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Comparative Analysis of a Current-Source and a Voltage-Source Converter for Three-Phase Grid-Connected Battery Energy Storage System

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Master of Science in Electrical Engineering, June 2020

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ABSTRACT

Depletion of fossil fuels and climate change globally, the renewable energy sources like solar and wind is increased. For generating clean energy renewable sources are the best solution. By using renewable energy solutions, we can use battery energy storage system which is the promising solution.

Industry and academia peoples main focus on voltage source converter and they have given a very little attention to current source converters. Current source converter eliminates the need of boost converter because DC to AC type current source inverter is itself a boost type converter. Whereas, when this converter operates in AC-DC mode it behaves as a buck converter, the output DC voltage can be wide range. This inherent buck-boost feature and easy control of current make CSC an attractive choice for grid-integration of battery energy storage system.

The project deals with the comparative analysis of voltage and sources and current sources source-based grid connected battery energy storage system. The main objective of this project is to design the simulation of voltage and current source converter and analyze the advantages and disadvantages of both converters with main focus on power electronics control of converters.

Keywords

Voltage source converter (VSC)
Current Source converter (CSC)
Battery energy storage system (BESS)

1 CHAPTER ONE

1.1 Introduction

World is facing energy crises and everywhere peoples are focusing on renewable energy system and also work on the integration of battery energy storage system with grid connected converters. As PV and wind output is not constant all the time, we need some storage system which can provide backup at off time. Energy storage plays vital role in the electrical power system, the development and advancement in power electronics technologies and various energy storage will be beneficial for increasing the efficiency of power system.

1.2 Various Energy storage technologies

Electricity cannot be stored, but we can convert energy stored into different forms like electrochemical, electromagnetic, kinetic and as potential energy. Based on these forms some energy storage technologies have been developed and some are under development. The various technologies are as follows.

- Compressed air energy storage (CAES)
- Flywheel
- Super Capacitor
- Battery
- Pumped hydro storage
- Super conducting magnetic energy storage (SMES)

The oldest form of energy storage is battery and the currently available battery technologies are based on flow batteries technologies or conventional battery technologies.

The most developed and used form of battery technology is the lead acid battery which has been used for more than 100 years. The disadvantage of this battery is it has short life and very low reliability. For load leveling and peaking in 1988 the world largest lead acid battery energy storage system has rated at 40MWh was installed in chino California [4].

The type of battery having high energy efficiency, long life cycle and a very low discharge rate is the sodium sulfur battery which is known as NaS. This type of battery has a pulse power capability over six times their continuous rating which enables the NaS battery to be sparingly used in combined power quality and peak splinter applications [5].

The mature technology in batteries is a nickel cadmium. From late 2003 in Fairbanks and Alaska, the Ni-cd battery energy storage system having capacity of 46MW for 15 minutes has been in operation [6].

-why it has very low potential use in utility scale.

Rechargeable Metal-air batteries are of large-scale lithium-based batteries, such as Lithium ion Battery, Lithium Ion polymer and lithium metal polymer are still under development [7].

Zebra batteries are specially designed for electric and hybrid vehicles. These are high temperature batteries and having energy density four times higher than the lead acid batteries. The quality of these batteries is, high energy density, high energy efficiency and very low gaseous emission [8].

The above discussed battery technologies are usually designed for either high power with short discharge duration or low power and log discharge duration where as the power rating and energy rating of flow battery technologies are self-governing of each other. The energy rating can be increased by increasing the storage capacity by increasing the number of batteries.

1.3 Project objective

The main objective of project are as follows

- Design a Simulink model for voltage source converter and current source converter based grid connected battery energy storage system with focus on power electronics and control.
- Comparative study between VSC and CSC for grid integration of BESS including total harmonic distortion of grid current, efficiency, component count, dynamic response, charging and discharging of batteries.

Chapter Two

2 LITERATURE REVIEW

2.1 Introduction

The two most prominent types of converters are voltage source converter and current source converter, most of researchers mainly focus on voltage source converter, there are some advantage and disadvantages of voltage source converter and current source converters.

2.2 Voltage Source Converter (VSC)

On the basis of several recent power system projects, the VSC based technology has been nominated. This purpose of selection of this type of converter is that it has compact modular design, its system interface is easy, its controllability and low environment impact. For the first time VSC have been for high voltage DC transmission in a real network. The results of designing and commissioning of the transmission line shows that this technology has now reached the stage where we can build high voltage converters by utilizing IGBTs. The operation and system results proved that the properties that we have discussed for many years regarding voltage source converter for high voltage DC are a reality now. The advantage of this type of converter is that it includes the independent control of active and reactive power, operation against isolated alternating current network with no generation of their own. It requires very limited filters and no requirement of transformers for the conversion process.

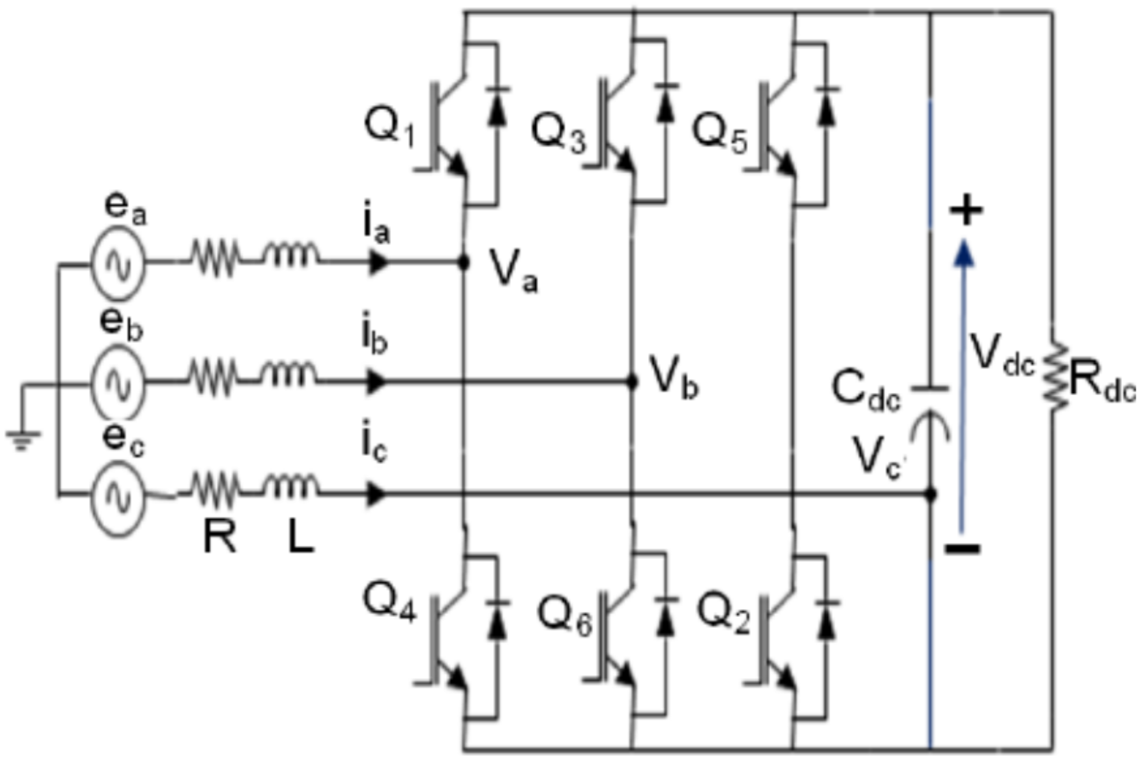


Figure 1 voltage source converter

[22]

Figure shows the schematic diagram of voltage source converter, there six fully controlled switches Q1, Q2, Q3, Q4, Q5 and Q6 in which each two IGBTs are connected with each phase of source. The IGBTs connected in one lag does not turn on at time if we do so there is short circuit occur between the positive and negative source, same as Q3 and Q6 cannot be turn on at a time and Q5 and Q2 also cannot be turn on at a time.

2.2.1 Advantages of VSC

There are many advantages of voltage source converter, some of them are given below

The VSC can operate with the quantified vector control approach and can perform self-governing control of active and reactive power at both end which is the primary condition of FACTS controller.

The output voltage VSC is constant at any load condition.

VSC does not require any series reactor so the efficiency of VSC is higher.

The control mechanism of voltage source converter is comparatively easy.

The harmonic component in voltage source converter is relatively small and can be minimized using various techniques.

2.2.2 Topologies for VSC

There are many control topologies for three phase voltage source converters are available which are PWM (pulse width modulation), SPWM (sinusoidal pulse width modulation) and SVPWM (space vector pulse width modulation).

2.2.2.1 PWM control

The simplest topology is the PWM controller three phase converters. In PWM control we generate the PWM signal from controller with is phase shift of 120 and provide it to the gate of IGBT. The turn ON and turn OFF of IGBT is controlled by using PWM signal.

In order to generate an analog signal from a digital signal, we use the pulse width modulation. Through this technique we modulate the width of a pulse signal. The pulse width modulation can be done by the use of microcontroller and through the 555 timer IC. The time for which the signal

time. PWM signal is the pulses type signal whose average voltage depends on its duty cycle. The duty cycle of the signal can be given by the following formula

$$Duty\ cycle = \frac{Turn\ ON\ time}{turn\ On\ time + turn\ Off\ time}$$

The signal will have the maximum voltage for the 100% duty cycle.[15]

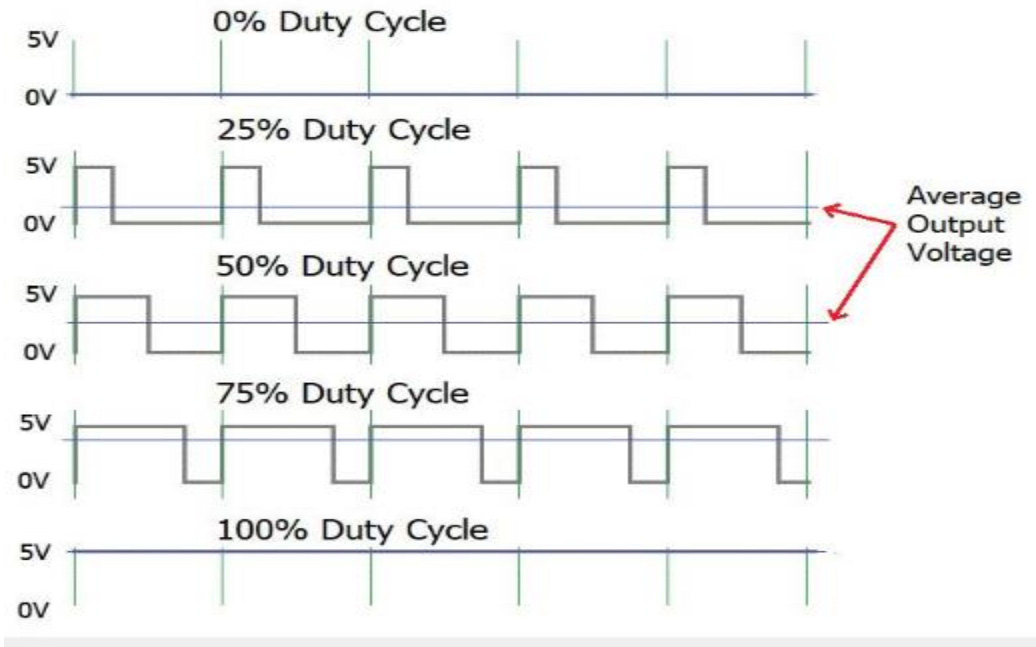


Figure 2:- Duty cycling of PWM

Frequency of the signal is the second important term. It is the rate of change of cycles while the duty cycle is the ON time of the pulse. [11]

The frequency can be calculated as follow

$$frequency = {}^{1}/_{time\ peroid}$$

$$time\ period = on\ time + off\ time$$

Frequency can be set according to the requirement of the project.

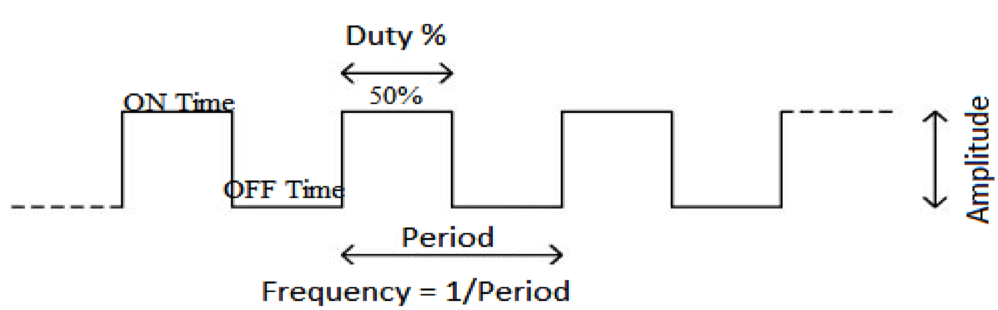


Figure 3:- Frequency setting of duty cycle

The output average voltage can be calculated as

$$Output\ voltage = duty\ cycle\ \times peak\ input\ voltage$$

In the today's electronic world, PWM programming techniques very helpful. They are mainly used in the speed control, frequency change, power control, applications.

2.2.2.2 SPWM

Normal PWM is the pulse width modulation technique having the same width of all pulses but in SPWM technique the width of pulses not remains same, it changes in the proportion the amplitude of sine wave slop evaluated at the center of each pulse.

This type of pulse width modulation gives a nearly sinusoidal signal. The harmonic content is also very less. The circuit design for this modulation is same, only programming technique is changes which is illustrated below. [10]

For sinusoidal pulse width modulation, we require two signals. One signal is a triangular wave and second is a sinusoidal signal. This triangular signal waveform is called carrier wave. Triangular e sinusoidal signal determine the output frequency. Sinusoidal signal acts as the control signal. When magnitude of the control signal is higher than the triangular signal, the gate signal is ON and we get positive voltage and when control signal is lower than the carrier signal, we get the negative output. [9]

The magnitude of the modulated signal varies in a sinusoidal manner. During half cycle, it has many pulses with their ON time increasing gradually and it again starts decreasing after half cycle.

We can change the load current amplitude with the amplitude modulation as follow

$$M_A = \frac{Amplitude\ of\ reference\ signal}{Amplitude\ of\ carrier\ signal}$$

Similarly, frequency of the load signal can be varied by the frequency modulation. [16]

$$M_f = \frac{frequency\ of\ carrier\ signal}{frequency\ of\ reference\ signal}$$

In the production of sinusoidal modulation, the ratio of the frequencies of the reference and carrier frequencies should be some integer that is

$$2N = \frac{f_c}{f_s}$$

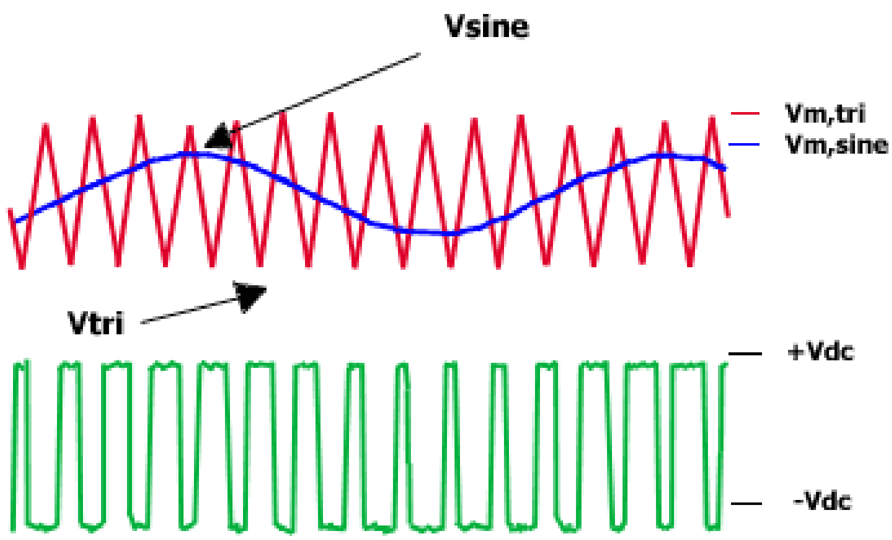


Figure 4 :- SPWM (Sinusoidal Pulse width modulation)

2.2.2.3 Space Vector Pulse Width Modulation (SVPWM)

In recent years, Space vector modulation (SVM) is used for controlling Single-phase PWM inverters. This is the one of the best available methods for PWM signals. It is an advanced control mechanism that generates single-phase AC voltages of the desired magnitude and frequency at the output of the inverter. To implement SVM a reference signal V_{ref} is sampled with frequency

$$f_s \ (f_s = 1/T_s) \ [2].$$

For generating switching patterns, the output voltages of the inverter are taken into account. The vectoral representation was first presented in the contributions of Park [3] and Kron [4].

2.2.2.4 Significance of IGBT for VSC

An insulated-gate bipolar transistor is a three terminal device (a power semiconductor) which is used as an electronic switch and has high efficiency and fast switching.IGBT is a semiconductor device with four alternating layers P-N-P-N, controlled by a metal-oxide-semiconductor gate structure [1].

As IGBT is designed to turn ON/OFF rapidly it is used in high switching applications. IGBT`s are mostly used in variable frequency drives where quick switching is required [6]. It allows power flow in on state and stops power when it is in off state. Voltage is applied to the semiconductor component in order to drive the IGBT therefore changing its properties to allow/block an electrical flow [1].

Construction

The insulated gate bipolar transistor is a three terminal device which combines a MOSFET which has an insulated gate N-channel with a PNP bipolar transistor output connected in a Darlington configuration [1].

A **Darlington configuration** is a compound structure which is made by two bipolar transistors which are connected in a way that the current which is amplified by first transistor is further amplified by the second transistor [1].

So, as a result the terminals of IGBT are as emitter, base and collector. Collector and emitter are interconnected with conductance path in such a way that they pass current while the gate controls the component.

Characteristics

IGBT is controlled by voltage i.e. it requires a small amount of voltage on its gate to maintain conduction through device unlike a bipolar junction transistor which requires continuous base current to maintain saturation.

IGBT is a unidirectional device, it can only switch current in one direction that is from collector to emitter(forward) unlike MOSFETS which can switch in both directions (forward as well backwards) [6].

The current ratings of IGBT`s are much higher than that of the MOSFET`s due to the resistance by conducting channel when current flows through the device when it is in on state [6].

The IGBT`s are generally of high voltage capability, low on resistances, have fast switching and are easy to drive which makes them more suitable for high voltage applications such as pulse width modulation and variable frequency drives.

IGBT Comparison

	Characteristics	Power of Bipolar Transistor	Power of MOSFET	Power of IGBT
Rating	Voltage	<1kV	<1kV	>1kV
	Current	<500A	<200A	>500A
Input	Drive	I,h_{FE} (20-200)	V,V_{GS} (3-10)	V,V_{GE} (4-8)
	Impedance	Low Z	High Z	High Z
Output	Impedance	Low Z	Medium Z	Low Z
Switching	Speed	Us	Ns	us-ns
	Cost	Low Cost	Medium Cost	High Cost

(Comparison of IGBT with other Transistors)

2.3 Current Source Converter

In current source converter the input current remains constant and the voltage does not remain constant, it depends on the load. There are more output harmonics in current source converter. As the current is measured so due to mis firing of switches does not create a serious problem. To filter out harmonics and balance the unbalance load, a shunt compensator is connected in a distribution system in most general cases. The additional capability increases the initial cost of the implemented system. However, for the balanced clean loads although their reactive power demand varies rapidly the shunt connected compensator is required only for power factor correction.

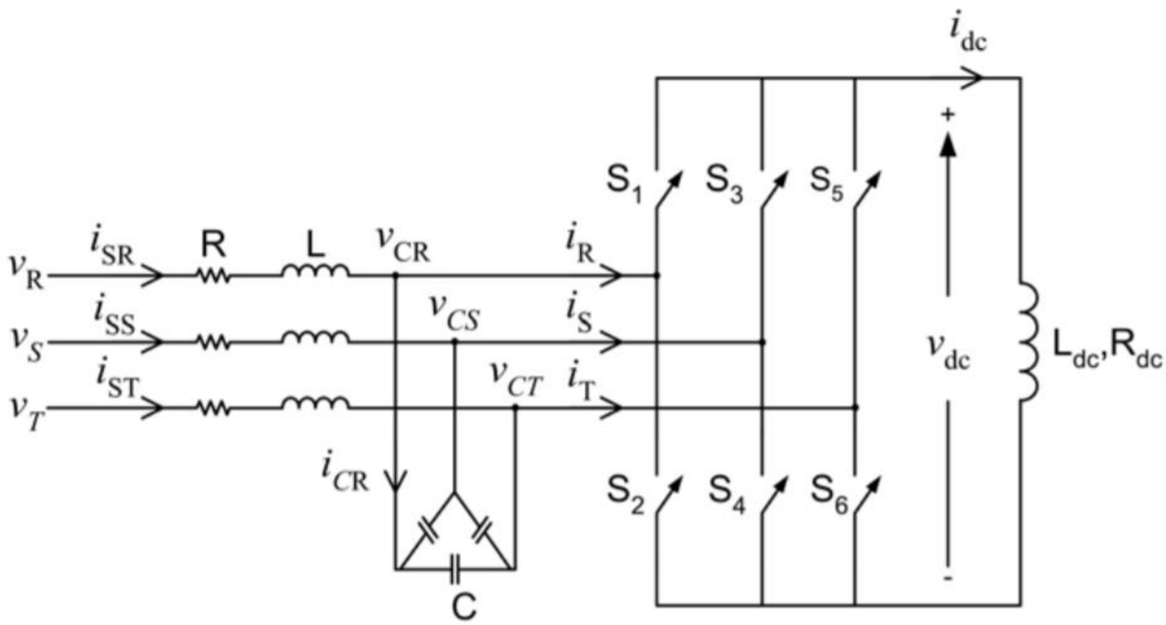


Figure 5 :- Basic idea of current source converter

Figure shows the generalized circuit of current source converter having six fully controlled switches s1,s2,s3,s4,s5 and s6. These switches have unidirectional current carrying and bidirectional voltage blocking capability. For energy storage, the dc link reactor has been placed. The dc link reactor consists of dc link inductance and its internal resistance. Due to relatively high time constant of dc link circuit, the dc link current becomes relatively constant over a switching period.

2.4 Comparison of voltage source and current source converter

The voltage source converter and current source converter each one has its own significance like in voltage source converter the voltage remains same and current does not remain constants while in current source converter the current remains same but voltage does not remain same at varying load. The comparison table of voltage source and current source converter is shown below

Voltage Source Converter	**Current Source Converter**
The voltage maintains constant but the current may or may not be constant, it depends on load.	The input voltage may change with the load but the input current is maintained constant.

The amplitude of output voltage does not depends on the load but the amplitude of output current waveform depends on the load.	The amplitude of current waveform is independent of load but the amplitude of voltage waveform depends on the load.
The misfiring of switching devices may cause a short circuit and create a series problem.	The input current is measured and the misfiring of switching devices does not create a serious problem.
The peak current depends on power electronic devices and circuit and not be limited in voltage source converter.	The input current is measured in a constant current of power devices is limited.
There is no need of series reactor with the source in voltage source converter.	A large series reactor is required in series with the source to obtain the constant current in current source converter.
Due to absence of series reactor there are less losses in voltage source converter than current source converter.	Due to the presence of series reactor, there are much higher losses in current source converter.

CHAPTER 3

3 VOLTAGE SOURCE CONVERTER

3.1 Grid connected Voltage Source Converter

This section consists of main modules of voltage source converter, like the basic circuit, grid filters and modulation techniques will be presented. The section describes the working of three phase voltage source converter using IGBT with gate control scheme.

3.1.1 Main Circuit of Voltage Source Converter

The main schematic of voltage source converter consists of 6 IGBT based switches having two switches are connected in same lag of circuit. There are three lags in circuits having each lag consist of two IGBTs. This converter is connected to a symmetric three phase load which has an impedance of R+j and the emf of all three is $e_1(t)$, $e_2(t)$ and $e_3(t)$.

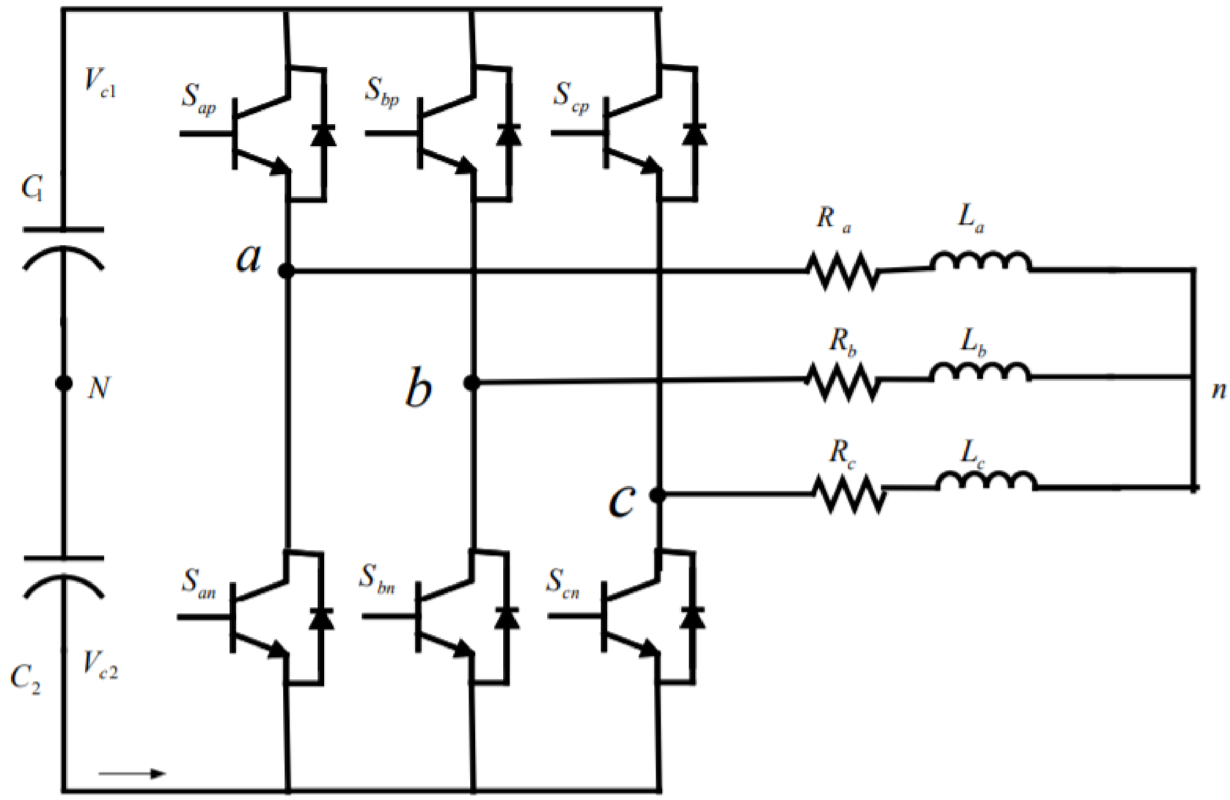


Figure 6 :- Schematic Three phase VSC

The switching state table of three phase voltage source converter is shown below

State	Sap	Sbp	Scp	San	Sbn	Scn
V1	0	0	1	1	1	0
V2	0	1	0	1	0	1
V3	0	1	1	1	0	0
V4	1	0	0	0	1	1
V5	1	0	1	0	1	0
V6	1	1	0	0	0	1

The two switches are connected in same leg and we cannot provide same signal at time to both IGBTs.

The equation of switches become

$$S_{11} + S_{12} = 1$$

$$S_{21} + S_{22} = 1$$

$$S_{31} + S_{32} = 1.$$

The voltage equation of star connected three phase balanced load can be expressed as

$$\frac{V_{dc}}{2}(S_{ap} - S_{an}) = v_{an} + v_{no}$$

$$\frac{V_{dc}}{2}(S_{bp} - S_{bn}) = v_{bn} + v_{no}$$

$$\frac{V_{dc}}{2}(S_{cp} - S_{cn}) = v_{cn} + v_{no}$$

Where Van, Vbn and Vcn are phase voltage of grid.

By adding the above three equations the resultant becomes

$$\frac{V_{dc}}{2}(S_{ap} + S_{bp} + S_{cp} - S_{an} - S_{bn} - S_{cn}) = v_{an} + v_{bn} + v_{cn} + 3v_{no}$$

As the load is balanced so Van+Vbn+Vcn=0 the above six equations become

$$\frac{V_{dc}}{2}(2S_{ap} - S_{bp} - S_{cp}) = v_{an}$$

$$\frac{V_{dc}}{2}(-S_{ap}+2S_{bp}-S_{cp})=v_{bn}$$

$$\frac{V_{dc}}{2}(-S_{ap}-S_{bp}+2S_{cp})=v_{cn}$$

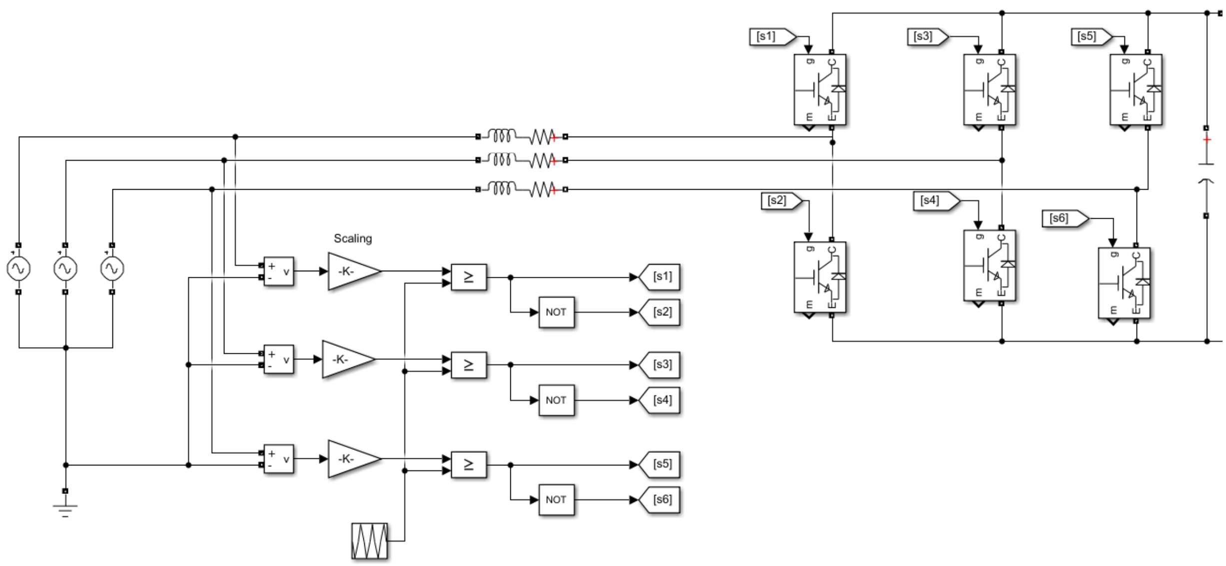


Figure 7:- Uncontrolled circuit of VSC

Figure 7 shows the schematic voltage source converter which consist of six switches having six gate control signals. The sequence of all gate signals is on such a way that two IGBT of each lag does not turn on at a time, if we do so a short circuit occur at this lag. This circuit is without any control mechanism it just convert AC voltage to DC voltage, It is also called IGBT based three phase rectifier.

3.1.2 Grid Filter

While connecting a voltage source converter to a grid an inductor must be placed between the VSC, this inductor act as a stiff voltage source, and the grid which also act as a stiff voltage source. The most common and simplest grid filter is inductor filter in which three inductors are connected with the series of three phase, each inductor per phase.

3.1.3 Modulation

The main advantage of VSC is that it at low frequency it has low harmonic distortion which result in sinusoidal current. This is due to the fact that by switching IGBTs properly only high frequency harmonics remains. The six-pulse modulation technique is the simplest modulation technique, in which each phase switch twice per cycle. By introducing more switching instances the harmonics becomes more reduced.

3.1.4 Working of voltage source converter

This voltage source converter is used to convert the three phase AC voltage to DC voltage for battery storage application. In this circuit we will use six IGBTs for switching to generate the desired output.

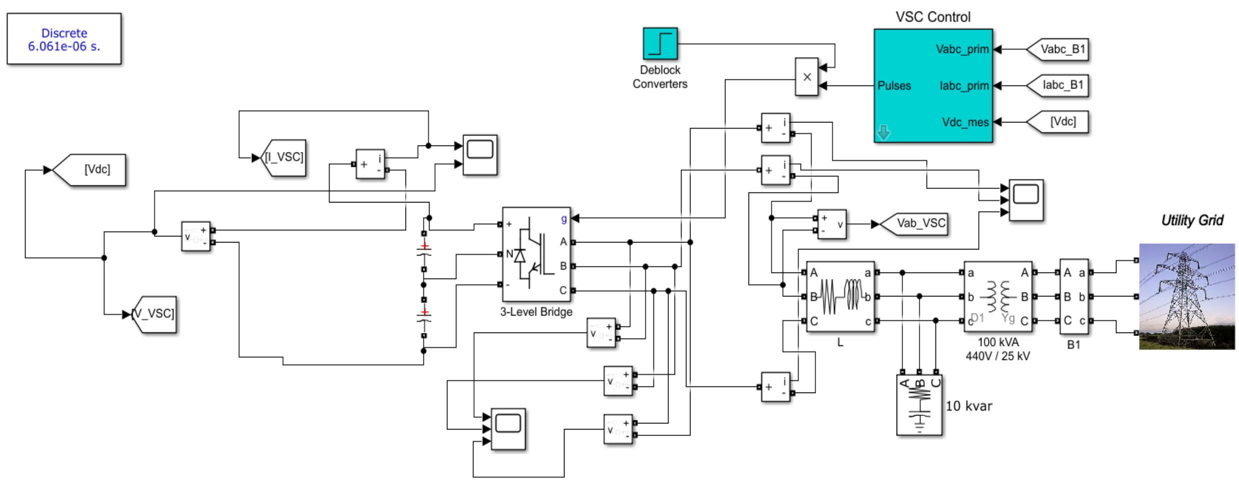


Figure 8 : working diagram of VSC

Figure shows three parts of circuit one AC source connection, second is control signal generation circuit for IGBTs and third is three phase switching circuit based on IGBT.

The RMS voltage standard follows in Norway = 230V AC

The peak value is =1.41*230V =325V

The nominal frequency = 50Hz

To generate the gate driving signal we have used the scaling formula of

($1/V_{peak}$ *k) as Vpeak=325V and k=1.2

The modulation index is m and its formula is as follows

M=f/fs where f=fundamental frequency and fs=Sampling frequency

For SPWM signal we use one triangular wave and second is scaled sine wave signal

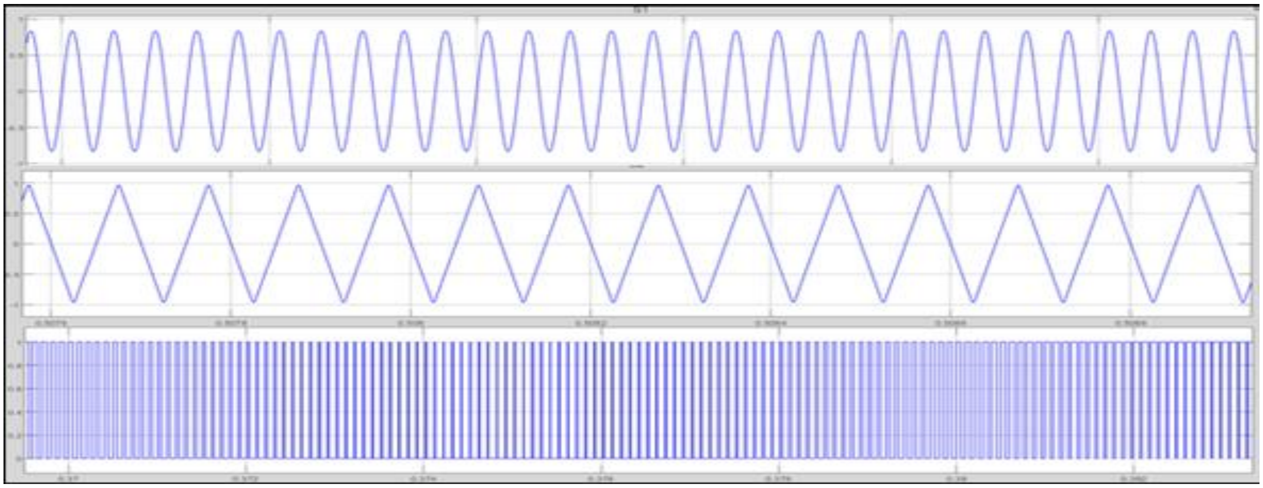


Figure 9 :- SPWM signal generation using sine and triangular waveform

Figure 9 shows three waveforms one is sinusoidal, triangular and the output is SPWM. By using the comparator with above two waveforms the output signal is generated for the gate of IGBT.

The frequency of sine wave signal is 50Hz

The frequency of triangular wave is 10KHz. We have used comparator to generate the SPWM signal for gate driving.

If $V_{rectangular} > V_{sine}$ Then the IGBT gate is ON

If $V_{rectangular} < V_{sine}$ Then the IGBT gate is OFF

This method is used for all six switches

For modulation it is important that if the modulating signal is continuous then the pulse width modulation is continuous pulse width modulation (CPWM). If the modulating signal is discontinuous then the PWM is discontinuous PWM (DPWM).

While using comparator for sine wave and triangular wave the output SPWM signal is generated for one IGBT gate driving.

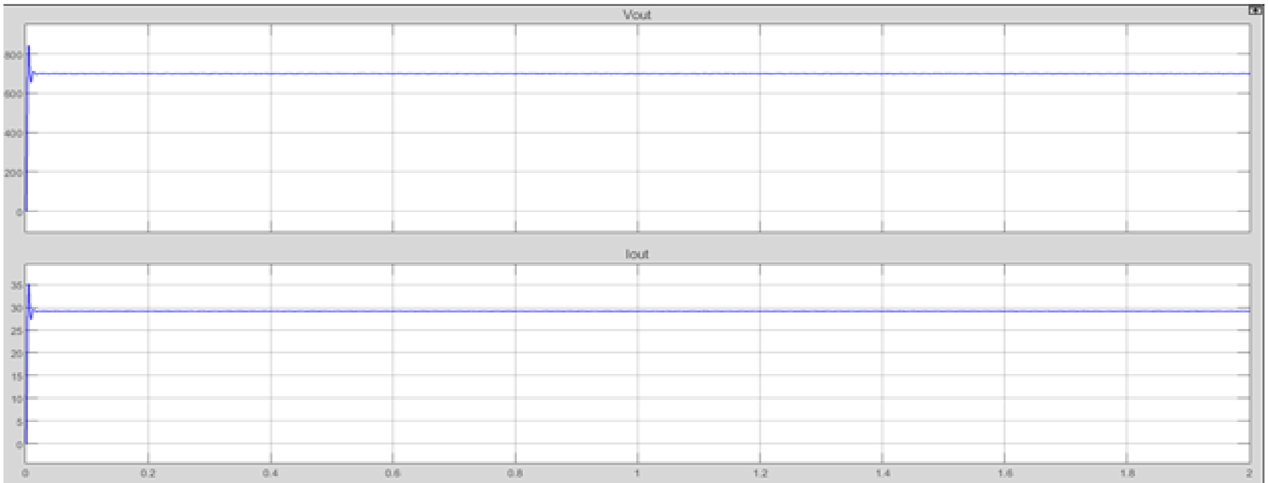


Figure 10:- Output Voltage and current waveform VSC

Figure shows the output curve of voltage source converter having the maximum DC voltage for battery charging is 700V and current changes with respect to load. At current load condition the current is almost 30A. Vout shows the output voltage curve and Iout shows the output current curve.

3.2 Battery charging and discharging circuit

There is a significance of two-way battery charger, because this single circuit can used for both purposes like charging and discharging of the battery. To make this circuit more effective we implement a PI controller for both charging and discharging. When the source is available the circuit start charging the battery and when the source is not available the battery act as source and start discharging.

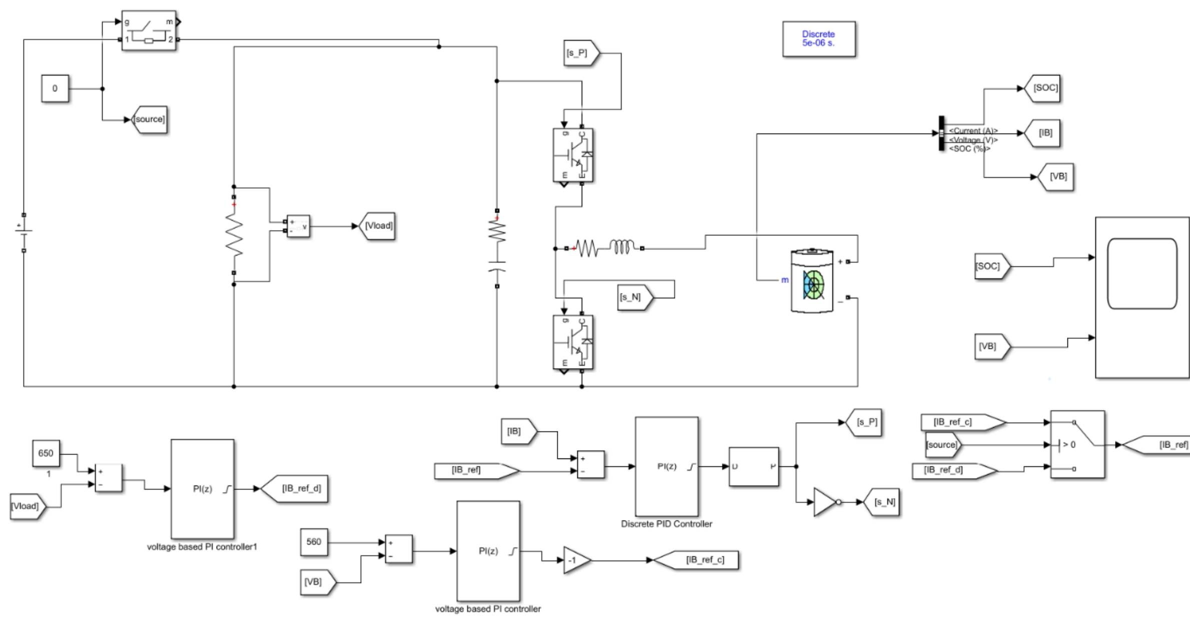


Figure shows the complete circuit of battery charging and discharging system, in which we have used two PI controller for charging and discharging purpose. The switch is used to shift the battery in charging and discharging mode on the availability of source. The two IGBTs are used for the switching on the basis of PWM. The third PI controller generate the PWM signal for battery charging. As we consider the battery internal resistance is constant. The battery characteristics that we have used are as follows.

Battery Type is Li-ion.

Nominal Voltage = 480V

Nominal current =100AH

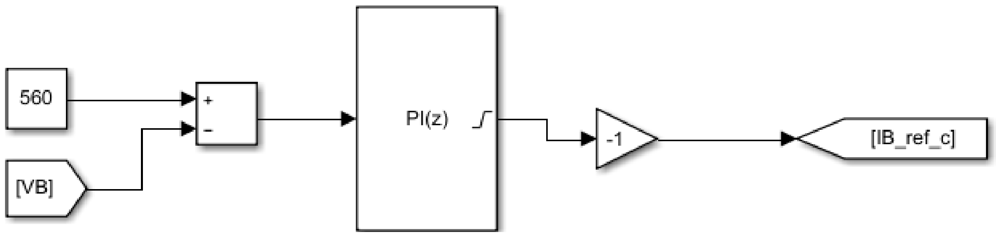
Full charging voltage =560V

Cut off voltage (deep discharge voltage) =360V

Battery internal resistance= 0.048 ohm

3.2.1 Battery charging

For battery charging we have used one PI controller which is used to generate the reference current signal from refence and input signal and start charging the battery.



The reference signal and VB generate the reference current signal for battery charging, the output reference current signal is generated by PI controller.

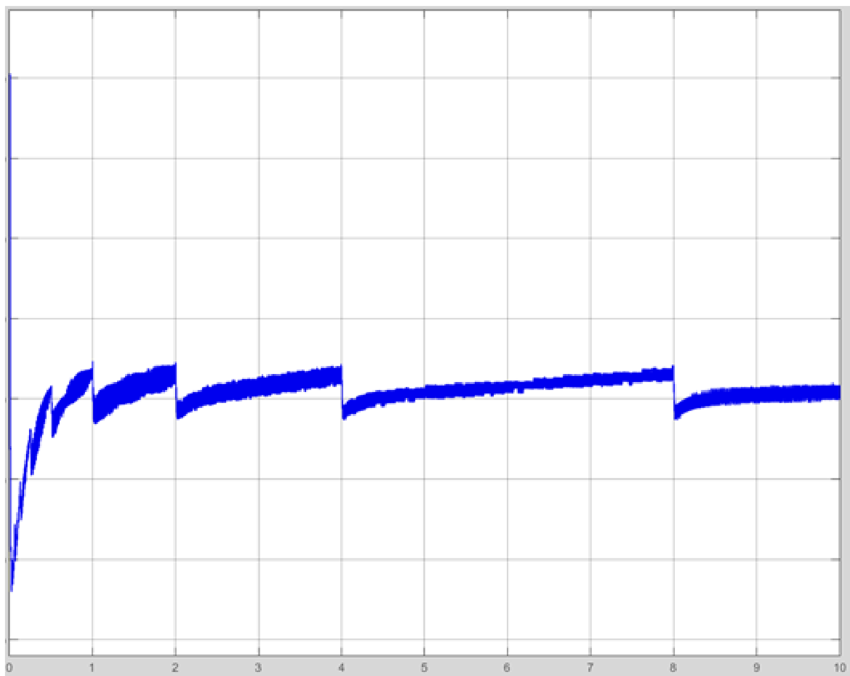


Figure 11 graph of SOC without scaling

This graph shows the SOC (state of charge), it shows the level of charge with respect to its capacity. The unit of SOC is in percentage which is between (0% to 100%). This is the graph of charging state SOC of battery.

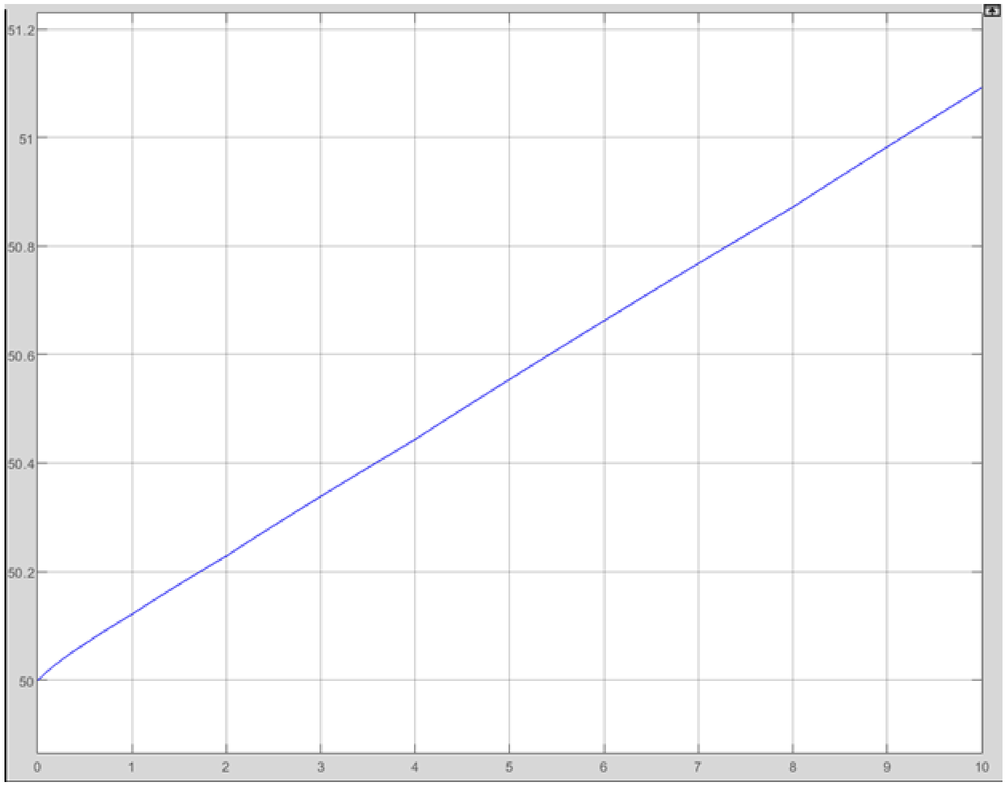
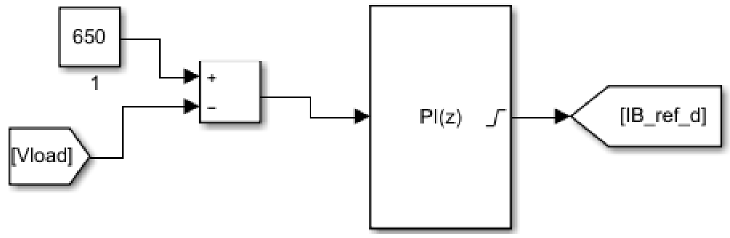


Figure 12 :- Battery charging graph

As we have set the initial charge of 50% for battery so the battery start charging from 50% and gradually increase the charge of battery as the battery is in charging state. We have selected the Lithium-ion battery.

3.2.2 Battery Discharging

As the battery discharge depends on the load connected with the battery, we have used one PI controller to generate the battery discharging reference signal which take the input of reference signal and load voltage. This PI controller generate the reference current signal for discharging of the battery.



Vload represent the voltage of load.

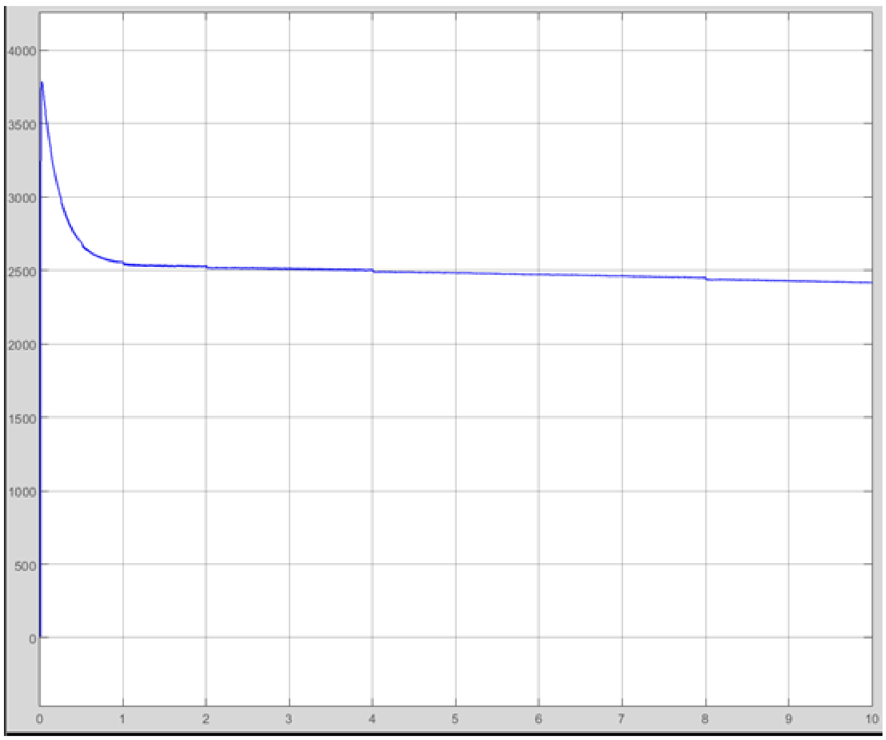


Figure 13 :- Battery discharging graph of SOC

This graph shows the SOC of discharging of the battery, as we know that the SOC decreases on the discharging state of battery. As the battery discharge the graph line falls down gradually and battery charge reduces.

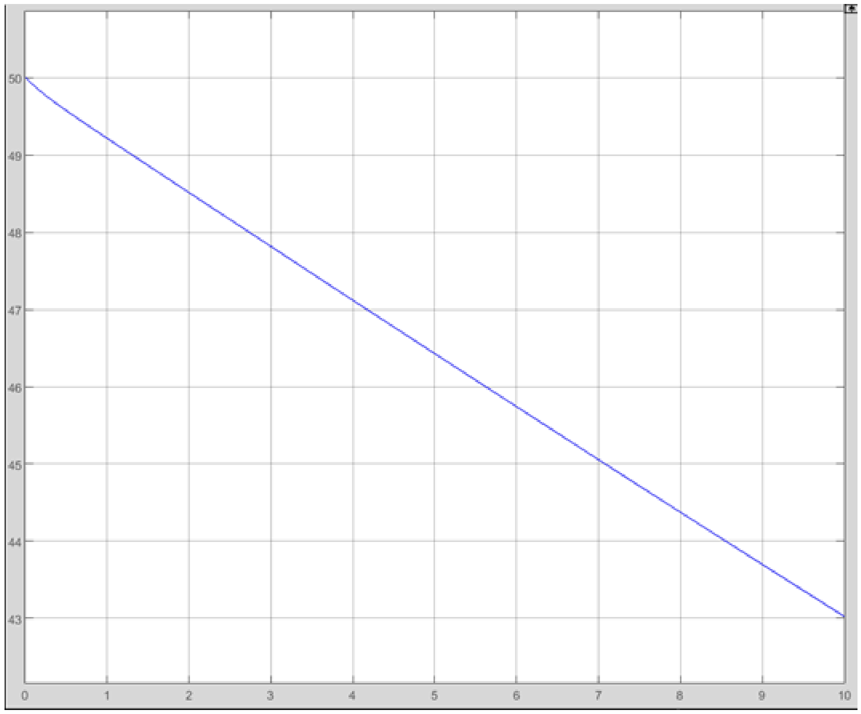


Figure 14 :- Battery discharging graph

This graph shows the discharging of battery, as the battery starts discharging the graph line falls down gradually. We have connected the resistive load so the graph line is almost linear. If the load was inductive or capacitive the discharge graph line would different.

3.3 Voltage source converter with grid connected BESSS

Battery energy storage system has most significance now a days due to energy crises. Researchers introduce a new concept of grid connected BESSS. The battery is connected with the grid using two-way battery charger circuit. This circuit will charge the battery when source is available and discharge the battery when the source is not present.

The basic connection of VSC with grid is shown below

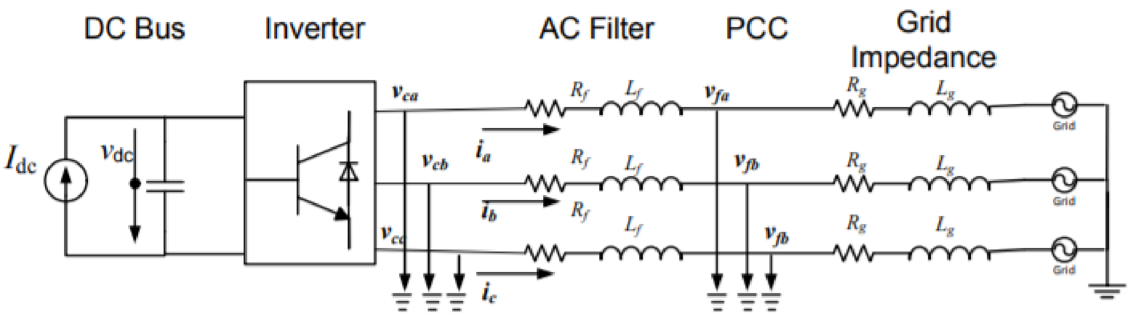


Figure 15 :- Basic circuit CSC

Figure shows the basic structure of grid connected VSC in which the main modules are DC bus , inverter , filter , PCC and grid impedance matching circuit.

3.3.1 Control Scheme: -

We have adapted the control scheme of DQ synchronous frame reference which include the mathematical model.

3.3.2 Mathematical model of three phase VSC

From above figure the equations can be written as

$$v_{ca} = i_a(R_f + L_f\frac{d}{dt}) + v_{fa}$$

$$v_{cb} = i_b(R_f + L_f\frac{d}{dt}) + v_{fb}$$

$$v_{cc} = i_c(R_f + L_f\frac{d}{dt}) + v_{fc}$$

For the voltages at the filter in terms of grid voltages the above equations can be written. The matrix of these equation is shown below.

$$\begin{bmatrix} v_{ca} \\ v_{cb} \\ v_{cc} \end{bmatrix} = \begin{bmatrix} R_f & 0 & 0 \\ 0 & R_f & 0 \\ 0 & 0 & R_f \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L_f & 0 & 0 \\ 0 & L_f & 0 \\ 0 & 0 & L_f \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} v_{fa} \\ v_{fb} \\ v_{fc} \end{bmatrix}$$

$$\begin{bmatrix} v_{fa} \\ v_{fb} \\ v_{fc} \end{bmatrix} = \begin{bmatrix} R_g & 0 & 0 \\ 0 & R_g & 0 \\ 0 & 0 & R_g \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L_g & 0 & 0 \\ 0 & L_g & 0 \\ 0 & 0 & L_g \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} v_{ga} \\ v_{gb} \\ v_{gc} \end{bmatrix}$$

3.3.3 DQ0 transformation

For the designing of control system its good to have a constant value and for constant values conversion we use dq0 transformation.

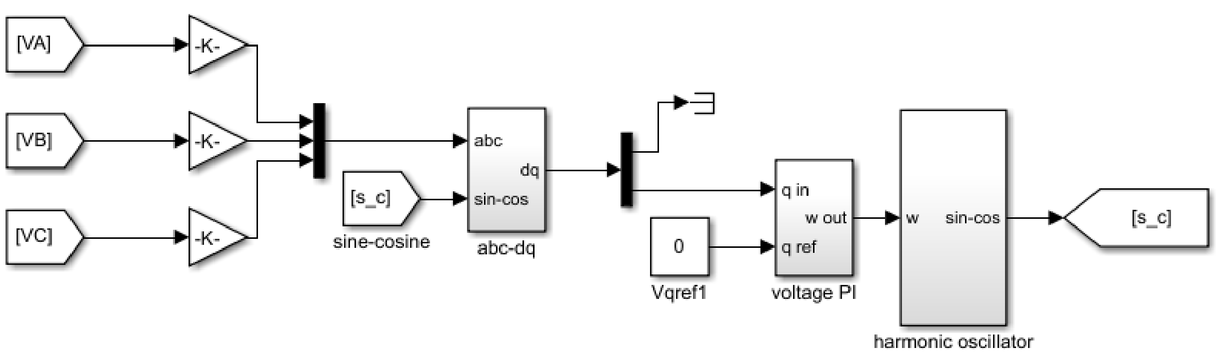


Figure 16 control schematic of VSC with harmonic oscillator

In matrix form the abc co-ordinates are written as

$$[\mathbf{v_c}] = [\mathbf{R_f}][\mathbf{i}] + [\mathbf{L_f}]\frac{d}{dt}[\mathbf{i}] + [\mathbf{v_f}]$$

The formula for dq0 transformation is given by

$$[x_{qd0}] = [P][x_{abc}]$$

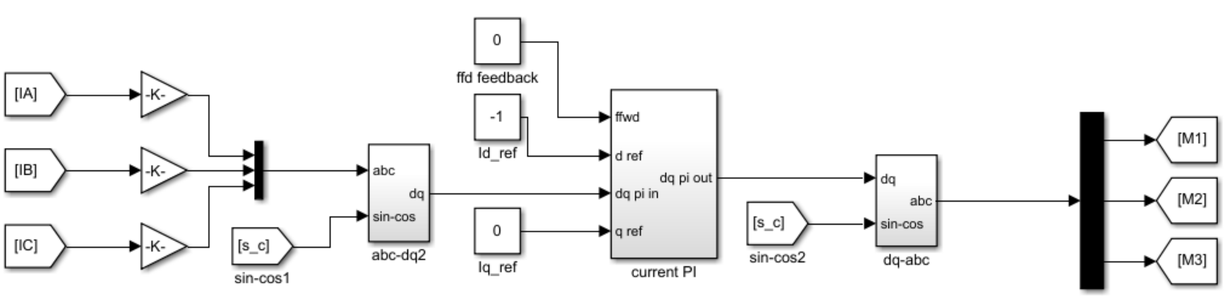


Figure 17 :- simulink block for PWM generation

The transformation matrix P is given by.

$$[P] = \sqrt{\frac{2}{3}}\begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin(\theta) & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}$$

On both sides multiply the transformation matrix

$$[P][v_c] = [P][R_f][i] + [P]\frac{d}{dt}\{[L_f][i]\} + [P][v_f]$$

$$[P][v_c] = [P][R_f][P]^{-1}[P][i] + [P]\frac{d}{dt}\{[L_f][P]^{-1}[P][i]\} + [P][v_f]$$

$$[v_{cqd0}] = [R_f][i_{dq0}] + [P]\frac{d}{dt}\{[L_f][P]^{-1}[i_{dq0}]\} + [v_{fdq0}]$$

$$[v_{cqd0}] = [R_f][i_{dq0}] + [P][L_f]\frac{d}{dt}\{[P]^{-1}[i_{dq0}]\} + [v_{fdq0}]$$

On the derivative of both terms apply the product rule

$$[v_{cqd0}] = [R_f][i_{dq0}] + [P]\frac{d}{dt}\{[P]^{-1}\}[L_f][i_{dq0}] + [P][L_f][P]^{-1}\frac{d}{dt}\{[i_{dq0}]\} + [v_{fdq0}]$$

$$[v_{cqd0}] = [R_f][i_{dq0}] + [\omega][L_f][i_{dq0}] + [L_f]\frac{d}{dt}\{[i_{dq0}]\} + [v_{fdq0}]$$

Where

$$[\mathbf{P}][\mathbf{L}_f][\mathbf{P}]^{-1} = [\mathbf{L}_f]$$

$$[\omega] = [\mathbf{P}]\frac{d}{dt}\{[\mathbf{P}]^{-1}\} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & -\frac{d\Psi}{dt} \\ 0 & \frac{d\Psi}{dt} & 0 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & -\omega_\Psi \\ 0 & \omega_\Psi & 0 \end{bmatrix}$$

$$\begin{bmatrix} v_{c0} \\ v_{cd} \\ v_{cq} \end{bmatrix} = \begin{bmatrix} R_f & 0 & 0 \\ 0 & R_f & 0 \\ 0 & 0 & R_f \end{bmatrix} \begin{bmatrix} i_0 \\ i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & -\omega_\psi \\ 0 & \omega_\psi & 0 \end{bmatrix} \begin{bmatrix} L_f & 0 & 0 \\ 0 & L_f & 0 \\ 0 & 0 & L_f \end{bmatrix} \begin{bmatrix} i_0 \\ i_d \\ i_q \end{bmatrix} + \begin{bmatrix} L_f & 0 & 0 \\ 0 & L_f & 0 \\ 0 & 0 & L_f \end{bmatrix} \frac{d}{dt} \left\{ \begin{bmatrix} i_0 \\ i_d \\ i_q \end{bmatrix} \right\} + \begin{bmatrix} v_{f0} \\ v_{fd} \\ v_{fq} \end{bmatrix}$$

And

$$\begin{bmatrix} v_{f0} \\ v_{fd} \\ v_{fq} \end{bmatrix} = \begin{bmatrix} R_g & 0 & 0 \\ 0 & R_g & -\omega_\psi L_g \\ 0 & \omega_\psi L_g & R_g \end{bmatrix} \begin{bmatrix} i_0 \\ i_d \\ i_q \end{bmatrix} + \begin{bmatrix} L_g & 0 & 0 \\ 0 & L_g & 0 \\ 0 & 0 & L_g \end{bmatrix} \frac{d}{dt} \left\{ \begin{bmatrix} i_0 \\ i_d \\ i_q \end{bmatrix} \right\} + \begin{bmatrix} v_{g0} \\ v_{gd} \\ v_{gq} \end{bmatrix} \qquad (3.3.1)$$

Voltage equations for zero components are

$$v_{c0} = R_f i_0 + L_f \frac{di_0}{dt} + v_{f0}$$

$$v_{f0} = R_g i_0 + L_g \frac{di_0}{dt} + v_{g0}$$

But

$$i_0 = 0 \Rightarrow v_{c0} = v_{f0} = v_{g0}$$

From the transformation equation

$$v_{c0} = \frac{v_{ca} + v_{cb} + v_{cc}}{\sqrt{3}} = 0$$

So the equation 3.3.1 can be simplified as

$$\begin{bmatrix} v_{cd} \\ v_{cq} \end{bmatrix} = \begin{bmatrix} R_f & -\omega_\psi L_f \\ \omega_\psi L_f & R_f \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} L_f & 0 \\ 0 & L_f \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} v_{fd} \\ v_{fq} \end{bmatrix}$$

The similar equations can be derived for the q and d components of Vf are.

$$\Psi = \theta_e = \arctan\left(\frac{v_{g\beta}}{v_{g\alpha}}\right) \Rightarrow \omega_\Psi = \frac{d\Psi}{dt} = \frac{d\theta_e}{dt} = \omega_g$$

$$\Psi = \omega_g t + \Psi_0 \quad \Rightarrow \quad \omega_\Psi = \frac{d\Psi}{dt} = \frac{d\{\omega_g t + \Psi_0\}}{dt} = \omega_g$$

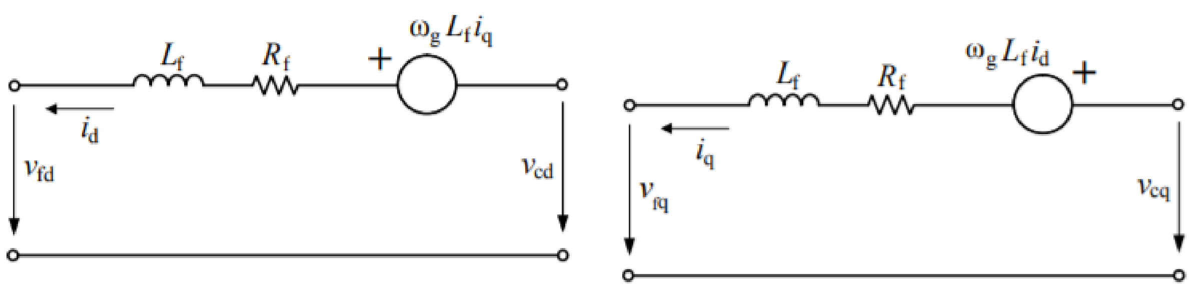
Where $\omega_g = \omega_{voltage} = 2\pi f$

The final set of equations are

$$v_{cd} = R_f i_d + L_f \frac{di_d}{dt} - \omega_g L_f i_q + v_{fd}$$

$$v_{cq} = R_f i_q + L_f \frac{di_q}{dt} + \omega_g L_f i_d + v_{fq}$$

By the following circuits the above set of equations can be represented



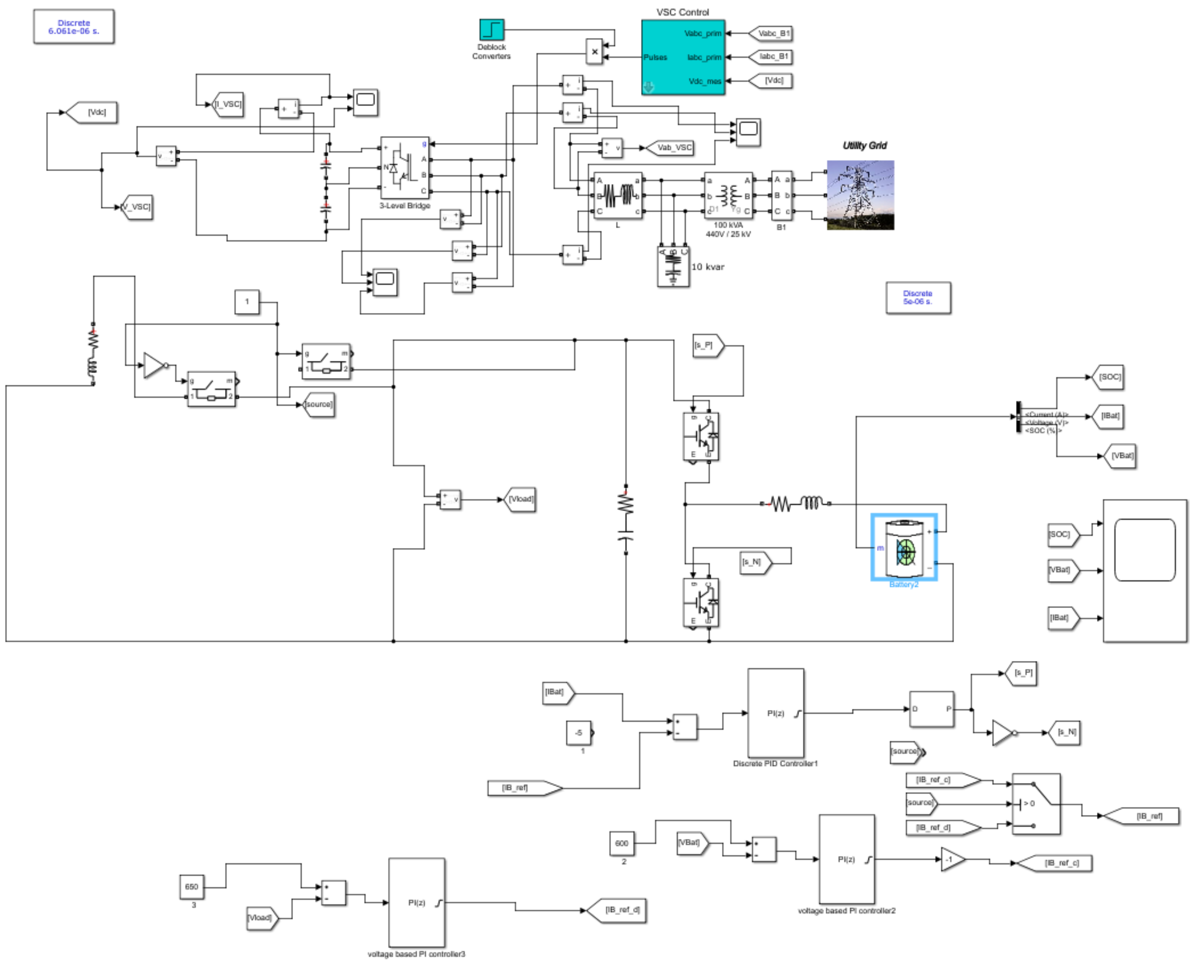


Figure 18 :- complete diagram of VSC in grid connected mode

This circuit shows the three-phase grid connected voltage source converter with BESSS. Here we have used the SPWM technique for the gate signal of IGBT. We have generated the SPWM signal by comparing sinusoidal wave form triangular waveform. The six SPWM signals are generated for 6 IGBTs. Two IGBTs are connected in the same leg of inverter and when cannot provide high signal to both IGBTs at a time.

The sum of DC component and fundamental component using Fourier series is the switching function of switches.

3.3.4 Instantaneous power expression

The expression for apparent power is shown below

S=VI

Where $\underline{v} = v_d + jv_q \quad ; \quad \underline{i} = i_d + ji_q$

in unbalanced condition the voltage and current of synchronous frame of reference can be calculated by following equation

$$\underline{v} = e^{j(\omega t + \theta_0)}\left(v_d^+ + jv_q^+\right) + e^{-j(\omega t + \theta_0)}\left(v_d^- + jv_q^-\right)$$

$$\underline{i} = e^{j(\omega t + \theta_0)}\left(i_d^+ + ji_q^+\right) + e^{-j(\omega t + \theta_0)}\left(i_d^- + ji_q^-\right)$$

From the above two equation the apparent power can be calculated as

$$\underline{s} = v_d^+ i_d^+ + v_q^+ i_q^+ + v_d^- i_d^- + v_q^- i_q^- + e^{j(2\omega t + 2\theta_0)}\left(v_d^+ i_d^- + v_q^+ i_q^-\right) + e^{-j(2\omega t + 2\theta_0)}\left(v_d^- i_d^+ + v_q^- i_q^+\right)$$

$$+ j\left[-v_d^+ i_q^+ + v_q^+ i_d^+ - v_d^- i_q^- + v_q^- i_d^- + e^{j(2\omega t + 2\theta_0)}\left(-v_d^+ i_q^- + v_q^+ i_d^-\right) + e^{-j(2\omega t + 2\theta_0)}\left(-v_d^- i_q^+ + v_q^- i_d^+\right)\right]$$

$$e^{\pm j\alpha} = \cos(\alpha) \pm j\sin(\alpha)$$

The apparent power components in terms of active and reactive power is as follows

$$\underline{s} = p + jq$$
$$= \begin{bmatrix} v_d^+ i_d^+ + v_q^+ i_q^+ + v_d^- i_d^- + v_q^- i_q^- \\ +\cos(2\omega t + 2\theta_0)\left(v_d^+ i_d^- + v_q^+ i_q^- + v_d^- i_d^+ + v_q^- i_q^+\right) \\ +\sin(2\omega t + 2\theta_0)\left(v_d^+ i_q^- - v_q^+ i_d^- - v_d^- i_q^+ + v_q^- i_d^+\right) \end{bmatrix} + j\begin{bmatrix} -v_d^+ i_q^+ + v_q^+ i_d^+ - v_d^- i_q^- + v_q^- i_d^- \\ +\cos(2\omega t + 2\theta_0)\left(-v_d^+ i_q^- + v_q^+ i_d^- - v_d^- i_q^+ + v_q^- i_d^+\right) \\ +\sin(2\omega t + 2\theta_0)\left(v_d^+ i_d^- + v_q^+ i_q^- - v_d^- i_d^+ - v_q^- i_q^+\right) \end{bmatrix}$$

Where

$$p = P + P_{cos}\cos(2\omega t + 2\theta_0) + P_{sin}\sin(2\omega t + 2\theta_0)$$

$$q = Q + Q_{cos}\cos(2\omega t + 2\theta_0) + Q_{sin}\sin(2\omega t + 2\theta_0)$$

This is one of the main objective of voltage source converter is to produce constant dc voltage at the output terminal for charging the battery.

The expression for continuous modulating signals switching function can be expressed as

$$S_{ap} = \frac{1}{2}[1 + M_{ap}]$$

$$S_{bp} = \frac{1}{2}[1 + M_{bp}]$$

$$S_{cp} = \frac{1}{2}[1 + M_{cp}]$$

Sap represent the IGBT S1, Sbp represent IGBT S2, Scp represent the IGBT S3.

Map, Mbp and Mcp represents the modulating signals.

$$M_{ap} = \frac{v_{an}}{V_d / 2} + \frac{v_{no}}{V_d / 2}$$

The above equation represents the modulating signals of switching device S1.

$$M_{bp} = \frac{v_{bn}}{V_d / 2} + \frac{v_{no}}{V_d / 2}$$

The above equation represents the modulating signals of switching device S2.

$$M_{cp} = \frac{v_{cn}}{V_d / 2} + \frac{v_{no}}{V_d / 2}.$$

The above equation represents the modulating signals of switching device S3.

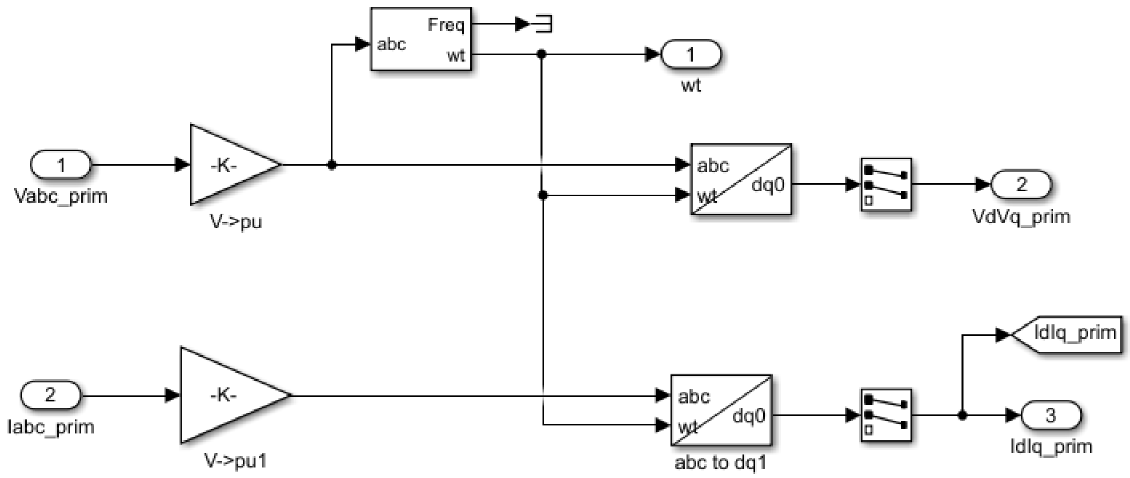


Figure 19 :- detail of control system for VSC

Figure 11 shows the control system of VSC using PLL. This controller with help to maintain the constant DC voltage at the output of converter for charging the battery. We have used dq transformation which is used to transform abc to dq.

4 CURRENT SOURCE CONVERTER

4.1 Current Source converter: -

The CSC has built in short circuit protection and also has the constant current. The advantage of this converter is that it is rugged and can reduce the harmonics. A shunt compensator is required for current source inve

filter out the harmonics.

It Is shunt connected compensator inject three phase sinusoidal balanced currents with adjustable magnitude and lagging or leading the corresponding line voltage by 90 degree.

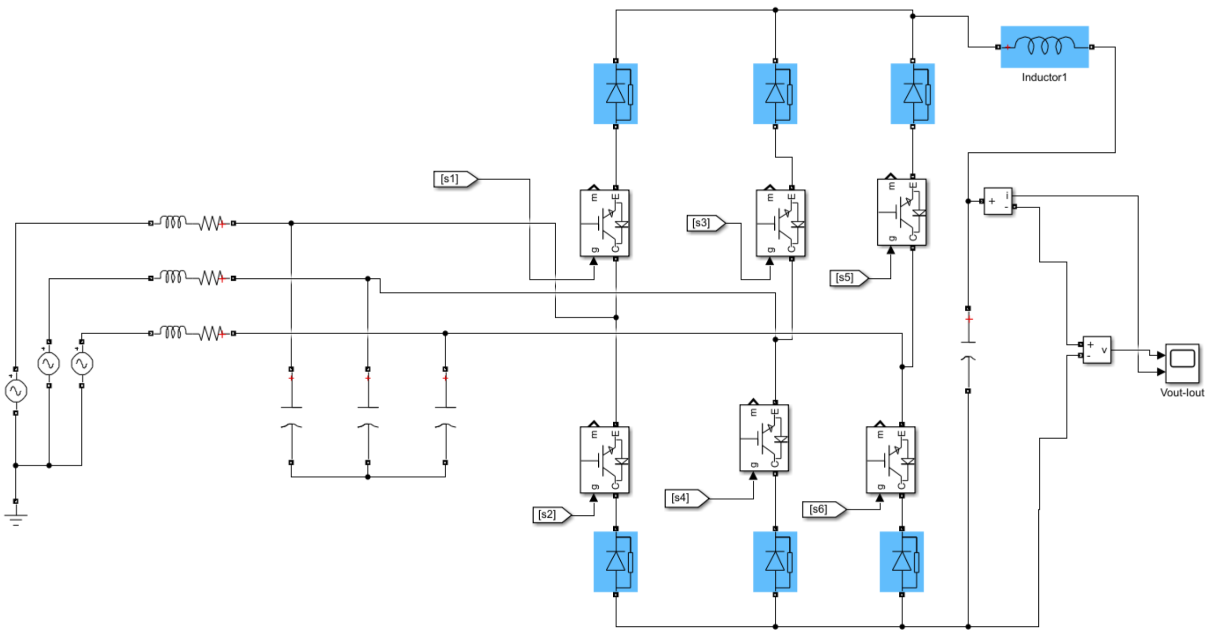
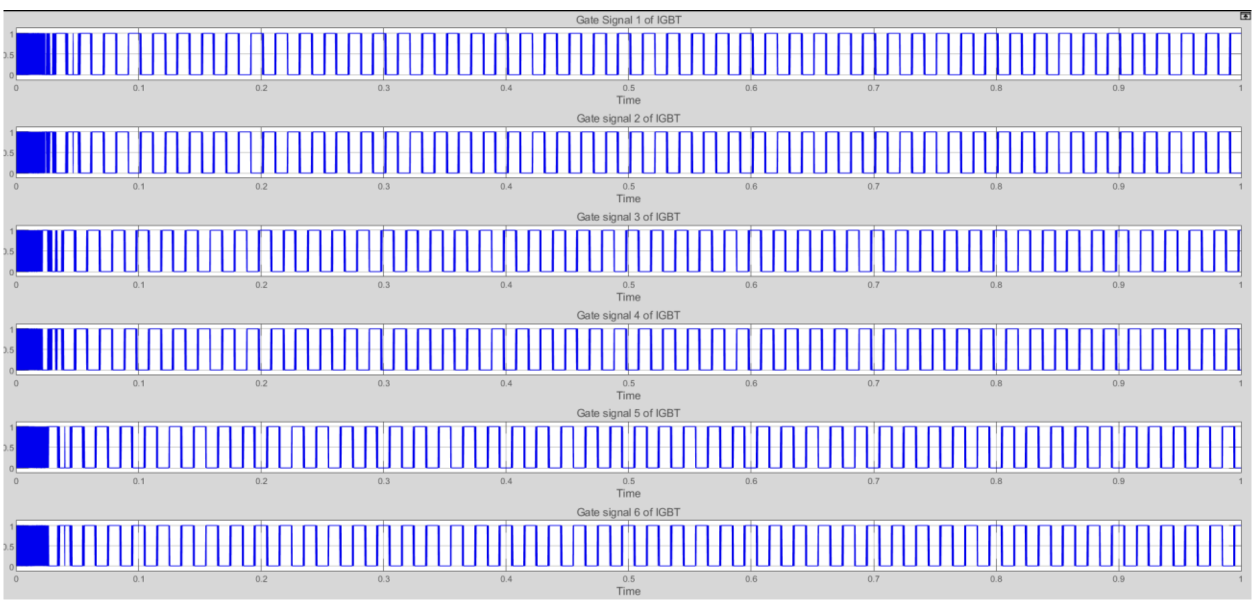


Figure 20 :- basic schematic of CSC

The basic configuration of CSC based circuit is shown above in which we have used six fully controllable switches s1, s2, s3, s4, s5 and s6. The PWM signal for 6 IGBT is shown below



As an energy storage element, a DC link reactor is having been placed in DC link. This reactor is composed of series connection of inductance and resistance. DC link current becomes constant due high time constant of dc link circuit.

The line current can be express using following equations

$$\left.\begin{aligned} i_R(t) &= (m_{S1} - m_{S2})I_{dc} \\ i_S(t) &= (m_{S3} - m_{S4})I_{dc} \\ i_T(t) &= (m_{S5} - m_{S6})I_{dc} \end{aligned}\right\}$$

The converter line current Fourier series expansion is given by

$$\left.\begin{aligned} i_R &= I_1 \sin(\omega t + \theta) + \sum_{h=2}^{\infty} I_h \sin(\omega_h t - \lambda_h) \\ i_S &= I_1 \sin(\omega t + \theta - 2\pi/3) + \sum_{h=2}^{\infty} I_h \sin(\omega_h t - \xi_h) \\ i_T &= I_1 \sin(\omega t + \theta - 4\pi/3) + \sum_{h=2}^{\infty} I_h \sin(\omega_h t - \psi_h) \end{aligned}\right\}$$

The modulation index is defined as

$$M = \frac{I_1}{I_{dc}}$$

A dominant harmonic current component at fundamental frequency is produced by CSC. In modulation index this harmonic component can be neglected. The fundamental component at the input of converter can be expressed in terms of modulation index M, dc link current Idc as by using above equations

$$\left.\begin{aligned} i_{R1} &= MI_{dc} \sin(\omega t + \theta) \\ i_{S1} &= MI_{dc} \sin(\omega t + \theta - 2\pi/3) \\ i_{T1} &= MI_{dc} \sin(\omega t + \theta - 4\pi/3) \end{aligned}\right\}$$

The steady state active power at the input is written as

$$P = \frac{3}{2} V M I_{dc} \sin\theta$$

Since we assume that the power converter switches are lossless so the power loss in dc link reactor can be express as

$$P = V_{dc} I_{dc} = R_{dc} I_{dc}^2$$

$$V_{dc} = \frac{3}{2} V M \sin\theta$$

$$I_{dc} = \frac{3}{2} \frac{V M \sin\theta}{R_{dc}}$$

By substituting the value, the power equation becomes

$$P = \frac{9}{4} \frac{V^2 M^2}{R_{dc}} \sin^2\theta$$

4.1.1 Control methods for current source inverter

There are two types of control methods available, one is conventional controlled method which is based on PI controller and other is state feedback controller.

4.1.1.1 Conventional control method

The conventional control method is based on PI controller, in CSC converter is mainly based on two variables, modulation index and phase shift angle.

4.1.1.2 Modern control method

In this control method we require the state-space representation of CSC.we can obtain state space representation using d-q frame. Since it has a smaller number of state variables which become steady the dc quantities. This would make the analysis and design of control system relatively easy.

$$\frac{d}{dt}\begin{bmatrix} i_{sd} \\ i_{sq} \\ v_{cd} \\ v_{cq} \\ i_{dc} \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & \omega & -\frac{1}{L} & 0 & 0 \\ -\omega & -\frac{R}{L} & 0 & -\frac{1}{L} & 0 \\ \frac{1}{3C} & 0 & 0 & \omega & -\sqrt{\frac{3}{2}}\frac{M}{3C}\sin\theta \\ 0 & \frac{1}{3C} & -\omega & 0 & \sqrt{\frac{3}{2}}\frac{M}{3C}\cos\theta \\ 0 & 0 & \sqrt{\frac{3}{2}}\frac{M}{L_{dc}}\sin\theta & -\sqrt{\frac{3}{2}}\frac{M}{L_{dc}}\cos\theta & -\frac{R_{dc}}{L_{dc}} \end{bmatrix}\begin{bmatrix} i_{sd} \\ i_{sq} \\ v_{cd} \\ v_{cq} \\ i_{dc} \end{bmatrix} + \begin{bmatrix} \frac{1}{L} & 0 \\ 0 & \frac{1}{L} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} v_d \\ v_q \end{bmatrix}$$

By rearranging the above equation, the control input variables Md and Mq are represented as

$$\frac{d}{dt}x = \begin{bmatrix} -\frac{R}{L} & \omega & -\frac{1}{L} & 0 \\ -\omega & -\frac{R}{L} & 0 & -\frac{1}{L} \\ \frac{1}{3C} & 0 & 0 & \omega \\ 0 & \frac{1}{3C} & -\omega & 0 \end{bmatrix} x + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ \frac{1}{3C} & 0 \\ 0 & \frac{1}{3C} \end{bmatrix} u + \begin{bmatrix} \frac{1}{L} & 0 \\ 0 & \frac{1}{L} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} w$$

$$y = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} x$$

Where

$$x = \begin{bmatrix} i_{sd} \\ i_{sq} \\ v_{cd} \\ v_{cq} \end{bmatrix}, \quad u = \begin{bmatrix} M_d\, i_{dc} \\ M_q\, i_{dc} \end{bmatrix}, \quad w = \begin{bmatrix} v_d \\ v_q \end{bmatrix}$$

$$\begin{bmatrix} M_d \\ M_q \end{bmatrix} = \begin{bmatrix} \sqrt{\frac{3}{2}} M \sin\theta \\ -\sqrt{\frac{3}{2}} M \cos\theta \end{bmatrix}$$

In first equation the state space equation contains the multiplication control variable input and state space variables. Between d and q component of the system there is cross coupling present, where dc link current depends on both input variables.

4.1.2 DC link reactor

Magnetic storage element of current source converter is dc link reactor. We would try design a dc link reactor very small for fast transient response.

$$\sqrt{\frac{3}{2}}M\left(v_{cd}\sin\theta + v_{cq}\cos\theta\right) = L_{dc}\frac{di_{dc}}{dt} + R_{dc}\,i_{dc}$$

The distortion in converter line current waveforms at the input of CSC, better approximation of dc link current to level current improves the RDD of input current waveform. The switching frequency and u=inductance should increase to minimize the ripple in dc-link current.

$$\Delta I_{dc} \propto \frac{V}{f_s\, L_{dc}}$$

One we set the system frequency and voltage we can calculate the value of dc link reactor.

4.2 GRID connected Current source converter with Battery energy storage system: -

We have designed grid connected current source converter which has the functionality of bi-directional power supply. When the grid is available CSC will charge the battery and when the grid is not available the supply the energy to grid.

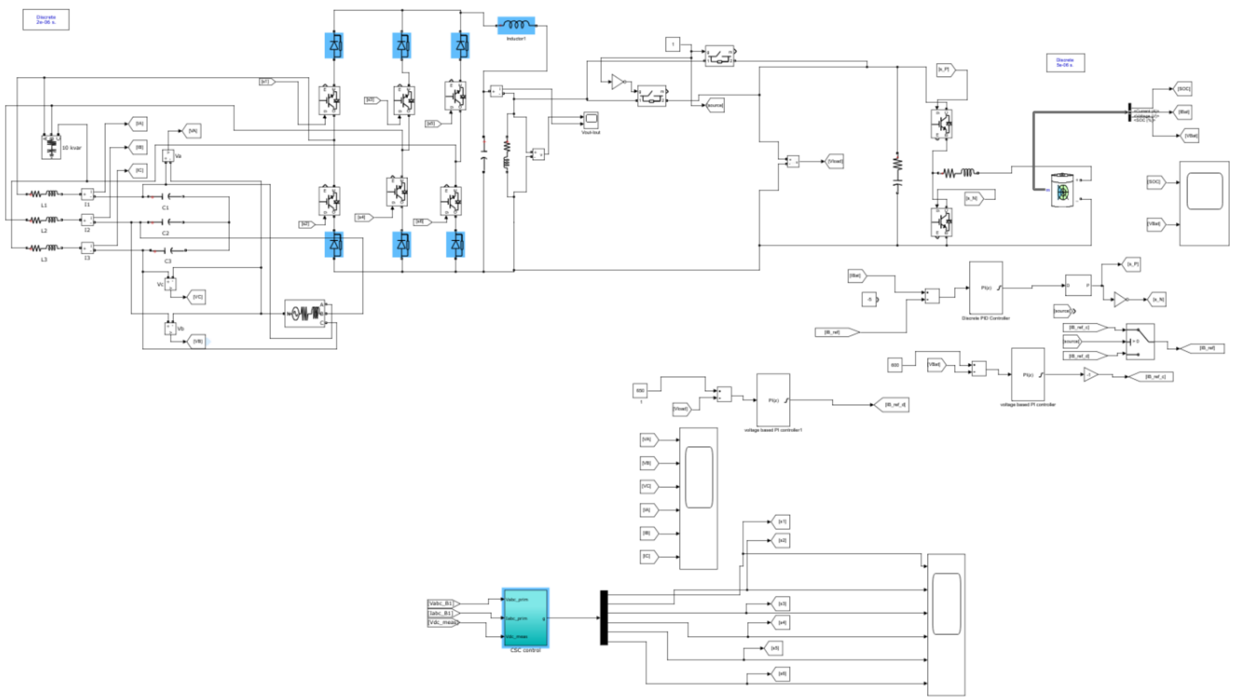


Figure 21:- complete schematic of grid connected current source converter with BESSS

Figure 11 shows the complete schematic diagram of grid connected current source converter with BESSS. In this circuit we have used PLL for grid synchronization because CSC converter work in bi directional model, it would charge the battery and when required it would provide the power to the grid from battery.

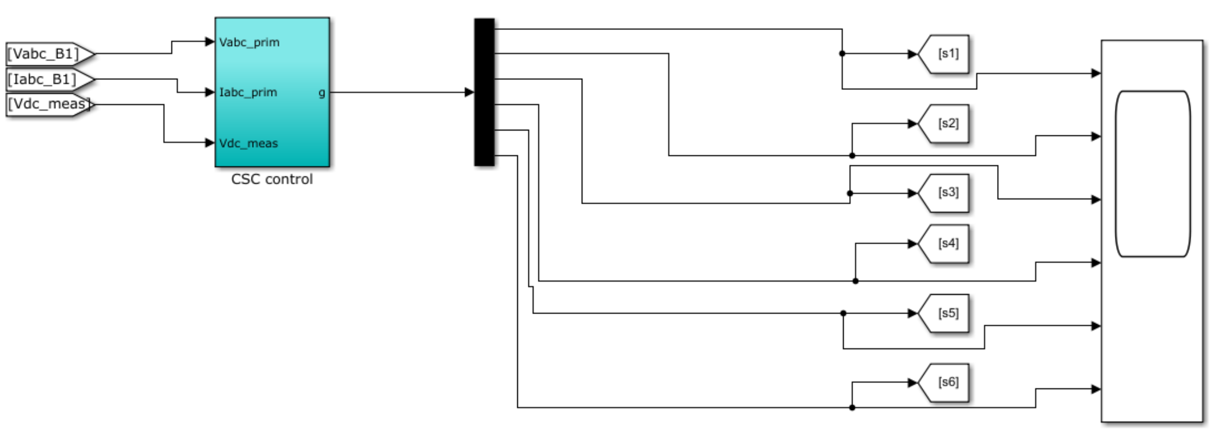


Figure 22 :- Control system for current source converter

Figure 12 shows the control system of CSC in which we have generated 6 PWM signal for IGBTs to drive. We provide these six signals at the gate of IGBTs. The waveforms of signals are shown below.

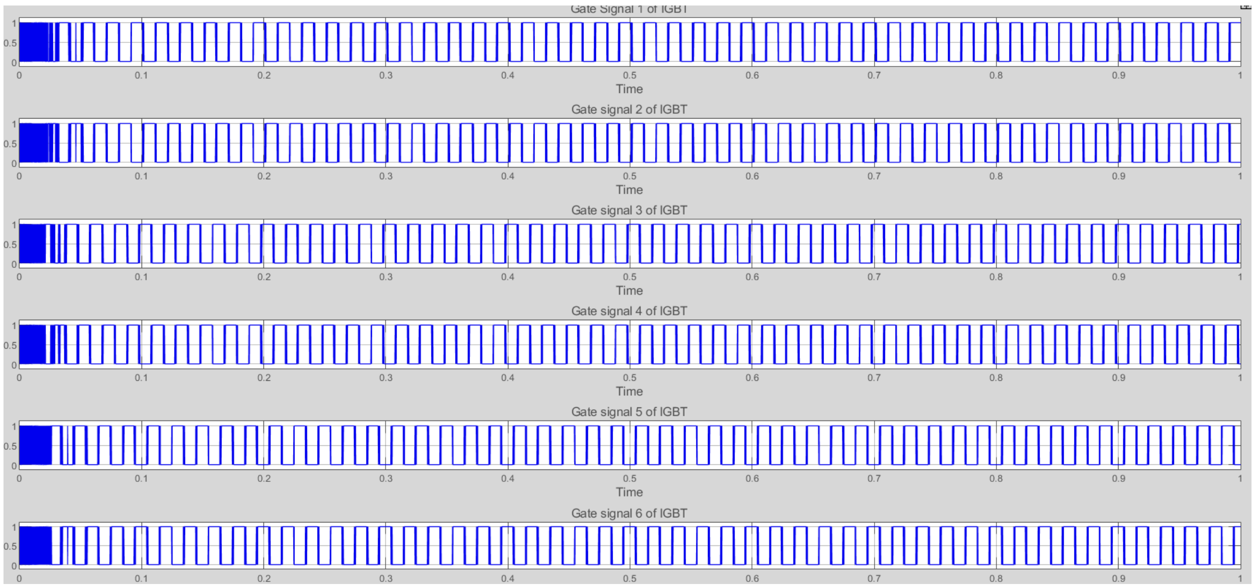


Figure 23 :- waveform of gate signal of IGBT

4.2.1 Reference current calculation

In case of unbalanced load, the power oscillations appear at the output waveform different sequence interaction of voltage and current. This create the requirement of injected current calculation strategies by the power converter into grid for the control of instantaneous active and reactive power.

4.2.2 Battery charging

In CSC the battery charging is low due to constant current of converter. We have set the initial charge of battery at 50%, so the battery start charging from 50%. We have used one switch which will decide mode of charging and discharging. When charging mode, the idea switch is connected to 1, on discharging mode the switch is connected to 0.

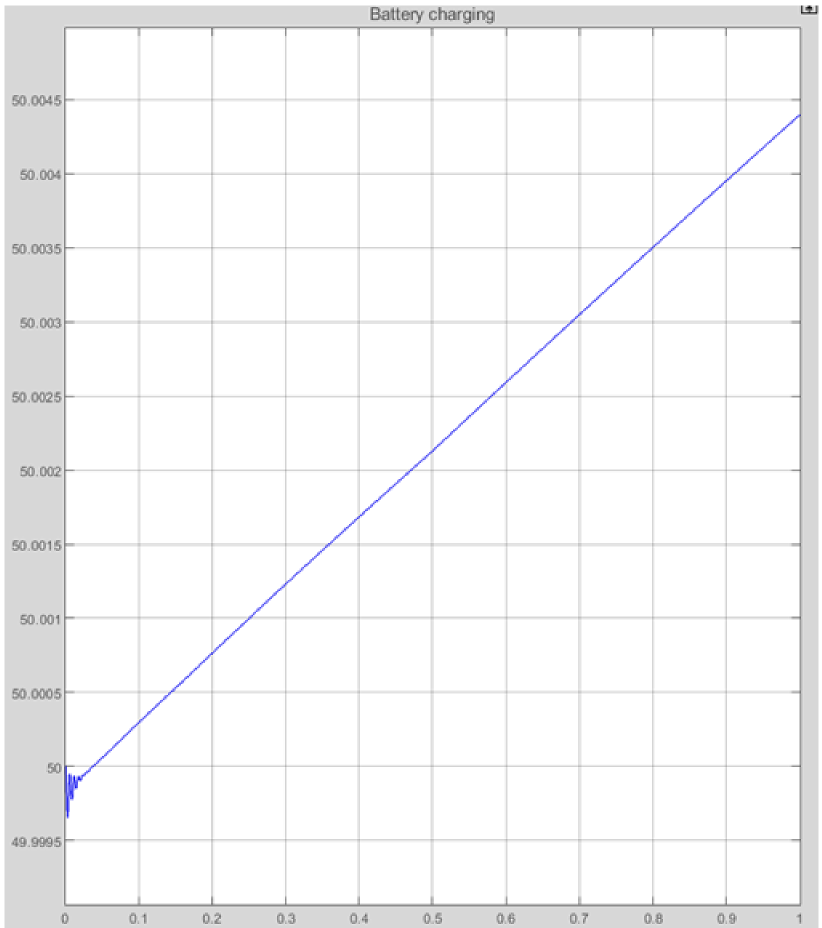


Figure 24 :- Waveform of Battery charging

For battery charging we required DC voltage so we convert the AC voltage into DC voltage for this purpose we have used grid connected current source converter. This converter start charging the battery which is connected with the bi directional converter. This bi direction converter work for both charging and discharging of battery.

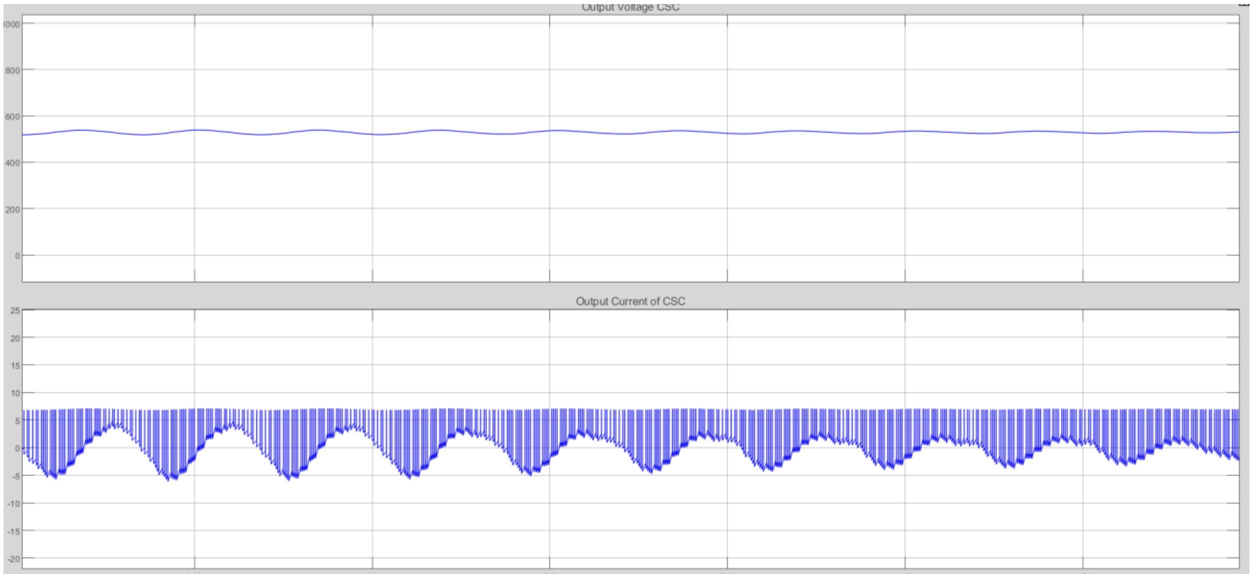


Figure 25 :- CSC voltage and current waveforms

Figure 15 shows the DC output voltage and current of CSC in which we have seen that the voltage has a very small ripples and current waveform also has small ripples. The waveform of voltage is pure DC for battery charging and the current waveform has ripple factor.

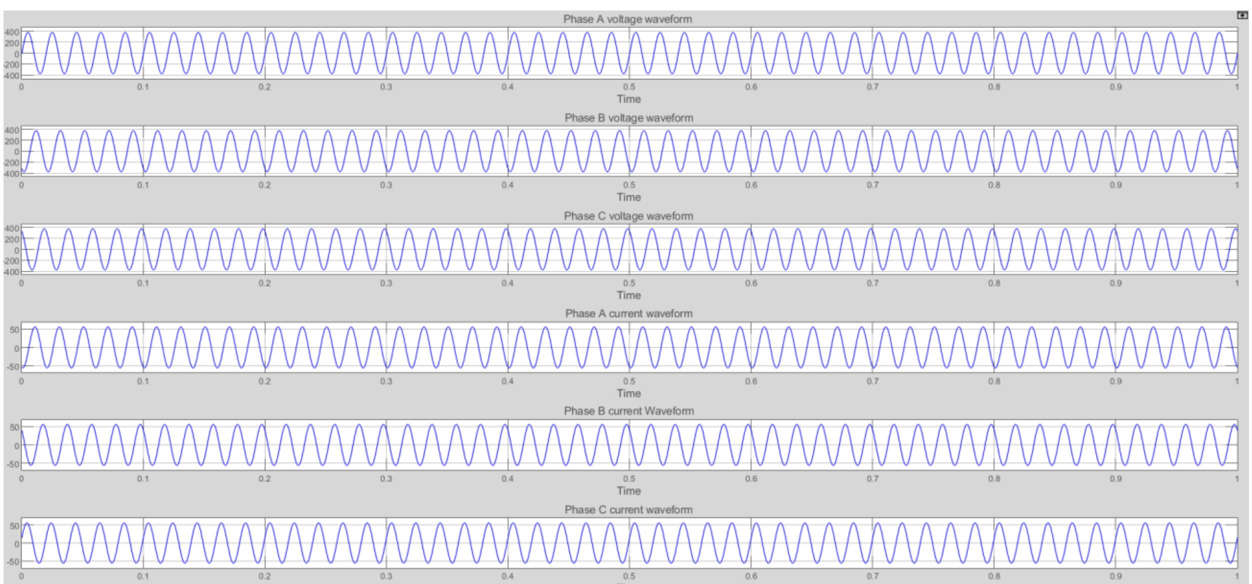


Figure 26 :- Output voltage and current waveform of CSC

Figure 16 shows the waveform of the three-phase output voltage and current This is the output grid connected mode. The CSC converter which we have designed has the ability to do a bi directional operation. This converter charges the battery and when the grid required the battery will act as a source.

5 RESULTS AND DISCUSSION

We have simulated the VSC and CSC in MATLAB. The simulation results of VSC is comparatively good than VSC. In both cases we have connected the battery with converter using bi-directional charging and discharging in grid connected mode.

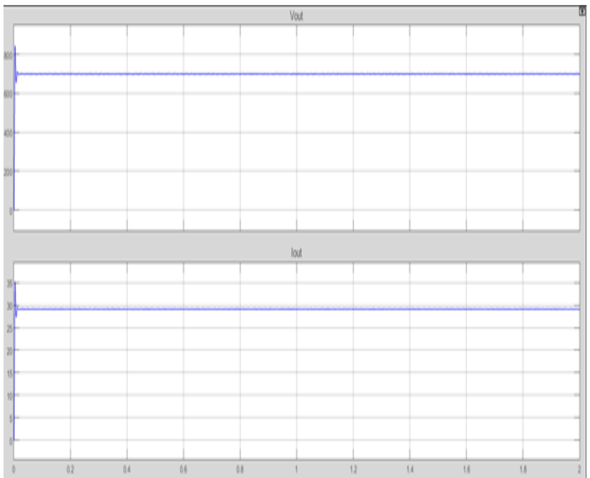


Figure 27 :- Results of CSC for DC output

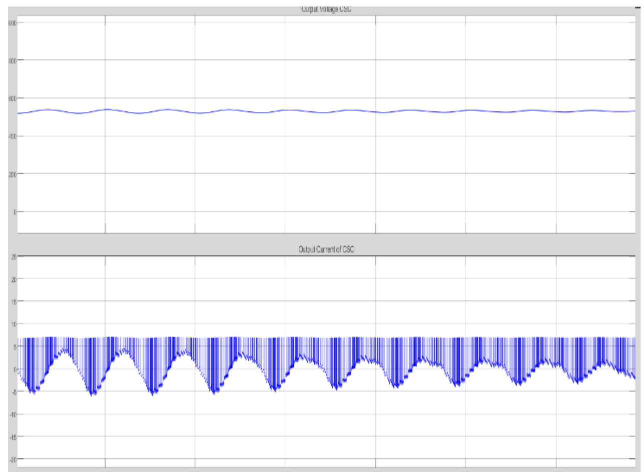


Figure 28 :- results of VSC for DC output

Figure 19 and 20 shows the comparative results of VSC and CSC in which we have seen that the VSC has a very less ripple at the DC output waveform of voltage and current and the CSC output voltage is comparatively good but its current waveform has more ripples which will compromise the efficiency of converter. The current result of CSC is due to the problem in control system of converter which is not properly designed.

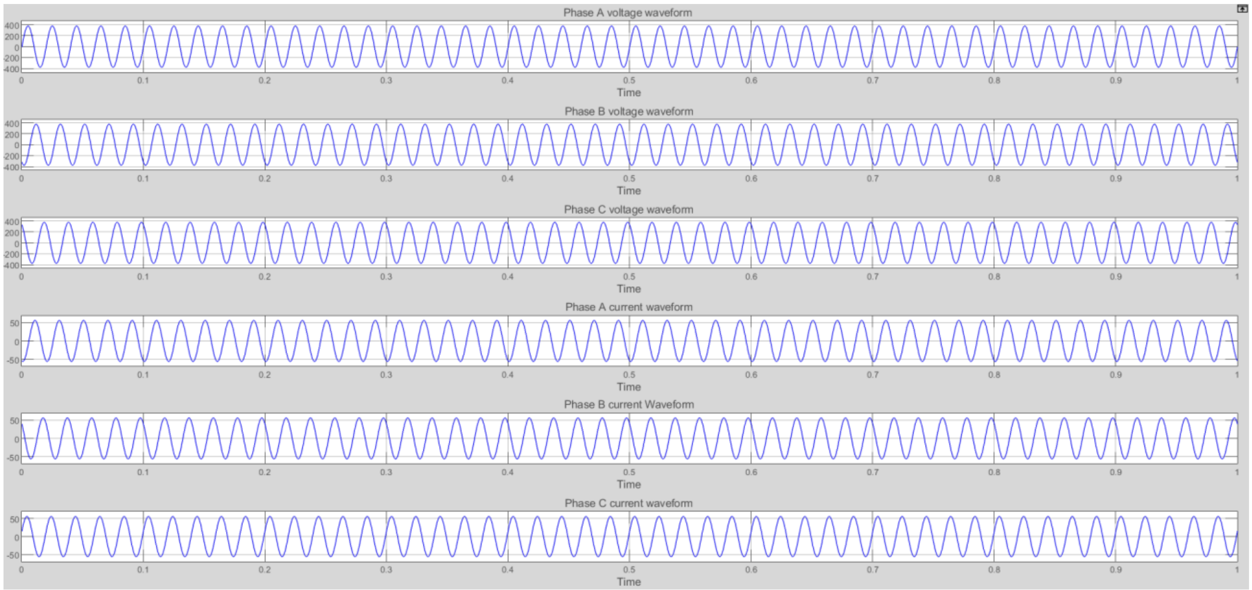


Figure 29 : output wave form of CSC

Figure 21 shows the waveform of CSC in which we have seen that CSC does not require external filter for harmonic elimination. Its output has a very low harmonics which increase the efficiency and converter.

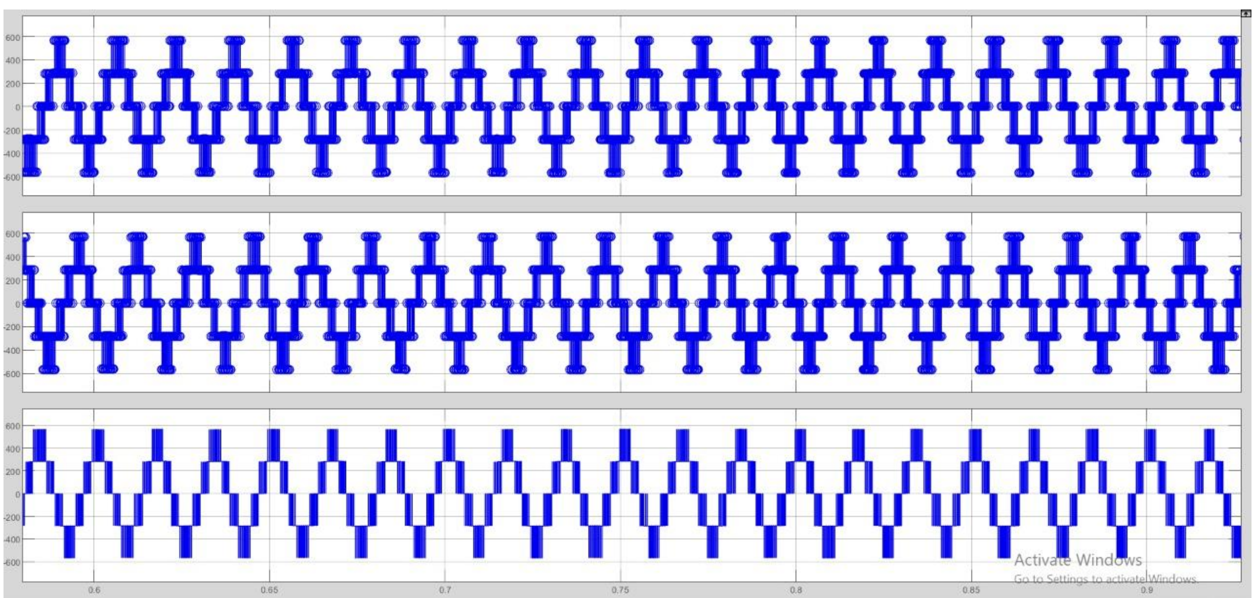


Figure 30 :- output waveform of VSC without filter

Figure 22 shows the output wave form VSC in which we have seen that VSC require external filter to remove the harmonics. This is the disadvantage of VSC.

6 CONCLUSION

We have designed and simulated the VSC and CSC in which we have seen that both the converters have some advantages and disadvantages, like the CSC have built in short circuit protection and does not require external filter to eliminate the total harmonic distortion. CSC also have constant current which is good for battery charging. In grid connected mode the control design of CSC is very difficult and its very difficult to generate accurate output using reference current comparatively VSC. In VSC we must require the external filter to eliminate the harmonics in the output of converter. Other wise VSC does not work efficiently in grid connected mode. In grid connected mode we must introduce the grid filter at the output. So CSC has better performance than VSC, VSC is comparatively easy but require some extra components.

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