network are obtained. The obtained reactive power setpoints are for a period of time with a 5-minute time step. The proposed method is capable of computing the reactive power setpoints in order to maintain a minimum power loss in the network. The authors also mention that the co-simulation based optimization method is suitable for optimizing the problem with specific objective functions. The criteria for selecting cosimulation-based optimization depend on the purpose of the application and the methodology that is implemented. Since the main continuation of this research is to identify the appropriate co-simulation based optimization, convergence time is considered the major indicator for identifying the best fit.

In this paper, the authors only make a comparison based on the time of convergence. **Table** 3 shows that the time required to solve the optimization by the proposed method is less than that proposed in [13].

6 Conclusion

This paper introduces a co-simulation-based optimal reactive power control from smart inverters in smart distribution networks, aiming to minimize power loss by optimizing reactive power set points of PV inverters. The proposed method effectively reduces the

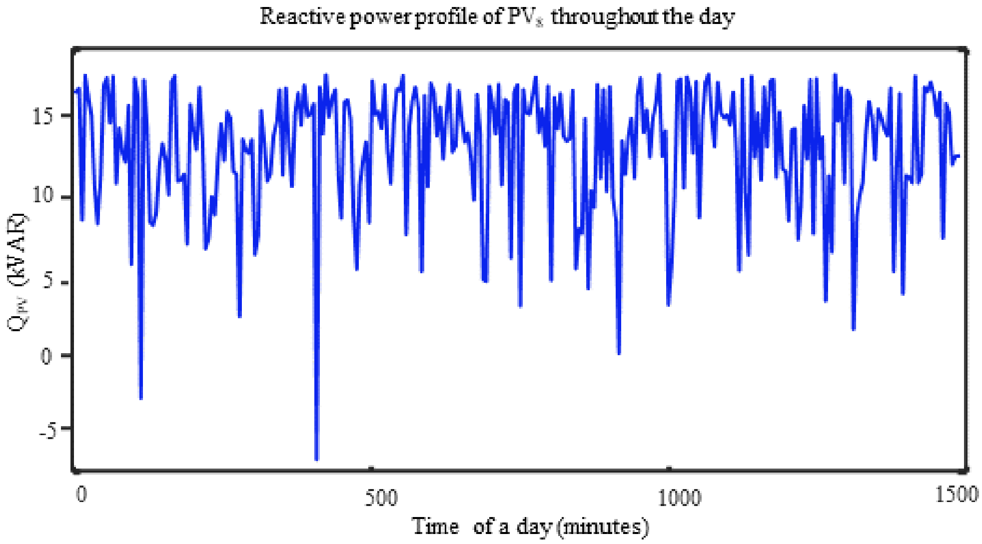

Fig. 9 Optimal Reactive power profile of PV8 throughout the day

Table 3 Comparision of time for optimization

Optimization method	time [*second*]
Proposed method	117.85
[13] method	199.87

total active power loss, as evidenced by a decrease in total active power loss from 117.16 kW to 107.85 kW in the test network without and with optimization, respectively. This reduction demonstrates the ability of the proposed approach to enhance system efficiency by minimizing the total power loss in the distribution network.

To simplify the mathematical modelling of the distribution network in the optimization model, the paper presents a co-simulation-based approach that eliminates the need for complex power flow equation modelling. Using the distribution network solver, the approach achieves faster convergence and facilitates real-time applications in distribution networks. With an impressive mean time to convergence of 0.036 seconds for a single optimization scenario, the proposed method is suitable for real-time control applications. Additionally, the co-simulation approach outperforms the detailed mathematical modelling using the current injection method in terms of optimizing the distribution network. The total time to obtain optimal solutions decreased from 199.87 to 117.85 seconds using the proposed method.

The results from the time-series co-simulation based optimization confirm the effectiveness of the proposed method in achieving optimal control in distribution networks. Furthermore, the flexibility of the proposed approach, independent of the network choice, enables the utilization of various optimization approaches in the distribution network. Future applications may involve real-time optimization, specifically in the implementation of digital twin-based real-time optimal reactive power control in distribution networks. These findings underscore the potential for further advancements and investigation of optimal control applications in real-time in smart distribution networks.

Acknowledgments. The Authors are very grateful to the Arctic Centre for Sustainable Energy (ARC) (project number 740108), UiT The Arctic University of Norway, Norway, for providing an opportunity for Mr. Raju to visit and work at DIgEnSys-Lab.

Declarations

- Funding: Not applicable.
- Conflict of interest: The authors declare no conflict of interest.
- Ethics approval: Not Applicable
- Consent to participate: Not Applicable
- Consent for publication: Not Applicable
- Availability of data and materials: The load data and PV size for the CIGRE MV network are taken from the report of the CIGRE Task Force C6.04
- Code availability: The optimization code can be obtained on request from the corresponding author.
- Authors' contributions: The conceptualization of the idea of doing further research, and development of the proposed co-simulation based optimal reactive power control in a smart distribution network was generated by Authors Raju and Francisco. Raju performed the co-simulation based on OpenDSS. Le and Gioacchino performed the co-simulation based optimization using DigSilent Power Factory. The original draft, data processing, and formal analysis were performed by Raju. All authors essentially contributed to the supervision, review, validation, and proof of the article.

Table 4 MV distribution network benchmark application: parameters of PV units [56]

Node	Type of DER	$P_{max}(kW)$
B3	PV	20
B4	PV	20
B5	PV	30
B6	PV	30
B7	PV	30
B8	PV	30
B9	PV	40
B10	PV	10
B11	PV	1500

Table 5 MV distribution network benchmark application: Parameters of residential load

Node	$S_{max}(kVA)$	$powerfactor$
B1	15300	0.98
B3	285	0.97
B4	445	0.97
B5	750	0.97
B6	565	0.97
B8	605	0.97
B10	490	0.97
B11	340	0.97
B12	15300	0.98
B14	215	0.97

Table 6 MV distribution network benchmark application: Parameters of commercial load

Node	$S_{max}(kVA)$	$powerfactor$
B1	5100	0.95
B3	265	0.85
B7	90	0.85
B9	675	0.85
B10	80	0.85
B12	5280	0.95
B13	40	0.85
B14	390	0.85

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