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Modelling and analysis of long cables on the generator side of generator transformers

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Preface

This thesis presents model results that aim to clarify the potential issues with transients and resonance problems when longer cables are placed on the generator side of a unit-transformer. Through my research, I have gained knowledge of hydropower systems, their individual components, and how they work together in a power system.

Throughout my undergraduate studies in renewable energy, I have been fascinated by the field of electrical engineering and its practical applications to real-world needs. My interest in power systems grew stronger during this time, which led me to pursue a master's degree in electrical engineering - the heart of renewable energy. A collaboration between UIT and Statkraft gave me the opportunity to work on an exciting and challenging project under the guidance of Associate Professor Trond Østrem and Ronny Goin at Statkraft.

The project has been a collaboration between the University of Tromsø and Statkraft, where the latter is a leading provider of electrical energy in Norway. The collaboration aimed to develop and test a computer model for specific power systems by testing certain configurations. I have conducted research and gathered the theoretical framework needed to understand the thesis. This included the design and implementation of a simulation model.

Working on this project has been a rewarding and enriching experience for me. I have learned a lot from my supervisor, who has provided me with guidance and feedback every week. I have also had a number of meetings with Ronny Goin, who has provided me with the thesis outline, theory, values for real-life power systems, and time whenever needed. I am grateful to them both for their help and encouragement.

Writing this thesis was not an easy task. It required a lot of hard work, dedication, and perseverance. I faced many challenges and difficulties along the way, such as technical issues, time constraints, and unexpected results. However, I also enjoyed the process of exploring new ideas, solving problems, and discovering new knowledge. I am proud of what I have accomplished.

This thesis marks the end of my journey as a student. I have been very fortunate, having gotten the chance to study at both NTNU and UIT. It has been an unforgettable and rewarding experience for me. I would like to thank my family and friends for their love and support throughout this journey. They have always been there for me, cheering me up when I was down, celebrating with me when I succeeded, and inspiring me to pursue my dreams. Lastly I would like to thank Ingvill for believing in me and providing me with hand drawn illustrations throughout.

This thesis is dedicated to everyone I hold dear.

Trondheim, 22 mai 2023
Kjetil N. Jørgensen

Abstract

This thesis presents a study on the modeling and analysis of longer power cables on the generator side of a unit-transformer in a generic power system. The study focuses on the theoretical framework needed to understand the problem.

The theoretical sections include fundamental electrical truths and their effects on the main components of a power system. The remaining theory discusses transients and resonance problems in power system components.

The main objective of this study is to develop a model that can accurately predict the behavior of a power system when capacitive loads or distribution means are introduced. The model is developed using Matlab/Simulink and is validated using experimental data. The results show that the developed model can accurately predict the behavior of long cables on the generator side of generator transformers.

This study contributes to the understanding of the behavior of long cables on the generator side of generator transformers and provides a basis for further research in this area.

Sammendrag

Denne oppgaven presenterer en studie om modellering og analyse av lengre kraftkabler på generatorsiden av en enhetstransformator i et generisk kraftsystem. Studien fokuserer på det teoretiske rammeverket som er nødvendig for å forstå problemet.

De teoretiske delene inkluderer grunnleggende elektriske sannheter og deres effekter på hovedkomponentene i et kraftsystem. Den gjenværende teorien diskuterer transiente og resonansproblemer i komponenter i kraftsystemet.

Hovedmålet med denne studien er å utvikle en modell som nøyaktig kan forutsi oppførselen til et kraftsystem når kapasitive belastninger eller distribusjonsmidler blir introdusert. Modellen er utviklet ved hjelp av Matlab/Simulink og er validert ved hjelp av eksperimentelle data. Resultatene viser at den utviklede modellen nøyaktig kan forutsi oppførselen til lange kabler på generatorsiden av generatortransformatorer.

Denne studien bidrar til forståelsen av oppførselen til lange kabler på generatorsiden av generatortransformatorer og gir grunnlag for videre forskning på dette området.

Contents

1

Introduction

RESONANT and transient problems between cables and transformers have been a challenge for decades. This thesis will present theory relating to power system components and operations, more specifically, hydropower plants, which supply most of Norway's energy needs. This theory will then be applied to a generic hydropower system and, later, to varying cable length cases.

1.1 Thesis framework

This thesis is organized in chapters that cover different aspects of the research topic. The first chapter is this introduction, which provides the background, context, and motivation for the study.

The second chapter introduces theory relating to a particular power system usually found in Norway. Chapter three will build on this, but narrowing down into relating issues and studies this thesis aims to examine.

Chapter four presents the documentation and modelling tools used to examine a computer simulated power plant. The software used is Matlab and Simulink with the specialized power systems tab under the Simscape extension.

Chapter five will deduct results from chapter four and chapter six will conclude the thesis with discussion and final thoughts on the derived results.

1.2 Thesis goal

- Overview of power systems, specifically hydropower. Covering theory on generators, transformers, and cables, and how they are linked in a typical system.
- Discussion of transients and resonance problems in power system components.
- Generalising a system model with Simulink.
- Modeling and analysis of long cables on the generator side of unit transformer.
- A discussion of the results and final recommendations when considering the introduction of capacitive loads or distribution means on the generator side of a step-up transformer.

1.3 Introducing central phenomena

1.3.1 Transients

Electromagnetic transients are short-duration phenomena that occur in a power system due to the interaction of electric and magnetic fields. They can be caused by lightning strikes, switching operations, faults, or other disturbances. Electromagnetic transients can propagate as waves along transmission lines, cables, or bus sections, and can affect the voltage and current levels in the system [1].

1.3.2 Resonance

Resonant frequency is the frequency at which a system oscillates with the highest amplitude. It is also known as the natural frequency of the system. When a system is subjected to an external force or vibration that matches its resonant frequency, it can experience a large increase in its oscillation, which can result in damage or failure of the system. Resonant frequency can occur in various types of systems, such as mechanical, electrical, optical, or acoustic [2].

1.4 Problem statement

The problem statement and scope is derived from supervisor Ronny Goin's thesis outline.

Modelling and analysis of long cables on the generator side of generataor transformers

> Statkraft wants to evaluate the effects of long cables on the generator side of unit transformers. Statkraft also wants to get suggestions for actions that are needed or highly desirable for those installations where such solutions are required or preferred.

A typical Norwegian hydropower plant usually has one or more generators that are connected to the grid through their own unit transformer, also known as Generator Step-up Transformer. Often, there is also an auxiliary transformer for local power supply that is connected between the generator and the unit transformer. Usually, there is a circuit breaker between the generator and the transformer, and between the transformer and the grid. For power plants that are inside mountains, it can be several hundred meters to the surface switchgear. For larger power plants, there may be additional several tens of meters to common facilities in the power station.

In some situations, it is desirable to have an auxiliary supply from the generator side of the transformer to surface switchgear, for example. This may be because of the supply of important auxiliary facilities, or when a new power-intensive industry wants to connect at a lower voltage level.

Such long cables can create transients and possibly also cause resonance problems between transformer and cable. There is also uncertainty about how the generator and this high capacitance interact. IEEE C62.92.2 indicates that if the ground capacitance is much larger than the ground resistance, then high transients can happen in the case of ground faults.

1.5 Limitations

The scope of the work will include the aspects related to utilizing long cables on the generator side of the unit transformer. With theory, deriving of a simulation model, calculations and discussions for the general problem problem statement.

2

Theory

The following chapter will lay the theoretical foundation for understanding the thesis as a whole. Starting with the concept of a ‘power system’, before narrowing down to the type of power system in question and its main components. In addition, aspects of long cables, switching and some concepts related to the problem statement will be covered.

2.1 Power systems

Modern power systems vary in size and components. However, they inhabit the same basic characteristics. And the main motivation behind a power system is to distribute generated electrical energy to consumers safely [3] [4].

Prabha Kundur sums up the main characteristics of a power system as these four bullet-points in his 1994 book on power system stability and control:

- Modern power systems are three-phase AC systems comprised of generation and transmission installations
- Synchronous machines are used in power systems to generate electricity. Prime movers convert energy from sources such as fossil fuels, nuclear power, and hydroelectric power into mechanical energy. This mechanical energy is then converted into electrical energy by synchronous generators
- Power is transmitted over long distances to reach consumers who are spread out over a wide area. This requires a transmission system that includes subsystems operating at different voltages.
- Components; Generating unit, transformer, transmission and switching devices.

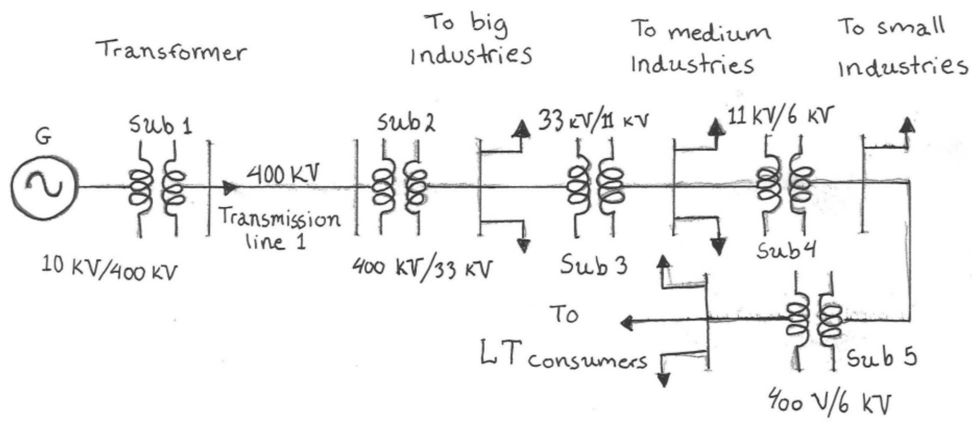


Figure 2.1: Illustration of single line power system. Figure Illustration from [5]

2.2 Hydropower station

Norway gets 89 percent of its normal annual energy production from hydroelectric power [6]. And per November 2022, the total installed capacity is 33 691 MW, by means of more than 1 761 hydropower plants [7].

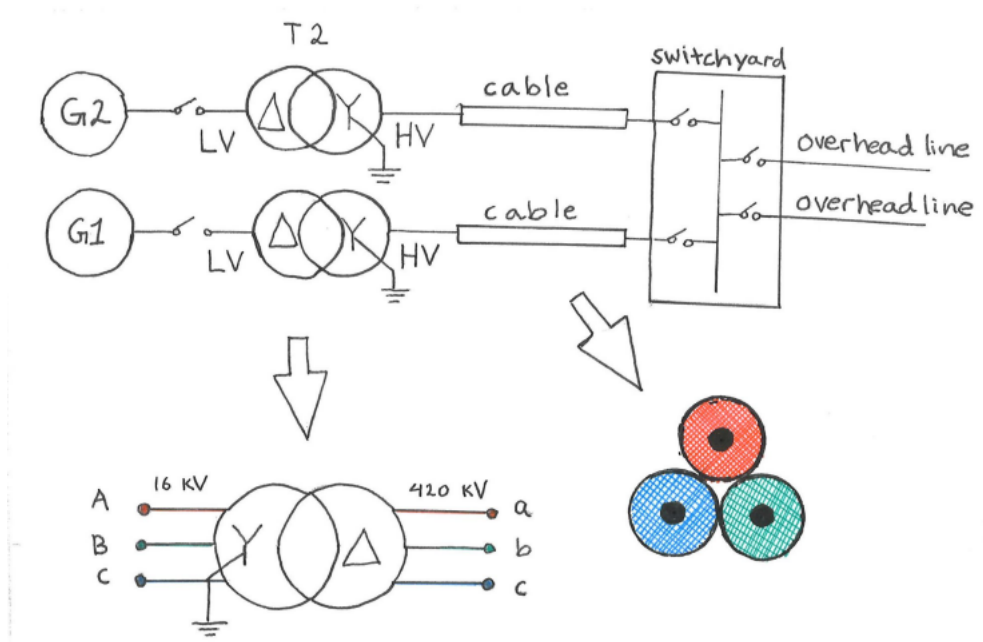


Figure 2.2: Generic label of typical hydro power station in Norway. Inspired by [8]

Figure 2.1 illustrates what a Norwegian hydropower station typically could look like. With one or more generating units, with each their own a step-up transformer. Further, they include main transformers, connected to the grid through a switchyard and long cables;

typically several hundred meters long. The switchyard is then connected to the grid via transmission lines [8].

This illustration accounts only for the main components, the remaining are neglected for simplicity's sake.

2.3 Fundamental truths

This section introduces the fundamental hardware of any electrical circuit. It presents the three main components and explains the basic workings of magnetic and electric fields [9].

2.3.1 Passive circuit elements

The three fundamental passive electrical components are resistors, capacitors, and inductors. These components do not generate electrical energy. Instead, resistors dissipate energy as heat, while capacitors and inductors temporarily store energy in electric and magnetic fields, respectively [9].

Resistor

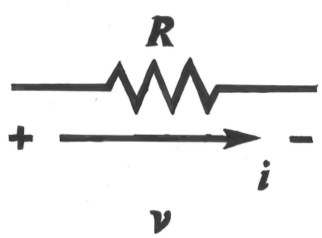


Figure 2.3: Resistor. Figure from Illustration from [10]

In an electric circuit, resistance measures an object's opposition to electric current. The resistance depends on the material the object is made of and can be determined using Ohm's law [1].

$$v = iR \tag{2.1}$$

Inductor

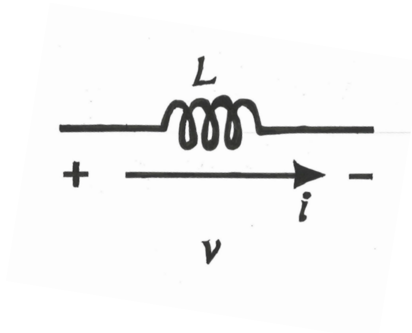


Figure 2.4: Inductor. Figure Illustration from [10]

In an electric circuit, inductance measures an object's resistance to changes in the electric current flowing through it. The current flow generates a magnetic field around the conductor, the strength of which varies with the current magnitude and changes accordingly. Inductance is governed by Faraday's law.

$$\begin{aligned} v_L =& iX_L \\ \text{Where: } X_L =& 2\pi f L \end{aligned} \tag{2.2}$$

Capacitor

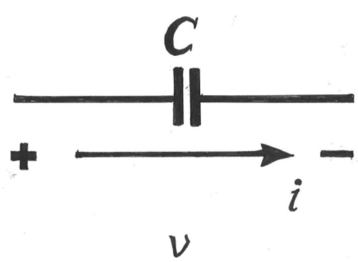


Figure 2.5: Capacitor. Figure Illustration from [10]

A capacitor store and release electric charge by using two conductive plates separated by an insulator via the help of an electric field. When a voltage is applied across the capacitor, one plate becomes positively charged and the other plate becomes negatively charged. The amount of charge stored depends on the voltage and the capacitance of the capacitor. When the voltage is removed, the capacitor retains the charge until it is discharged through a circuit.

$$\begin{aligned} v_C =& iX_C \\ \text{Where: } X_C =& \frac{1}{2\pi f C} \end{aligned} \tag{2.3}$$

2.3.2 Impedance, resistance and reactance

Resistance R is the measure of how a conductor opposes electrical current in a DC (Direct Current) circuit and is measured in ohms (Ω). This also applies to an AC (Alternating Current) circuit. In an AC circuit, inductors and capacitors exhibit a resistive force called reactance, denoted as inductive reactance (X_L) and capacitive reactance (X_C). The combination of resistance and reactance makes up the impedance of a circuit.

Impedance (Z) is the total opposition that a circuit presents to the flow of electric current when a voltage is applied in an AC circuit. It is a complex quantity composed of both resistance and reactance and is measured in ohms Ω [10].

$$Z = \sqrt{R^2 + (X_L^2 - X_C^2)} \tag{2.4}$$

2.3.3 Relations to frequencies

From equations 2.2 and 2.3, we can see that inductance and capacitance are frequency-dependent, meaning that they affect a circuit according to the table 2.1.

Frequency f:	0	**Low**	**High**	∞
L	Short circuit	low	High	∞
C	Open circuit	High	Low	0

Table 2.1: effect of frequency.

2.3.4 Magnetic fields and magnetic flux

A magnetic field can be thought of as a force field that exerts a magnetic force on moving electric charges, electric currents, and materials that are magnetized. It is represented by a vector field, which means it has both magnitude and direction. When a charge moves through a magnetic field, it experiences a force that is perpendicular to both its velocity and the magnetic field [11].

$$B = \frac{\mu_0 I}{2\pi r} \tag{2.5}$$

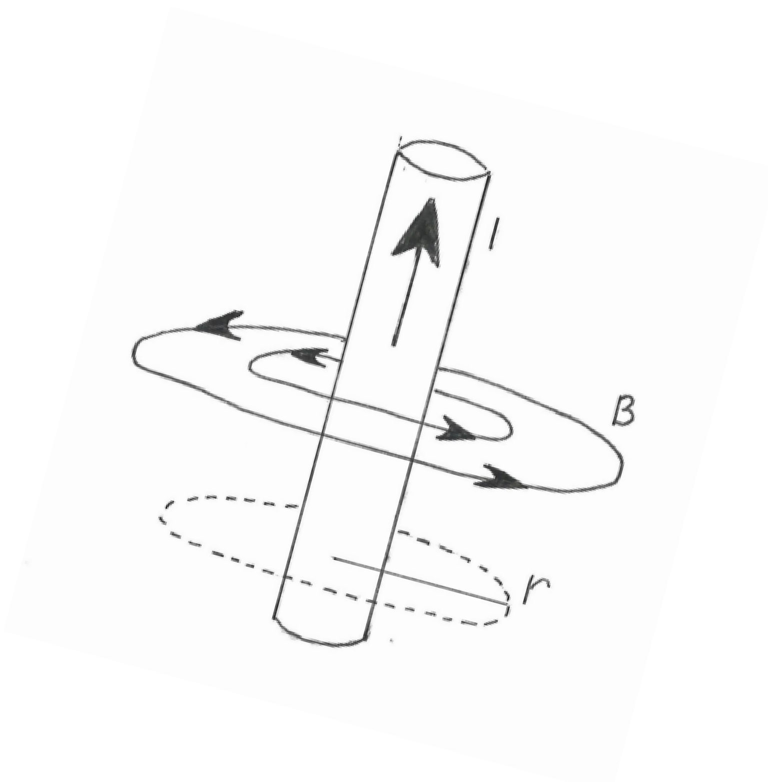


Figure 2.6: magnetic field in a conductor [11]

Where the parameters from equation 2.5 is:

- μ_0 Permabillity of free space
- I Electric current
- B Magnetic field
- r distance from the electrical conductor.

Magnetic flux relates to magnetic fields, and is the measure of how much magnetic field lines passes through a defined surface area.

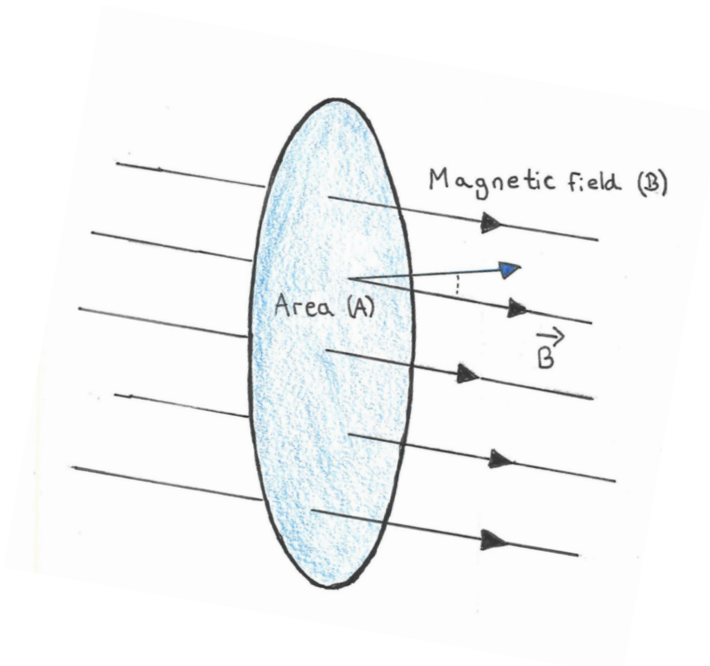


Figure 2.7: Magnetic flux [12]

Faraday's law of induction describes the relationship between a changing magnetic field and the electric current it generates. This law states that when a magnetic field changes, it creates an electromotive force (EMF) in an electric circuit. This principle is used in many electrical devices such as transformers, inductors, motors, generators, and solenoids [12].

$$\Phi = BA\cos\phi \tag{2.6}$$

2.3.5 Faraday's law

Any change in the magnetic field through a circuit induces an electromotive force (EMF), which is an induced voltage in the conductor. This induced voltage, created by the changing current, has the effect of opposing the change in current, as stated by Lenz's law.

$$\epsilon = -\frac{d\Theta_B}{dt} \tag{2.7}$$

where f is the frequency measured in Hz and ω is angular frequency measured in rads/s [13]

2.4 Synchronous generator

Synchronous generators are the main tool for power generation, and various loads are often driven by synchronous motors. Collectively referred to as synchronous machines. Power stability mainly comes down to keeping all the contributing units in synchronous.
For this reason, it is crucial to understand their workings whenever a power system is being analysed [3].

Throughout this paper, the generating unit in theory and modelling will be a synchronous generator.

The generator itself is depicted in figure 2.8, and consists of a stator and a rotor. The design is based on the principle of electromagnetic induction.

Both the rotor and stator is fitted with windings, armature windings and field windings respectively. The rotor is rotated by a prime mover, at the same time as the field windings are excited by a direct current, producing a magnetic field which then rotates with the rotor. Following Faraday's Law [13].

$$n = \frac{120f}{p_f} \tag{2.8}$$

The synchronous speed of the machine is often stated as equation 2.8 [3].

where n is the speed of the stator field in revolutions/minute, f is the frequency in Hz, and p_f is the number of field poles.

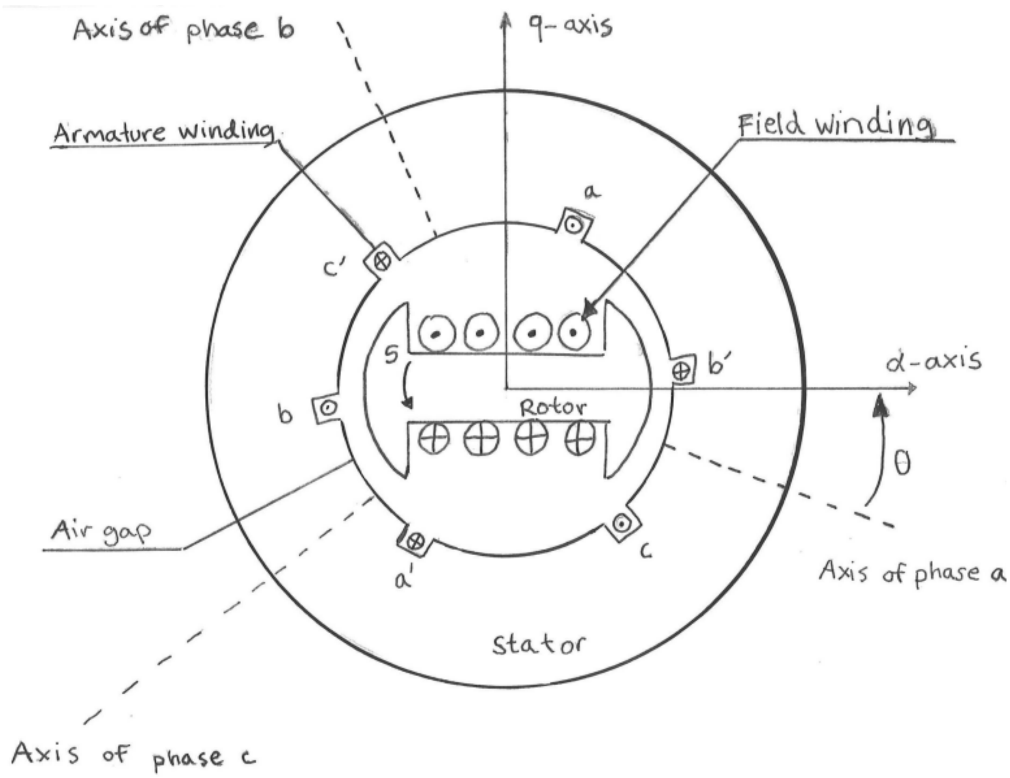


Figure 2.8: 3-ϕ synchronous machine. Illustration from [3]

When developing a mathematical model for a synchronous generator, Thomas Øyvang summarized it quite well in the introduction of his paper on synchronous generator models:

> The structure of the most traditional and practical synchronous machine model considered adequate for stability studies is shown in Fig 2.3. The three phase stator coils (a, b, c) are transformed to a (d, q) system with Park's transformation, Kundur (1994). This system is the rotating reference frame with the zero sequence equation (0-system) is not included in the model since only balanced system is considered. [14]

He is referring to a mathematical transformation of the ordinary a, b and c axis of the stator coils, making a reference plane that rotates with the rotor. making modelling and inspection of stability and control much easier.

When further developing equations for a synchronous machine, the following assumptions are often made:

In an electric motor, the stator windings are arranged in a sinusoidal pattern around the air gap to interact with the rotor. The stator does not cause significant changes in the rotor's inductances as it rotates. Additionally, magnetic hysteresis and saturation effects are not taken into account [3] [15].

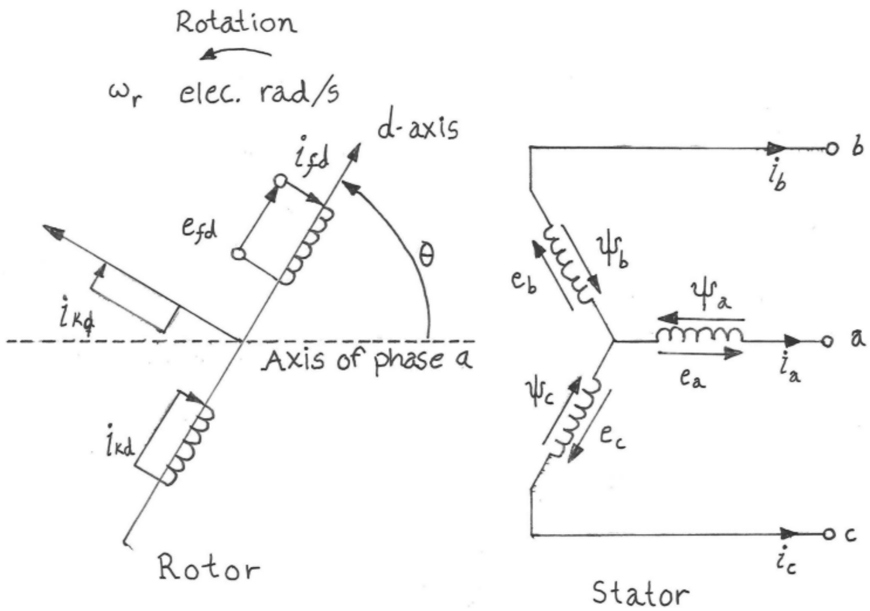


Figure 2.9: Equivalent circuit Stator and Rotor of a synchronous machine. Illustration from [3]

- a,b,c : Stator phase winding
- fd: Field winding
- kd: d-axis amortisseur circuit (damper winding)
- kq: q- axis amortisseur circuit (damper winding)
- $k = 1, 2, \ldots n$
- n = number of amortisseur circuits (damper winding)
- θ = Angle by which d-axis leads the magnetic axis of phase a winding, in electrical radians
- ω = Angular velocity, in electrical radians/sec [3].

2.4.1 D-Q transformation

The dq transformation, also known as the direct-quadrature-zero transformation, is a mathematical tool used by electric power engineers to transform AC waveforms into DC signals. It is particularly useful for three-phase systems, where the use of DC signals simplifies calculations. The dq transformation is the product of two other transformations: the Clarke transformation and the Park transformation [15].

$$\begin{bmatrix} V_d \\ V_q \\ 0 \end{bmatrix} = \sqrt{\frac{2}{2}} \begin{bmatrix} \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin\theta & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{2.9}$$

2.4.2 Swing equation

The swing equation is a mathematical tool used to determine the stability of a rotating synchronous machine within a power system. It describes how the rotor of a synchronous machine moves, or swings, with respect to the synchronously rotating reference frame in the presence of a disturbance. When the swing equation is solved, the expression for the power angle δ is obtained as a function of time [3].

$$\frac{d^2\delta}{dt^2} = \frac{\omega_s}{2H}(p_m - p_e) - D\frac{d\delta}{dt} \tag{2.10}$$

2.5 Transformers

According to IEEE standards;

> A transformer can be defined as a static electric device consisting of a winding, or two or more coupled windings, with or without a magnetic core, for introducing electric couplings between electric circuits. Transformers are extensively used in electric power systems to transfer power by electromagnetic induction between circuits at the same frequency, usually with changed values of voltage and current [16].

With this definition, a transformer can further be illustrated as shown on 2.10

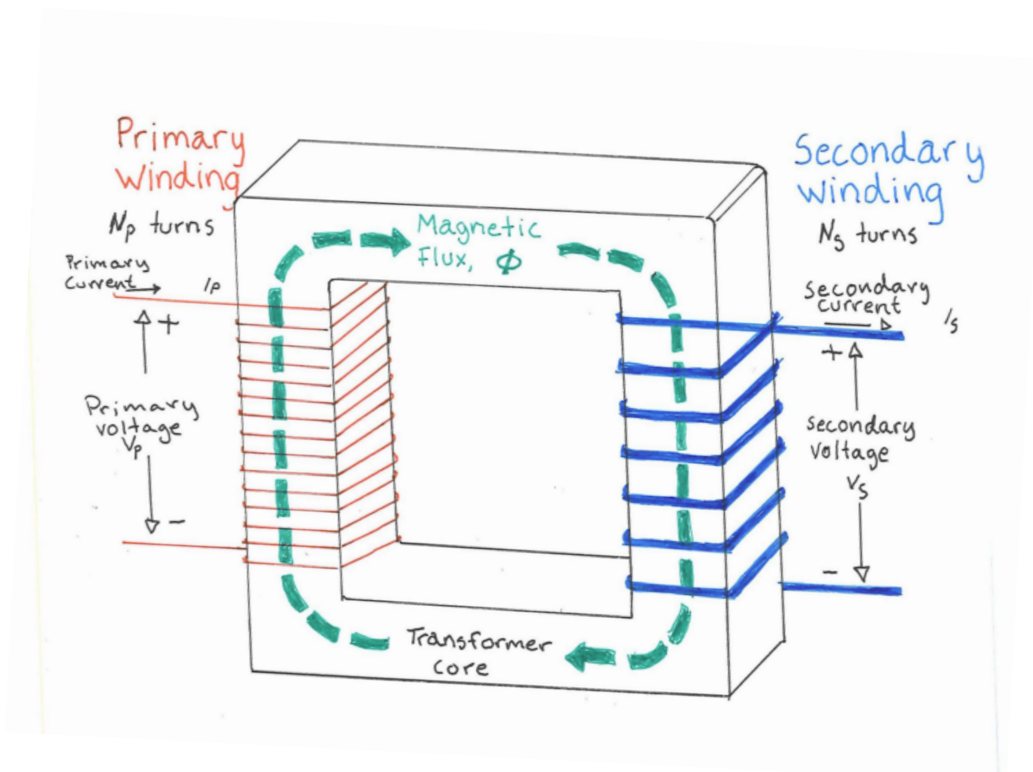


Figure 2.10: Basic schematic for one-phase transformer. Illustration from [17].

When carrying power long distances, there are losses in the transmission lines. These losses are reduced by ramping up the voltage, so that the current can be minimized. Since losses in a transmission line is a function of resistance times current squared.

$$P_{Loss} = \sum_{i=1}^{n_{br}} |I_i|^2 R_i \tag{2.11}$$

$$Q_{Loss} = \sum_{i=1}^{n_{br}} |I_i|^2 x_i \tag{2.12}$$

That's the fundamental motivation behind including transformers in the power system. [18]

2.6 Power cables

The main study of this thesis is long cables on the generator side of a generator transformer. How will different lengths of long cables affect the overall power system.

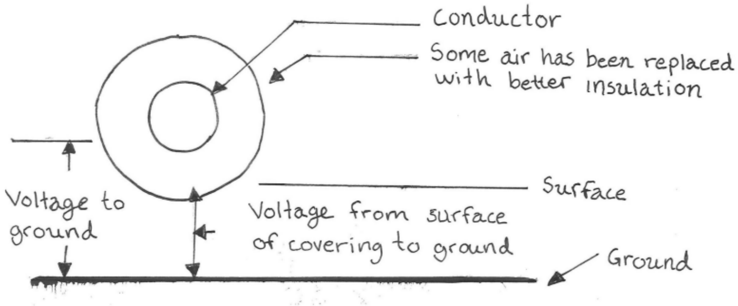


Figure 2.11: Power cable, Illustration from: [19]

A cable can be characterized by four parameters:

- Series resistance R due to the conductor resistivity.
- Shunt conductance G due to leakage currents between phases and ground.
- Series inductance L due to magnetic field surrounding the conductors.
- And shunt capacitance C due to the electric field between conductors.[3]

The cable's resistance is determined by the material it is made of and its length, which is usually provided in manufacturing tables. Shunt conductance accounts for losses caused by leakage currents along insulator strings and corona, but this effect is typically small and ignored in power cables. The line inductance is influenced by the partial flux linkages within the conductor's cross-section and external flux linkages. For overhead lines, the inductances of the three phases are considered.

The parameters relevant for this study will be the R, L and C values per unit length.

2.7 Introduction to switching

While the term "electric transient" may bring to mind extreme events such as lightning strikes, which can cause significant damage to power systems, in reality, most transients are caused by switching operations. These operations are typically performed by switches, circuit breakers or surge arresters [4].

Where the latter two components act as a safety mechanism by breaking the circuit when a threshold is exceeded, preventing damage from harmful current or voltage levels and clearing short-circuited currents in faulty parts of the system. The switch can turn parts of the system on or off as needed, under both loaded and unloaded conditions [20].

The following subsections will detail the switching operations in fundamental circuits that combine the previously introduced components to understand certain characteristics.

Lou Van der slui's book on transients in power systems provides valuable insight on switching in three fundamental circuits during the following three subsections.

2.7.1 Switching an LR circuit

When an AC voltage is applied to a series connection of an inductor and a resistor, it works as a representation of a single-phase circuit breaker in a high voltage underground cable or transmission line. E represents the voltage source or emf from a generator. While the inductance L may be considered as generator, transformer and transmission inductance. R is though of as collective losses in the system. Since all of these three elements are linear. Current in the circuit after switching can be seen as both steady- state current and transient current [4].

Transient current component is not influenced by the source, but rather a bi-product of the inductor and resistor. Applying Kirchhoff's voltage law gives us the non-homogeneous differential equation of the circuit in figure 2.12 [4]:

$$E = Ri + L\frac{di}{dt} \tag{2.13}$$

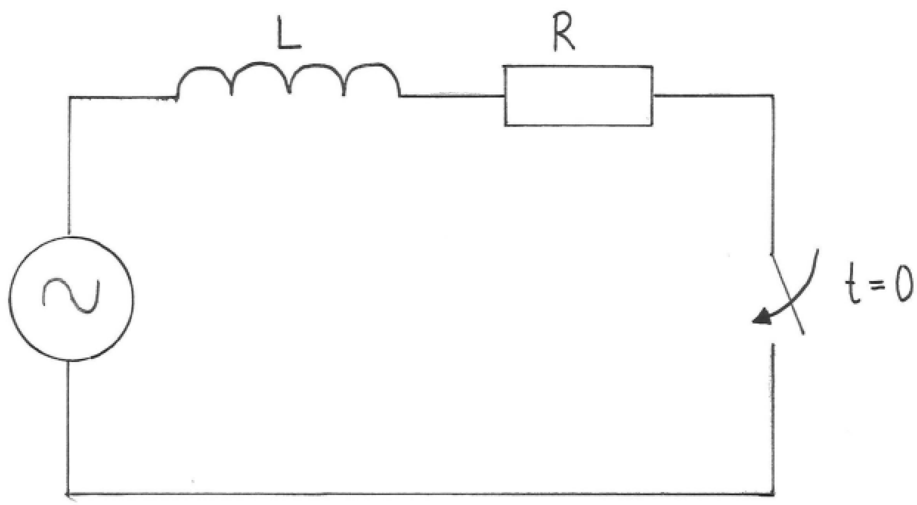


Figure 2.12: Ac voltage on a LR series circuit. Illustration from [4]

2.7.2 Switching an LC circuit

Another basic network is the series connection of an inductance of an inductance and a capacitance; this is in fact the most simple representation of a high-voltage circuit breaker switching a capacitor bank or a cable network [4]:

$$E = L\frac{di}{dt} + \frac{1}{C}\int idt \tag{2.14}$$

Solving the circuit for current gives:

$$i(t) = E\sqrt{\frac{C}{L}}\sin(\omega_0 t) \tag{2.15}$$

Where $Z_0 = (L/C)^{1/2}$ is the characteristic impedance and $\omega_0 = \sqrt{LC}$.

From these equations we can map two very important properties of the LC series network.

- After closing the switch at time $t = 0$, an oscillating current starts to flow with a natural frequency
- The characteristic impedance, together with the value of the source voltage E, determines the peak value of the oscillating current.

$$V_c(t) = E - (E - V_c(0))\cos(\omega_0 t) \tag{2.16}$$

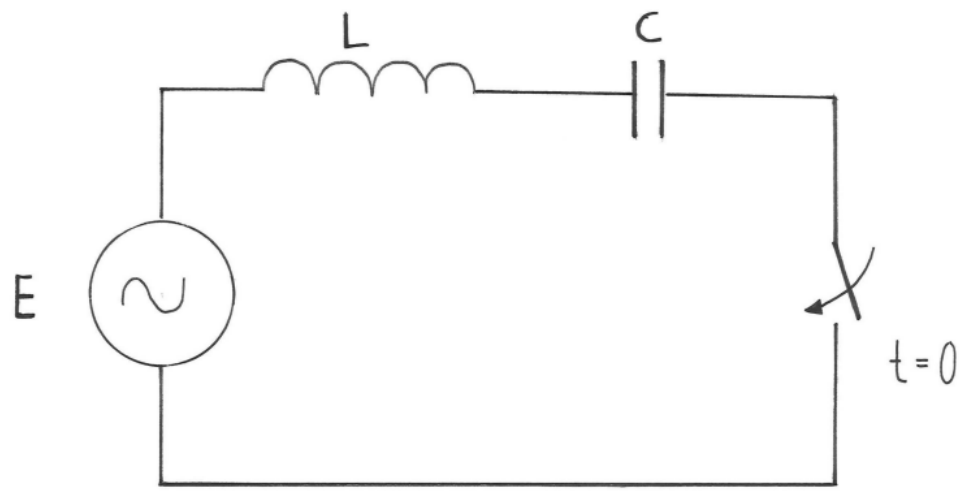


Figure 2.13: A direct current source switched on an LC series network. Illustration from [4]

Figure 2.14 show the voltage waveforms for the three initial values of the capacitor voltage. This follows equation 2.16. From these voltage waveforms it can be seen that for $V_c(0) = 0$ the voltage waveform has what is called a (1-cosine) shape and that it can reach twice the value of the peak of the source voltage. For a negative charge, the peak voltage exceeds this value, as the electric charge cannot change instantly after closing the switch. In addition, when the characteristic impedance of the circuit has a low value, for example, in the case of switching a capacitor bank (a large C) and a strong supply (a small L), the peak of the inrush current after closing the switch can reach a high value.

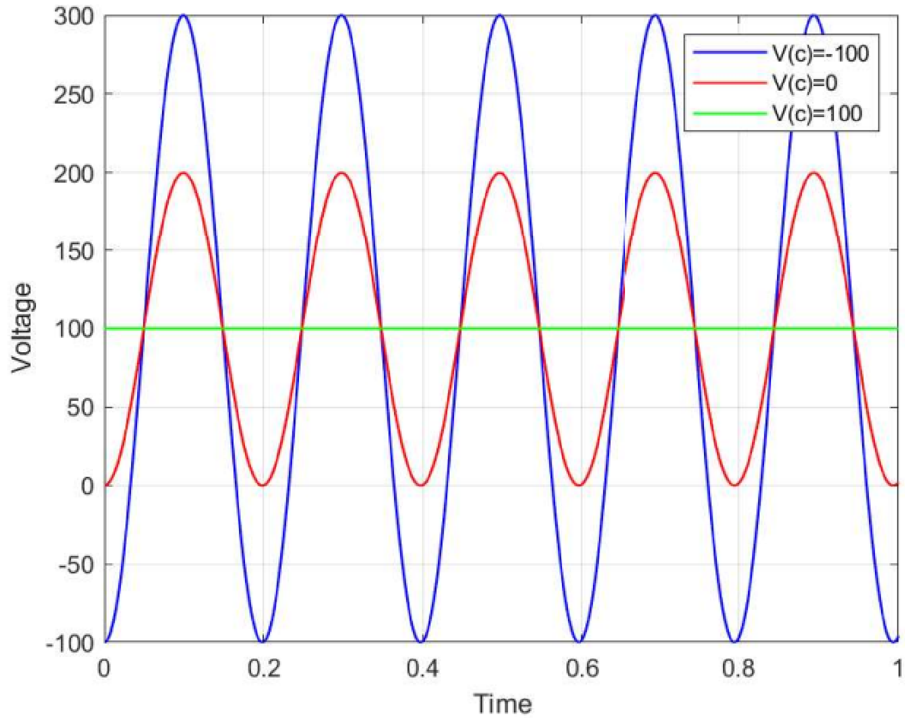


Figure 2.14: Different voltages across a capacitor when initial conditions are different

2.7.3 Switching an RLC circuit

In practice, there is always damping in the series circuit and that can be represented by adding a resistance in series. When a sinusoidal voltage source E is switched on in the RLC series circuit at t=0, Kirchhoff's voltage law leads to.

$$E = L\frac{di}{dt} + Ri + \frac{1}{C}\int idt \tag{2.17}$$

To find the transient (or natural) response of the network, we have to solve the something called the characteristic equation of the circuit.

In an RLC circuit, if Kirchhoff's voltage law is applied. Following equation 2.17.

Which can be manipulated to the resulting

$$\frac{d^2i}{dt^2} + \frac{R}{L}\frac{di}{dt} + \frac{i}{LC} = 0 \tag{2.18}$$

Assigning $i(t) = Ae^{st}$ and retrieving the two differentials of $i(t)$ gives:

$$\begin{aligned} \frac{di}{dt} &= sAe^{st} \\ \frac{d^2 i}{dt^2} &= s^2 A e^{st} \end{aligned} \tag{2.19}$$

Further we have the characteristic equation:

$$s^2 + \frac{R}{L}s + \frac{1}{LC} = 0 \tag{2.20}$$

This is an quadratic equation, which can be solved for three different set of roots.

Voltage response with different RLC configurations equation:

$$(\frac{R}{2L})^2 > \frac{1}{LC} \tag{2.21}$$

Three different situations can be distinguished:

1. When $(R/2L) > 1/LC$, the transient oscillation is *overdamped* and the roots of the characteristic equation (2.23) are both real and negative. The expression for the current becomes

$$\begin{aligned} i(t) &= e^{\alpha t}(C_1 e^{\beta t} + C_2 e^{-\beta t}) \\ &+ \frac{E_{max}}{\sqrt{R^2 + \left(\frac{1}{\omega C} - \omega L\right)}} \sin\left[\omega t + \psi + \tan^{-1}\left(\frac{\frac{1}{\omega C} - \omega L}{R}\right)\right] \end{aligned} \tag{2.22}$$

   with $\alpha = -(R/2L)$ and $\beta = [(R/2L)^2 - (1/LC)^{1/2}]$

2 . When $(R/2L)^2 = 1/LC$, the roots of the characteristic equation are equal, real and the transient oscillation is said to be *critically damped*. The expression for the critically damped current is

$$\begin{aligned} i(t) &= e^{\alpha t}(C_1 + C_2) + \frac{E_{max}}{\sqrt{R^2 + \left(\frac{1}{\omega C} - \omega L\right)^2}} \\ &\times \sin\left[\omega t + \psi + \tan^{-1}\left(\frac{\frac{1}{\omega C} - \omega L}{R}\right)\right] \end{aligned} \tag{2.23}$$

   With $\alpha = -(R/2L)$.

3. In the case that $(R/2L)^2 < 1/LC$, the roots λ_1 and λ_2 in the general solution are complex.

   $\lambda_1 = \alpha + j\beta$ and $\lambda_2 = \alpha - j\beta$ with $\alpha = -(R/2L)$ and $\beta = [(1/Lc) - (R/2L)^2]^{1/2}$ and equation 2.25 can be written as

$$\begin{aligned} i_h(t) =& C_1 e^{\alpha t + j\beta t} + C_2 e^{\alpha t - j\beta t} \\ \text{and because } C_2 =& C_1^* \end{aligned} \tag{2.24}$$

$$i_h(t) = C_1 e^{\alpha t + j\beta t} + (C_1 e^{\alpha t + j\beta t)^*} \tag{2.25}$$

   Making use of the property of complex numbers that $Z + Z^* = 2\mathrm{Re}(Z)$, and making the Euler notation $e^{j\beta t} = \cos(\beta t) + j\sin(\beta t)$, Equation (2.33) can be written as.

$$i_h(t) = 2e^{\alpha t}\mathrm{Re}(C_1 e^{j\beta t}) \tag{2.26}$$

   with

$$C_1 = \mathrm{Re}(C_1) + j\mathrm{Im}(C_1) \tag{2.27}$$

   Equation (2.34) can be written as

$$i_h(t) = 2e^{\alpha t}\mathrm{Re}(C_1)\cos(\beta t) - 2e^{\alpha t}\mathrm{Im}(C_1)\sin(\beta t) \tag{2.28}$$

   When we substitute for $\mathrm{Re}(C_1) = (k_1/2)$ and for $\mathrm{Im}C_1 = (-k_2/2)$, the expression for the general solution is $i_h(t) = e^{\alpha t}(k_1 \cos\beta t + k_2 \sin\beta t)$. The complete solution for the oscillating current is

$$\begin{aligned} i(t) =& e^{at}[k_1\cos(\beta t) + k_2\sin(\beta t)] + \frac{E_m ax}{\sqrt{R^2 + \left(\frac{1}{\omega C} - \omega L\right)^2}} \\ & \times \sin\left[\omega t + \psi + \tan^{-1}\left(\frac{\frac{1}{\omega C} - \omega L}{R}\right)\right] \end{aligned} \tag{2.29}$$

   With $\alpha = -(R/2L)$ and $\beta = [(1/LC) - (R/2L)^2]^{1/2}$.

In the three cases shown in the figure 2.15, the specific solution is the same, but the general solution is different. The transient component of the current contains sinusoidal functions with an angular frequency that differs from the power frequency of the specific solution. This causes the current to have an irregular shape. When the DC component has damped out and the transient part of the current has reduced to zero, the steady-state current either lags or leads the voltage of the source. This depends on whether the circuit is dominant inductive or capacitive. After a certain time, only a small percentage of the initial amplitude of the transient waveform remains in the network. Transient oscillations do not always occur after a change of state, such as after switching. However, in practice, they often do. Power systems are designed to avoid steady-state overvoltages due to resonance but can still experience resonance at higher harmonic frequencies generated by power electronic equipment.

RLC Case 1:

Over damped

$$(\frac{2\Omega}{2 \times 0.1H})^2 > \frac{1}{0.1H \times 0.04F} \quad \approx 400 > 25$$

RLC Case 2:

Critically damped

$$(\frac{1\Omega}{2 \times 0.1H})^2 = \frac{1}{0.1H \times 0.04F} \quad 25 = 25$$

RLC Case 3:

Under damped

$$(\frac{0.2\Omega}{2 \times 0.1H})^2 < \frac{1}{0.1H \times 0.04F} \quad \approx 1 < 25$$

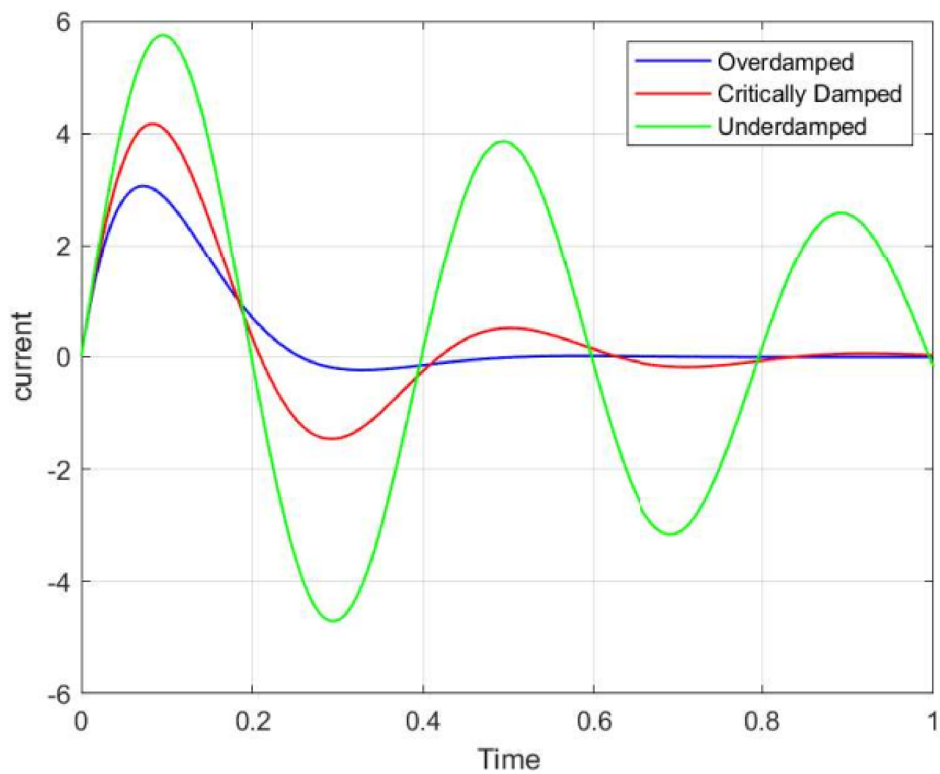


Figure 2.15: RLC Circuit, under damped, critically damped and over damped

2.8 Transients and resonance frequency

Phenomenon	Frequency Range
Ferroresonance	0.1Hz to 1kHz
Load rejection	0.1Hz to 3kHz
Fault clearing	50Hz to 13kHz
Overhead transmission line switching	0.1Hz to 20kHz
Transient recovery voltages	50Hz to 100kHz
Lightning-induced overvoltages	10kHz to 3MHz
Switching in gas insulated substation	100kHz to 50MkHz

Table 2.2: Transient phenomenon and Frequency spectrum, from [21]

From table 2.2, we can see what frequency range the different transient phenomenon falls into.

2.8.1 Transients

A transient occurs in the power system when the network changes from one steady state to another. [4] And a power system transient could be refereed to as a power-quality disturbances that can be harmful to electric equipment. Defined as a voltage or current surge over a short time duration in regards to power systems. There are no clear limitation, but phenomena with a duration of less than one (sinusoidal cycle of the power-system frequency, 50 or 60 Hz) are generally referred to as transients [22] [4] [23].

Figure 2.16 show what a transient in a power system could look like.

2.8.2 Power line transients

Transients can travel along electrical paths between devices and have the potential to affect a large number of electrical equipment. Due to the many possible causes of transients, the wave-forms used to describe these events can vary greatly depending on the application and environment. The severity of transients can also differ based on the environment in which the equipment is used, with harsher environments such as industrial or outdoor settings often being more susceptible. For example, an outdoor event could impact the electrical grid and travel to other locations. Conducted interference events can produce various pulse shapes, but they are generally classified as either impulse or oscillatory transients. These types of transients are not limited to power lines and can also travel along data or communication lines [25].

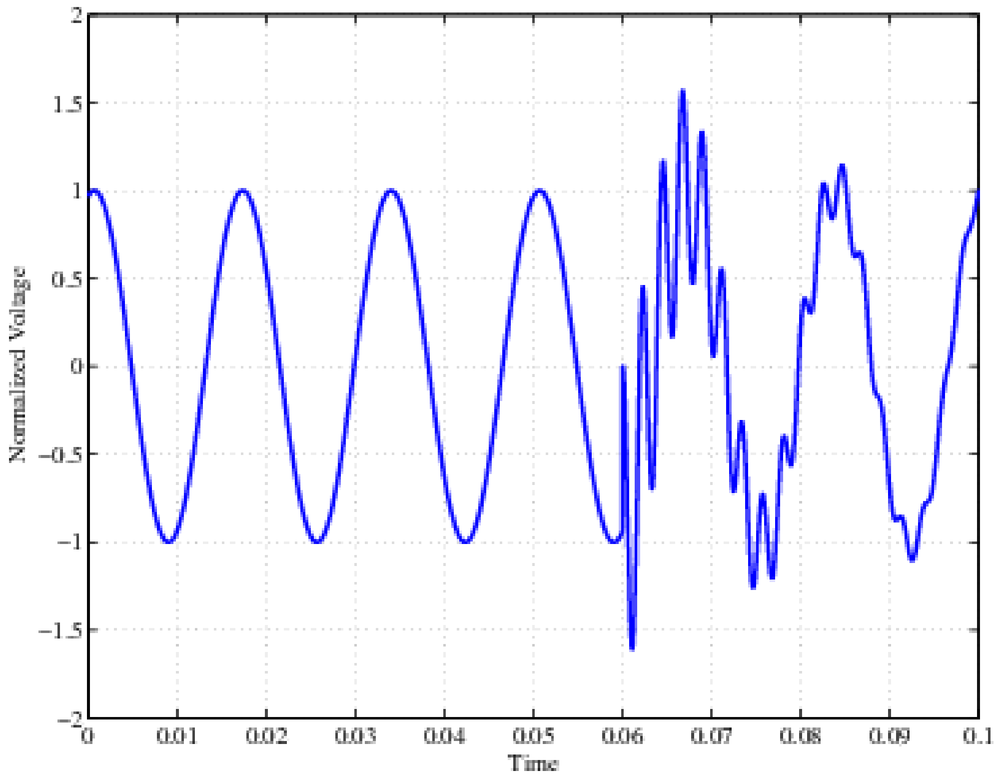


Figure 2.16: Simulation of voltage transient. Illustration from [24]

2.8.3 Resonant frequency

Resonance is a physical phenomenon that occurs when an external force is applied to an object at a frequency that matches one of its natural frequencies. This causes the object to vibrate with a large amplitude. In other words, when the frequency of the applied force is in sync with the natural frequency of the object, resonance occurs, resulting in a significant increase in the magnitude of the vibrations [26].

This concept also translates to electronics in the form of electrical resonance. Electrical resonance occurs in an electric circuit at a particular resonant frequency when the impedances or admittances of circuit elements cancel each other out.

Impedance from equation 2.4:

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

The impedance formula provides the correlation between reactance and resonant frequency in series circuits.

$$
\begin{aligned}
X_L &= X_C \\
2\pi L f &= \frac{1}{2\pi f C} \\
f &= \sqrt{\frac{1}{4\pi^2 LC}} \quad = \frac{1}{2\pi\sqrt{LC}}
\end{aligned}
\tag{2.30}
$$

At resonance, the voltages across the inductor and capacitor in a series RLC circuit can become significantly larger than the supply voltage. This is due to the energy transfer between the different components of the circuit. Energy can be stored in an electric field as a capacitor is charged and in a magnetic field as current flows through an inductor. This energy transfer can result in oscillations at the resonant frequency, which is a specific frequency at which the circuit resonates [27].

2.8.4 Harmonic resonance

Resonance in a power system can result in series or parallel-resonant currents that can damage the electrical system. In systems with a large amount of capacitance used to correct power factor, high-voltage distortion can cause resonance at system harmonic frequencies. The difference between series and parallel resonance is that series resonance creates a low impedance and draws maximum current into the system, while parallel resonance creates a large impedance. Even with small currents, this can cause a large harmonic voltage drop and voltage-related stress damages.

This article on harmonic resonance, was the motivation for the harmonic resonance in power systems [28].

2.8.5 Harmonic resonance in power systems

Non-linear electric loads produce harmonic currents that enter the power grid. The impact of these currents on the grid depends on how the grid responds to the different frequencies of the harmonics. If the grid responds well, the currents will flow harmlessly. However, if the grid's response is poor, it could result in damaging overvoltage or overcurrent conditions due to electrical power system resonance. The way the grid responds to power system harmonics is determined by certain characteristics of the system [29]

- Impedance of the system to each harmonic frequency
- Presence of any capacitor banks or capacitive loads
- Magnitude of resistance

To understand electrical power system harmonic resonance, there are some important concepts to keep in mind.

Non-linear loads produce harmonic currents that are injected into the power grid. The current flowing into the grid produces a voltage drop proportional to the impedance offered to that particular harmonic frequency component. If the source impedance and capacitance form a series or parallel resonant circuit, the injected current can cause very high current and voltage distortion. Every system with capacitors will have a parallel resonant point, and it's important to determine if this resonant point is close to one of the harmonic frequencies injected by the system loads [28].

Symptoms and causes

Most harmonic resonance problems are self-correcting. This means that the resonant condition will cause enough current or voltage in the system to blow fuses or fail capacitors, thereby coming out of resonance. However, low-level system resonance can go unnoticed for a long time and may not cause any immediate failure. Resonant conditions usually result in high capacitor currents and fuse operation, and capacitors can be damaged due to overheating or voltage stress. Voltage distortion can also occur due to one or two closely spaced harmonic orders. By analyzing the current and voltage on a power quality analyzer, the harmonic order causing the resonance can usually be identified. Low-level resonance can go unnoticed for a long time and may result in unexplained failure of sensitive power supplies, electronic loads, transformer overheating, etc. Harmonic resonance is considered a steady-state phenomenon, though switching-induced transient resonance is possible. Power system impedance is primarily inductive at the nominal frequency (50/60Hz) and varies depending on the harmonic frequency. Power system capacitors could be power factor correction capacitors, cable capacitors, breakers, etc., and their impedance varies inversely depending on the harmonic frequency [28].

- Parallel resonance
- series resonance

2.8.6 Parallel Resonance in power system

A system can drift into a state of parallel resonance. This could happen in a large industrial facility where multiple low voltage substations inject harmonic current into the medium voltage facility bus. A potential parallel resonant condition could arise between the power factor capacitor bank of the medium or low voltage facility and the source inductance X_s [28].

Resonant frequency is given by equation 2.30 derived earlier:

$$f_p \approx \frac{1}{2\pi} \times \sqrt{\frac{1}{LC}}$$

When the circuit reaches the parallel resonant frequency, its effective impedance becomes

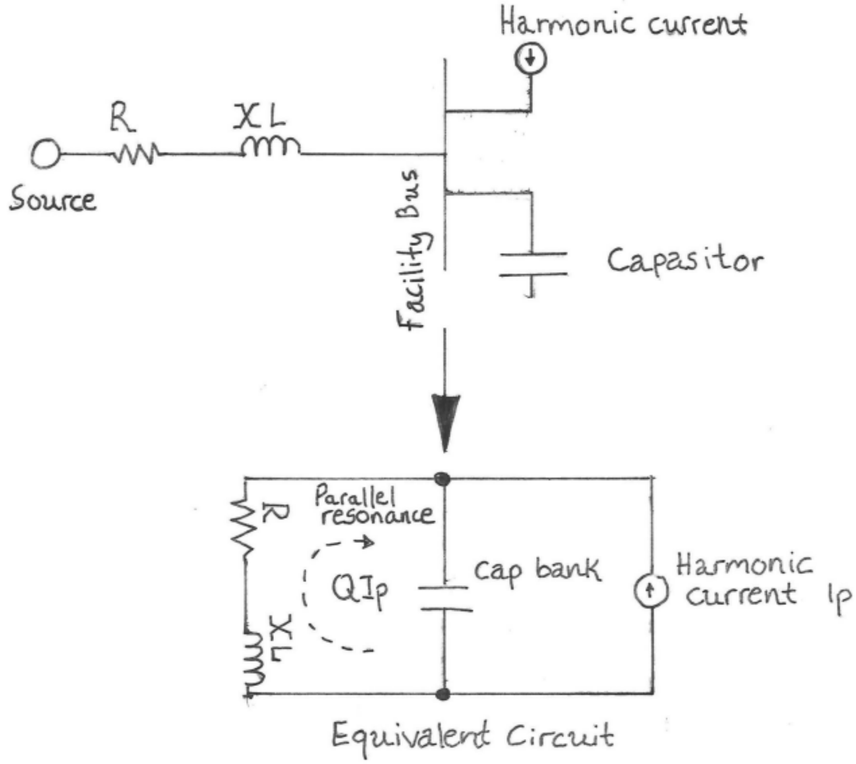


Figure 2.17: Circuit having potential for parallel resonance. Illustration from: [28]

very high. It's important to note that at resonance, X_L equals Xc. For the circuit shown on figure 2.17

$$\begin{aligned} Z_p =& (R_s + jX_L) \parallel -jX_c \\ Z_p =& \frac{(X_L)^2}{R_s} = \frac{(X_c)^2}{R_s} = QX_L = QX_c \end{aligned} \tag{2.31}$$

Q is the quality factor that determines how sharp the frequency response is. In a distribution system, Q could be 5, while at the secondary of a large distribution transformer it could be 30. The value of Q will differ for series and parallel resonant circuits.

Voltage across capacitor

During a parallel resonant condition, the voltage on the capacitator can become very high. Because the value of QX_L is very high, even a small harmonic current I_p can cause a large voltage drop across the capacitor.

$$V_{cap} = QX_L I_p \tag{2.32}$$

Current through capacitor

During a parallel resonant condition, the current flowing in the capacitor and transformer is magnified by a factor of Q times the injected harmonic current (I_p).

$$I_{Cap} = \frac{V_p}{X_c} = \frac{QX_cI_p}{X_c} = \frac{QX_LI_p}{X_L} = QI_p \tag{2.33}$$

This magnification of I_p could cause damage to components or blow fuses.

The parallel resonant turning point is determined by the shunt capacitor bank relative to the source MVA. For a system with shunt capacitor banks applied at the secondary of a power transformer, the parallel resonant frequency is given by

$$h_p = \sqrt{\frac{X_c}{X_L}} = \sqrt{\frac{MVA_{3\phi sc}}{Q_{cap}}} \tag{2.34}$$

Where:

- h_p is the order of the parallel resonant frequency
- $MVA_{3\phi sc}$ is the three- phase short circuit MVA
- X_s is the system short circuit reactance
- X_c is the equivalent wye reactance of the capacitor bank
- Q_{cap} is the capacitor bank size in MVAR

$MVA_{3\phi sc}$ represents the effective short circuit MVA at the point of interest. In most cases, a quick estimate of $MVA_{3\phi sc}$ can be made by identifying the upstream transformer KVA and its % of impedance. This is because the transformer impedance has the greatest influence on the system impedance and therefore on the effective short circuit MVA. Including the utility source impedance, if available, can result in more accurate results [28].

2.8.7 Series resonance in power systems

Series resonance can happen when the series combination of a facility transformer's inductance and a shunt capacitor bank in the facility resonates at a harmonic frequency that is injected from the distributed system. In this scenario, even if the facility itself is not generating significant harmonic current, it can still experience harmonic effects if the series LC combination sinks significant harmonic current from the upstream distribution system. An example of a system that has the potential to go into series resonance is shown below.

The voltage across the capacitor is magnified and distorted and can be calculated as:

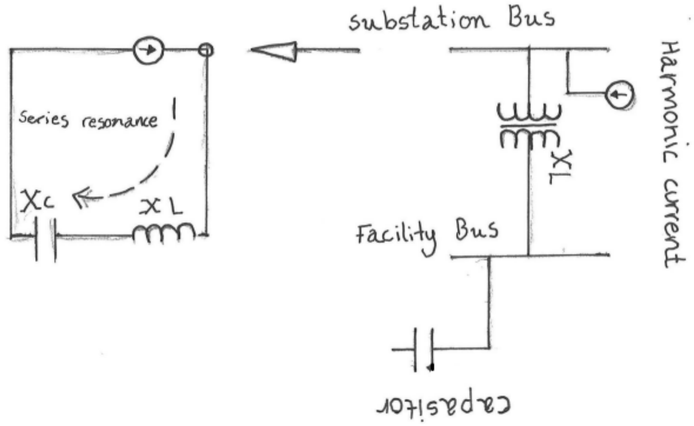


Figure 2.18: Circuit having potential for series resonance conditions. Illustration from [28]

$$V_{cap} = \frac{X_c}{X_L + X_c + R} V_h \approx \frac{X_c}{R} V_h \approx \frac{X_L}{R} V_h \tag{2.35}$$

V_h represents the harmonic voltage present in the system. R is the inherent series resistance of the circuit, but it is not shown. It's important to note that at resonance, the values of X_L and X_c will be equal and opposite in magnitude, so they will cancel each other out

2.8.8 Series and parallel resonance in practical power system application

Practically speaking a series resonant condition will also have a parallel resonance condition due to circuit topology. In the figure 2.18, X_L is the facility transformer reactance and X_c is the facility capacitor bank reactance. Source reactance is given by X_s.

Series resonant point is given by:

$$h_s = \sqrt{\frac{X_c}{X_t}} \tag{2.36}$$

Parallel resonant point is given by:

$$h_p = \sqrt{\frac{X_c}{X_t + X_L}} \tag{2.37}$$

In a practical power system installation, the equations for series and parallel resonance show that the parallel resonant point is always lower than the series resonant point.

The main difference between parallel and series resonance in a power system is that series resonance creates a low impedance, drawing maximum current into the system. On the other

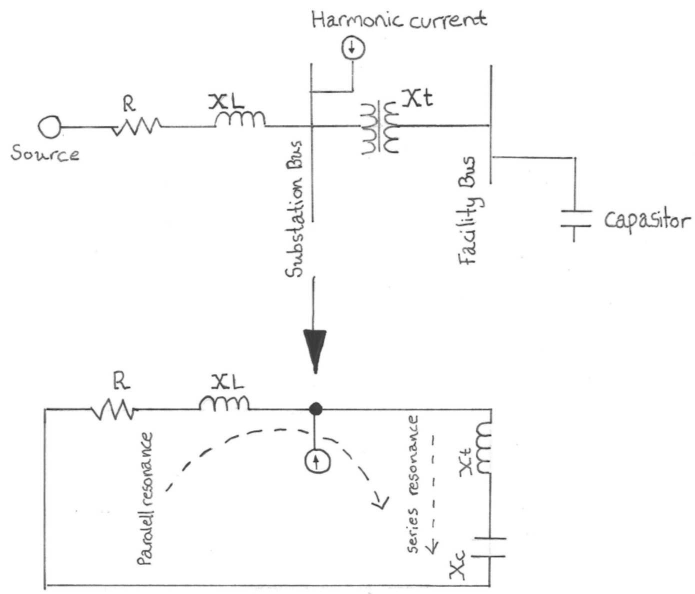


Figure 2.19: Circuit having potential for Series and parallel resonance. Illustration from [28]

hand, parallel resonance creates a large impedance, which can cause large harmonic voltage drops even with small currents. This can result in voltage stress-related damages.

3

Resonance and overvoltage in a power system

Chapter three will describe what the thesis aims to inspect. looking into previous research on similar or relating issues. To underline the importance of the field of study.

What are the different phenomena and problems that could pose a threat to a power system, when generators, generator transformers and long cables interact.

1) Transformer resonant overvoltage [30].

2) Switching on of unloaded transformer via feeder cable called the Unknown silent killer of transformer [31].

3) If the capacity towards ground is far greater than the resistance towards ground, high transients could occur in case of gound fault.[22].

4) Harmonic resonances due to transmission-system cables [32].

3.1 Transformer resonant overvoltage

Caused by cable to transformer high frequency interaction.

Transformers can suffer dielectric failure due to high-frequency switching operations, fault events or even lightning strikes [30].

3.1.1 Resonance overvoltage phenomenon

LC circuit

According to [30], the transformer resonant overvoltage phenomenon. Can be understood from a simple LC- circuit. And the author explains it as:

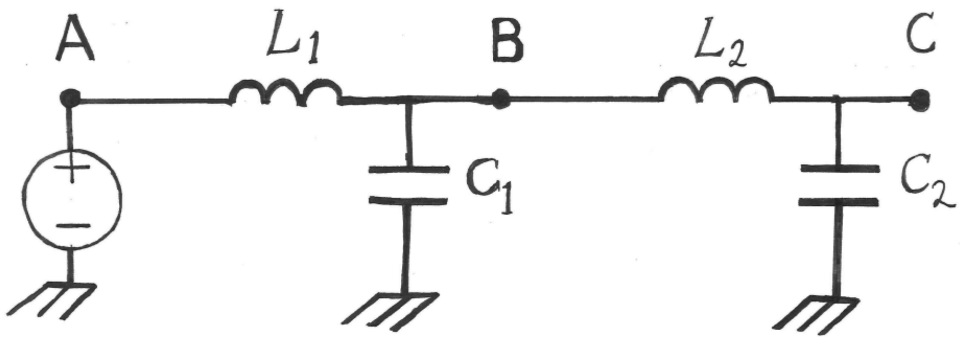


Figure 3.1: LC-circuit with unit step excitation voltage. Taken from [30]

The overvoltage phenomenon can lead to the magnification of transient voltages. Consider the circuit from point A to B and the circuit from B to C as separate. The first circuit is excited by a unit step voltage, this gives rise to an oscillating voltage at point B. This voltage has a frequency of:

$$\omega_1 = \frac{1}{\sqrt{L_1 C_1}} \tag{3.1}$$

The second circuit is then connected from point B to C. With resonance frequency of:

$$\omega_2 = \frac{1}{\sqrt{L_2 C_2}}, \tag{3.2}$$

If $\omega_1 \approx \omega_2$ and the surge impedance of circuit #2 is much higher than that of circuit #1, $\sqrt{L_2 C_2} \gg \sqrt{L_1 C_1}$, a resonant overvoltage phenomenon will take place [30].

This is illustrated in figure 3.2 for a step voltage of 1 volts. Energy is exchanged back and forth between circuit #1 and #2, causing the observed beat phenomenon.

This is illustrated in figure 3.2. for a unit step voltage excitation. Energy is exchanged back and forth between the two circuits, causing the observed beat phenomenon. The voltage

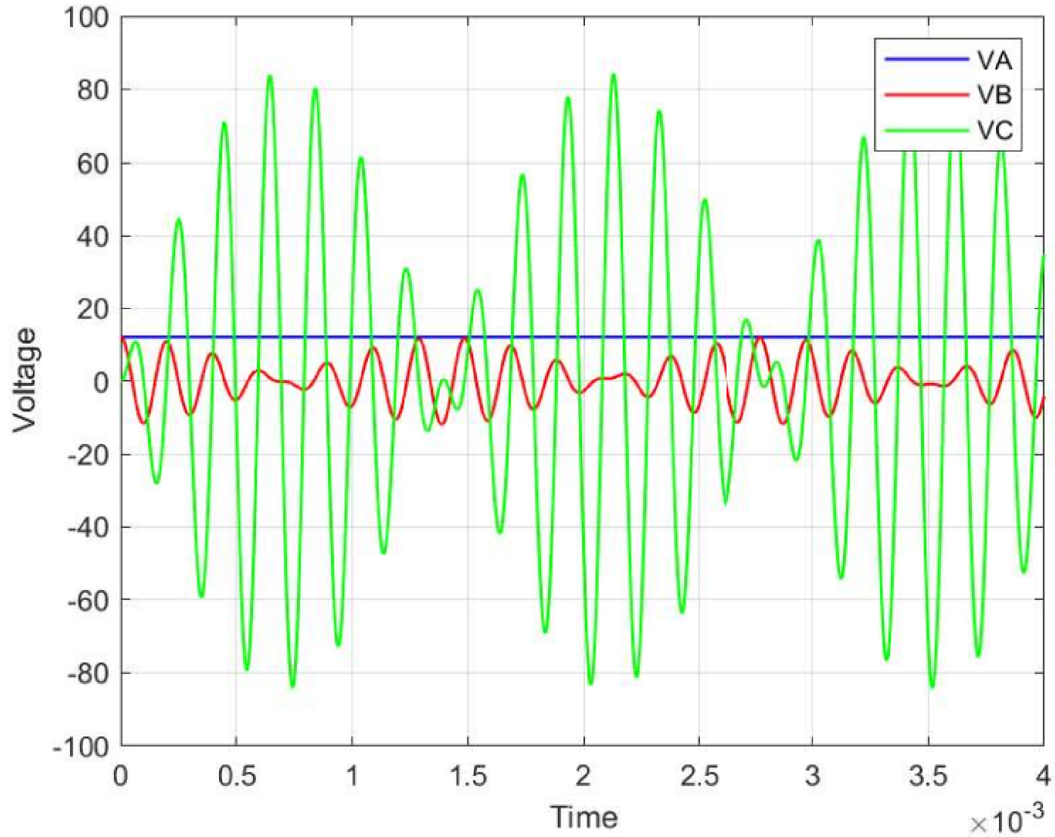


Figure 3.2: Resonance overvoltage phenomenon

peak value in circuit #2 is higher than that of circuit #1, due to the smaller circuit values. From the energy relation $W = C_1V_1^2/2 = C_2V_2^2/2$, the peak value of the oscillating voltage component in circuit #2 is approximately $\sqrt{C_1/C_2}$, or 7.1 with the given circuit values. In Fig. 3.2, the voltage is accordingly seen to vary between -6 V and +8V as it oscillates around the applied voltage (+1 V) [30]

This study explains well how resonance can occur in a power system.

3.1.2 Resonance between cable and transformer

In a transformer, voltage is transferred between the internal windings. The voltage transfer varies strongly with frequency because it is not controlled by the balance between amperes and windings at high frequencies. As the frequency increases, the flux in the iron core decreases and the voltage ratio is eventually determined by stray inductances and capacitances. This can result in resonance peaks in the voltage transfer from the high-voltage side to the low-voltage side, which can be much higher than the voltage ratio at the operating frequency. The impedance seen at the transformer terminals is usually higher on the high-voltage side and can be particularly high when the low-voltage winding is unloaded. This can lead to high external overvoltages in the transformer under certain conditions. [30].

1) A transient occurs on the high-voltage side with the low voltage side open or connected to a high-impedance load.

2) The transient has a dominating frequency which matches a resonance peak in the voltage transfer from high to low.

3) The input impedance seen into the high-voltage winding (with open low-voltage side) is sufficiently high so that the

3.2 Overvoltages in power transformers caused by No-load switching

When an unloaded power transformer is switched on through a relatively long cable, very high voltages can sometimes occur on the transformer's secondary side due to a resonance effect. This happens when the resonant frequencies of the transformer and cable are the same. The cable feeder's resonant frequency is equal to the inverse of 4 times its travel time, while the transformer's resonant frequency is determined by its short-circuit inductance and the capacitance connected to its secondary winding.

Switching on an unloaded transformer through a cable feeder can sometimes cause damage to the transformer if the resonant frequencies of the cable feeder and transformer are the same. This can result in very high voltages at the transformer's secondary terminals, damaging the insulation of the transformer winding and potentially causing a flashover from the winding to the core.

To avoid these situations, measures can be taken to change the values of the cable capacitances by changing the length of the cables or installing extra capacitors at the secondary terminals for low secondary nominal voltages. Additionally, surge arresters can be installed at the secondary terminals of the transformer. By using simple formulas and basic parameters from the transformer and cables, it is possible to predict potentially critical situations [31].

3.3 Harmonic resonances due to transmission-system cables

A study by Bollen, Mousavi-Gargari, and Bahramirad provides examples of potential harmonic problems in the transmission grid when long ac cables are used. It includes two case studies and a simple guideline.

The authors claim that cables introduce a large amount of capacitance to the transmission system, about 20 times more than overhead lines. As a result, they suggest that harmonic resonance should be taken into account before installing such cables.

Concluding with: It is important to consider the impact of transmission cables on the harmonic levels in the grid. When long cables are connected a harmonic study is recommended. and, A simple criterion is proposed here to decide about the need for a detailed study. Such a study should have at least the same accuracy and detail as the harmonic studies done with the connection of new industrial customers or HVDC links [32].

3.4 Analysis of Internal Overvoltages in Transformer Windings during Transients in Electrical Network

Transformer windings can experience overvoltages due to the way electromagnetic waves travel in electrical networks and transformer windings. It's important to study how transformer windings react to transients in power systems, particularly when using common overvoltage protection systems. Examining internal overvoltages in transformers during switching and certain failures is essential for determining the risk to insulation systems from overvoltages during operation. Because overvoltage events in electrical networks are unpredictable, computer simulations are used to assess the risk of overvoltages to electrical devices during use [33].

3.5 High ground capacitance

High-resistance grounding typically involves connecting a low-ohmic resistor to the secondary side of a distribution transformer, with the primary winding of the transformer connected from the generator neutral to ground. This configuration has the advantage of using a low-ohmic, rugged resistor in the secondary of the distribution transformer, rather than a high-ohmic, low-current resistor directly in the generator neutral. The current through the primary of the grounding transformer is usually limited to between 5 and 15 amperes for a single phase-to-ground fault on a generator terminal, depending on the generator size and zero-sequence capacitance-to-ground in the circuit operating at generator voltage [22].

4

Methods, modelling tools and tests for a generic hydropower system

To investigate the problem statement, a model is needed. A dynamic model of a system with some variations in model settings and components will be built using Matlab/Simulink, based on realistic data.

The main goal of chapter four is to apply the theory studied in chapter two and address the possible issues identified in chapter three using a model.

4.1 Segment about model components

As stated in the introduction to chapter four, Simulink is the simulation environment in which the simulations will take place. Specifically elements from the Simscape library, under the specialized power systems.

As an advanced rule, it is important to note that the model developed in this study is a computer simulation of a power system. While the model is based on realistic data and aims to accurately represent the behavior of a real-world power system, there may be some variations between the simulation results and actual system performance. These variations can arise due to assumptions and simplifications made during the modeling process.

Using simplified computer models to represent complex real-world systems has several benefits. For example, computer models can be safer and cheaper than experimenting with real-world systems. They allow us to test whether a product or system works before building it and can be used to find unexpected problems. Computer models also enable us to explore 'what-if' questions and speed up or slow down simulations to see changes over long or short periods of time.

There is something to be said for simplified computer models versus actual power system components.

4.1.1 Lumped parameters

When analyzing a power system in steady-state, its components are often represented as lumped elements. This is because the physical dimensions of system components are much smaller than the wavelengths of sinusoidal currents and voltages. However, using lumped sum models to study transients can produce inaccurate results because they do not account for the time it takes for electromagnetic waves to travel through system elements. For example, pi models cannot accurately represent the travel time of electromagnetic waves. When modeling an overhead line with sections of pi lines, it is assumed that the characteristics of the electric and magnetic fields are concentrated in a single capacitor and inductor, respectively [21].

This means that a disturbance on one side of the power system network will not immediately appear on the other side. It has been shown that this delay is not caused by connecting the source to the line, but rather by the characteristics of the elements themselves. The time lapse in the traveling wave from the source to the end of the line is caused by the characteristics of the pi model [21].

4.2 Model Blocks

This subsection will primarily consist of documentation from SIMULINK's archives. The purpose is to provide insight into how the different system components function. It also compensates some for the missing modelling part under chapter two.

4.2.1 Simplified Synchronous Machine SI units

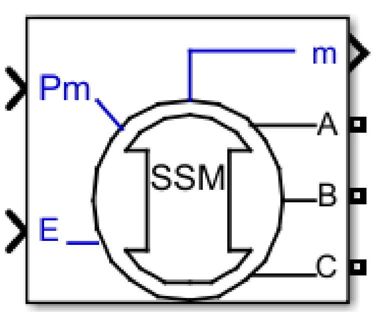


Figure 4.1: Simscape/Elecrtrical/Specialized Power Systems/Power Grid Elements/ Simplified Synchronous Machine SI Units [34]

The simplified synchronous machine block represents both the electrical and mechanical features of a basic synchronous machine. Each phase of the electrical system is made up of a voltage source and an RL impedance in series, representing the machine's internal impedance. The mechanical system is also implemented by the simplified synchronous machine block [34].

The simplified synchronous machine block implements the mechanical system described by:

$$\Delta\omega(t) = \frac{1}{2H}\int_{o}^{t}(T_m - T_e) - kd\Delta\omega(t)dt$$
$$\omega(t) = \Delta\omega(t) + \omega_0 \tag{4.1}$$

Where:

Variable	description
$\Delta\omega$	Speed variation with respect to speed operation
H	Constant of inertia
T_m	Mechanical Torque
T_e	Electromagnetic torque
$\omega(t)$	mechanincal speed of the rotor
ω_0	Speed of operation

Table 4.1: Mechanical parameters of synchronous machine

Figure 4.2 shows the implementation of the mechanical component of the model. The model calculates a difference in relation to the operating speed, rather than the actual speed.

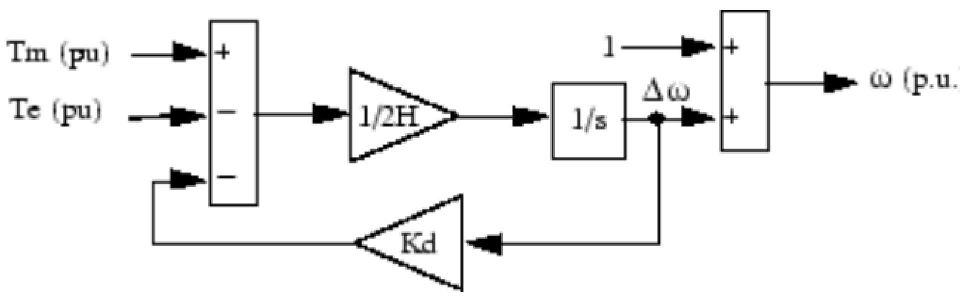


Figure 4.2: Mechanical part synchronous machine [34].

The k_d damping coefficient mimics the effect of damper windings that are typically used in synchronous machines. When the machine is connected to an infinite network with zero impedance, the change in the machine's power angle delta (δ) due to a change in mechanical power (p_m) can be estimated using a second-order transfer function [34].

$$\frac{\delta}{P_m} = \frac{\omega_s/(2H)}{S^2 + 2\xi\omega_n s + \omega_n^2} \tag{4.2}$$

where

Variable	description
δ	Power anlge delta
P_m	Mechanical power in p.u
ω_n	Frequency of electromechanical oscillations
ξ	Damping ratio = $(k_d/4)\sqrt{2/(\omega_s H P_{max})}$
ω_s	Electrical frequency in rad/s
P_{max}	Maximum power in p.u
H	Inertia constant (s)
k_d	Damping factor

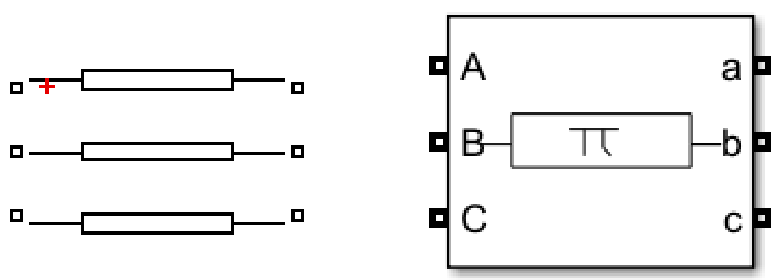
Table 4.2: Parameters included in the transfer function

In table 4.2 $P_{max} = V_t E/X$, and V_t, E and X are all in p.u.

This approximate transfer function, which has been derived by assuming $\sin(\delta) = \delta$, is valid for small for angles ($\delta < 30$ degrees). It follows from the preceding ξ expression that the K_d value required to obtain a given ξ damping ratio [34]:

$$K_d = 4\xi\sqrt{\omega_s H P_{max}/2} \tag{4.3}$$

4.2.2 Distributed parameter line & PI-line



(a) (b)

Figure 4.3: Simscape/Electrical/Specialized Power Systems/Power Grid Elements/Distributed parameter line & Three-Phase PI Section Line [35] [36]

A transmission cable can be modeled in several ways. One approach is to use a single inductance or capacitance. Another approach is to use a combination of a series inductance and two shunt capacitors. The most detailed approach is to use a distributed series impedance and shunt capacitance model, which is the best choice for studying harmonics over a wide range of frequencies [32].

The distributed parameter line block implements an N-phase distributed parameter line model with lumped losses, based on Bergon's traveling wave method used in Electromagnetic Transient Program (EMPT) [37]. In this model, the lossless distributed LC line is characterized by two values for a single-phase line: the surge impedance $Z_c = \sqrt{l/c}$ and the wave propagation speed $v = 1/\sqrt{lc}$ [36].

Figure4.4 shows the two-port model of a single-phase line.

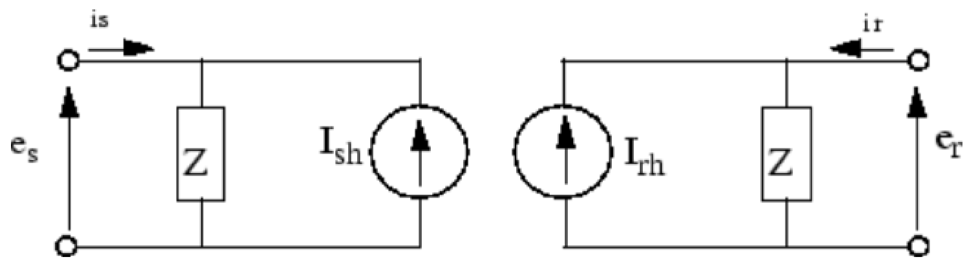


Figure 4.4: Two port model of a single-phase line. [36]

For a line without loss (where r=0), the sum of the line voltage e at one end and the product of the surge impedance z and the line current i entering the same end must remain constant when it reaches the other end after a transport delay τ.

$$\tau = \frac{d}{v} \tag{4.4}$$

Where d is the line length and v is the propagation speed. When losses are taken into account , I_{sh} and I_{rh} from figure 4.4 are obtained by lumping $R/4$ at both ends of the line and $R/2$ in the middle of the line if R is the total resistance [36]:

$$R = r \times d \tag{4.5}$$

The current sources I_{sh} and I_{rh} are then calculated as such [36]:

$$\begin{aligned} I_{sh}(t) =& (\frac{1+h}{2})(\frac{1+h}{Z}e_r(t-\tau) - hI_{rh}(t-\tau)) + (\frac{1-h}{2})(\frac{1+h}{Z}e_s(t-\tau) - hI_{sh}(t-\tau)) \\ I_{rh}(t) =& (\frac{1+h}{2})(\frac{1+h}{Z}e_s(t-\tau) - hI_{sh}(t-\tau)) + (\frac{1-h}{2})(\frac{1+h}{Z}e_r(t-\tau) - hI_{rh}(t-\tau)) \end{aligned} \tag{4.6}$$

where

$$Z = Z_c + \frac{r}{4} \qquad h = \frac{Z_c - \frac{r}{4}}{Z_c + \frac{r}{4}}$$

$$Z_c = \sqrt{\frac{l}{c}} \qquad \tau = d\sqrt{lc}$$

Compared to the PI section line model, the distributed line model more accurately represents wave propagation phenomena and reflections at the ends of the line [36].

Simulations will be done with the latter, which will be made with R, L and C components for convenience. Resulting in figure 4.5.

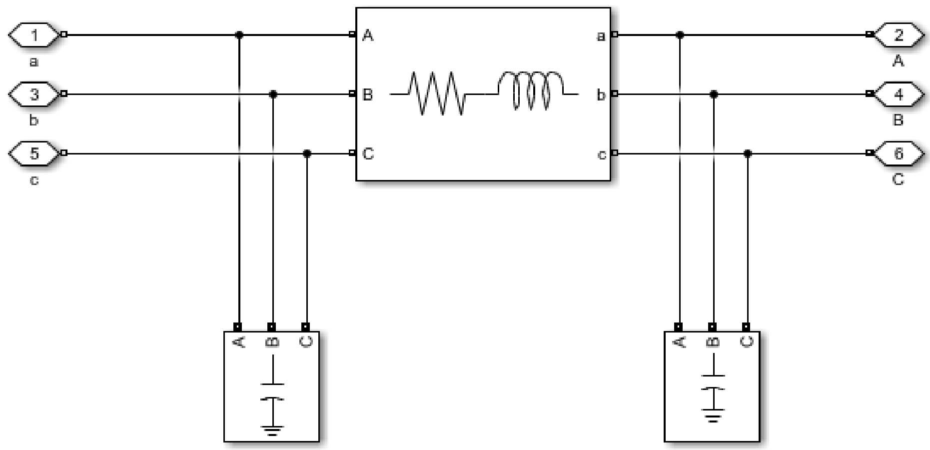


Figure 4.5: PI- Line cable

4.2.3 Three- Phase Transformer (Two Windings)

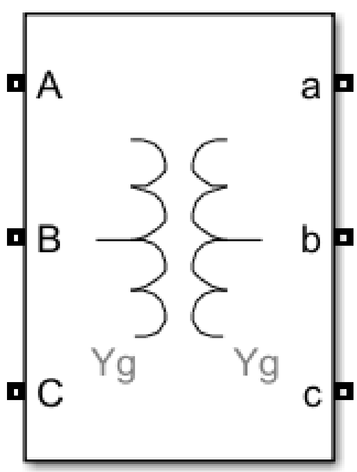


Figure 4.6: Simscape/ Electrical/ Specialized Power Systems/ Power Grid Elements/ Three-Phase Transformer (Two Windings) [38]

The Three-Phase Transformer Inductance Matrix Type (Two-Windings) block represents a three-phase transformer with a three-limb core and two windings per phase. This block takes into account the coupling between windings of different phases. Figure 4.7 shows the transformer core and windings. [38].

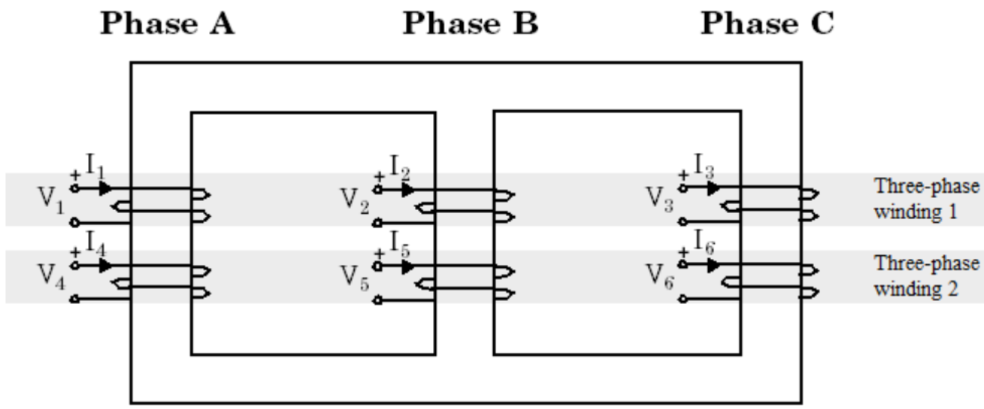


Figure 4.7: Transformer core and windings [38]

The phase windings of the transformer as numbered specifically as:

- 1 and 4 on phase A
- 2 and 5 on phase B
- 3 and 6 on phase C

The geometry implies that winding 1 is coupled to all other phase windings [38].

Transformer Model

The transformer block implements the following mathematical matrix relationship,

$$V_n = R_n \cdot I_n + L_{ij} \cdot \frac{d}{dt} I_n$$

$$\begin{bmatrix} V_1 \\ V_1 \\ \vdots \\ V_6 \end{bmatrix} = \begin{bmatrix} R_1 & 0 & \dots & 0 \\ 0 & R_2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & R_6 \end{bmatrix} \cdot \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_6 \end{bmatrix} + \begin{bmatrix} L_{11} & L_{12} & \dots & L_{16} \\ L_{21} & L_{22} & \dots & L_{26} \\ \vdots & \vdots & \ddots & \vdots \\ L_{61} & L_{62} & \dots & L_{66} \end{bmatrix} \cdot \frac{d}{dt} \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_6 \end{bmatrix} \tag{4.7}$$

The winding resistance is represented by $R1$ to $R6$. The self-inductance term L_{ii} and the mutual inductance terms L_{ij} are calculated using voltage ratios, inductive components of no-load excitation currents, and short-circuit reactance at nominal frequency. The diagonal and 15 off-diagonal terms of the symmetrical inductance matrix can be calculated using positive-sequence and zero-sequence values. The self and mutual terms of the $(6x6)$ L matrix are calculated using excitation currents where one three-phase winding is excited and the other is left open.

The self and mutual terms of the inductance matrix are calculated using excitation currents and positive- and zero-sequence short-circuit reactances ($X1_{12}$) and ($X0_{12}$), which are measured with three-phase winding 1 excited and three-phase winding 2 short-circuited. The calculation assumes certain positive-sequence parameters

$Q1_1$ = Three-phase reactive power absorbed by winding 1 at no load when winding 1 is excited by a positive-sequence voltage $Vnom_1$ with winding 2 open.

$Q1_2$ = Three-phase reactive power absorbed by winding 2 at no load when winding 2 is excited by a positive-sequence voltage $Vnom_2$ with winding 1 open.

$X1_1$ = Positive- sequence short-circuit reactance seen from winding 1 when winding 2 is short-circuited.

$Vnom_1$, $Vnom_2$ = nominal line-line voltages of winding 1 and 2.

The positive-sequence self and mutual reactances are given by:

$$\begin{aligned} X_1(1,1) &= \frac{V_{nom_1}^2}{Q1_1} \\ X_1(2,2) &= \frac{V_{nom_2}^2}{Q1_2} \\ X_1(2,2) = X_1(2,1) &= \sqrt{X_1(2,2)\cdot(X_1(1,1) - X1_{12})} \end{aligned} \tag{4.8}$$

The zero-sequence self-reactances $X_0(1,1)$ and $X_0(2,2)$, as well as the mutual reactances $X0(1,2)$ and $X_0(2,1)$, are calculated using similar equations. This is an extension from the $(2x2)$ reactance matrix in positive-sequence and zero-sequence.

Extension to this:

$$\begin{bmatrix} X_1(1,1) & x_1(1,2) \\ X_1(2,1) & x_1(2,2) \end{bmatrix} \quad \begin{bmatrix} X_0(1,1) & x_0(1,2) \\ X_0(2,1) & x_0(2,2) \end{bmatrix} \tag{4.9}$$

to a (6×6) matrix, is performed by replacing each of the four $\begin{bmatrix} x_1 & x_2 \end{bmatrix}$ pairs by a $(3x3)$ submatrix of the form:

$$\begin{bmatrix} X_s & X_m & X_m \\ X_m & X_s & X_m \\ X_m & X_m & X_s \end{bmatrix} \tag{4.10}$$

where the self and mutual terms are given by:

$$\begin{aligned} X_s =& (X_0 + 2X_1)/3 \\ X_m =& (X_0 - X_1)/3 \end{aligned} \tag{4.11}$$

To model core losses in positive- and zero-sequences, represented by active power (P_1) and (P_0), additional shunt-reactances are connected to the terminals of one of the three-phase windings. If winding 1 is selected, the resistances are calculated using specific equations:

$$R1_1 = \frac{V_{nom_1}^2}{P1_1} \quad R0_1 = \frac{V_{nom_1}^2}{P0_1} \tag{4.12}$$

Excitation current in zero-sequence

In some cases, the manufacturer may not provide the zero-sequence excitation current of a transformer with a 3-limb core. In such situations, a reasonable value can be estimated using a specific method

In figure 4.8 , there is a three-limb core with a single three-phase winding. When phase B is excited with a voltage, it induces voltages on phases A and C. The flux produced by phase B is shared equally between phases A and C, giving $\Phi/2$. This means that the voltage induced in phases A and C would be $-V_B/2$ if the leakage inductance of winding B were considered. However, when all three phases are excited, the average value of the induced voltage ratio k is slightly lower than 0.5 due to the leakage inductance of the three windings.

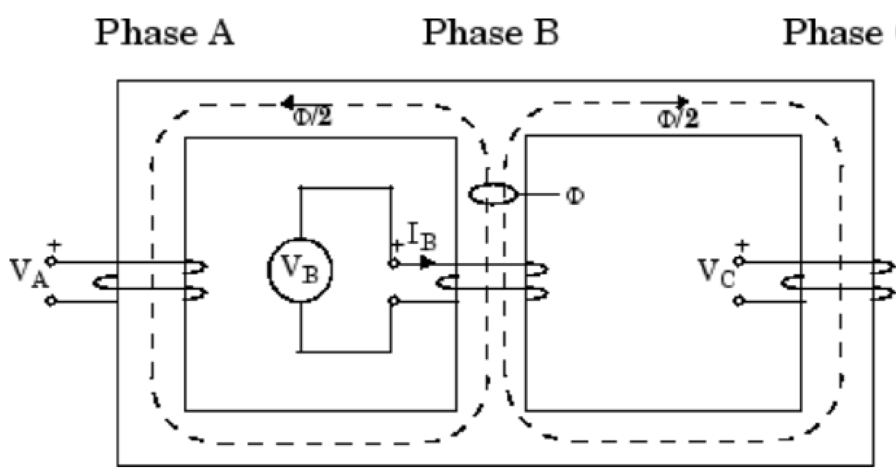


Figure 4.8: Excitation current in zero sequence [38]

Assuming:

- Z_s = Average value of the three self-impedances
- Z_m = Average value of mutual impedance between phases
- Z_1 = Positive-sequence impedance of three-phase winding
- Z_0 = Zero- sequence impedance of thee-phase winding
- I_1 = Positive-sequence excitation current
- I_0 = Zero-sequence excitation current

$$\begin{aligned} V_B &= Z_s I_B \\ V_A &= Z_m I_B = -V_B/2 \\ V_C &= Z_m I_B = -V_B/2 \\ Z_s &= \frac{2Z_1 + Z_0}{3} \\ Z_m &= \frac{Z_0 - Z_1}{3} \end{aligned} \tag{4.13}$$

$$V_A = V_c = \frac{Z_m}{Z_s} V_b = -\frac{\frac{Z_1}{Z_0} - 1}{2\frac{Z_1}{Z_0} + 1} V_b = -\frac{\frac{I_0}{I_1} - 1}{2\frac{I_0}{I_1} + 1} V_B = -kV_B, \tag{4.14}$$

where k = ratio of induced voltage (with k slightly lower than 0.5)

Therefore, the I_0/I_1 ratio can be deduced from K:

$$\frac{I_0}{I_1} = \frac{1+k}{1-2k} \tag{4.15}$$

The value of k cannot be exactly 0.5 because it would result in an infinite zero-sequence current. When the three windings are excited with a zero-sequence voltage, the flux path should return through the air and tank surrounding the iron core, resulting in a zero-sequence current due to the high reluctance of the zero-sequence flux path. Assuming I0 = 0.5%, a reasonable value for I_0 could be 100%, making $I_0/I_1 = 200$. From this, we can deduce that $k = (200 - 1)/(2 \times 200 + 1) = 199/401 = 0.496$. Zero-sequence losses should also be higher than positive-sequence losses due to additional eddy current losses in the tank. The value of the zero-sequence excitation current and losses are not critical if the transformer has a winding connected in Delta because it acts as a short circuit for zero-sequence. [38].

Limitations

This transformer model doesn't account for saturation. To model saturation, you can connect the primary winding of a saturable Three-Phase Transformer (Two Windings) in parallel with the primary winding of your model. Make sure to use the same connection type (Y_g, Δ_1 or Δ_{11}) and winding resistance for both windings. For the secondary winding, specify a Y or Y_g connection and leave it open. Choose appropriate voltage, power ratings, and saturation characteristics. The saturation characteristic is achieved when the transformer is excited by a positive-sequence voltage.

This model produces acceptable saturation currents for transformers with three single-phase cores or a five-limb core because the flux remains trapped inside the iron core. For a three-limb core, the model still produces acceptable results even if zero-sequence flux circulates outside the core and returns through the air and transformer tank. Since the magnetic circuit is mainly linear and has high reluctance when zero-sequence flux circulates in the air, high magnetizing currents are required. These high zero-sequence currents are already accounted for in the linear model. Connecting a saturable transformer outside the three-limb linear model with a positive-sequence flux-current characteristic produces currents required for magnetization of the iron core. This model gives acceptable results whether or not the three-limb transformer has a delta [38].

4.2.4 Three- Phase Programmable Voltage Source

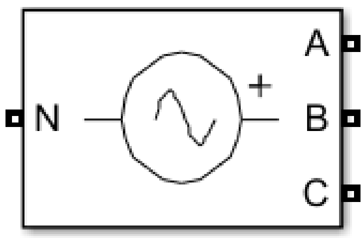


Figure 4.9: Simscape/ Electrical/ Specialized Power Systems/ Power Grid Elements/ Three-Phase Programmable Voltage Source [39]

This block generates a three-phase sinusoidal voltage with parameters that vary over time. The amplitude, phase, and frequency of the fundamental component can be programmed to change with time. Additionally, two harmonics can be added to the fundamental signal [39].

4.2.5 Model tools

When inspecting the results, tools such as voltage measurement blocks, RMS blocks, and impedance measurement blocks will be used for impedance measurement. Additionally, the powergui block sets the initial conditions for the main blocks and can plot impedance versus frequency.

4.3 Simulink model: Powerplant Thea

The finished model includes a synchronous machine, a pi line cable, a transformer, and a stiff grid. It was built with the components explored earlier in the chapter.

The generator is fed by a mechanical input ramping up to $250MW$ over two seconds. And a voltage signal at $16kV$. The voltage input includes a feedback loop subtracting the terminal voltage and sending it into a p-controller, ensuring voltage control in the power system.

The generator delivers $250MW$ at $16kV$, to a step-up $\Delta - Y$ transformer, ramping up the voltage to 420 kV.

4.3.1 Model settings and tests

The ode23t solver is a numerical technique that can solve ordinary differential equations (ODEs) and differential algebraic equations (DAEs). It uses the trapezoidal rule for numerical integration. This solver is especially useful for moderately stiff problems where the solution changes at different rates in different regions. In such cases, the ode23t solver can provide a solution without introducing numerical damping, which can artificially reduce oscillations in the solution [40].

In simulations, the synchronous generator and RMS voltage measurements throughout the system will be monitored. Impedance measurements will also be taken.

4.3.2 Model Configuration

Synchronous machine	**Value**
Nominal Power P_n	$250MVA$
Line-line voltage	$16kV$
Frequency	$50Hz$
Inertia	$6kg \cdot m^2$
Pole pairs	20 pairs
Internal impedance	$[0.02\Omega, 0.8mH]$
PI line	**Value**
Number of phases $[N]$	3
Line length (km)	Variable
Frequency used for RLC specification (Hz)	$50Hz$
Resistance per unit length (Ohms/km) [NxN matrix]	Variable
Inductance per unit length (H/km) [NxN matrix]	Variable
Capacitance per unit length (F/km) [NxN matrix]	Variable
Transformer	**Value**
Nominal Power P_n	$300MVA$
Frequency	$50Hz$
Nominal line-line voltages, $[V_1, v_2]$	$[420kV, 16kV]$
Winding resistances $[R_1, R_2]$	$[0.01, 0.01]$
Positive-sequence no-load excitation current (% of Inom)	2
Positive-sequence no-load losses (W)	1500
Positive-sequence short-circuit reactance X12 (pu)	0.06
Zero-sequence no-load excitation current with Delta windings opened	100
Zero-sequence no-load losses with Delta windings opened (W)	3.250MW
Zero-sequence short-circuit reactance X12 (pu)	0.03

Table 4.3: Component settings

4.3.3 Final model

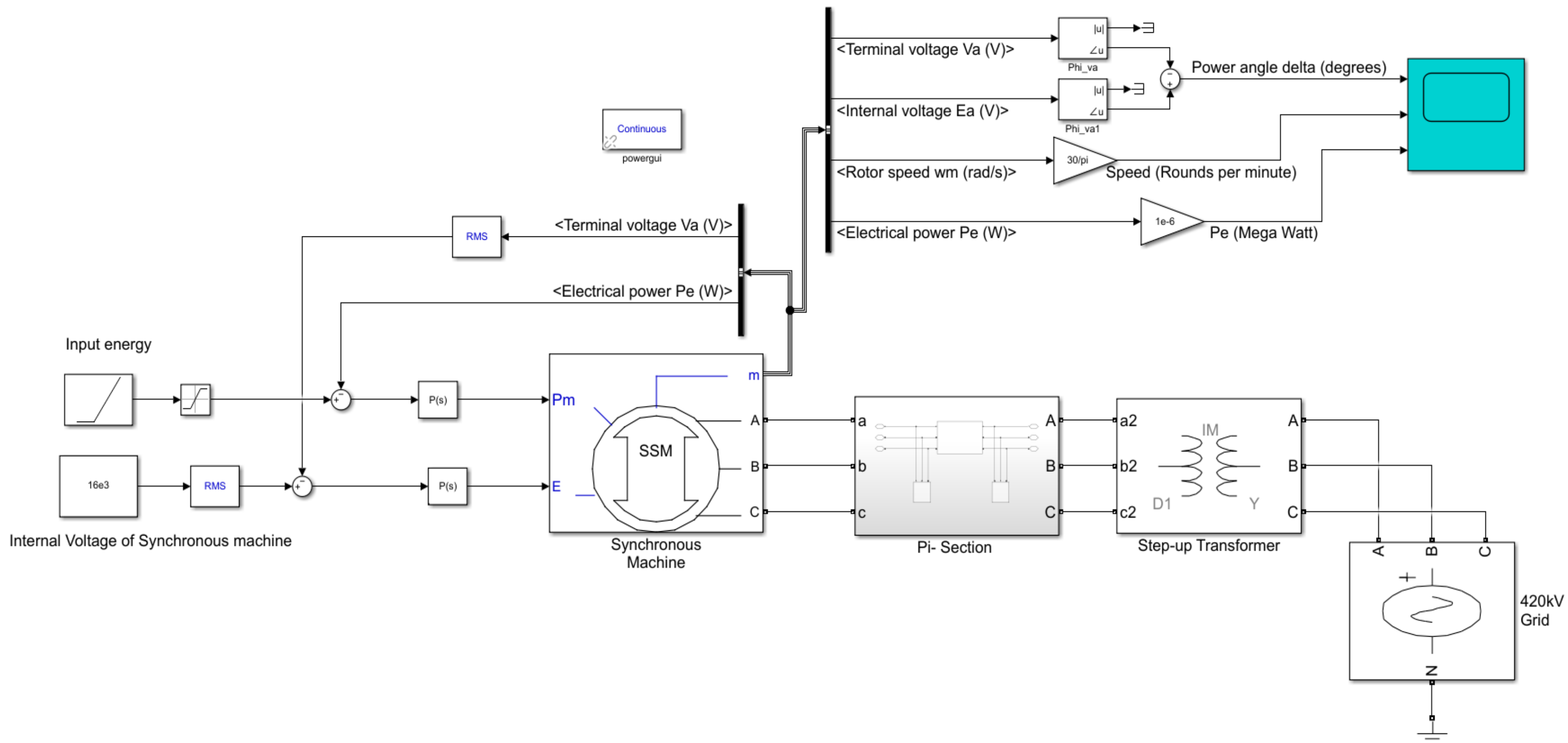


Figure 4.10: Power plant Thea

5

Results and Discussion

In order to prepare final words and discussions, It is necessary to look at results for different case studies. this chapters purpose is to examine different configurations of a simulated powerplant.

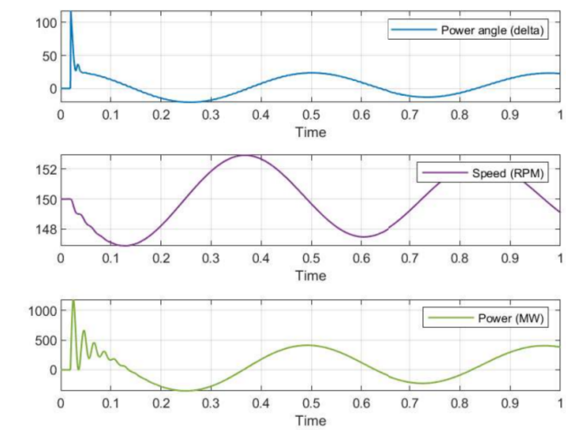
The primary purpose of simulation and using different models:

- How will different models and lengths of cable affect voltage stability and the system in general.
- How will resonance frequency compare with or without long cables
- Will there occur potentially unwanted or dangerous voltage transients in any of the cases.

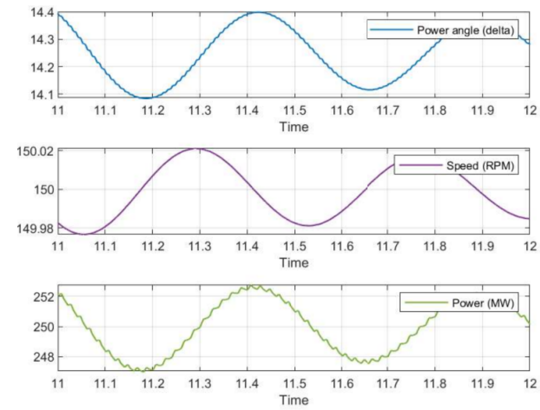
5.1 Case 1: Without cable

To determine a reference point, the model is run without cable at first. Substituting the cable with a grounded parallel capacitive load drawing $100VAR$. Simulating starting the machine, and seeing stability after 12 seconds.

Machine stability



(a)



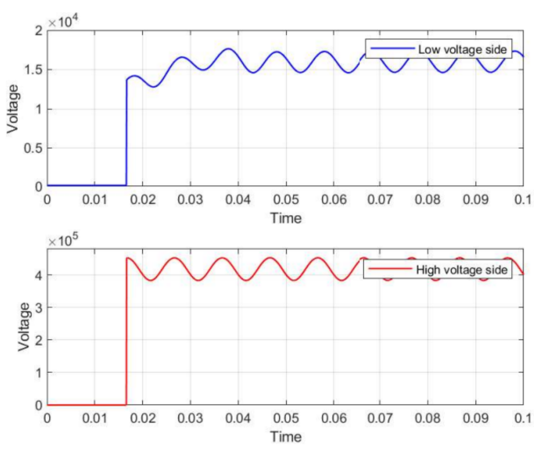
(b)

Figure 5.1: First two and last two seconds of simulation, over a 12 seconds period.

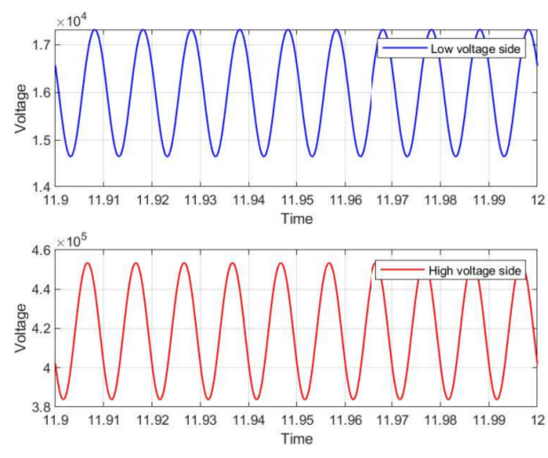
Figures 5.1a and 5.1b gives the operational parameters of the generator the first and last two seconds. Showing power angle (δ), speed (RPM) and power delivered in (MW)

Voltage stability

Voltage stability is also satisfactory, holding rated values at the transformer.

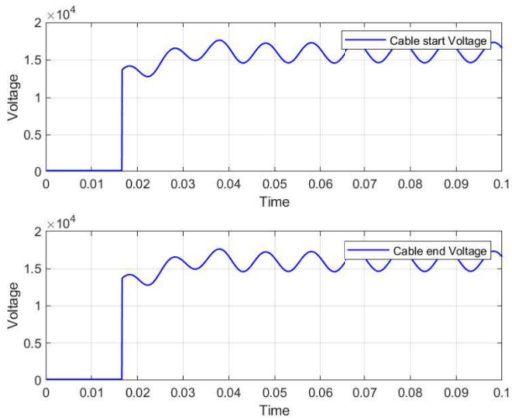


(a)

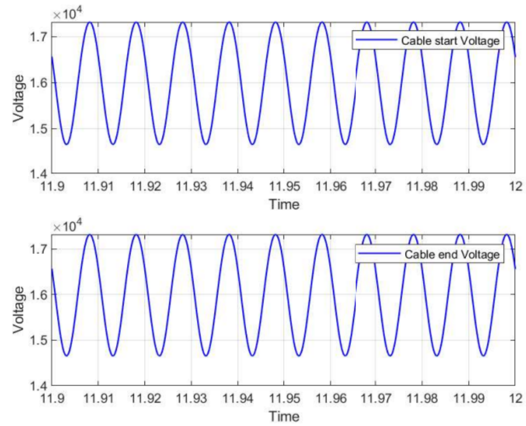


(b)

Figure 5.2: Voltage no cable first and last 0.1 seconds



(a)



(b)

Figure 5.3: Voltage no cable before transformer first and last 0.1 seconds

5.2 Case 2: With PI -line cable

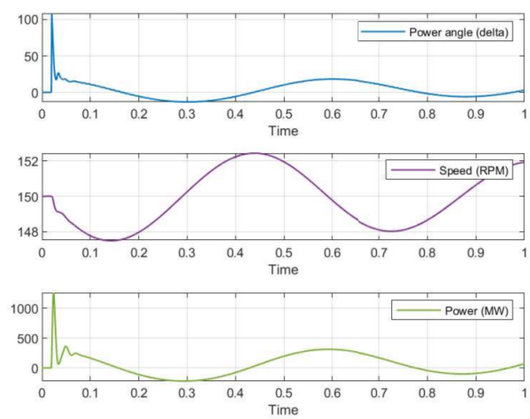
Case two includes three different lengths of cable; 800m, 2km and 5km respectively. The Impedance of the lumped parameter pi-line will be calculated following table 5.1.

Resistance	Inductance	capacitance
0.121Ω/km	0.38mH/km	0.25 μF/km

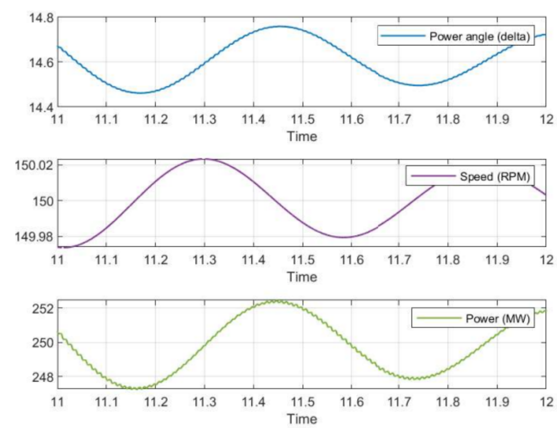
Table 5.1: Impedance/km

5.2.1 800 m cable

Machine stability



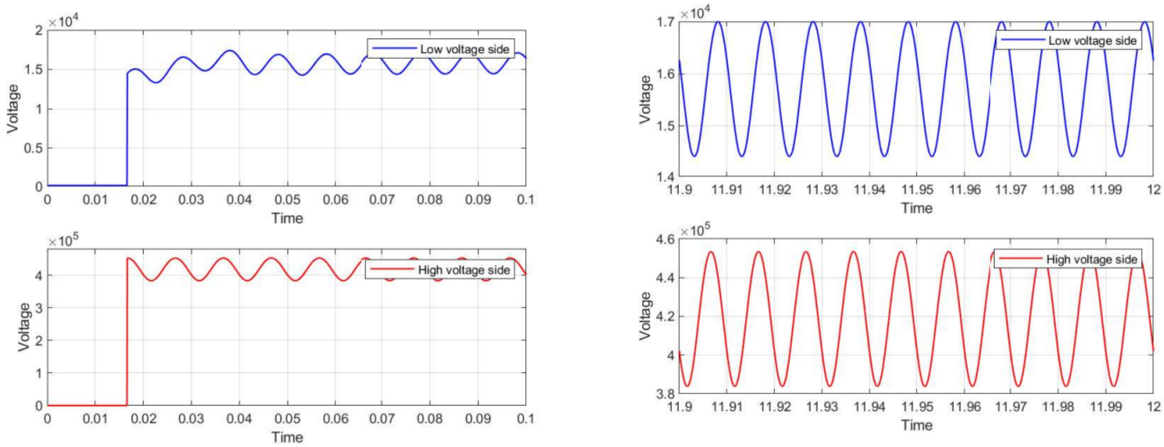
(a)



(b)

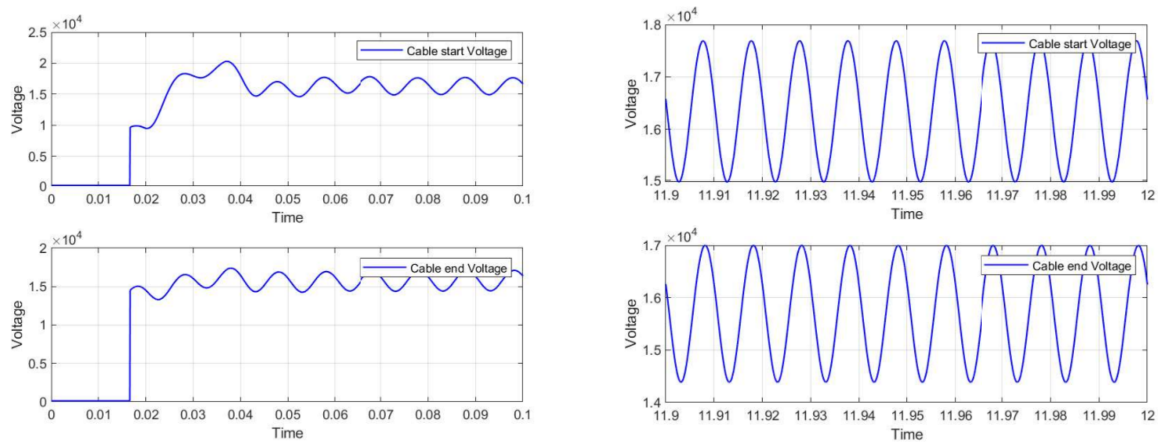
Figure 5.4: First and last two seconds of simulation, over a 12 seconds period.

Voltage stability



(a) (b)

Figure 5.5: Voltage cable con-fig 1 first and last 0.1 seconds



(a) (b)

Figure 5.6: Voltage cable start and end

Impedance vs frequency

Another measurement to made

measure the resonant frequencies at different points in the system. For example, you can measure the resonant frequency of the cable by connecting an impedance analyzer to both ends of the cable. Similarly, you can measure the resonant frequency of the transformer by connecting an impedance analyzer to the primary and secondary windings of the transformer.

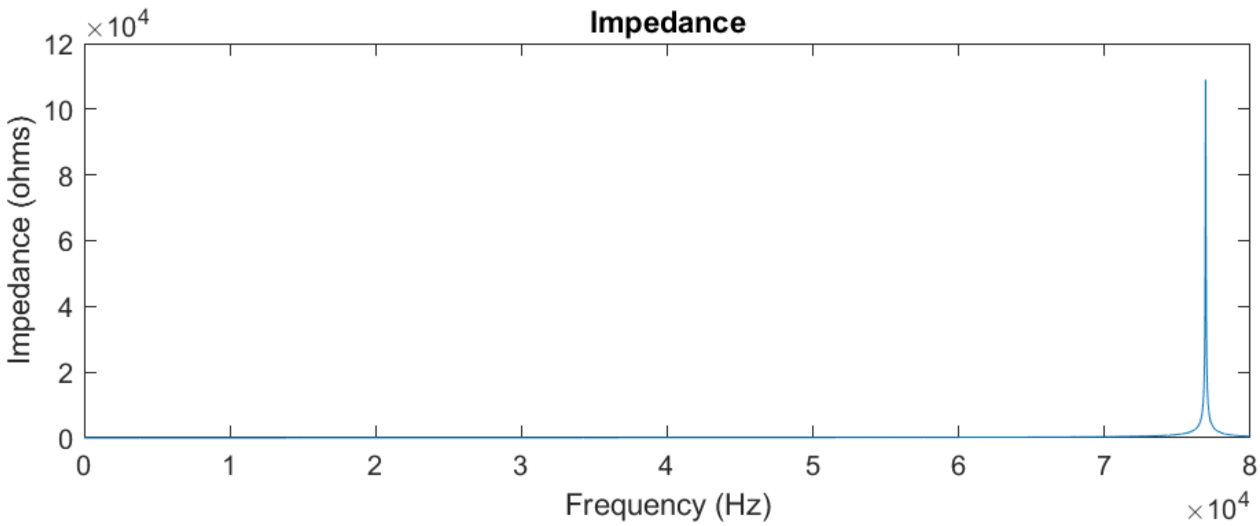
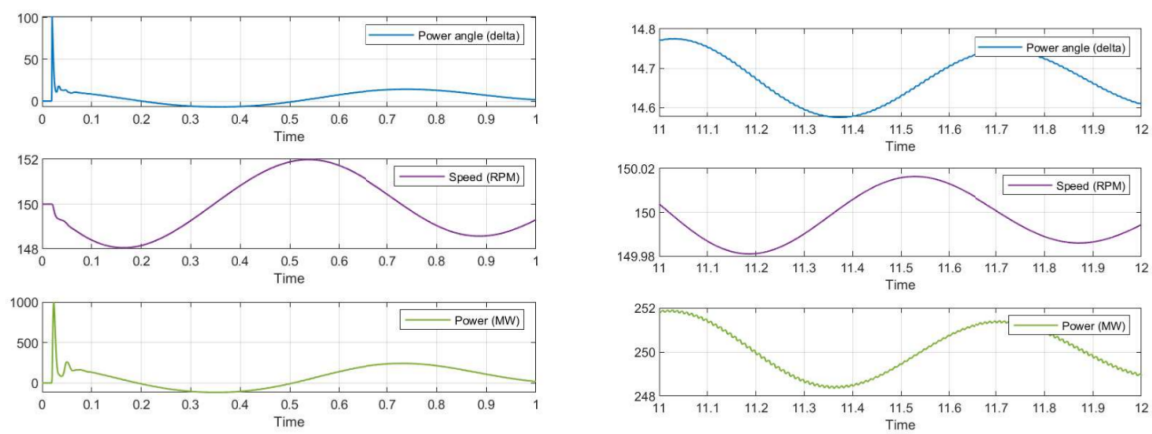


Figure 5.7: BODE PLOT

5.2.2 2 km cable

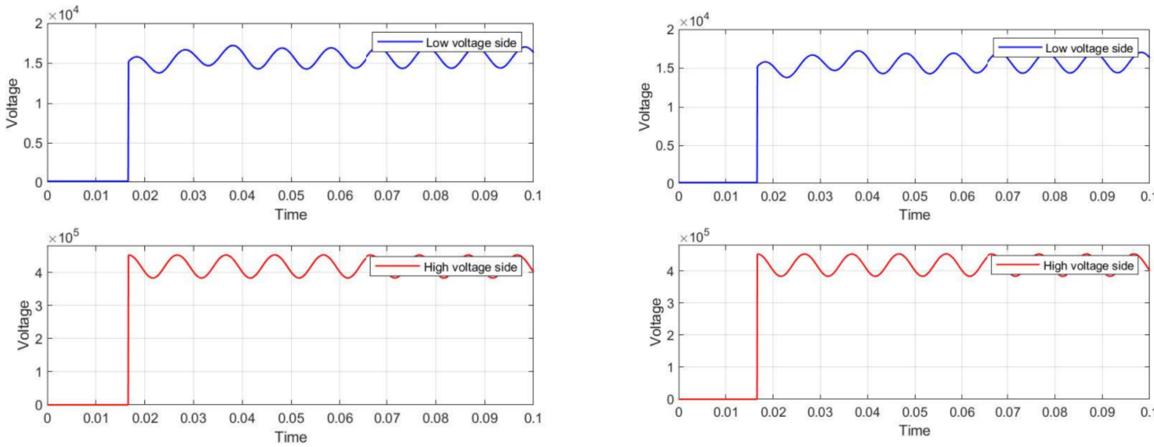
Machine stability



(a) (b)

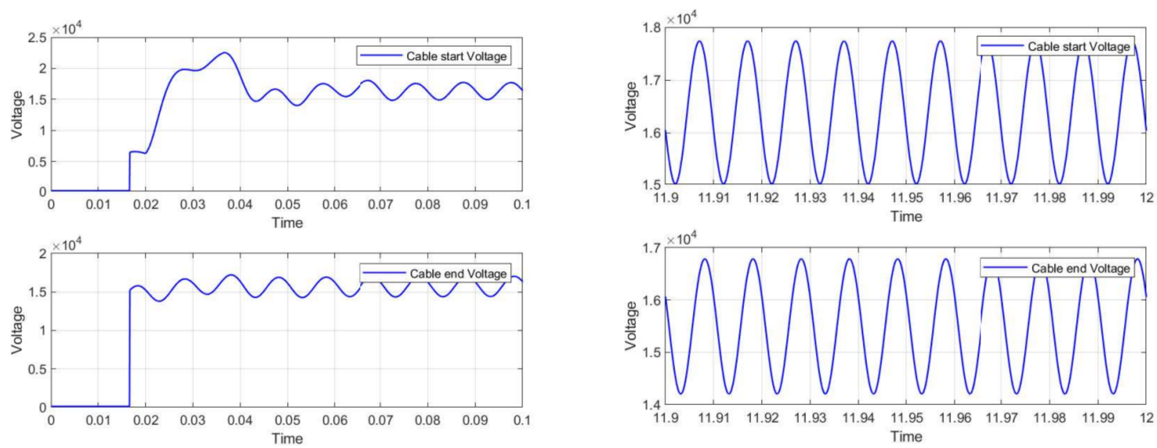
Figure 5.8: First and last two seconds of simulation, over a 12 seconds period.

Voltage stability



(a) (b)

Figure 5.9: Voltage cable con-fig 1 first and last 0.1 seconds



(a) (b)

Figure 5.10: Voltage cable start and end

Impedance vs frequency

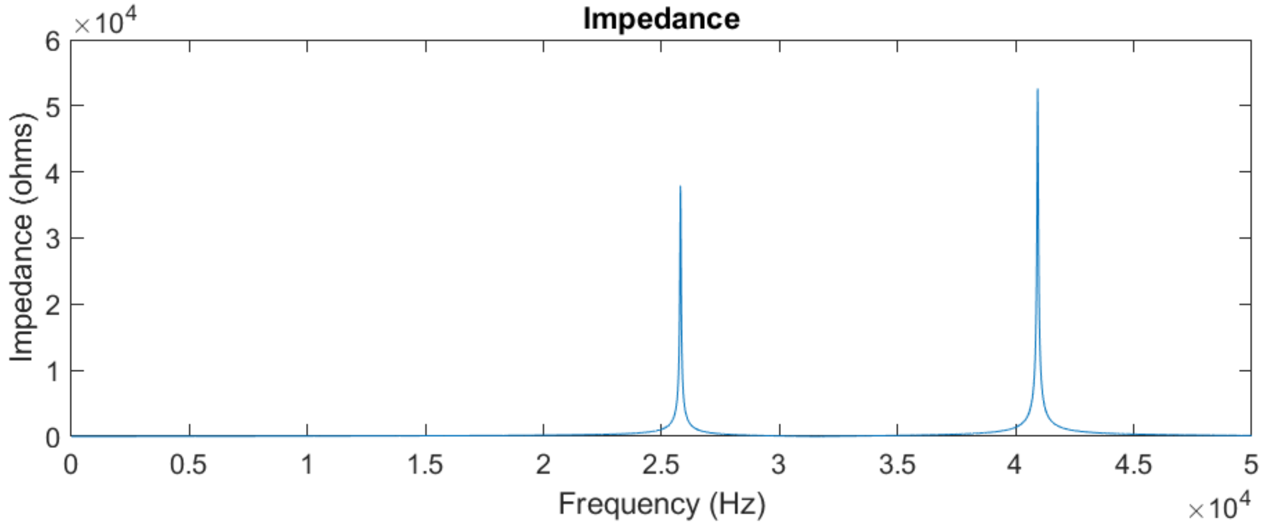
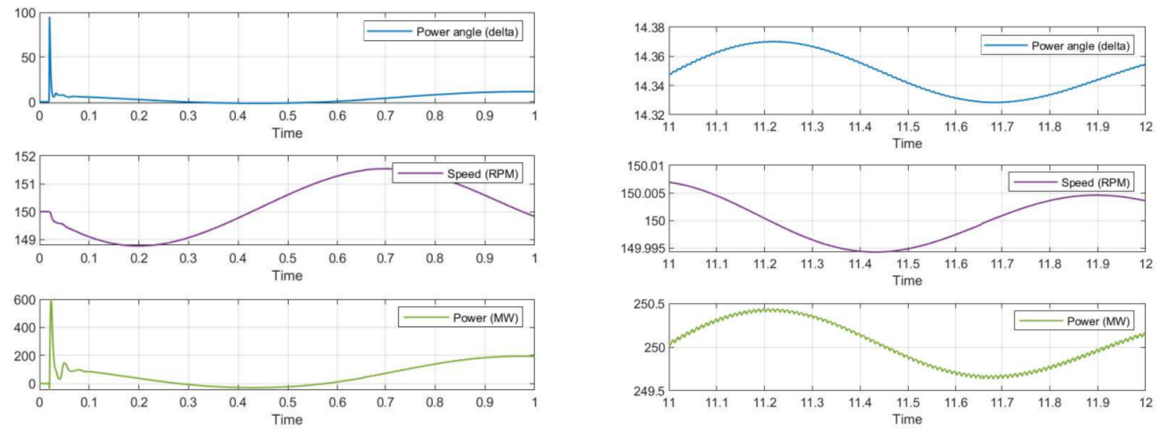


Figure 5.11: BODE PLOT

5.2.3 5 km cable

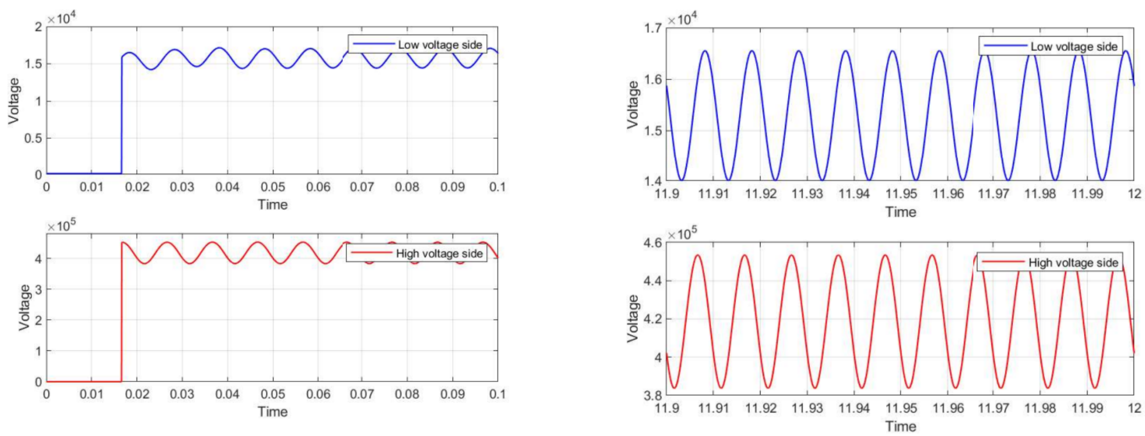
Machine stability



(a) (b)

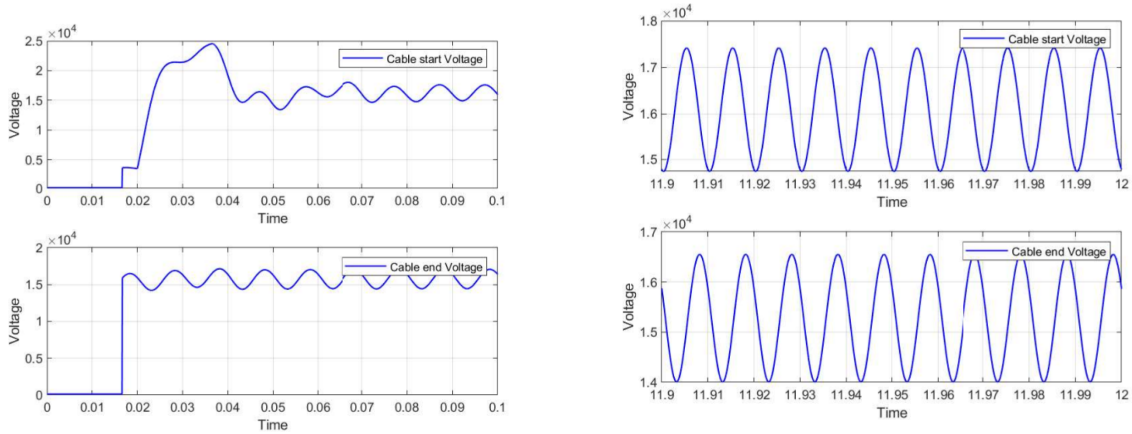
Figure 5.12: First and last two seconds of simulation, over a 12 seconds period.

Voltage stability



(a) (b)

Figure 5.13: Voltage cable con-fig 1 first and last 0.1 seconds



(a) (b)

Figure 5.14: Voltage cable start and end

Impedance vs frequency

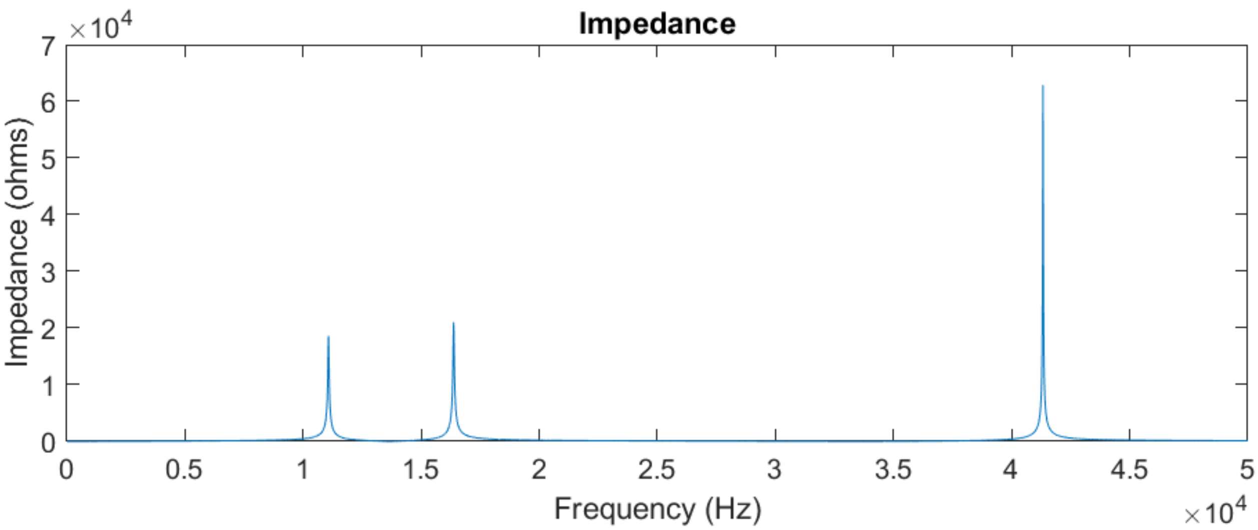
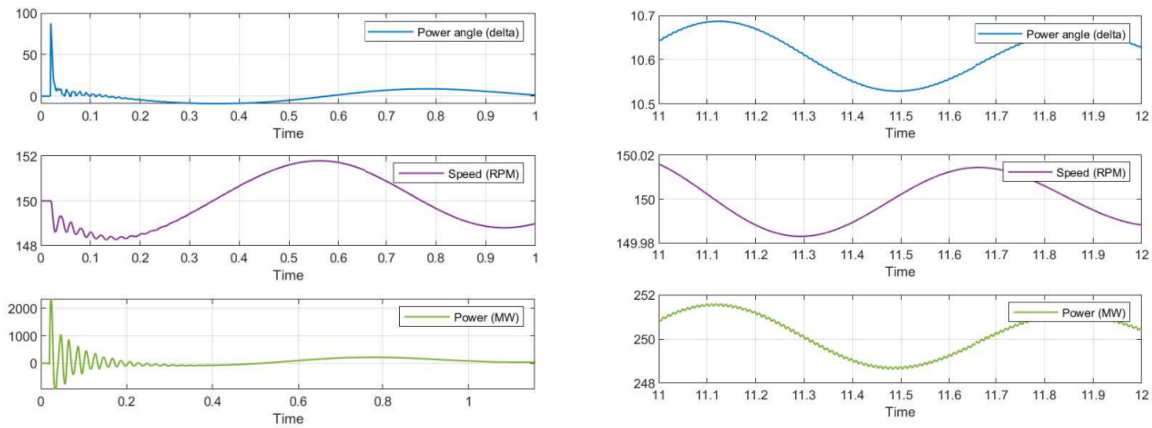


Figure 5.15: BODE PLOT

5.3 Case 3: Extra load on generator side

Introducing an additional capacitive load before the long cables. With voltage at $1kV$. and $Q_c = 8000VAR$

Machine stability



(a) (b)

Figure 5.16: First and last two seconds of simulation, over a 12 seconds period.

Voltage stability

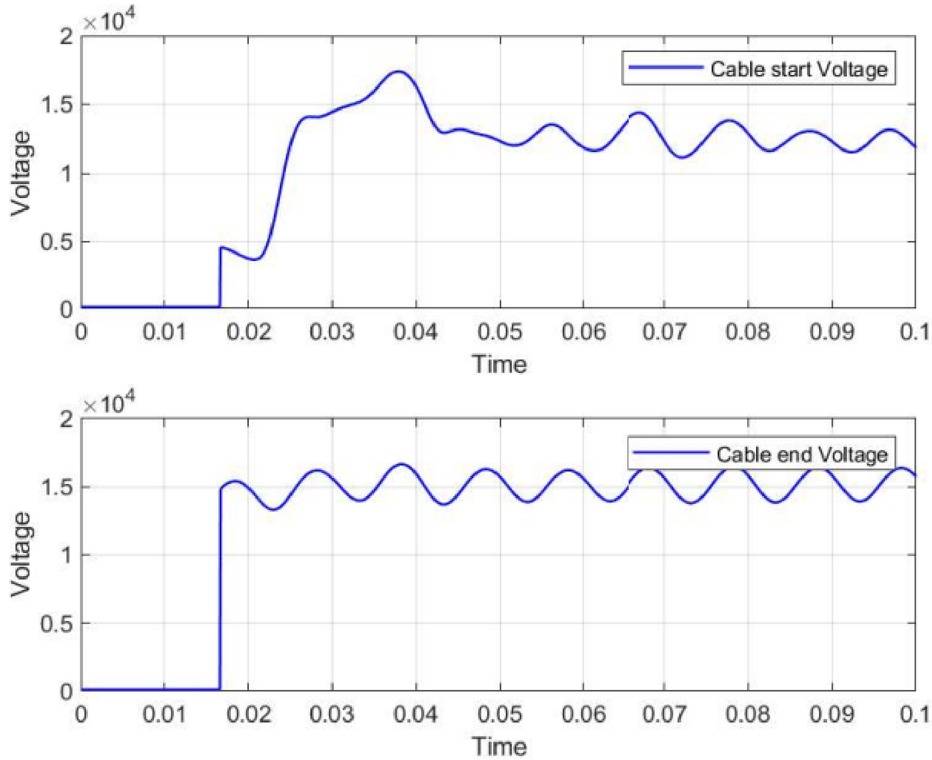


Figure 5.17: 5 km cable, with additional capacitive load before

6

Conclusion

Chapter 6, the final chapter of this thesis, will conclude on the research that has been carried out. This chapter will summarize the main findings and contributions of this study, discuss their implications, and suggest directions for future research.

6.1 Conclusion

This thesis has provided a fundamental understanding of issues related to voltage transients and resonant frequencies in a power plant connected to a stiff grid. Relevant studies have been presented as a foundation for further investigation on the matter. Additionally, a model has been developed and used to investigate the effect of cable length on voltage stability and resonance frequency issues. The results of this analysis provide valuable insights into the impact of cable length on these issues.

6.1.1 Voltage transients

The results provided in chapter 5 together with earlier research in chapter 3 proves that longer cables introduces capacitances that could induce voltage transients. From the model results, especially. A voltage spike is seen on the generator side of the longer cable. If system machine and voltage stability is tracked in the last chapter, over the cases. We can see lesser stability in the overall system.

6.1.2 Resonance frequency issues

The other core issue has also been related to the introduction of more impedance at lower voltage level. Inviting more resonance harmonics to the power system. Following the bode plots, we see resonant frequencies at lower levels and more multiples when extending the cable length.

6.1.3 Recommendation

Though this research has been carried out on a simplified model, the recommendation when considering such installments of cable is to carry out specific system modelling and see the effects of capasitive installments. To assess the risks of transients and avoiding the resonant frequencies.

6.2 Further work

Further work on this topic would be to expand on the model with specifics on actual components and introduce a distributed line.

6.3 Limitations

in section 4, a distributed line model was referred to as the preferred model before the lumped pi-line model. The distributed line brought with it some difficulties in the rest of the system. But is surely possible to work with more development of the model. The lumped pi section is a simplification of a real work cable. But it's a sufficient approximation as far as noticing the affects.

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