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Fault Current Generation by STATCOM

Master's thesis in Electrical Power Engineering

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Fault Current Generation by STATCOM

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Abstract

The penetration level of renewable energy resources increases in the power grid since they do not have a negative impact on the environment as the conventional power plants. Renewable energy resources are not required, by the current grid codes, to contribute to restore the voltage stability. Moreover, they do not contribute to the short circuit current during fault disturbance. As a consequence, the reliability as well as the voltage stability of the power grid have been negatively affected during the disturbance.

In this thesis, STATCOM model has been developed, with different priority control strategy, to increase the fault current as well as to enhance the voltage stability to support the renewable energy resources to meet the grid requirements. Three priority control strategy has been considered: 1) STATCOM with only positive sequence control strategy; 2) STATCOM with only negative sequence control strategy; 3) STATCOM with positive and negative sequence control strategy with equal ratio of 0.5. Each strategy has its own advantage and disadvantage in terms of increasing the positive voltage and reducing the negative voltage in power grid. Furthermore, there level of contribution to the short circuit current depends on the type of fault and the grounding of transformer.

Using the STATCOM device to enhance the performance of renewable energy resources during the disturbance will help to increase the penetration of renewable energy resources to the grid without having a negative impact on the voltage stability and the grid reliability.

Keywords:

Grid Code, LVRT, STATCOM, Positive voltage, Negative voltage, Short circuit current, Priority control, Second harmonic.

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Author

Osama Mohammed Almutairi

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Contents

List of Figures

List of Tables

List of Abbreviations

RES	Renewable Energy Sources
SCC	Short Circuit Current
FACTS	Fixable AC transmission system
SVC	Static Var Compensator
STATCOM	Static Synchronous Compensator
PCC	Point of Common Coupling
PWM	Pulse width modulation
PLL	Phase Locked Loop
SLG	Single Line to Ground
DLG	Double Line to Ground
DL	Double Line

Chapter 1

Introduction

1.1 Background

The need for renewable energy sources (RES) have been increased as conventional power plants has an impact on the environment with greenhouse gases. So, almost every country on the world has future plan to integrate more renewable sources and shutting down the conventional plants, such as nuclear plant. For instant, Germany is already supplying third of their electricity demand with renewable energy and has future plant to increase the share of the renewable energy to cover up to 50% of their demand with renewable source by 2030 [1]. By 2020, Denmark will supply 50% of electricity with renewable energy. Furthermore, Denmark has goal to be fossil fuel free by 2050 by integrating large amount of renewable energy source into their grid and replacing the natural gas, oil and coal with renewable energy and bio-energy [2].

RES, such as wind and solar, have an affect on the short circuit capacity of the power gird. The RES behave differently from synchronous machines in term of contributing to the short circuit current (SCC) during any disturbance in the system, which has an impact on the protection device reliability since these devices depend on sensing the currents flowing in the transmission lines. RES have been treated as a small generation in the grid and they are allowed to be disconnected from the grid, if the voltage level drops below 80%. Because, they are not required to contribute to restore the voltage stability and they considered unimportant generation in terms of loss of production [3]. This disconnection will cause another disturbance to the grid after already been through a crucial situation. Thus, new technological problem are introduced to the system due to the high level of renewable energy penetration into the grid. Especially, with power compensation, low voltage ride through (LVRT) capability, and short circuit capacity of the network. As result, the power grid becomes weak. Some countries, such as Germany, UK and Denmark, have created some new regulation in order to connect RES to their power system. These requirements will result in improving the reliability of RES in the grid in terms of voltage stability as well as SCC contribution during the disturbance.

During an unbalanced fault, the voltage across the dc link in full converter synchronous wind turbine increases to a level that can either trip the protection relay or damage the converter because of the output power in the grid side is reduced while the power supplied by synchronous generator remains unchanged[4]. Therefore, the contribution to the negative sequence components is limited. In addition, STATCOM is usually used to contribute to the positive sequence component, which does not help to balance the power grid in the event of unbalance fault. The development of STATCOM with different control strategy has been implemented to compensate for positive and negative sequences components to support voltage restoration as well as the power grid stabilization.

1.2 Aim

The aim of the project is to develop a STATCOM control strategy to quickly inject current during fault condition to enhance RES to meet the grid code requirements. Furthermore, reactive current injection during fault disturbance to support the system to recover the voltage as well as improving the system reliability. Moreover, testing the grid with different priority setting for positive and negative sequence to investigate the impact of negative sequence on the grid voltage stability as well as the fault current contribution.

1.3 Thesis Outline

This paper is divided into seven sections. The first chapter gives a brief overview of the problem and the aim of the project. The second chapter describing the Grid Code technical specification on the behavior of the power plant. In the third chapter a short review on the theoretical background on symmetrical component, shunt compensation devices and the STATCOM characteristics is provided. The modeling of the STATCOM is described in the fourth chapter. In the fifth chapter the result is discussed and analyzed. Chapter six discuss the environmental and ethical aspect of the project in general. Finally, a brief conclusion about the final result and some suggestions for future work.

Chapter 2

Grid Code

This chapter provides a comprehensive literature review about grid code requirements for RES.

2.1 Introduction

Grid code requirements are technical specification, which define the behavior of the generating power plant under continuous as well as dynamic conditions in the network. It has been found to ensure the safety and the reliability of the national network. Furthermore, common grid disturbances are described in detail, on how the power plant should withstand the disturbances without disconnecting from the network. In severe condition, disconnecting the power plant is feasible, but the transmission system operator need to be informed to give the permission. Grid code elaborates more on wind and solar power plants. It leads to a great development of wind turbine technology recently.

In this chapter the gird code requirements on wind power plant for different countries are interpreted.

2.2 Requirement during steady state operation

There are three main requirement of the grid code during Normal operation condition: 1) The active power output should not drop during the deviation of the frequency; 2) Reactive power demand for typical voltage operation limit; 3) Reactive power demand during active power production. Steady state operation will not be considered in this thesis.

2.3 Requirement during dynamic condition

In this section, the dynamic condition requirement to interconnect to the grid will be presented. This thesis will focus on the requirement for LVRT as well as for supporting the voltage during severe voltage drop.

Since there is not such described requirement for connecting STATCOM to the grid, the grid code requirement for connecting wind turbine will be considered. The STATCOM will be included in wind park system, which will complement the wind farm to fulfill together the grid code.

2.3.1 Low voltage ride through requirement

Low voltage ride through (LVRT), which also known as fault ride through (FRT), is the ability of electric generator to stay connected during a fault condition for short period of time in order to support the system to restore stability. LVRT profiles is characterization in terms of fault time, retained voltage and recovery ramp rates, this is illustrated in Figure 2.1.

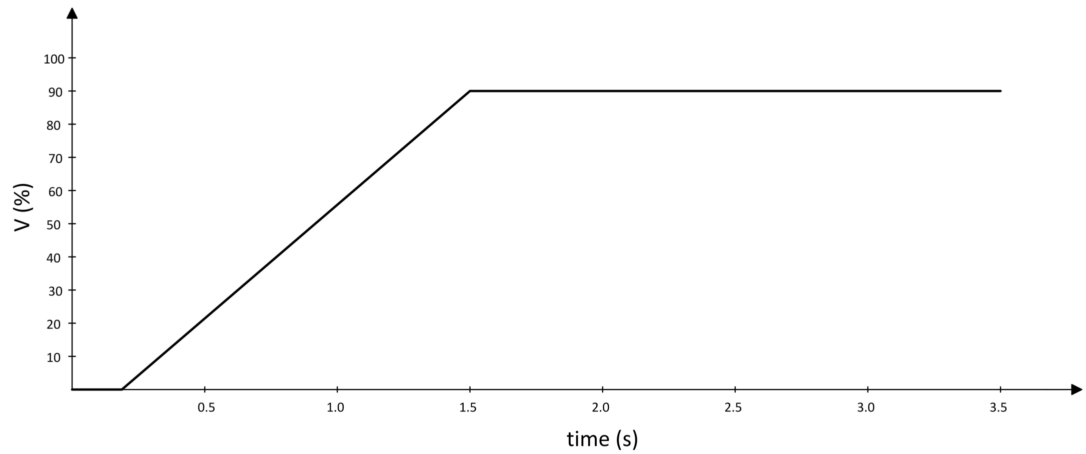


Figure 2.1: Typical curve for LVRT requirements[5]

Generally speaking countries with high penetration of renewable energy have developed their own grid code with relatively detailed specification of the voltage characteristic during a disturbance. A comprehensive comparison of LVRT is presented in [5]. Figure 2.2 illustrates voltage profile for various Grid Codes. Usually, LVRT requirement is applied for wind turbine. The manufacture of wind energy needs to considered this technical specification in their own products. Grid code require wind parks to support the gird during the disturbance by injecting reactive current.

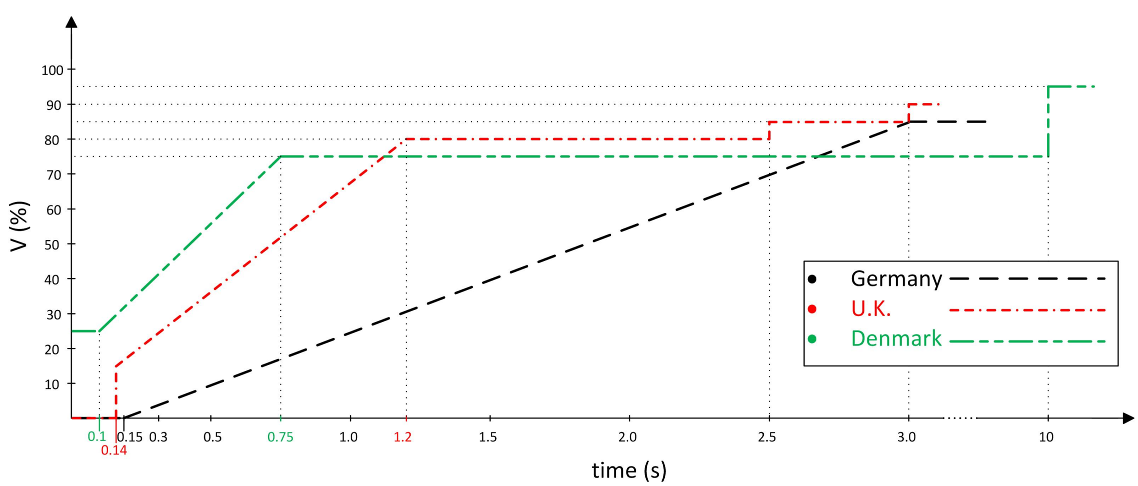


Figure 2.2: Voltage profiles for different Grid Codes [5][6][7]

- **Germany:**

  German grid code [5][6] requires a LVRT to restore up to 85% of the voltage in $3s$, as shown in Figure 2.2. In addition, it demands reactive current support during the restoration of the grid voltage. If the grid voltage varied more than $0.1pu$, the voltage control should be activated within 20 ms, according to the German Grid

Code [6]. Furthermore, the controller must inject a reactive current of at least 2% of the rated current for every 1% drop in voltage, as shown in Figure 2.3.

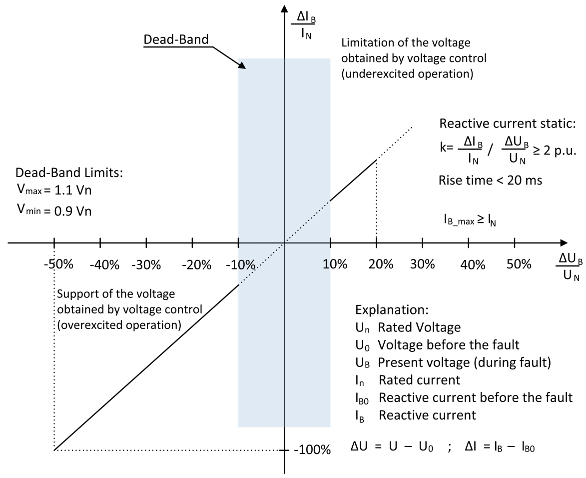


Figure 2.3: Voltage profiles for different Grid Codes[6][8]

- **UK:**

  UK grid code [7][5] requires wind turbines to stay connected during voltage dip caused by either symmetrical or unsymmetrical disturbance, even if the voltage drops down to 0%, as depicted in Figure 2.2. After the recovery of the nominal voltage level at the low voltage side, active power must be restored to at least 90% of the pre fault value, unless there has been a cutback in the power sources.

- **Denmark:**

  Figure 2.2 illustrates the LVRT requirements for the Danish grid code[5][9]. For voltage levels below $100kV$, wind farms should stay connected even after a sequence fault events and for voltage levels above $100kV$ has slightly different sequence fault events [5].

All the grid codes requirements are enforced to the wind power plants. Since, the most common type of wind turbines are decoupled from the grid by power electronic converter and the STATCOM is based on power electronic devices, this paper is studying the possibility for the STATCOM to fulfill these requirement in order to enhance the reliability of the wind power plants. German Grid code is considered on this thesis.

2.4 Short circuit current requirement

In general, any generating plant must not get disconnected form the grid during fault events outside the plant's protection zone. They must contribute to the short circuit current during the fault period, which must be coordinated with transmission system operators in each individual case [8]. As per German grid code [6], the wind turbine should contribute to the SCC during the fault disturbances. If the wind turbine contribute to the SCC with positive sequence control, it will increase the voltage across the healthy line to a level that will trip an over-voltage relay, effect the sensitive load in the system or damage the power electronic switches. In order to prevent the over-voltage across the healthy line negative sequence control is needed.

2.4.1 Negative sequence control

According to Germany grid code [6], if the negative sequence voltage is below 5% then the negative sequence controller should not contribute to the negative sequence voltage in the system. However, if the negative sequence voltage is above 5% then the negative sequence control should be activated, as illustrated in Figure 2.4. The negative sequence current are linearly proportional to the negative sequence voltage, which based on the slope (k). The reactive current injection should be within the green lines with the slopes of $k = 2$ and $k = 6$, as described in the below equation.

$$\Delta i = k * \Delta v \tag{2.1}$$

Where K is the gain factor.

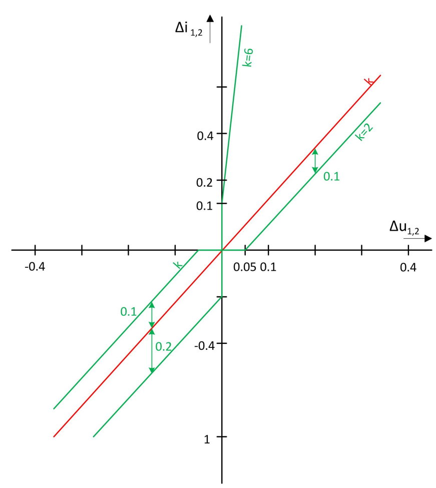


Figure 2.4: Reactive current injection limits[6]

2.4.2 Short term over voltage profile requirement

According to the Germany grid code [6], the voltage should not exceed 30% above the nominal voltage for more than 100ms and 25% above the nominal voltage for about 60s, as illustrated in Figure 2.5.

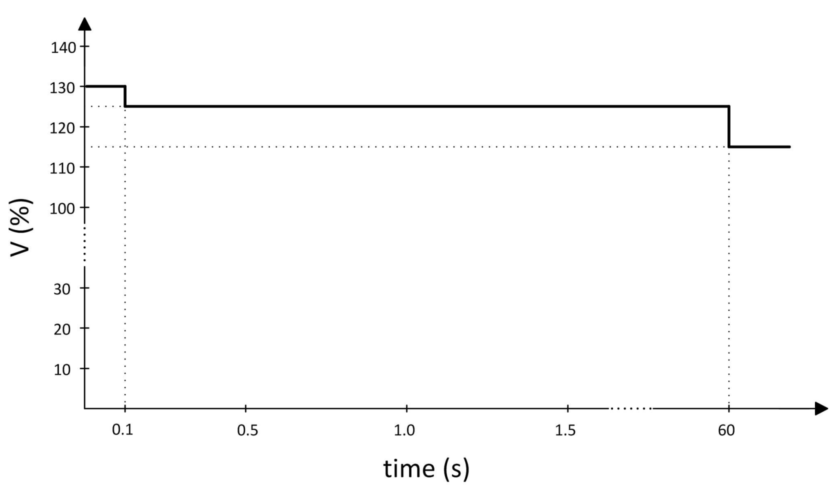


Figure 2.5: Over voltage Curve [6]

Chapter 3

Theory

This chapter provides a comprehensive literature review about symmetrical components, Shunt compensation devices, characteristic as well as operation of the STATCOM, and dq transformation.

3.1 symmetrical component

Symmetrical components are methodology used to analyze an unbalance system by separating the three phase quantities, such as voltage and current, into three sets of balanced phasors, which called positive, negative and zero sequences, as illustrated in Figure 3.1[10]. The power system can be considers as balance system, if it contain only the positive sequence component. The reason of the power system become unbalanced are unbalanced load or unbalanced disturbance, such as single line to ground (SLG) fault, double line to ground (DLG) fault or double line (DL) fault.

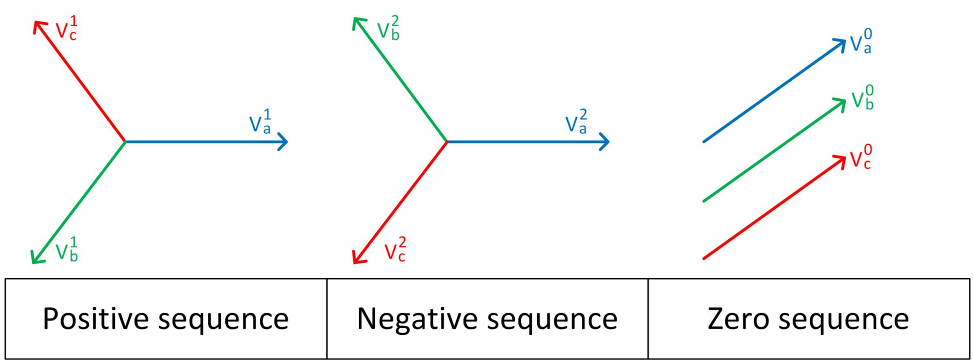


Figure 3.1: Schematic diagram of STATCOM[10]

The positive sequence rotates in anti clock-wise direction, as shown in Figure 3.1. So the three phasors of the positive sequence can be seen in this order abc. The three phasors can be formulated as

$$\begin{aligned} v_a^1 &= v_a^1\angle 0^\circ &&= v_a^1 \\ v_b^1 &= v_a^1\angle 240^\circ &&= a^2 v_a^1 \\ v_c^1 &= v_a^1\angle 120^\circ &&= a v_a^1 \end{aligned} \tag{3.1}$$

where $a = 1\angle 120$ and $a^2 = 1\angle 240$, On the other hand, the negative sequence rotates in clock-wise direction. The phasors order is acb, they can be presented as

$$
\begin{aligned}
v_a^2 &= v_a^2\angle 0^\circ &&= v_a^2\\
v_b^2 &= v_a^2\angle 120^\circ &&= a v_a^2\\
v_c^2 &= v_a^2\angle 240^\circ &&= a^2 v_a^2
\end{aligned}
\tag{3.2}
$$

The zero sequence component can be found in some types of unbalanced disturbance[10]. Unlike the others sequences, all three phasors of the zero sequence component are equal in magnitude and in phase with each other. they can be written as

$$v_a^0 = v_b^0 = v_c^0 \tag{3.3}$$

The notations 1, 2 and 0 represents positive, negative and zero sequence, respectively. According to the symmetrical component, each phase of the voltage in the power system consists of the three sequence components such that

$$
\begin{aligned}
v_a &= v_a^0 + v_a^1 + v_a^2\\
v_b &= v_b^0 + v_b^1 + v_b^2\\
v_c &= v_c^0 + v_c^1 + v_c^2
\end{aligned}
\tag{3.4}
$$

According to the equations 3.1, 3.2 and 3.3, this equation 3.4 can be written in a matrix format

$$
\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} v_a^0 \\ v_a^1 \\ v_a^2 \end{bmatrix}
\tag{3.5}
$$

In order to calculate the symmetrical components for the voltage, inverse this equation 3.5 is used. It can be formulated as

$$
\begin{bmatrix} v_a^0 \\ v_a^1 \\ v_a^2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}
\tag{3.6}
$$

The same equations can be used to calculate the symmetrical components of the current.

3.2 Shunt compensation device

Shunt compensation devices have been developed in order to increase the reliability of the transmitted power as well as improving the voltage profile in the controlled line by injecting or absorbing reactive power. The objective of reactive power compensation is to change the transmission line characteristics to make it more adaptable with load demand. So, shunt reactors are activated to reduce the over voltage during low load condition and shunt capacitors are activated to maintain the voltage levels during excessive load condition.

According to the equations 3.7 and 3.8, the midpoint shunt compensation can considerably boost the active power transfer through the transmission line, which will increase the demand of reactive power on the midpoint. Thus, shunt compensation devices are usually used to regulate the transmission line voltage, whereas series compensation devices are used to enhance the active power transfer though the transmission line.

$$P = \frac{2V^2}{x} sin(\delta/2) \tag{3.7}$$

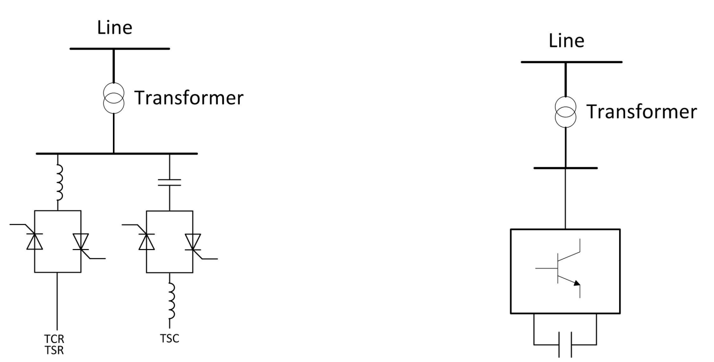
$$Q = \frac{2V^2}{x}(1 - cos(\delta/2)) \tag{3.8}$$

There is two type of compensations:

- Shunt Capacitive Compensation: This method is used to keep up the voltage level under heavy load conditions.
- Shunt Inductive Compensation: This method is used to minimize over-voltage under light load or no load conditions.

There is two main type of shunt compensation devices, check Figure 3.2.

- Static Var Compensator (SVC), composed of:
  - Thyristor Controlled Reactor (TCR), the reactor is connected thought bidirectional valves, which is phase controlled.
  - Thyristor Switched Reactor (TSR), the reactor is connected thought bidirectional valves. However, the valves is either fully on or off.
  - Thyristor Switched Capacitor (TSC), the capacitor is connoted through bidirectional valves. However, the valves is either fully on or off.
  - Filter, Shunt passive device consists of indicators and capacitors that are tuned to resonate at dominant harmonic frequency produced by the SVC.
- Static Synchronous Compensator (STATCOM), which is based on power electronic Voltage Source Converter (VSC) device. It can absorb or inject reactive power as well as providing active power if it connected to power source such as storage unit.



(a) Basic SVC (b) Basic STATCOM

Figure 3.2: SHUNT COMPENSATION DEVICES

3.3 STATCOM

STATCOM is an advanced shunt device of FACTS family based on VSC. It can control the power flow thought the line as well as enhance transient stability on the grid [11]. The STATCOM regulates the voltage at the point of common coupling (PCC) by either injecting or absorbing reactive power from the grid. When the grid voltage is low, the STATCOM response by generating a capacitive current to the grid (injecting a reactive power). If the grid voltage is high, the STATCOM responses by generating an inductive current to the grid (absorb a reactive power).

3.3.1 Configuration

STATCOM uses three phases voltage source converter(VSC) as its basis, as shown in Figure 3.3. Its output voltage connected to the grid via phase reactor and transformer. STATCOM has the ability to regulate the ac voltage magnitude to produce and absorb reactive power for the power system. Moreover, it can compensate for the harmonic in the system. The response of STATCOM is relatively faster than the classic SVC. The required space for STATCOM installation is less than a similar classic SVC.

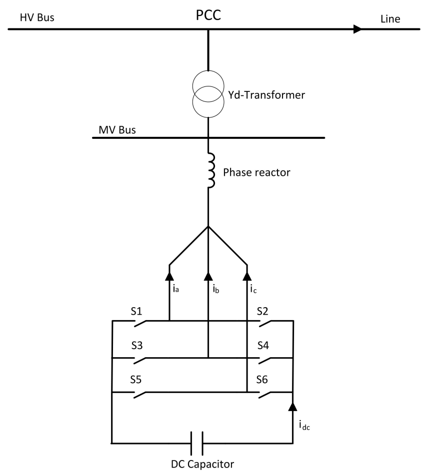


Figure 3.3: Schematic diagram of STATCOM

Normally speaking IGBTs are used as power electronic valves in the VSC. Unlike thyristors (used in classic SVCs), IGBTs can be switched on and off at any time on point of wave. They improve the response time of the STATCOM as well as the control efficiency. VSC has capacitor to provide a current path and store energy.

3.3.2 Operation

There is a relationship between the quantities of ac side and dc side of the converter. The modulation index of the control links the dc voltage to the fundamental component of modulated voltage, as shown in equation 3.9.

$$V_e = m_a \frac{U_{dc}}{2} \tag{3.9}$$

The instantaneous active power flow form dc side to the ac side needs to be balanced in the STATCOM[12][13]. So, the instantaneous active power at the ac side equal the dc side as illustrated in the equation 3.10.

$$\begin{aligned} P_s &= P_{dc} \\ \frac{3}{2} v_s i_s \cos(\phi) &= U_{dc} i_{dc} \end{aligned} \tag{3.10}$$

To simplify the analysis, the phase voltage is considered to be balanced as described in equation 3.11. Usually the voltage contain high order harmonics.

$$\begin{aligned} v_{sa} &= m_a \frac{U_{dc}}{2}\cos(\omega t) \\ v_{sb} &= m_a \frac{U_{dc}}{2}\cos(\omega t - \frac{2\pi}{3}) \\ v_{sc} &= m_a \frac{U_{dc}}{2}\cos(\omega t + \frac{2\pi}{3}) \end{aligned} \tag{3.11}$$

Furthermore, the currents can be considered to be balanced and the phase inductance, which connected to the ac side will eliminate the high order harmonics, leaving out the fundamental component. The STATCOM current is lagging the voltage by power angle of ϕ, check equation 3.12.

$$\begin{aligned} i_{sa} &= i_s \cos(\omega t - \phi) \\ i_{sb} &= i_s \cos(\omega t - \phi - \frac{2\pi}{3}) \\ i_{sc} &= i_s \cos(\omega t - \phi + \frac{2\pi}{3}) \end{aligned} \tag{3.12}$$

The value of the angle ϕ will decide if the STATCOM should consume or absorb reactive power from the system. The instantaneous power flow correlated to one phase will be

$$\begin{aligned} P_{sa} &= v_{sa} i_{sa} \\ P_{sa} &= m_a \frac{U_{dc}}{2}\cos(\omega t) i_s \cos(\omega t - \phi) \\ P_{sa} &= m_a \frac{U_{dc} i_s}{4}[\cos(\phi) + \cos(2\omega t - \phi)] \end{aligned} \tag{3.13}$$

This equation related to the exchange of active power between dc side and ac side of the converter. From the equation 3.13, the oscillating term appears to be oscillated at double fundamental frequency. The second harmonic fluctuation is expected to be present in the system[12][13] . The phase shift in the current as well as the voltage will result in the instantaneous power. As result, if the voltage and current are shifted symmetrically, as shown in equations 3.11 and 3.12. The power flow equation of the three phases will be

$$\begin{aligned} P_{sa} &= m_a \frac{U_{dc} i_s}{4}[\cos(\phi) + \cos(2\omega t - \phi)] \\ P_{sb} &= m_a \frac{U_{dc} i_s}{4}[\cos(\phi) + \cos(2\omega t - \phi - \frac{2\pi}{3})] \\ P_{sb} &= m_a \frac{U_{dc} i_s}{4}[\cos(\phi) + \cos(2\omega t - \phi + \frac{2\pi}{3})] \end{aligned} \tag{3.14}$$

The power of each phase will oscillate at twice the fundamental frequency as in the equation 3.14. By summing up the instantaneous power in the three phase, the second harmonic terms in the total power equation will be eliminated, as described in the equation 3.15. This methods works only with two or three level voltage source converters [12].

$$\begin{aligned} P_s &= P_{sa} + P_{sb} + P_{sb} \\ P_s &= \frac{3}{4} m_a U_{dc} i_s \cos(\phi) \end{aligned} \tag{3.15}$$

During an unbalance fault in the system, the instantaneous power in the ac side of the converter will contain dc component as well as second harmonic component, due to the interaction between the positive sequence and the negative sequence voltage and current components[12][14]. The presence of second harmonic component in the system during unbalanced fault will be elaborated more in detail in Section 4.2.8.

3.3.3 The V-I Characteristic

The STATCOM has the ability to produce both inductive and capacitive current compensation, as shown in Figure 3.4. Theoretically, output current of the STATCOM can be controlled independently in between the rated maximum inductive and capacitive range regardless to the grid voltage. The characteristic illustrate that the STATCOM can supply full capacitive current at very low voltage. This feature is needed in the situation where the STATCOM need to support the grid voltage with full capacitive reactive power during and after the faults.

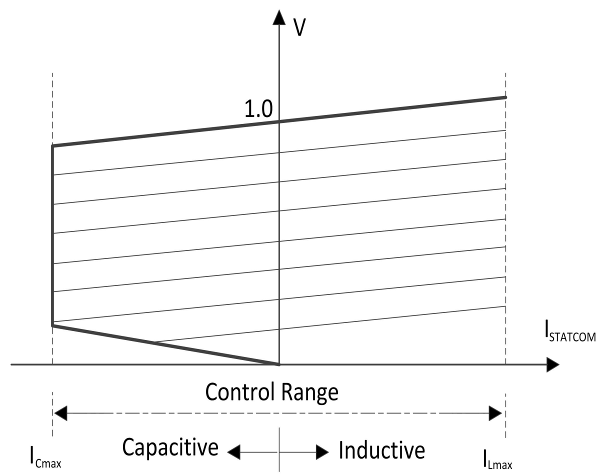


Figure 3.4: The V-I Characteristic [11]

The exchange of active and reactive power between the grid and the STATCOM can be controlled separately. There are so many possibility of active power generation or absorption with reactive power generation or absorption can be achieved if the STATCOM has energy storage unit, check Figure 3.5. In order to enhance the system stability, adequate control strategy need to be used for active and reactive power output [15].

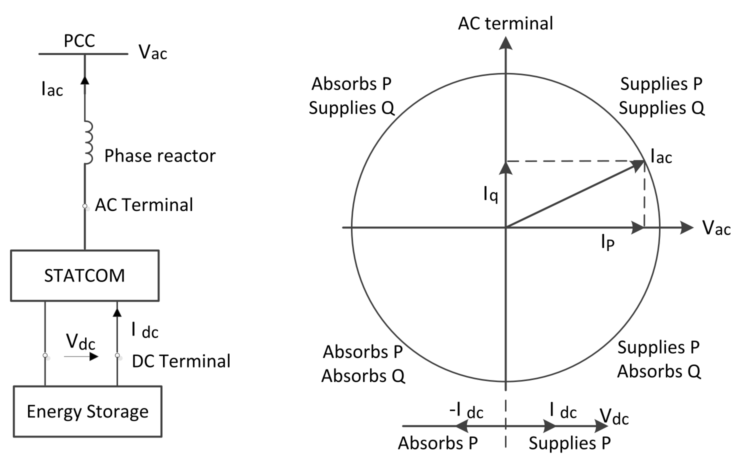


Figure 3.5: The exchange power between the grid and the STATCOM [15]

3.3.4 Pules Width Modulation

Pulse-width modulation (PWM) is a control technique used to create voltage signals, that are sent to the valve control unit of VSC to create the desired voltage waveform. PWM strategy consists of two main signals, the voltage controlled signal and the wave carrier signal, which is a triangular wave. ac voltage can be controlled by manipulating the pulse width as well as amplitude of the dc voltage [16][11].

$$\widehat{V_{LL_1}} = \frac{\sqrt{3}}{2\sqrt{2}} m_a V_{dc} \begin{cases} m_a \leq 1.0 \end{cases} \tag{3.16}$$

The modulation index m_a is parameter that links the dc voltage to the ac voltage and defined as follows:

$$m_a = \frac{\widehat{v_{control}}}{\widehat{v_{carrier}}} \tag{3.17}$$

3.3.5 ABC to DQ frame transformation

In symmetrical ac system, the three phases of the electrical system are shifted by $\frac{2\pi}{3}$ from each other. The analysis of the ac system can be done using $\alpha\beta$ transformation, which also known as Clarke transformation, to reduce the ac system from three phase to two phase. $\alpha\beta$ translates the three phase u_a, u_b, and u_c to u_α, u_β and u_0 using the equation 3.18. $u_0 = 0$ if the sum of $u_a + u_b + u_c = 0$, which means that the ac system is balanced.

$$\begin{bmatrix} u_\alpha(t) \\ u_\beta(t) \\ u_0(t) \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} u_a(t) \\ u_b(t) \\ u_c(t) \end{bmatrix} \tag{3.18}$$

where, u_a, u_b, and u_c are sinusoidal wave with phase shift of $\frac{2\pi}{3}$:

$$\begin{aligned} u_a(t) &= Ucos(\omega t) \\ u_b(t) &= Ucos(\omega t - \frac{2\pi}{3}) \\ u_c(t) &= Ucos(\omega t + \frac{2\pi}{3}) \end{aligned} \tag{3.19}$$

dq transformation translates the ac system from fixed $\alpha\beta$ frame to rotating dq frame. The vectors $\underline{\text{v}}$(t) and $\underline{\text{u}}$(t), which is aligned with d-axis in the dq frame, are rotating counter clockwise with the angular frequency ω(t) in the $\alpha\beta$ frame. Accordingly, $\underline{\text{v}}$(t) and $\underline{\text{u}}$(t) will occur as fixed vectors in the dq frame, as shown in Figure 3.6

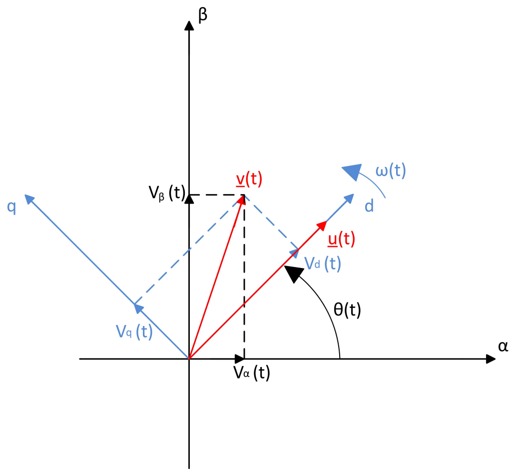


Figure 3.6: Rotating dq frame to fixed $\alpha\beta$ frame [17]

The mathematical representation of the dq transformation is given by the matrix in equation 3.20.

$$\begin{bmatrix} u_d(t) \\ u_q(t) \\ u_0(t) \end{bmatrix} = \frac{2}{3} \begin{bmatrix} cos(\theta(t)) & sin(\theta(t)) & 0 \\ -sin(\theta(t)) & cos(\theta(t)) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} u_\alpha \\ u_\beta \\ u_0 \end{bmatrix} \tag{3.20}$$

3.3.6 Phase Locked-Loop

One of the most popular technique used for synchronization of three phase systems is Phase locked-Loop (PLL)[18]. PLL is close loop system that compares the reference angle ($\theta*$) with measured angle ($\theta(t)$) to reduce the error margin($\Delta\theta(t)$) until $\theta* = \theta(t)$. The Figure 3.8 illustrate the operation principle of PLL, which translate the three phase voltage of the gird to dq rotating reference frame. The angular location of the dq frame is regulated by the feedback loop, which regulates the q axis to zero, as illustrated in Figure 3.7.[19]

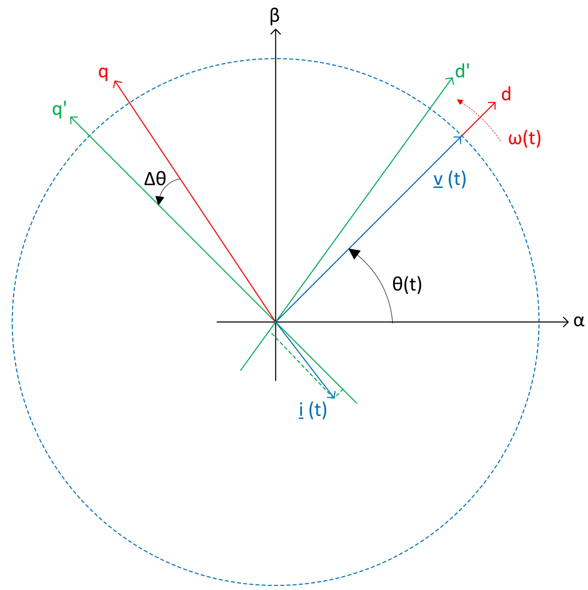


Figure 3.7: PLL operation principle

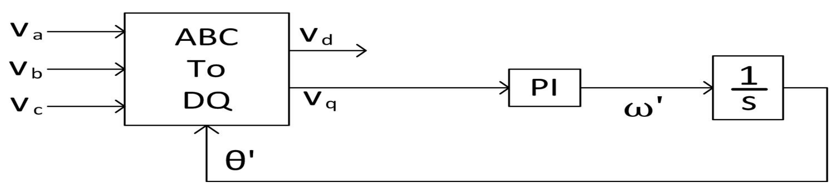


Figure 3.8: Basic PLL control scheme. [19] [18]

Chapter 4

STATCOM Modeling

4.1 Introduction

This chapter will cover the STATCOM control modeling in a details. The STATCOM control consists of voltage regulator of positive and negative sequence control, dc voltage regulator, a single current control loop for both sequences and priority control. Furthermore, separation of the positive and negative sequence components will be presented. The transformation of the positive and negative sequences to their respective rotating reference frame dq is explained. The voltage regulators, the current controller and priority control are tackled in detail. During the development of the model, YY transformer is used in the begging. Then, transformer configuration is being changed to YΔ, which is preferred configuration in order to prevent the zero sequence component from the network to be transmitted into the STATCOM. Moreover, transformer is required to be grounded in the primary side. The configuration changing has been explained. The second harmonic problem is presented with the solution.

4.2 STATCOM Modeling

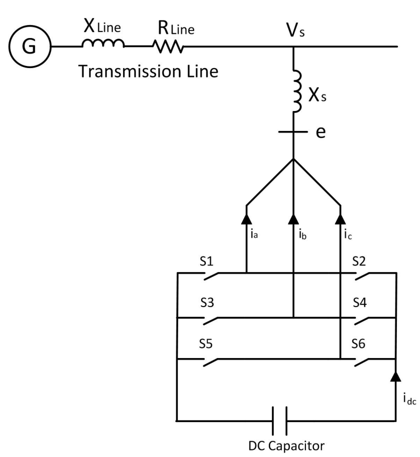


Figure 4.1: STATCOM connected to network

Figure 4.1 shows a typical STATCOM model connected to power network system. The STATCOM consist of voltage source converter (VSC) with dc capacitor. It is connected to the gird to support the system voltage with reactive power. In the model, V_s stands for PCC voltage, e stand for the output of the VSC and X_s stand for phase reactor and transformer, as shown in Figure 4.1.

$$e - V_s = L_s \frac{di}{dt} \tag{4.1}$$

Rearranging the equation 4.1 in matrix format:

$$\begin{bmatrix} e_a - v_a \\ e_b - v_b \\ e_c - v_c \end{bmatrix} = L_s \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ ic \end{bmatrix} \tag{4.2}$$

by applying abc to dq transformation 3.18 and 3.20:

$$L_s \frac{d}{dt} \begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} 0 & -\omega L_s \\ \omega L_s & 0 \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} e_d - v_{sd} \\ e_q - v_{sq} \end{bmatrix} \tag{4.3}$$

The modulation indices are represented by m_a, m_b and m_c. The voltage across the dc capacitor is noted by v_{dc}. The modulation indices are applied to generate firing pulses to the switches (S_1-S_6). The output of VSC is given as:

$$\begin{aligned} e_a &= m_a \frac{v_{dc}}{2} \\ e_b &= m_b \frac{v_{dc}}{2} \\ e_c &= m_c \frac{v_{dc}}{2} \end{aligned} \tag{4.4}$$

Applying the Clarke and Park transformation 3.18 and 3.20 to transfer 4.4 from abc to dq frame:

$$\begin{aligned} e_d &= m_d \frac{v_{dc}}{2} \\ e_q &= m_q \frac{v_{dc}}{2} \end{aligned} \tag{4.5}$$

m_d and m_q represents the modulation indices in dq reference rotating frame.

4.2.1 DQ component, extracting positive and negative sequences

The three phase voltage V_a, V_b and V_c are converter into an equivalent two phase system V_α and V_β by using Clarke transformation 3.18. In balance system, V_α and V_β have the same magnitude but shifted 90° from each other, which will be different in case of unbalance system. In order to analyse the unbalance system, the positive and negative sequence components need to be separated from the measured signal[20].

$$Sig = Pe^{j\omega t} + Ne^{-j\omega t} \tag{4.6}$$

To extract the pure positive and negative the voltage measured signal in equation 4.6 is multiplied by $e^{-j\frac{\pi}{2}}$ to introduce delay of 90°

$$\begin{aligned} Sig &= Pe^{j\omega t} + Ne^{-j\omega t} \\ Sig_{90^\circ} &= Pe^{j\omega t}e^{-j\frac{\pi}{2}} + Ne^{-j\omega t}e^{j\frac{\pi}{2}} \\ \because e^{j\frac{\pi}{2}} &= +j; e^{-j\frac{\pi}{2}} = -j \\ \therefore Sig_{90^\circ} &= -jPe^{j\omega t} + jNe^{-j\omega t} \\ jSig_{90^\circ} &= Pe^{j\omega t} - Ne^{-j\omega t} \end{aligned} \tag{4.7}$$

After the multiplication, we obtain

$$jSig_{90^\circ} = Pe^{j\omega t} - Ne^{-j\omega t} \tag{4.8}$$

By summing up the two equations 4.6 and 4.8, we get

$$\begin{aligned} 2Pe^{j\omega t} &= Sig + jSig_{90^\circ} \\ Pe^{j\omega t} &= \frac{Sig + jSig_{90^\circ}}{2} \end{aligned} \tag{4.9}$$

By substituting $Sig = V_\alpha + jV_\beta$ and $jSig_{90^\circ} = V_{\alpha\_90^\circ} + jV_{\beta\_90^\circ}$ into the equation 4.9, we obtain the positive sequence components

$$\begin{aligned} Pe^{j\omega t} &= \frac{V_\alpha + jV_\beta + jV_{\alpha\_90^\circ} - V_{\beta\_90^\circ}}{2} \\ Pe^{j\omega t} &= \frac{V_\alpha - V_{\beta\_90^\circ} + j(V_\beta + V_{\alpha\_90^\circ})}{2} \end{aligned} \tag{4.10}$$

Where,

$$\begin{aligned} V_{\alpha p} &= \frac{V_\alpha - V_{\beta\_90^\circ}}{2} \\ V_{\beta p} &= \frac{V_\beta + V_{\alpha\_90^\circ}}{2} \end{aligned} \tag{4.11}$$

After extracting the negative sequence components, Park Transformation 3.20 is applied in equation 4.11 with PLL angle of θ. ($\theta = \omega t$)

$$\begin{bmatrix} V_{dp} \\ V_{qp} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} cos(\theta) & sin(\theta) \\ -sin(\theta) & cos(\theta) \end{bmatrix} \begin{bmatrix} V_{\alpha p} \\ V_{\beta p} \end{bmatrix} \tag{4.12}$$

By subtracting the two equations 4.6 and 4.8, we get

$$\begin{aligned} 2Ne^{-j\omega t} &= Sig - jSig_{90^\circ} \\ Ne^{-j\omega t} &= \frac{Sig - jSig_{90^\circ}}{2} \end{aligned} \tag{4.13}$$

By substituting $Sig = V_\alpha + jV_\beta$ and $jSig_{90^\circ} = V_{\alpha\_90^\circ} + jV_{\beta\_90^\circ}$ into the equation 4.13, we obtain the negative sequence components

$$\begin{aligned} Ne^{-j\omega t} &= \frac{V_\alpha + jV_\beta + jV_{\alpha\_90^\circ} - V_{\beta\_90^\circ}}{2} \\ Ne^{-j\omega t} &= \frac{V_\alpha + V_{\beta\_90^\circ} + j(V_\beta - V_{\alpha\_90^\circ})}{2} \end{aligned} \tag{4.14}$$

Where,

$$\begin{aligned} V_{\alpha n} &= \frac{V_\alpha + V_{\beta\_90^\circ}}{2} \\ V_{\beta n} &= \frac{V_\beta - V_{\alpha\_90^\circ}}{2} \end{aligned} \tag{4.15}$$

After extracting the negative sequence components, Park Transformation 3.20 is applied in equation 4.15 with negative the PLL angle $-\theta$. ($-\theta = -\omega t$)

$$\begin{bmatrix} V_{dn} \\ V_{qn} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} cos(\theta) & -sin(\theta) \\ sin(\theta) & cos(\theta) \end{bmatrix} \begin{bmatrix} V_{\alpha n} \\ V_{\beta n} \end{bmatrix} \tag{4.16}$$

4.2.2 STATCOM Control

Figure 4.2 illustrates the block diagram of the STATCOM control. In this diagram, the positive and negative sequence voltages are separated and transferred from three phase voltage to their respective dq rotating frame using the angle from the PLL block, which has PCC voltage as an input and produce signal θ as reference angle that synchronized with phase A of the voltage. The positive and negative sequence voltage are fed to the positive and negative voltage regulator, respectively. dc voltage regulator is used to keep the voltage constant across the capacitor. Then the negative sequence current multiplied with $e^{-j2\omega t}$ to make the negative sequence current to rotate in the same direction of the positive sequence current reference in order to sum all the reference currents to be fed to a single current control. The reason of using single current control is to limit the harmonic content in the control. For any existing harmonic, if two current controllers are used, they will be amplified by the two current controllers rather than by only one controller.

At the same time, PCC voltage V_n and STATCOM current $I_{STATCOM}$ are transferred as full signal (i.e. positive and negative sequences) to dq rotating frame to be fed to the current control, since the control is designed with one current control only. More detailed explanation of the blocks are described below.

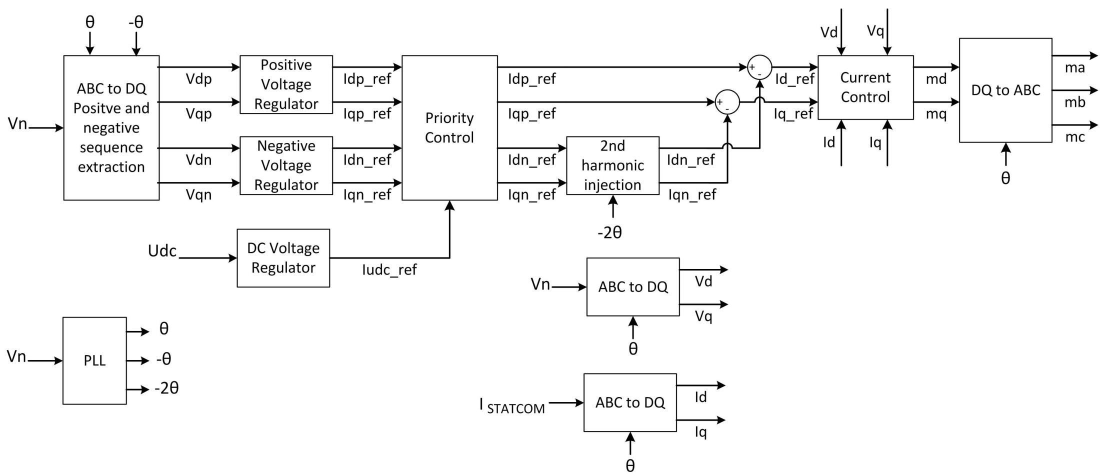


Figure 4.2: Scheme diagram of STATCOM control

4.2.3 Voltage control

Figure 4.3 shows that the voltage regulator is divided into three parts. The first part is the dc voltage regulator, where the voltage across the capacitor is kept at constant value. The second part is the positive sequence control, which aims to keep the grid voltage at $1pu$ at all the time. The last part negative sequence control, which enhances the voltage across all three phases to be balanced by reducing the negative sequence voltage in the system. The output signals I_{d_ref} and I_{q_ref} are the result of adding all the signals together, which will be the input of the current control.

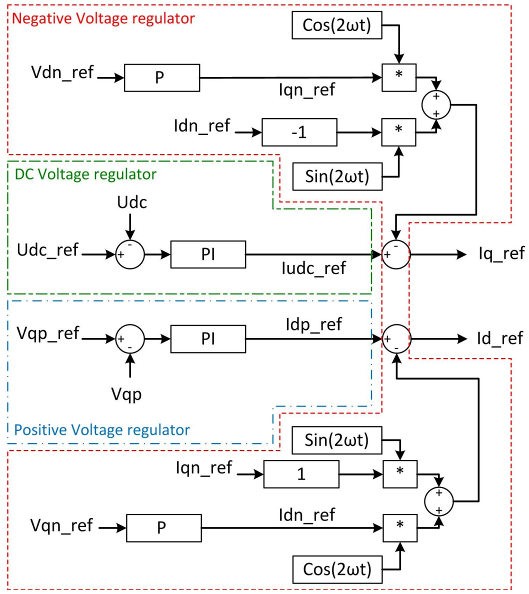


Figure 4.3: The voltage control

- **dc voltage regulator:** The capacitor is used as dc voltage source for the STATCOM. The transformer and the electronic switches causes some losses in the STATCOM, which will drain the energy from the capacitor. In order to have decent operation of the STATCOM, the voltage level of the dc capacitor should be maintained at a fixed value. That being said, the STATCOM needs to absorb a small value of active power from the network. Figure 4.3 illustrates the dc voltage regulator part, U_{dc_ref} is the reference voltage of the capacitor, that determined by the secondary side voltage and the STATCOM size in MVA. The capacitor sizing will be elaborated more in section 4.2.9. The reference value of dc voltage is compared with the measured value. PI controller is applied to determine the required amount of active current to maintain the voltage level across the capacitor.

- **Positive sequence voltage regulator:**
The STATCOM exchange reactive power with the grid to regulate the PCC voltage to nominal value. v_{qp_ref} is representing the reference voltage at PCC and its usually set to equal $1pu$. The measured signal v_{qp} is subtracted from the reference voltage in order to calculate the error signal. Then, PI control is applied to obtain reference current I_{dp_ref}, as shown in Figure 4.3.

- **Negative sequence voltage regulators:**
The voltage regulator of the negative sequence is similar to the positive sequence. However, the negative sequence voltage measured is usually compared with zero in order to reduce negative sequence components from the system. Since the positive sequence rotates at different direction from the negative sequence, the reference current I_{dn_ref} and I_{qn_ref} of the negative sequence voltage regulators are multiplied with $e^{-j2\omega t}$ to make the negative sequence current rotate in the same direction as the positive reference current, according to the equation 4.17.

$$\widehat{i}_{dn} + j\widehat{i}_{qn} = (i_{dn\_ref} + i_{qn\_ref}).e^{-j2\omega t} \tag{4.17}$$

After the multiplication of the reference current signals, the imaginary part signals are summed up together and the real part signals are summed up together, as the control illustrated in Figure 4.3.

$$\begin{aligned} \widehat{i}_{dn} &= i_{dn\_ref} cos(2\omega t) + i_{qn\_ref} sin(2\omega t) \\ j\widehat{i}_{qn} &= j i_{qn\_ref} cos(2\omega t) - j i_{dn\_ref} sin(2\omega t) \end{aligned} \tag{4.18}$$

According to the Grid Code in chapter 2.4.1, the negative sequence controller should not be activated until the negative sequence voltage is exceeding 5% of the nominal voltage.

The equation below is formulated to substrate 5% of the nominal voltage.

$$\begin{aligned} \overrightarrow{V}_{n\_measured} &= V_{dn\_measured} + jV_{qn\_measured} \\ V_{dn\_ref} &= V_{dn\_measured} - 0.05\frac{V_{dn\_measured}}{|V_{n\_measured}|} \\ V_{qn\_ref} &= V_{qn\_measured} - 0.05\frac{V_{qn\_measured}}{|V_{n\_measured}|} \end{aligned} \tag{4.19}$$

Figure 4.4 illustrates the voltage reference control of the negative sequence, which is derived from equation 4.19.

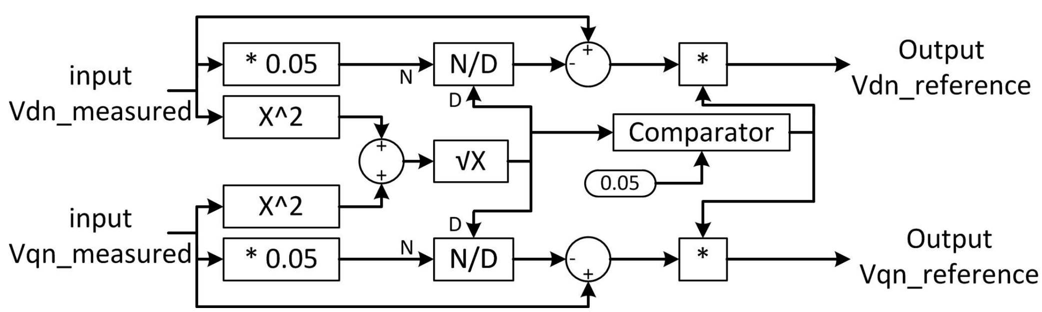


Figure 4.4: Reference voltage controller for negative sequence

4.2.4 Current control

The current control can be obtained by substituting equation 4.5 to 4.3:

$$\begin{aligned} L_s\frac{di_d}{dt} &= \omega L_s I_{q\_ref} + \frac{v_{dc}}{2}m_d - v_{sd} \\ L_s\frac{di_q}{dt} &= -\omega L_s I_{d\_ref} + \frac{v_{dc}}{2}m_q - v_{sq} \end{aligned} \tag{4.20}$$

To simplify the inner current loop, the dq reference current I_{d_ref} and I_{q_ref} are decoupled instead of the I_{dq} measured, as shown in equation 4.20. The decoupling term is existed due to ωL_s term.

I_{dq_ref} are feed forward to compute the negative sequence currents to balance the power among the phases during unbalance operation. By rearrange the equation 4.20 to obtain m_d and m_q:

$$\begin{aligned} m_d &= \frac{2}{v_{dc}}(u_d + L_s\frac{di_d}{dt} - \omega L_s i_{q-ref} + v_{sd}) \\ m_q &= \frac{2}{v_{dc}}(u_q + L_s\frac{di_q}{dt} + \omega L_s i_{d-ref} + v_{sd}) \end{aligned} \tag{4.21}$$

Where u_d and u_q are the output from PI controller, which has the error signal from subtracting $I_{dq\_measured}$ from I_{dq_ref} as an input, in the current control. Once the value of u_d and u_q are obtained, equation 4.21 is resolved to obtain the value of m_d and m_q.

Figure 4.5 illustrates that only one inner current loop is used for both positive and negative sequences, which derived from equation 4.21. This control is consist of PI controller, decoupling term ωL, current reference feedforward as well as grid voltage feedforward, which contain both sequences. The output signals from the voltage regulators of positive and negative sequences summed up together to become one signal to be used as an input reference current for current control. Figure 4.6 illustrates the total I_{dq_ref} reference current of the positive and negative voltage regulators compared with $I_{dq\_measured}$. In order to differentiate between both sequences, the negative sequence quantities are defined as second harmonic in I_{dq_ref} signal, unlike the positive sequence quantities which defined as dc offset of I_{dq_ref} signal. Since, the control is implemented in continuous time domain, the switching harmonic can be seen in measured current ($I_{dq\_measured}$), which should be disappear in the sampled waveforms.

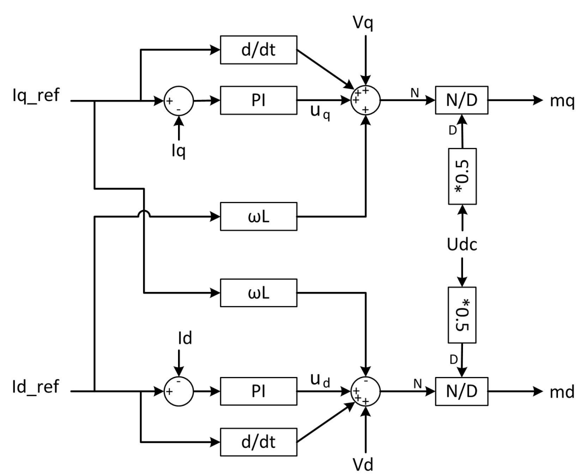


Figure 4.5: The decoupled current control

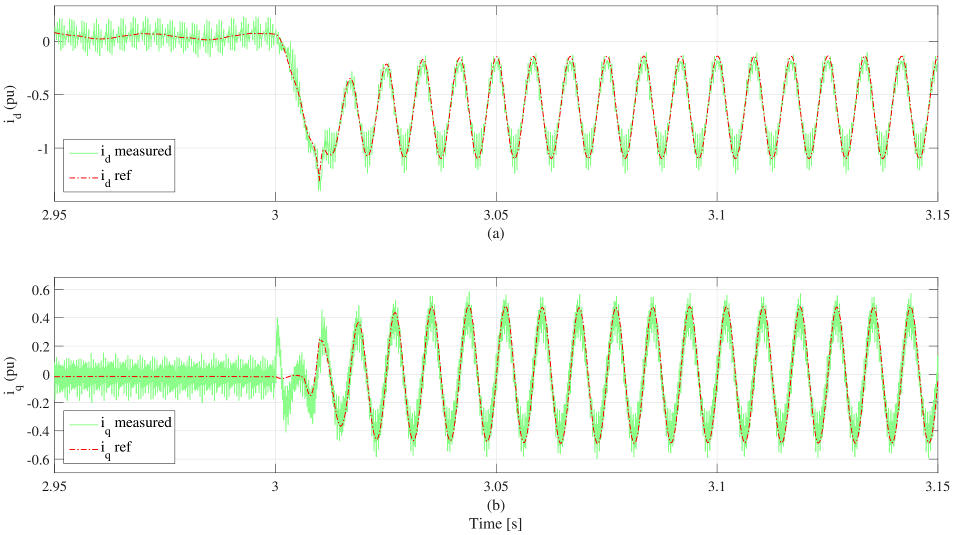


Figure 4.6: (A) I_d measured and reference signals (B) I_q measured and reference signals

4.2.5 Sinusoidal Pulse Width Modulation

Figure 4.2 illustrates dq reference signals, m_d and m_q, are transferred to three phase reference signals, m_a, m_b and m_c to be used in PWM technique.

$$\begin{bmatrix} m_a \\ m_b \\ m_c \end{bmatrix} = \begin{bmatrix} cos(\omega t) & -sin(\omega t) \\ cos(\omega t - \frac{2\pi}{3}) & -sin(\omega t - \frac{2\pi}{3}) \\ cos(\omega t + \frac{2\pi}{3}) & -sin(\omega t + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} m_d \\ m_q \end{bmatrix} \tag{4.22}$$

In PWM, the modulation reference signals are compared with carrier triangular signal of unity amplitude. Then, the output signal is controlling the IGBTs on the VSC to generate pulses. For instance, The output voltage at phase a is illustrated in Figure (4.7). When, the modulation reference signal is greater than the triangular signal, the phase voltage is equal to $\frac{+V_{dc}}{2}$ and equal to $\frac{-V_{dc}}{2}$, when the reference signal lesser than triangular signal.

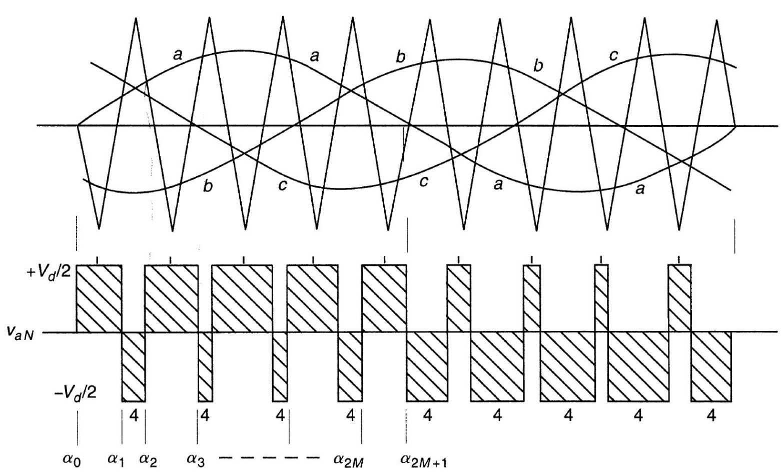


Figure 4.7: PWM waveform[11]

4.2.6 Priority control

Since the STATCOM contribution to the system is limited due to size of the device and rating of the valve, a priority control is used to limit the output current. During large disturbances, the priority control will be activated to limit the output current of converter to its nominal value. The output current will be distributed between the positive and negative sequences current depending the priority control strategy. If the first priority is set for the positive sequence, it will compensate for negative sequence if there is any spare capacity in the converter. Moreover, the converter rating is usually based on the positive sequence current. On the other hand, if the first priority is set for negative sequence, it will compensate negative sequence to full capacity. Then, the controller will compensate for positive sequence if there is any spare capacity lift.

Figure 4.8 illustrates that the priority control has the reference current I_{udc_ref}, I_{dp_ref}, I_{dn_ref} and I_{dn_ref} as an input signals, which are regulated by the voltage regulator controls. These current references are converted from dq rotating frame to abc frame using Clarke and Park transformation. Figure 4.9 shows that the maximum value of the reference current, I_{a_ref}, I_{b_ref} and I_{c_ref}, is going to be the input to the priority control, which is subtracted from the priority control limit $1pu$ (i.e. the maximum output current by the STATCOM).

By looking at Figure 4.9, the input of the integrator will be a value between 0 and 1 during a normal operation, which is below the maximum limit of the STATCOM. If the integrator, which is limited between 0 and 2, has positive input, then the integrator will be saturated at 2 after certain time constant. The output value of the integrator will be passed to K_1 through the hard limiter, which has limits between 0 and 1. Then, the value of K_2 is obtained by subtracting the output of the hard limiter from the output of the integrator. During an over load operation, the input of the integrator will be negative value, which means the output of the integrator will decrease to a value between 0 and 2. As a result, as shown in Figure 4.8, the reference currents I_{dp_ref}, I_{dn_ref} and I_{qn_ref} are limited by using the output signals of the priority control in the main control. However, the signals, K_1 and K_2, will not be used in limiting I_{udc_ref} as the dc current reference has always the first priority to keep voltage constant across the capacitor.

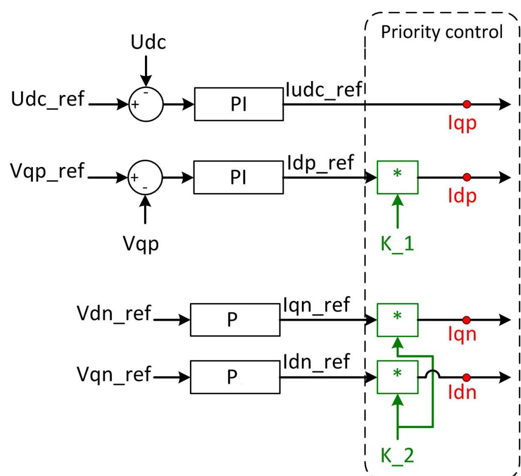


Figure 4.8: Voltage regulators, priority control inputs and feedback points

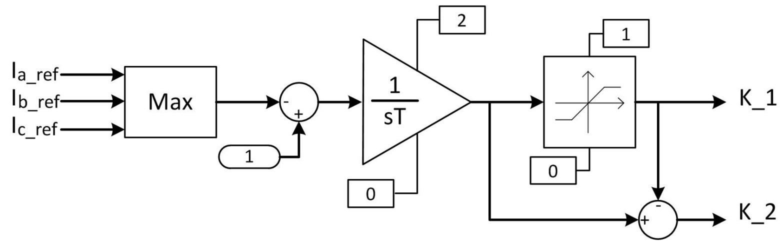


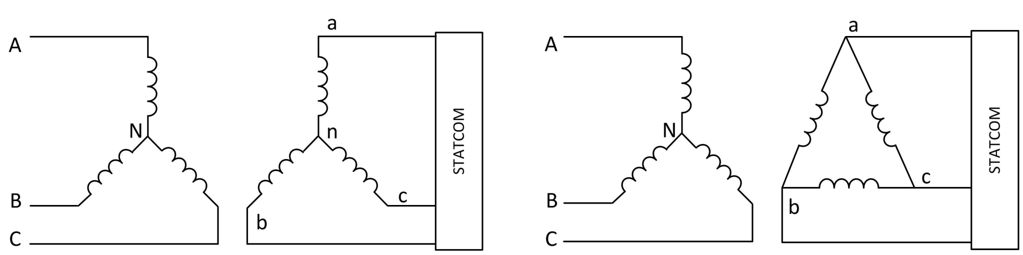
Figure 4.9: Priority control

In this project, three priority control strategies have been considered:

- Strategy I: Only positive sequence control. The converter capacity is dedicated to compensate for positive sequence only.
- Strategy II: Only negative sequence control. The converter capacity is dedicated to compensate for negative sequence only.
- Strategy III: Positive and negative sequence controls with ratio of 0.5 each. During large unsymmetrical disturbance, the converter will compensate for 50% of the positive sequence and 50% of the negative sequence. The total current compensated must not exceed the converter limit. The current reference of both sequences will have k_1 as feedback.

4.2.7 Transformer Configuration

In the STATCOM modeling, star-star (YY) transformer is used to step down the voltage at the converter side, that can be handled by low voltage switches. Figure 4.10a illustrate the YY transformer connection with the STATCOM. However, star-delta (YΔ) transformer is usually used in STATCOM to prevent the zero sequence component from the network to be transmitted into the STATCOM as well as the primary side of the transformer is required to be grounded, as shown in Figure 4.10b.



(a) YY transformer (b) YΔ transformer

Figure 4.10: Transformer configuration

In YY transformer,

$$
\begin{aligned}
V_p &= \frac{N_1}{N_2} V_s \\
n &= \frac{N_1}{N_2} \\
V_A &= n V_a
\end{aligned}
\tag{4.23}
$$

In YΔ transformer,

$$\begin{aligned} V_A &= nV_{ab} \\ V_{ab} &= V_a - V_b \\ V_{ab} &= V_a\angle 0 - V_a\angle -120 \\ V_{ab} &= \sqrt{3}V_a\angle 30 \\ V_A &= n\sqrt{3}V_a\angle 30 \end{aligned} \tag{4.24}$$

As result, the YΔ transformer introduces ±30° phase shift between the STATCOM and gird voltages. In case of positive sequence, the primary voltage(star configuration) lead the secondary voltage(Δ configuration) by 30°, as illustrated in Figure 4.11. The primary voltage lag the secondary voltage in the negative sequence. STATCOM control need to consider and compensate for the phase shift.

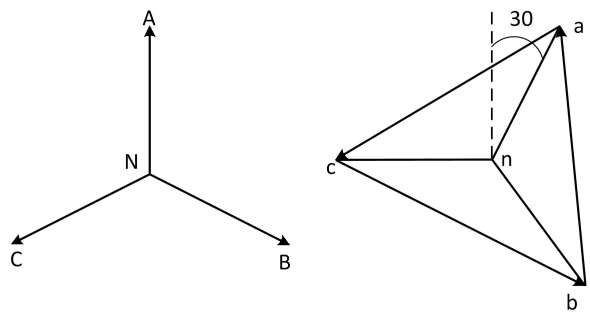


Figure 4.11: Phasor diagram of YΔ transformer

In order to compensate for the phase shift in the control, all the quantities measured from the primary side of the transformer, including the PLL, are shifted by 30° to be in phase with quantities on the secondary side. The shift of primary voltage is applied in $\alpha\beta$ frame.

After using Clark Transformation 3.18, The three phase voltage v_a, v_b and v_c are converter to v_α and v_β. Then, they multiplied with $e^{j\frac{\pi}{6}}$ to phase shift the voltage by 30°, as shown in the equation below.

$$\begin{aligned} v_{\alpha\_sh} &= v_\alpha e^{j\frac{\pi}{6}} \\ v_{\beta\_sh} &= v_\beta e^{j\frac{\pi}{6}} \end{aligned} \tag{4.25}$$

Then, using the inverse of Clarke Transformation to transfer v_{α_sh} and v_{β_sh} back to three phase system v_{a_sh}, v_{b_sh} and v_{c_sh} to be used in PLL as well as extracting the positive and negative sequence signals from the shifted voltage, as illustrated in Figure 4.12.

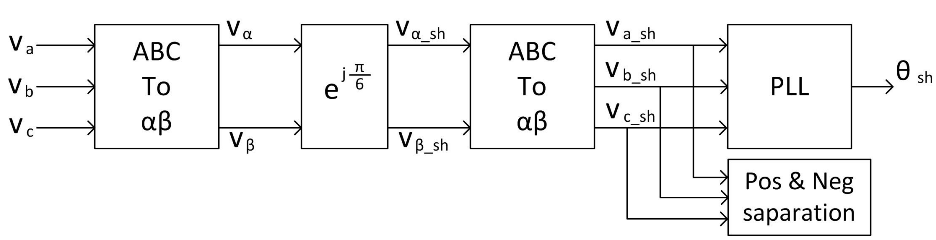


Figure 4.12: Phase shift implementation

4.2.8 Second Harmonic on the DC voltage

As mentioned in section 3.3.2, the instantaneous power at the ac side equals the dc side. During any unbalance disturbance, the oscillation of second harmonic can easily be seen on the dc voltage measurement, according to the equation 3.10. As result, the current reference out of dc voltage regulator will contain the second harmonic oscillation. Due to the dq to abc transformation, the second harmonic in the dq frame will appear as third harmonic on abc vector frame, if the dc voltage control generates a second harmonic in the q-axis current reference. So, the second harmonic must be damped out from the signal of the dc voltage measurement. Table 4.1 shows the dc voltage as well as I_{Udc} the reference current signal of dc voltage regulator with and without second harmonic filter, as illustrated in Figure 4.13.

	Without 2_{nd} harmonic filter (pu)	With 2_{nd} harmonic filter (pu)
U_{dc}	$24.4x10^{-3}$	$37x10^{-3}$
I_{udc}	$24.6x10^{-3}$	$3.29x10^{-4}$

Table 4.1: second harmonic magnitude in the STATCOM control

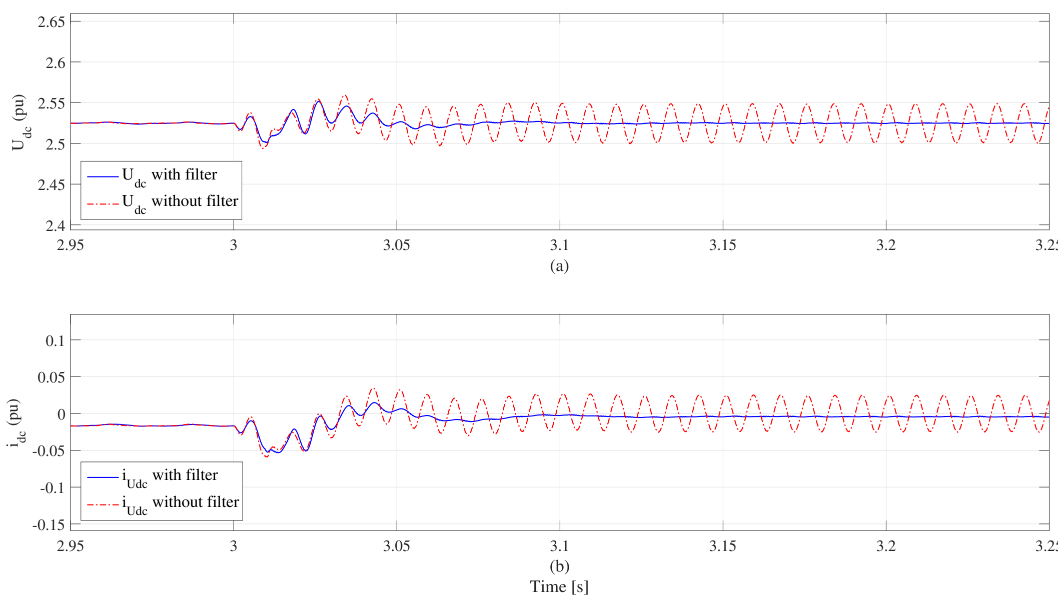


Figure 4.13: (A) dc voltage (B) I_{Udc} reference current of dc voltage regulator, with and without filter

4.2.9 STATCOM parameters

The STATCOM, with 2 level VSC, is reated at $200MVA$ to connected to the grid via transformer of Yd configuration. The voltage at the primary side is $345kV$ and at the secondary side is $32.5kV$.

- **Phase reactor sizing:**

  The size of the phase reactor is calculated using ohm law and inductive reactance equation to calculate to the reactance. The voltage drop of 10% across the inductance need to considered.

$$L = \frac{V_{sec}^2}{S_{STATCOM\_rating}} * \frac{X_L}{2\pi f} \tag{4.26}$$

Where,
V_{sec} stand for the secondary voltage,
$S_{STATCOM\_rating}$ stand for STATCOM rated apparent power,
f stand for the system frequency, which is $60Hz$,
X_L stand for inductive reactance, that equal to $0.1pu$
L strand for inductance,

By solving the equation 4.26,

$$L \approx 1.4mH \tag{4.27}$$

- **dc capacitor sizing:**

  To size the capacitor, the voltage drop across the phase reactor as well as the transformer, which is 10% each, need to be considered. The STATCOM should increase the voltage at PCC to $1.05pu$. So, the STATCOM output voltage should be $1.25pu$.

$$V_e * V_{base} = m\frac{U_{dc}}{2} \tag{4.28}$$

Where $V_e = 1.25pu$, $V_{base} = 32.5\sqrt{\frac{2}{3}}kV$ and $m = 1$

By rearranging the equation 4.28 to solve for U_{dc}

$$\begin{aligned} &1.25 * 32.5\sqrt{\frac{2}{3}} = 1\frac{U_{dc}}{2} \\ &U_{dc} \approx 67kV \end{aligned} \tag{4.29}$$

By applying the capacitor energy equation with time constant of $10ms$

$$\frac{\frac{1}{2}CU_{dc}^2}{S_{STATCOM\_rating}} = 10ms \tag{4.30}$$

Then, solve for C

$$\begin{aligned} &\frac{\frac{1}{2}C67k^2}{200M} = 10ms \\ &C \approx 982\mu F \end{aligned} \tag{4.31}$$

In the STATCOM model, two capacitor are used in series with size of $1784\mu F$

Chapter 5

Result and Analysis

In this Chapter, the STATCOM control model is analyzed by introducing three types of unsymmetrical disturbances, such as SLG fault, DLG fault and DL fault. These disturbances are applied to the grid with and without STATCOM for different priority control strategy, only positive sequence control strategy, only negative sequence control strategy and positive and negative sequence control strategy with an equal ratio. The system voltage drop is analyzed along with STATCOM current and the SCC contribution. Furthermore, the transformer, which links the STATCOM to the grid, has been considered directly grounded and grounded with high impedance (ungrounded).

The investigation of the SCC contribution and the priority control strategy has been conducted on two different networks, the parameters are shown in Table 5.1. The same STATCOM size is used on both networks, the parameters are presented on Table 5.2. Figure 5.1 illustrates the simulation set up of the STATCOM as well as the fault location in power grid.

Table 5.1: Grids parameters

	Weak Grid	Strong Grid
Short Circuit Capacity	400 MVA	1000 MVA
Voltage	345 kV	345 kV
Frequency	60 Hz	60 Hz
X/R ratio	7	7
Resistance	42.08 Ω	16.83 Ω
Inductance	781.4 mH	312.6 mH

Table 5.2: STATCOM parameters

	STATCOM
Size	200 MVA
Primary voltage	345 kV
Secondary voltage	32.5 kV
Maximum current	1 pu
Configuration	Yd

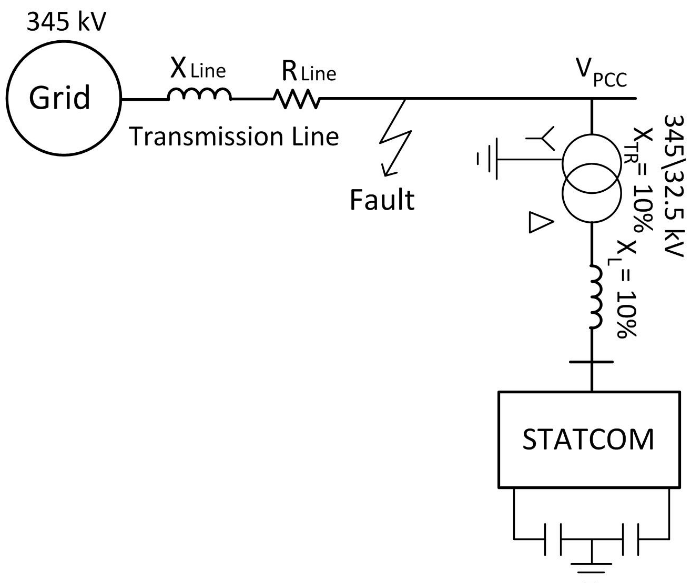


Figure 5.1: Schematic diagram of the simulation set up

During the examination of the grid, five types of scenarios have been considered for all cases:

- First Scenario: Grid without STATCOM, which called "Grid Only".
- Second Scenario: Grid with transformer connected but without STATCOM, which called "Ungrounded Transformer" in cases 1, 3 and 5, and "Grounded Transformer" in cases 2, 4 and 6.
- Third Scenario: STATCOM with only positive sequence control strategy, which called "Only Positive".
- Forth Scenario: STATCOM with only negative sequence control strategy, which called "Only Negative".
- Fifth Scenario: STATCOM with positive and negative sequences control strategy with an equal ratio of 0.5 each, which called "Both".

5.1 Weak Network

The network has been examined when the system voltage drop to 50% of the nominal voltage and when the system voltage goes to zero. If the weak network experience unsymmetrical disturbance with fault impedance of $52.08 + j294.6\Omega$, the voltage of the faulted line will drop to 50% of its nominal voltage. If solid ground fault occurs in the system, the faulted line voltage will drop to zero. During the disturbances, the voltage level on the healthy lines will experience either increase or decrease in the voltage level depending on the STATCOM priority control strategy. The transformer, which connect the STATCOM to the network, has been grounded with high impedance (ungrounded) and directly grounding to examine its impact to the SCC. During the examination of the system, it has been noticed that the transformer will contribute the SCC if it directly grounded or grounded with low impedance.

5.1.1 Case Study 1: Ungrounded Transformer

In Case 1, 50% voltage drop is introduced to weak system while the primary side of the transformer is ungrounded.

Single line to ground fault

There is no significant differences between grid only and grid with ungrounded transformer in term of voltage drop, and positive and negative voltage, since the transformer is ungrounded, as shown Table 5.3 and Table 5.4.

Table 5.3: Case 1 - The primary peak voltage and current during SLG fault

Scenario	Pre - Fault			During - Fault					
	Peak Voltage (kV)			Peak Voltage (kV)			Peak Current (kA)		
	A	B	C	A	B	C	A	B	C
Grid Only	263.5	263.5	263.5	131.8	263.5	263.5	-	-	-
Ungrounded Transformer	262.1	262.1	262.1	131.3	262.3	262.2	-	-	-
Only Positive	265.9	265.9	265.9	159.9	318.5	316.9	0.19	0.19	0.19
Only Negative	264.5	264.5	264.5	155.6	246.2	242.5	0.15	0.16	0.15
Both	264.5	264.5	264.5	183.0	299.2	298.8	0.35	0.20	0.15

Table 5.4: Case 1 - Voltage and current magnitude during SLG fault

Scenario	During- Fault					
	Positive sequence		Negative sequence		Zero sequence	
	Vp (pu)	Ip (pu)	Vn (pu)	In (pu)	Vzero (pu)	Izero (pu)
Grid Only	0.83	-	0.17	-	0.11	-
Ungrounded Transformer	0.83	-	0.17	-	0.11	-
Only Positive	1.00	0.62	0.20	0.011	0.13	-
Only Negative	0.80	0.01	0.02	0.4884	0.13	-
Both	0.98	0.62	0.05	0.4953	0.18	-

The first set of analysis investigated the impact of SLG fault on STATCOM with only positive sequence control. The STATCOM immediately responds to the disturbance by injecting capacitive current to the grid. Thus, an over-voltage occurs in the healthy lines, as shown in Figure 5.2. In the mean time, the magnitude of positive voltage increased to the referenced value $1pu$. Moreover, the magnitude of negative voltage increased compared to negative voltage of grid without compensation device, as illustrated in Table 5.4.

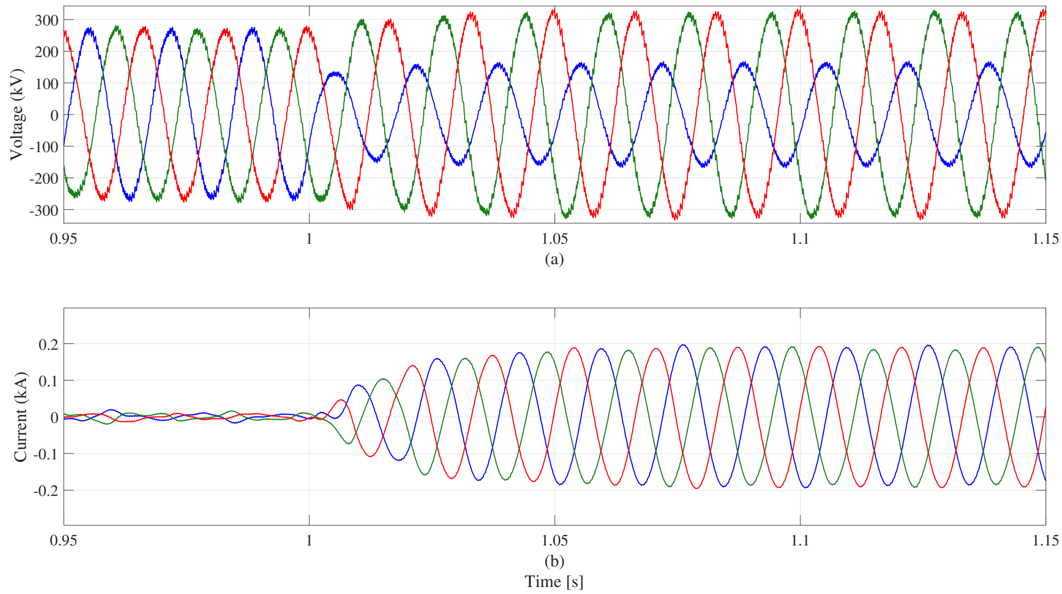


Figure 5.2: (A)Voltage (B)Current, 50% voltage drop (SLG Fault) during STATCOM with only positive sequence control while transformer is ungrounded

When the control strategy is set to compensate for only negative sequence, the STATCOM began to inject an inductive current during unsymmetrical disturbance. Due to the strategy of the negative sequence control, which increases the voltage of the faulted line and reduces the voltage of the healthy lines in order to balance the system, as shown in Figure 5.3. Thus, the magnitude of positive voltage ($0.8pu$) slightly decreased compared to grid without STATCOM compensation ($0.83pu$). On the other hand, the magnitude of negative voltage in the system is reduced, as shown in Table 5.4.

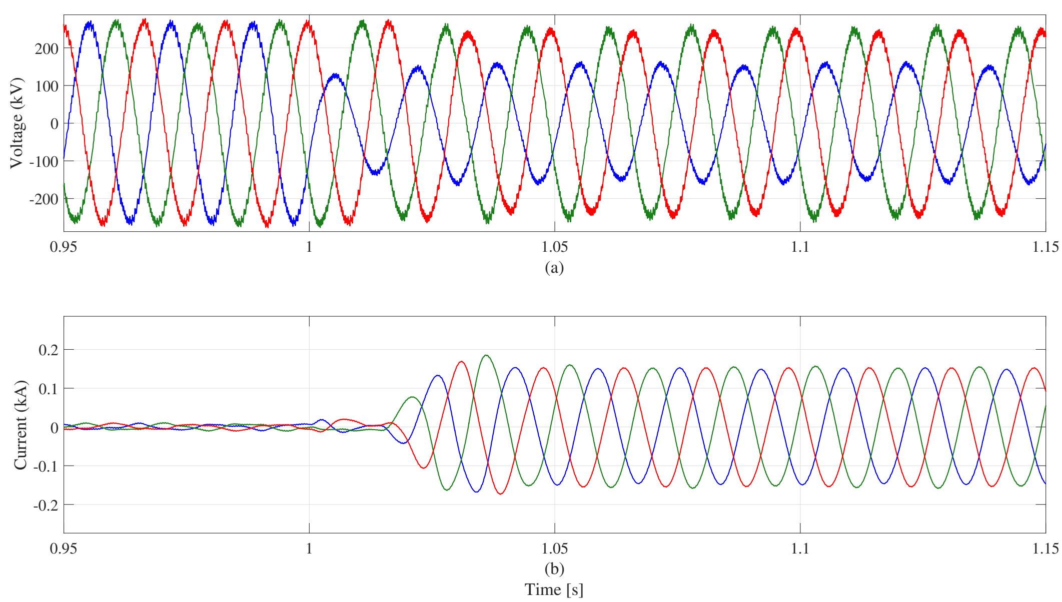


Figure 5.3: (A)Voltage (B)Current, 50% voltage drop (SLG Fault) during STATCOM with only negative sequence control while transformer is ungrounded

Figure 5.4 illustrates the instantaneous voltage and current, when the strategy of the STATCOM is set to compensate for positive and negative sequence with ratio of 1 : 1 and not to exceed the maximum current of the device. As shown in Table 5.3 the peak current of the faulted phase is higher than the healthy phases, which means more reactive current injected to faulted line. The magnitude of the positive voltage increases while the negative voltage is reduced, as shown in Table 5.4.

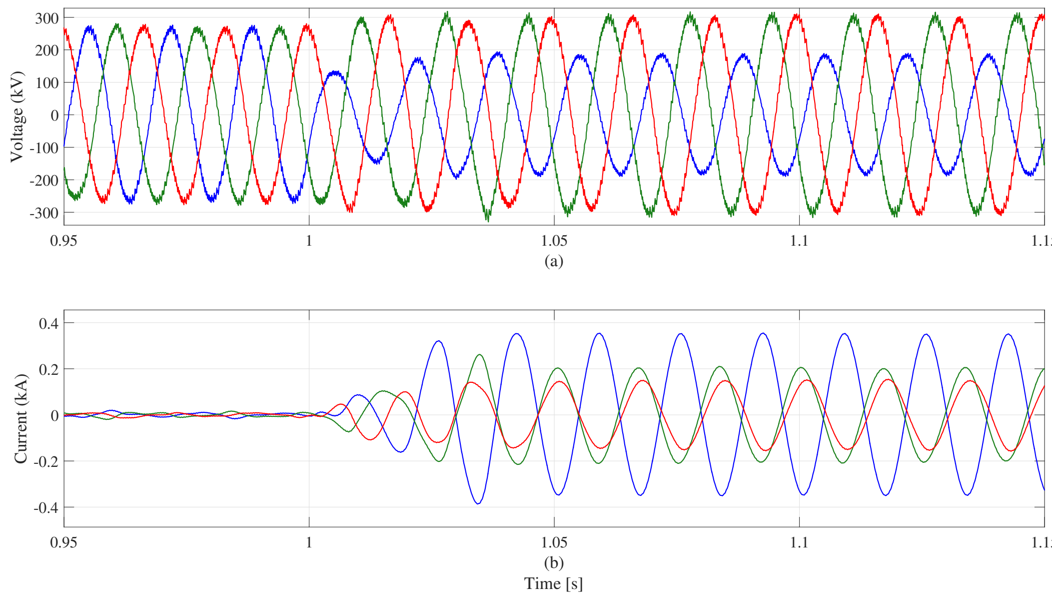


Figure 5.4: (A)Voltage (B)Current, 50% voltage drop (SLG Fault) during STATCOM with both positive and negative control while transformer is ungrounded

Because the type of the fault is SLG fault as well as the primary side of the transformer is ungrounded, the presence of zero sequence voltage can be noticed, check Table 5.4, which causes a small phase shift of instantaneous voltage during the fault.

For more simulation results check Appendix A.1.1

Double line to ground fault

In terms of positive voltage drop, DLG fault experiences voltage drop of $0.67pu$ compared to SLG fault, which experiences voltage drop of $0.83pu$, as illustrated in Table 5.5. Despite the big impact on the positive sequence voltage, the magnitude of negative voltage has almost the same value compared to SLG fault, which increased up to $0.17pu$, as highlighted in Table 5.6.

Table 5.5: Case 1 - The primary peak voltage and current during DLG fault

Scenario	Pre - Fault			During - Fault					
	Peak Voltage (kV)			Peak Voltage (kV)			Peak Current (kA)		
	A	B	C	A	B	C	A	B	C
Grid Only	263.5	263.5	263.5	263.5	131.8	131.8	-	-	-
Ungrounded Transformer	262.1	262.1	262.1	262.3	131.4	131.4	-	-	-
Only Positive	265.9	265.9	265.9	352.4	177.6	175.6	0.31	0.31	0.31
Only Negative	264.5	264.5	264.5	199.8	151.7	147.2	0.21	0.20	0.22
Both	264.5	264.5	264.5	252.9	170.4	157.4	0.04	0.27	0.26

Table 5.6: Case 1 - Voltage and current magnitude during DLG fault

Scenario	During- Fault					
	Positive sequence		Negative sequence		Zero sequence	
	Vp (pu)	Ip (pu)	Vn (pu)	In (pu)	Vzero (pu)	Izero (pu)
Grid Only	0.67	-	0.17	-	0.11	-
Ungrounded Transformer	0.66	-	0.17	-	0.11	-
Only Positive	0.89	1.00	0.23	0.01	0.15	-
Only Negative	0.62	0.04	0.03	0.67	0.08	-
Both	0.73	0.44	0.08	0.54	0.11	-

Figure 5.5 illustrates the impact on the instantaneous voltage and the instantaneous reactive current injected to support the grid. During this strategy, it is clear that this strategy cause an over-voltage to the healthy line.

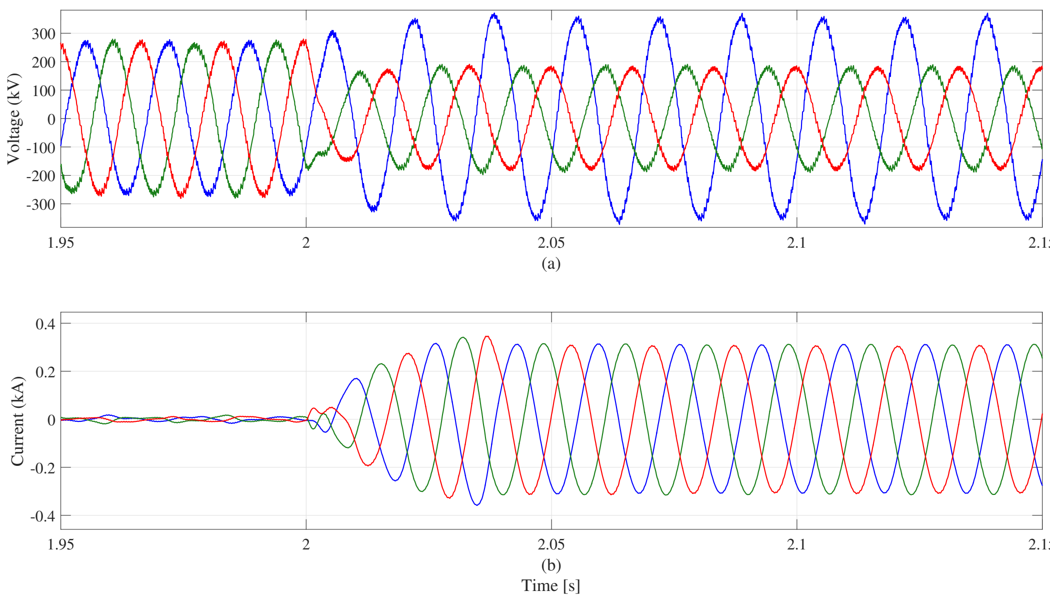


Figure 5.5: (A)Voltage (B)Current, 50% voltage drop (DLG Fault) during STATCOM with only positive sequence control while transformer is ungrounded

Figure 5.6 illustrates the STATCOM response to unsymmetrical DLG fault during only negative sequence control. Although the magnitude of negative sequence voltage is $0.17pu$, which is smellier to SLG fault, the peak value of the instantaneous current injected from the STATCOM is higher, as shown in Table 5.5. As expected, the magnitude of positive voltage decrease to $0.62pu$ and the negative voltage value is reduced 0.03, as illustrated in Table 5.6.

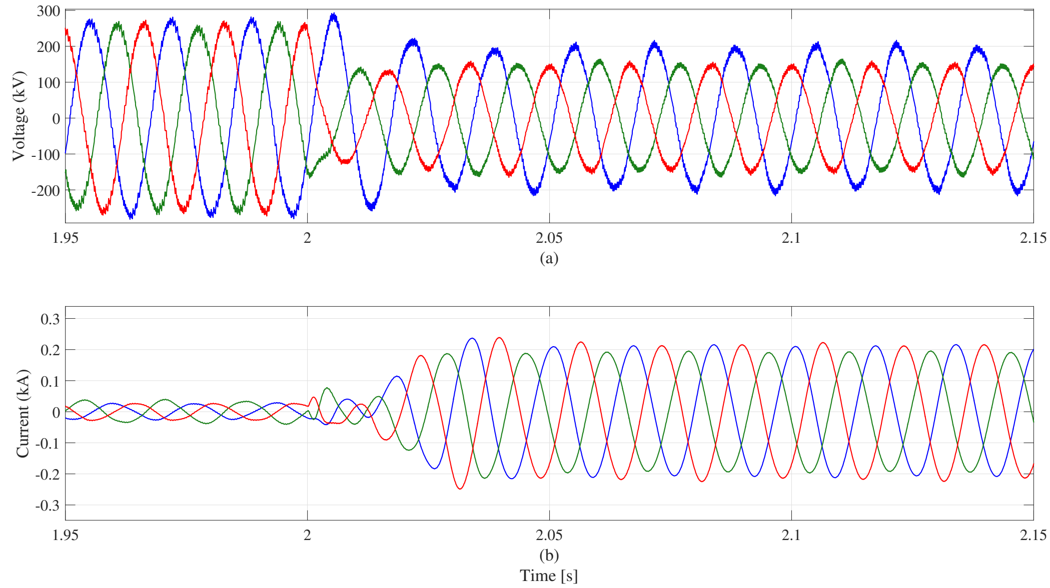


Figure 5.6: (A)Voltage (B)Current, 50% voltage drop (DLG Fault) during STATCOM with only negative sequence control while transformer is ungrounded

The third priority control strategy is to compensate for both sequences with an equal ratio of 0.5 each. Figure 5.7 shows the STATCOM injecting more reactive current to the faulted lines compared to the healthy line, as highlighted in Table 5.5. The STATCOM injects a positive sequence capacitive current to compensate for positive voltage and a negative sequence inductive current to compensate for negative voltage. Table 5.6 shows the current injected from the STATCOM to the grid are divided between both sequences.

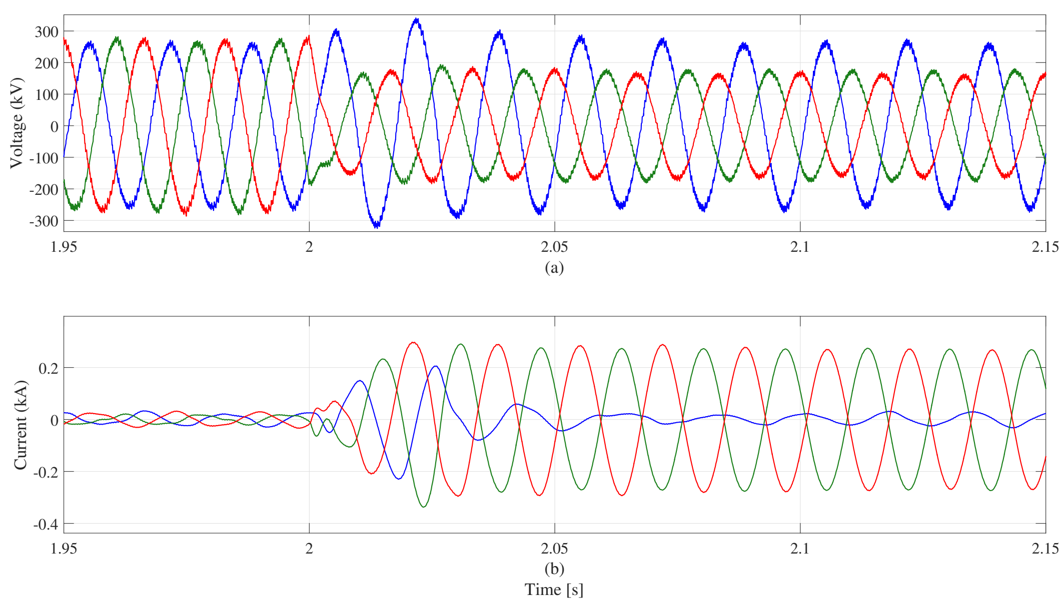


Figure 5.7: (A)Voltage (B)Current, 50% voltage drop (DLG Fault) during STATCOM with both positive and negative control while transformer is ungrounded

As shown in Table 5.6, the zero sequence voltage is reduced as the STATCOM try to compensate for only negative sequence components.

For more simulation results check Appendix A.1.2

Double line fault

Table 5.7 shows the primary peak voltage and current during DL fault. The positive voltage drop is not strong in DL fault ($0.75pu$) compared to DLG fault ($0.67pu$). However, DL fault has more impact on the magnitude of negative voltage with $0.25pu$, as can be seen in Table 5.8.

Table 5.7: Case 1 - The primary peak voltage and current during DL fault

Scenario	Pre - Fault			During - Fault					
	Peak Voltage (kV)			Peak Voltage (kV)			Peak Current (kA)		
	A	B	C	A	B	C	A	B	C
Grid Only	263.5	263.5	263.5	263.5	174.1	174.5	-	-	-
Ungrounded Transformer	262.1	262.1	262.1	262.1	173.4	173.8	-	-	-
Only Positive	265.9	265.9	265.9	351.3	233.3	229.7	0.30	0.31	0.30
Only Negative	264.5	264.5	264.5	182.0	178.9	168.4	0.27	0.25	0.28
Both	264.5	264.5	264.5	253.3	208.0	186.8	0.04	0.27	0.26

Table 5.8: Case 1 - Voltage and current magnitude during DL fault

Scenario	During- Fault					
	Positive sequence		Negative sequence		Zero sequence	
	Vp (pu)	Ip (pu)	Vn (pu)	In (pu)	Vzero (pu)	Izero (pu)
Grid Only	0.75	-	0.25	-	-	-
Ungrounded Transformer	0.75	-	0.25	-	-	-
Only Positive	1.00	1.00	0.33	0.02	-	-
Only Negative	0.67	0.05	0.03	0.86	-	-
Both	0.81	0.44	0.15	0.54	-	-

The STATCOM behavior during different control strategies is similar for SLG fault and DLG fault. Unlike grounded faults, DL fault has no impact on zero sequence components. Because, there is no path for zero sequence circulation in the network.

For more simulation results check Appendix A.1.3

5.1.2 Case Study 2: Grounded Transformer

In Case 2, 50% voltage drop is introduced to a weak system while the primary side of the transformer is directly grounded.

The general behaviour of the STATCOM during all three control strategies is almost similar for all cases in terms of compensation for positive and/or negative sequence voltage by injecting either positive and/or negative reactive current to support the grid, as shown in the Tables below.

Unlike the first case, the zero sequence current has been noticed on grounded fault due to the grounding of the primary side of transformer, as shown in Table 5.10 for SLG fault and Table 5.12 for DLG fault. Thus, the primary current is shifted during the fault, as shown in Figure 5.8. However, the zero sequence current has no impact the DL fault, since there is no ground path during this type of fault.

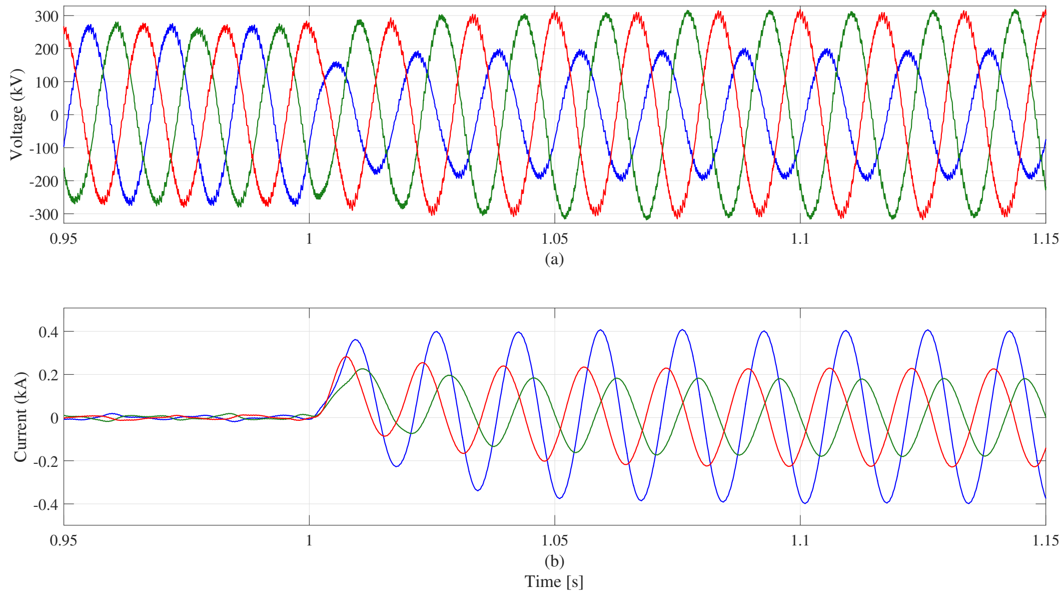


Figure 5.8: (A)Voltage (B)Current, 50% voltage drop (SLG Fault) during STATCOM with only positive sequence control while transformer directly grounded

For simulation results check appendix A.2.

Single line to ground fault

Table 5.9: Case 2 - The primary peak voltage and current during SLG fault

Scenario	Pre - Fault			During - Fault					
	Peak Voltage (kV)			Peak Voltage (kV)			Peak Current (kA)		
	A	B	C	A	B	C	A	B	C
Grid Only	263.5	263.5	263.5	131.8	263.5	263.5	-	-	-
Grounded Transformer	262.1	262.1	262.1	152.6	244.8	242.7	-	-	-
Only Positive	265.9	265.9	265.9	189.4	307.6	303.3	0.40	0.18	0.23
Only Negative	264.5	264.5	264.5	184.8	212.3	203.2	0.36	0.17	0.20
Both	264.5	264.5	264.5	208.7	245.1	261.8	0.52	0.06	0.03

Table 5.10: Case 2 - Voltage and current magnitude during SLG fault

Scenario	During- Fault					
	Positive sequence		Negative sequence		Zero sequence	
	Vp (pu)	Ip (pu)	Vn (pu)	In (pu)	Vzero (pu)	Izero (pu)
Grid Only	0.83	-	0.17	-	0.11	-
Grounded Transformer	0.80	-	0.19	-	0.02	0.30
Only Positive	1.00	0.72	0.24	0.01	0.03	0.38
Only Negative	0.76	0.01	0.03	0.60	0.03	0.37
Both	0.91	0.49	0.08	0.56	0.03	0.41

Double line to ground fault

Table 5.11: Case 2 - The primary peak voltage and current during DLG fault

Scenario	Pre - Fault			During - Fault					
	Peak Voltage (kV)			Peak Voltage (kV)			Peak Current (kA)		
	A	B	C	A	B	C	A	B	C
Grid Only	263.5	263.5	263.5	263.5	131.8	131.8	-	-	-
Grounded Transformer	262.1	262.1	262.1	226.1	145.0	146.2	-	-	-
Only Positive	265.9	265.9	265.9	286.4	194.9	196.4	0.09	0.49	0.44
Only Negative	264.5	264.5	264.5	176.5	156.0	148.4	0.29	0.17	0.12
Both	264.5	264.5	264.5	213.3	181.4	172.8	0.18	0.33	0.33

Table 5.12: Case 2 - Voltage and current magnitude during DLG fault

Scenario	During- Fault					
	Positive sequence		Negative sequence		Zero sequence	
	Vp (pu)	Ip (pu)	Vn (pu)	In (pu)	Vzero (pu)	Izero (pu)
Grid Only	0.67	-	0.17	-	0.11	-
Grounded Transformer	0.63	-	0.13	-	0.03	0.36
Only Positive	0.86	1.00	0.19	0.01	0.03	0.48
Only Negative	0.60	0.04	0.04	0.48	0.02	0.30
Both	0.73	0.53	0.04	0.53	0.03	0.36

Double line fault

The DL fault in case study 2 has the exact same result as in case study 1. This is due to the fact that fault is not grounded, which mean it does not matter if the transformer is grounded with high impedance or directly grounded, as illustrated in Table 5.13 and 5.14.

For the simulation results check appendix A.2.3.

Table 5.13: Case 2 - The primary peak voltage and current during DL fault

Scenario	Pre - Fault			During - Fault					
	Peak Voltage (kV)			Peak Voltage (kV)			Peak Current (kA)		
	A	B	C	A	B	C	A	B	C
Grid Only	263.5	263.5	263.5	263.5	174.1	174.5	-	-	-
Grounded Transformer	262.1	262.1	262.1	262.1	173.4	173.8	-	-	-
Only Positive	265.9	265.9	265.9	352.3	233.3	230.7	0.30	0.31	0.30
Only Negative	264.5	264.5	264.5	183.3	180.7	170.8	0.27	0.25	0.28
Both	264.5	264.5	264.5	254.3	209.2	188.2	0.04	0.27	0.26

Table 5.14: Case 2 - Voltage and current magnitude during DL fault

Scenario	During- Fault					
	Positive sequence		Negative sequence		Zero sequence	
	Vp (pu)	Ip (pu)	Vn (pu)	In (pu)	Vzero (pu)	Izero (pu)
Grid Only	0.75	-	0.25	-	-	-
Grounded Transformer	0.75	-	0.25	-	-	-
Only Positive	1.00	0.98	0.33	0.02	-	-
Only Negative	0.67	0.05	0.03	0.86	-	-
Both	0.81	0.44	0.15	0.55	-	-

5.1.3 Case Study 3: Ungrounded Transformer

In Case 3, solid line to ground fault is applied to a weak system while the primary side of the transformer is ungrounded.

The general behaviour of the STATCOM during all three control strategies is almost similar for all cases in term of compensation for positive and/or negative sequence voltage by injecting either positive and/or negative reactive current to support the grid.

Tables 5.16, 5.18 and 5.20 shows a high value of positive sequence current during only negative sequence control strategy, due to the STATCOM model has a lot of losses which cause the dc capacitor energy to drain very quickly. As result, the dc voltage regulator send signal to the STATCOM control to absorb some positive current to keep the dc voltage constant. Another reason, the PLL is not fast enough to lock to the pre fault value, which may be reflected on the synchronization between the grid and the STATCOM.

For simulation results check appendix A.3.

Single line to ground fault

Table 5.15: Case 3 - The primary peak voltage and current during SLG fault

Scenario	Pre - Fault			During - Fault					
	Peak Voltage (kV)			Peak Voltage (kV)			Peak Current (kA)		
	A	B	C	A	B	C	A	B	C
Grid Only	263.5	263.5	263.5	0	263.8	263.8	-	-	-
Ungrounded Transformer	262.1	262.1	262.1	0	262.3	262.2	-	-	-
Only Positive	265.9	265.9	265.9	0	353.8	356.5	0.31	0.31	0.31
Only Negative	264.5	264.5	264.5	0	207.6	255.4	0.33	0.36	0.26
Both	264.5	264.5	264.5	0	265.2	297.3	0.33	0.17	0.17

Table 5.16: Case 3 - Voltage and current magnitude during SLG fault

Scenario	During- Fault					
	Positive sequence		Negative sequence		Zero sequence	
	Vp (pu)	Ip (pu)	Vn (pu)	In (pu)	Vzero (pu)	Izero (pu)
Grid Only	0.67	-	0.33	-	0.22	-
Ungrounded Transformer	0.66	-	0.33	-	0.22	-
Only Positive	0.90	1.00	0.45	0.02	0.30	-
Only Negative	0.55	0.18	0.12	0.99	0.30	-
Both	0.71	0.48	0.26	0.59	0.30	-

Double line to ground fault

Table 5.17: Case 3 - The primary peak voltage and current during DLG fault

Scenario	Pre - Fault			During - Fault					
	Peak Voltage (kV)			Peak Voltage (kV)			Peak Current (kA)		
	A	B	C	A	B	C	A	B	C
Grid Only	263.5	263.5	263.5	263.5	0.0	0.0	-	-	-
Ungrounded Transformer	262.1	262.1	262.1	262.5	0.0	0.0	-	-	-
Only Positive	265.9	265.9	265.9	353.4	0.0	0.0	0.31	0.33	0.30
Only Negative	264.5	264.5	264.5	192.6	0.0	0.0	0.24	0.20	0.31
Both	264.5	264.5	264.5	256.3	0.0	0.0	0.04	0.25	0.28

Table 5.18: Case 3 - Voltage and current magnitude during DLG fault

Scenario	During- Fault					
	Positive sequence		Negative sequence		Zero sequence	
	Vp (pu)	Ip (pu)	Vn (pu)	In (pu)	Vzero (pu)	Izero (pu)
Grid Only	0.33	-	0.33	-	0.22	-
Ungrounded Transformer	0.33	-	0.33	-	0.22	-
Only Positive	0.45	1.00	0.45	0.05	0.30	-
Only Negative	0.24	0.21	0.24	0.45	0.16	-
Both	0.32	0.46	0.32	0.53	0.21	-

Double line fault

Table 5.19: Case 3 - The primary peak voltage and current during DL fault

Scenario	Pre - Fault			During - Fault					
	Peak Voltage (kV)			Peak Voltage (kV)			Peak Current (kA)		
	A	B	C	A	B	C	A	B	C
Grid Only	263.5	263.5	263.5	263.5	131.9	131.9	-	-	-
Ungrounded Transformer	262.1	262.1	262.1	262.1	131.0	130.8	-	-	-
Only Positive	265.9	265.9	265.9	347.3	173.7	173.7	0.30	0.33	0.30
Only Negative	264.5	264.5	264.5	191.9	96.0	96.0	0.24	0.21	0.31
Both	264.5	264.5	264.5	254.3	127.1	127.1	0.04	0.26	0.28

Table 5.20: Case 3 - Voltage and current magnitude during DL fault

Scenario	During- Fault					
	Positive sequence		Negative sequence		Zero sequence	
	Vp (pu)	Ip (pu)	Vn (pu)	In (pu)	Vzero (pu)	Izero (pu)
Grid Only	0.50	-	0.50	-	-	-
Ungrounded Transformer	0.50	-	0.50	-	-	-
Only Positive	0.65	1.00	0.65	0.06	-	-
Only Negative	0.37	0.20	0.37	0.79	-	-
Both	0.48	0.45	0.48	0.53	-	-

5.1.4 Case Study 4: Grounded Transformer

In Case 4, solid line to ground fault is introduced to a weak system while the primary side of the transformer is directly grounded.

The general behaviour of the STATCOM during all three control strategies is almost similar for all cases in term of compensation for positive and/or negative sequence voltage by injecting either positive and/or negative reactive current to support the grid. This case has bigger impact on the dc voltage capacitor during DLG fault compared with case 3 due to the directly grounded transformer with positive current absorbed of $0.31pu$ in case 4 and $0.21pu$ in case 3.

For simulation results check appendix A.4

Single line to ground fault

Table 5.21: Case 4 - The primary peak voltage and current during SLG fault

Scenario	Pre - Fault			During - Fault					
	Peak Voltage (kV)			Peak Voltage (kV)			Peak Current (kA)		
	A	B	C	A	B	C	A	B	C
Grid Only	263.5	263.5	263.5	0.0	263.8	263.8	-	-	-
Grounded Transformer	262.1	262.1	262.1	0.0	231.6	226.3	-	-	-
Only Positive	265.9	265.9	265.9	0.0	312.8	305.6	0.76	0.36	0.45
Only Negative	264.5	264.5	264.5	0.0	152.6	160.2	0.78	0.43	0.38
Both	264.5	264.5	264.5	0.0	221.3	222.0	0.80	0.31	0.30

Table 5.22: Case 4 - Voltage and current magnitude during SLG fault

Scenario	During- Fault					
	Positive sequence		Negative sequence		Zero sequence	
	Vp (pu)	Ip (pu)	Vn (pu)	In (pu)	Vzero (pu)	Izero (pu)
Grid Only	0.67	-	0.33	-	0.22	-
Grounded Transformer	0.54	-	0.46	-	0.05	0.72
Only Positive	0.72	1.00	0.62	0.04	0.07	0.96
Only Negative	0.39	0.20	0.28	1.00	0.07	0.97
Both	0.53	0.50	0.42	0.59	0.07	0.98

Double line to ground fault

Table 5.23: Case 4 - The primary peak voltage and current during DLG fault

Scenario	Pre - Fault			During - Fault					
	Peak Voltage (kV)			Peak Voltage (kV)			Peak Current (kA)		
	A	B	C	A	B	C	A	B	C
Grid Only	263.5	263.5	263.5	263.5	0.0	0.0	-	-	-
Grounded Transformer	262.1	262.1	262.1	98.9	0.0	0.0	-	-	-
Only Positive	265.9	265.9	265.9	130.8	0.0	0.0	0.44	0.99	0.62
Only Negative	264.5	264.5	264.5	74.8	0.0	0.0	0.63	0.46	0.30
Both	264.5	264.5	264.5	96.4	0.0	0.0	0.57	0.66	0.50

Table 5.24: Case 4 - Voltage and current magnitude during DLG fault

Scenario	During- Fault					
	Positive sequence		Negative sequence		Zero sequence	
	Vp (pu)	Ip (pu)	Vn (pu)	In (pu)	Vzero (pu)	Izero (pu)
Grid Only	0.33	-	0.33	-	0.22	-
Grounded Transformer	0.12	-	0.12	-	0.08	1.17
Only Positive	0.17	1.00	0.17	0.04	0.11	1.56
Only Negative	0.09	0.31	0.09	0.70	0.06	0.88
Both	0.12	0.48	0.12	0.50	0.08	1.12

Double line fault

Table 5.25: Case 4 - The primary peak voltage and current during DL fault

Scenario	Pre - Fault			During - Fault					
	Peak Voltage (kV)			Peak Voltage (kV)			Peak Current (kA)		
	A	B	C	A	B	C	A	B	C
Grid Only	263.5	263.5	263.5	263.5	131.9	131.9	-	-	-
Grounded Transformer	262.1	262.1	262.1	262.1	131.1	131.1	-	-	-
Only Positive	265.9	265.9	265.9	347.3	173.7	173.7	0.30	0.33	0.30
Only Negative	264.5	264.5	264.5	192.1	96.0	96.0	0.24	0.21	0.31
Both	264.5	264.5	264.5	254.3	127.1	127.1	0.04	0.26	0.28

Table 5.26: Case 4 - Voltage and current magnitude during DL fault

Scenario	During- Fault					
	Positive sequence		Negative sequence		Zero sequence	
	Vp (pu)	Ip (pu)	Vn (pu)	In (pu)	Vzero (pu)	Izero (pu)
Grid Only	0.50	-	0.50	-	-	-
Grounded Transformer	0.50	-	0.50	-	-	-
Only Positive	0.66	1.00	0.66	0.06	-	-
Only Negative	0.37	0.20	0.37	0.79	-	-
Both	0.48	0.45	0.48	0.53	-	-

5.2 Strong Network

Strong network cases has been add as comparison to weak grid in case 3 and 4. The STATCOM behavior during all three control strategies is exactly similar for all cases in terms of compensation for positive and/or negative sequence voltage by injecting either positive and/or negative reactive current to support the grid. However, the impact was not severe compared to case 3 and 4 in weak grid, which is expected.

5.2.1 Case Study 5: Ungrounded Transformer

In Case 5, solid line to ground fault is applied to a strong system while the primary side of the transformer grounded with high impedance.

For simulation results check appendix B.1

Single line to ground fault

Table 5.27: Case 5 - The primary peak voltage and current during SLG fault

Scenario	Pre - Fault			During - Fault					
	Peak Voltage (kV)			Peak Voltage (kV)			Peak Current (kA)		
	A	B	C	A	B	C	A	B	C
Grid Only	263.0	263.0	263.0	0.0	263.0	263.0	-	-	-
Ungrounded Transformer	263.0	263.0	263.0	0.0	263.0	263.0	-	-	-
Only Positive	270.0	270.0	270.0	0.0	303.0	304.0	0.31	0.30	0.31
Only Negative	270.0	270.0	270.0	0.0	235.0	260.0	0.32	0.26	0.33
Both	270.0	270.0	270.0	0.0	264.0	274.0	0.33	0.16	0.16

Table 5.28: Case 5 - Voltage and current magnitude during SLG fault

Scenario	During- Fault					
	Positive sequence		Negative sequence		Zero sequence	
	Vp (pu)	Ip (pu)	Vn (pu)	In (pu)	Vzero (pu)	Izero (pu)
Grid Only	0.67	-	0.33	-	0.22	-
Ungrounded Transformer	0.67	-	0.33	-	0.22	-
Only Positive	0.75	0.99	0.38	0.03	0.25	-
Only Negative	0.62	0.15	0.25	0.97	0.25	-
Both	0.69	0.47	0.31	0.58	0.25	-

Double line to ground fault

Table 5.29: Case 5 -The primary peak voltage and current during DLG fault

Scenario	Pre - Fault			During - Fault					
	Peak Voltage (kV)			Peak Voltage (kV)			Peak Current (kA)		
	A	B	C	A	B	C	A	B	C
Grid Only	263.0	263.0	263.0	263.0	0.0	0.0	-	-	-
Ungrounded Transformer	263.0	263.0	263.0	263.0	0.0	0.0	-	-	-
Only Positive	270.0	270.0	270.0	305.0	0.0	0.0	0.31	0.31	0.31
Only Negative	270.0	270.0	270.0	240.0	0.0	0.0	0.24	0.18	0.30
Both	270.0	270.0	270.0	266.0	0.0	0.0	0.04	0.25	0.27

Table 5.30: Case 5 - Voltage and current magnitude during DLG fault

Scenario	During- Fault					
	Positive sequence		Negative sequence		Zero sequence	
	Vp (pu)	Ip (pu)	Vn (pu)	In (pu)	Vzero (pu)	Izero (pu)
Grid Only	0.33	-	0.33	-	0.22	-
Ungrounded Transformer	0.33	-	0.33	-	0.22	-
Only Positive	0.38	0.99	0.38	0.05	0.25	-
Only Negative	0.30	0.21	0.30	0.78	0.20	-
Both	0.33	0.45	0.33	0.53	0.22	-

Double line fault

Table 5.31: Case 5 - The primary peak voltage and current during DL fault

Scenario	Pre - Fault			During - Fault					
	Peak Voltage (kV)			Peak Voltage (kV)			Peak Current (kA)		
	A	B	C	A	B	C	A	B	C
Grid Only	263.0	263.0	263.0	263.0	131.6	131.6	-	-	-
Ungrounded Transformer	263.0	263.0	263.0	263.0	131.5	131.5	-	-	-
Only Positive	270.0	270.0	270.0	300.0	150.0	150.0	0.31	0.31	0.30
Only Negative	270.0	270.0	270.0	234.5	117.3	117.3	0.24	0.20	0.29
Both	270.0	270.0	270.0	258.4	129.2	129.2	0.04	0.25	0.27

Table 5.32: Case 5 - Voltage and current magnitude during DL fault

Scenario	During- Fault					
	Positive sequence		Negative sequence		Zero sequence	
	Vp (pu)	Ip (pu)	Vn (pu)	In (pu)	Vzero (pu)	Izero (pu)
Grid Only	0.50	-	0.50	-	-	-
Ungrounded Transformer	0.50	-	0.50	-	-	-
Only Positive	0.57	0.99	0.57	0.05	-	-
Only Negative	0.44	0.20	0.44	0.78	-	-
Both	0.50	0.45	0.50	0.53	-	-

5.2.2 Case Study 6: Grounded Transformer

In Case 6, solid line to ground fault is introduced to a strong system while the primary side of the transformer grounded with high impedance.

For simulation results check appendix B.2

Single line to ground fault

Table 5.33: Case 6 - The primary peak voltage and current during SLG fault

Scenario	Pre - Fault			During - Fault					
	Peak Voltage (kV)			Peak Voltage (kV)			Peak Current (kA)		
	A	B	C	A	B	C	A	B	C
Grid Only	263.0	263.0	263.0	0.0	263.0	263.0	-	-	-
Grounded Transformer	263.0	263.0	263.0	0.0	238.3	231.2	-	-	-
Only Positive	270.0	270.0	270.0	0.0	270.7	264.3	1.03	0.59	0.66
Only Negative	270.0	270.0	270.0	0.0	207.2	207.2	1.02	0.66	0.59
Both	270.0	270.0	270.0	0.0	233.8	233.8	1.05	0.56	0.56

Table 5.34: Case 6 - Voltage and current magnitude during SLG fault

Scenario	During- Fault					
	Positive sequence		Negative sequence		Zero sequence	
	Vp (pu)	Ip (pu)	Vn (pu)	In (pu)	Vzero (pu)	Izero (pu)
Grid Only	0.67	-	0.33	-	0.22	-
Grounded Transformer	0.57	-	0.43	-	0.09	1.34
Only Positive	0.65	0.99	0.49	0.03	0.11	1.52
Only Negative	0.50	0.18	0.35	0.98	0.11	1.51
Both	0.58	0.49	0.41	0.58	0.11	1.53

Double line to ground fault

Table 5.35: Case 6 - The primary peak voltage and current during DLG fault

Scenario	Pre - Fault			During - Fault					
	Peak Voltage (kV)			Peak Voltage (kV)			Peak Current (kA)		
	A	B	C	A	B	C	A	B	C
Grid Only	263.0	263.0	263.0	263.0	0.0	0.0	-	-	-
Grounded Transformer	263.0	263.0	263.0	158.3	0.0	0.0	-	-	-
Only Positive	270.0	270.0	270.0	180.5	0.0	0.0	0.70	1.24	1.14
Only Negative	270.0	270.0	270.0	142.4	0.0	0.0	1.03	0.81	0.60
Both	270.0	270.0	270.0	156.0	0.0	0.0	0.90	0.98	0.81

Table 5.36: Case 6 - Voltage and current magnitude during DLG fault

Scenario	During- Fault					
	Positive sequence		Negative sequence		Zero sequence	
	Vp (pu)	Ip (pu)	Vn (pu)	In (pu)	Vzero (pu)	Izero (pu)
Grid Only	0.33	-	0.33	-	0.22	-
Grounded Transformer	0.20	-	0.20	-	0.13	1.87
Only Positive	0.23	0.99	0.23	0.05	0.15	2.13
Only Negative	0.18	0.25	0.18	0.75	0.12	1.68
Both	0.20	0.46	0.20	0.52	0.13	1.84

Double line fault

Table 5.37: Case 6 - The primary peak voltage and current during DL fault

Scenario	Pre - Fault			During - Fault					
	Peak Voltage (kV)			Peak Voltage (kV)			Peak Current (kA)		
	A	B	C	A	B	C	A	B	C
Grid Only	263.0	263.0	263.0	263.0	131.6	131.6	-	-	-
Grounded Transformer	263.0	263.0	263.0	263.0	131.5	131.5	-	-	-
Only Positive	270.0	270.0	270.0	300.0	150.0	150.0	0.31	0.33	0.30
Only Negative	270.0	270.0	270.0	234.5	117.3	117.3	0.24	0.21	0.30
Both	270.0	270.0	270.0	258.4	129.2	129.2	0.04	0.26	0.29

Table 5.38: Case 6 - Voltage and current magnitude during DL fault

Scenario	During- Fault					
	Positive sequence		Negative sequence		Zero sequence	
	Vp (pu)	Ip (pu)	Vn (pu)	In (pu)	Vzero (pu)	Izero (pu)
Grid Only	0.50	-	0.50	-	-	-
Grounded Transformer	0.50	-	0.50	-	-	-
Only Positive	0.56	0.99	0.56	0.05	-	-
Only Negative	0.44	0.21	0.44	0.78	-	-
Both	0.50	0.45	0.50	0.53	-	-

5.3 Short Circuit Current Contribution

The SCC is very low in a grid with a large penetration of RES, which may effect the voltage stability and the reliability of the grid. So, an examination has been conducted on STATCOM to investigate its ability of injecting SCC with different strategy control to enhance the reliability of the grid. Table 5.39 illustrates the total SCC of the grid in first case with STATCOM using different strategy and without STATCOM during different fault conditions.

During different fault conditions, the STATCOM always increases the SCC across the faulted lines. However, the level of SCC contribution differs with different control strategies, fault types and the grounding of the transformer. Only positive sequence control strategy has the highest SCC contribution of ($0.45kA$) during DLG fault. On the other hand, only negative sequence control strategy has the lowest SCC contribution during all types of faults. However, STATCOM with priority control strategy set to compensate for positive and negative sequences with equal ratio of 0.5 has the highest SCC contribution of ($0.46kA$) during SLG fault. In DL fault, the STATCOM produces almost the same amount of SCC during all different control strategy.

Table 5.39: Case 1: Total short circuit current. 50% voltage drop with transformer grounded with high impedance

Case 1: Iscc_rms (kA)									
Scenario	Single line to ground			Double line to ground			Double line		
	A	B	C	A	B	C	A	B	C
Grid Only	0.33	-	-	-	0.33	0.33	-	0.29	0.29
Ungrounded Transformer	0.33	-	-	-	0.33	0.33	-	0.29	0.29
Only Positive	0.41	-	-	-	0.45	0.45	-	0.39	0.39
Only Negative	0.39	-	-	-	0.38	0.37	-	0.38	0.38
Both	0.46	-	-	-	0.43	0.40	-	0.39	0.38

Evidently, the transformer contributes to the Short circuit current while its directly grounded or grounded via low impedance, as highlighted in Table 5.40 for weak grid as well as Table 5.41 for strong grid. Interestingly, the STATCOM with only negative sequence control strategy does not contribute to the Short circuit current compared to grid with transformer, that means the SCC contribution during this strategy comes from the transformer, as illustrated in Tables 5.40 and 5.41. It can be notices that the STATCOM injecting the maximum fault current, which can be delivered during the fault.

Table 5.40: Case 4: Total short circuit current in weak grid. Solid line to ground fault with directly grounded transformer

Case 4: Iscc_rms (kA)									
Scenario	Single line to ground			Double line to ground			Double line		
	A	B	C	A	B	C	A	B	C
Grid Only	0.67	-	-	-	0.67	0.67	-	0.58	0.58
Grounded Transformer	0.93	-	-	-	0.94	0.96	-	0.58	0.58
Only Positive	1.24	-	-	-	1.27	1.17	-	0.78	0.78
Only Negative	1.25	-	-	-	0.95	0.89	-	0.74	0.74
Both	1.26	-	-	-	1.07	1.03	-	0.77	0.77

Table 5.41: Case 6: Total short circuit current in strong grid. Solid line to ground fault with directly grounded transformer

Case 6: Iscc_rms (kA)									
Scenario	Single line to ground			Double line to ground			Double line		
	A	B	C	A	B	C	A	B	C
Grid Only	1.67	-	-	-	1.67	1.67	-	1.45	1.45
Grounded Transformer	2.15	-	-	-	2.06	2.12	-	1.45	1.45
Only Positive	2.45	-	-	-	2.35	2.40	-	1.65	1.65
Only Negative	2.43	-	-	-	2.12	2.06	-	1.60	1.60
Both	2.46	-	-	-	2.22	2.20	-	1.63	1.63

For SCC contribution for the rest of cases check appendix C

5.4 Conclusion

The amount of SCC contributed from STATCOM depends on three variable: 1) the STATCOM control strategy; 2) they type of fault; 3) the transformer grounding. Using only positive sequence control strategy will lead to increasing the voltage across the healthy line, which may lead to overvoltage protection relay to disconnect the line. On the other hand, only negative sequence control is a good strategy, if the transformer is ungrounded. Because, it does not have the overvoltage issue compared to only positive control strategy. However, The best STATCOM control strategy is to compensate for both sequences with an equal ratio of 0.5. This control strategy could not increase the magnitude of the positive voltage to $1pu$ during 50% voltage drop compared with only positive sequence control strategy. However, it manage to increase the voltage across the faulted line only as well as contributing to the SCC in all the cases, unlike only negative sequence control strategy while the transformer is directly grounded.

Chapter 6

Discussion

This chapter a general overview of the environmental and ethical aspects of the thesis.

6.1 Environmental aspects

The need of power increases as the growth of population increase, which has negative impact on the environment by releasing greenhouse gases from burning gases, coal and oil in the power plant. The earth temperature will increase, which have negative impact on every creatures on the planet, if people continue producing energy using conventional power plants. In order to reduce the greenhouse gases, engineers have been developing and improving the RES to cover the electricity demand in a way its harmless to the environment in the last three decades. As the renewable energy penetration increases in the electrical system, it raise new technical problems. Moreover, it reduce the reliability of protection devices during the disturbance on the system. As result, all the protection devices need to be replace with more advanced devices to sense any disturbance in the system, which mean there will be a lot of junks of useless devices thrown away. These methods of generating energy have impact the strength and stability of the electrical system.

STATCOM device, which is a part of FACTS family devices, has been develop to improve the system strength and reliability. Furthermore, helping the old protection devices to sense if there is any disturbance in the system by injecting SCC during the fault. By integrating STATCOM device with LVRT function to producing current during the fault in the weak grid, the strength and reliability of the electrical system increases as well as no need to replace the old protection devices.

6.2 Ethical aspects

As the development of the STATCOM improved by adding LVRT, more RES will be penetrated to the system, which is great things to reduce greenhouse gases. However, it has indirect impact to the wildlife by cutting down the trees to build more renewable energy plants. Even though STATCOM device is relatively small in size compared to other FACTS devices, it take land close to the perfect point of connection. If the premises of the station is not well closed animal my jump over the fence and get electrocuted to death.

The work place environment, form the ethical point of view, need to be suitable for those who operate and maintain the station. All the hazard places and equipment need to be labelled in clear sign. During the maintains of the equipment, the place should be locked up with safety prior to keep other employee out of the danger zone. Furthermore, the worker need to be trained in how to evacuate the station in case of fire. The root of the nearest exit door clearly labelled and easy to follow.

Since the station need to be connected to the main control room via satellite or internet, it need to be well protected form any cyber attack, which could have an impact on the whole network system.

Chapter 7

Conclusions and Future Work

This chapter summarizes conclusions and give some suggestions for further work

7.1 Conclusions

This paper present a development of STATCOM control strategy to enhance the RES to meet the requirements of the grid code. These requirements on RES has been reviewed in UK , Denmark and Germany. Furthermore, the LVRT and SCC contribution during disturbance has been explained with details. During the development of STATCOM control, the separation of the positive and negative sequence components has been successfully accomplished to investigate the unsymmetrical disturbance in the grid. The power grid has been examined with STATCOM, while applying different control strategy, and without STATCOM during different type of fault conditions.

During only positive sequence control strategy, the STATCOM has improved the positive voltage in all cases and increased the negative voltage. The downside of using this strategy is that the voltage across the healthy line increases from 15% to 35% of nominal value. On the other hand, only negative sequence control strategy has been reduced the value of the negative voltage in the system, which decrease the positive voltage in the system as well. Finally, positive and negative sequence control strategy, with an equal ratio of 0.5 each, has increases the positive voltage and reduce the negative voltage the same time. This strategy does not cause an over-voltage across the healthy lines, like only positive sequence control, and does not decrease the voltage, like only negative sequence control.

In term of SCC contribution, the level of contribution depends on three factors: 1) The type of fault as well as fault impedance; 2) Transformer grounding; 3) STATCOM control strategy. Only positive sequence control strategy and both sequences control strategy have proven that they can contribute to the SCC in all cases. On the other hand, only negative sequence control strategy does not contribute to the SCC in the cases where the transformer is directly grounded. During both sequence control strategy.

To conclude, positive and negative sequences control strategy is the best strategy in term of improving the three phase voltage as well as SCC contribution to the power grid.

7.2 Future Work

- The examination has been done in STATCOM with two level converter. So, STATCOM with multilevel converter may be used to test the concept of short circuit current contribution and LVRT strategy to investigate the performance of the control.
- Performing a sensitivity analysis of control and component parameters to get more a generalized conclusion.
- The STATCOM model need to be tested in grid with renewable energy resources.
- In this thesis, positive and negative sequence control strategy has been used with an equal ratio of 0.5 each. The STATCOM model should be tested with different compensation ratio of positive and negative to find the optimal ratio during the disturbance.
- Add control strategy to detect the type of fault and decide to switch in the transformer grounding depend on the need of short circuit current in the system which need to be analyzed in advanced.
- Further study in the thermal limitation of the STATCOM valve during the disturbance.

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Appendix A

Weak Network

Appendix A tables is the result of examining a weak network of 400 MVA. The network has experience 50% voltage drops with fault impedance of $52.08 + j294.6\Omega$ as well as Solid line to ground fault. During the examination, the transformer, which link the STATCOM to the network, has been directly grounded and grounded with high impedance to observe the impact of the transformer to the network.

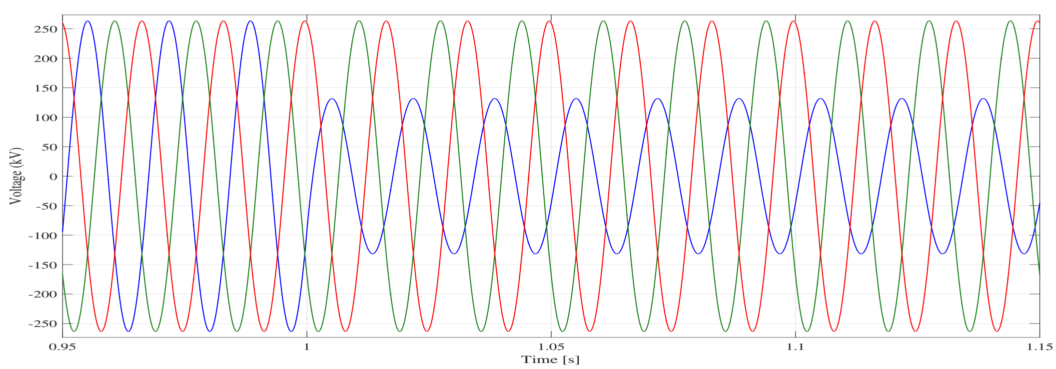

Figure A.1: Voltage, 50% voltage drop (SLG Fault) grid without STATCOM

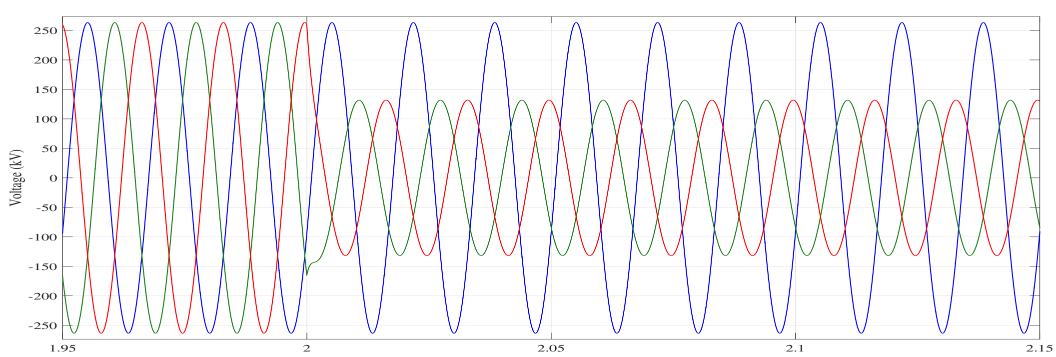

Figure A.2: Voltage, 50% voltage drop (DLG Fault) grid without STATCOM

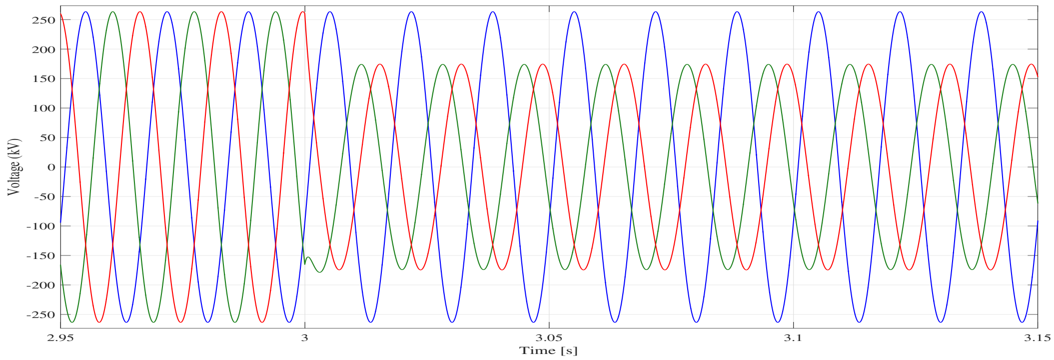

Figure A.3: Voltage, 50% voltage drop (DL Fault) grid without STATCOM

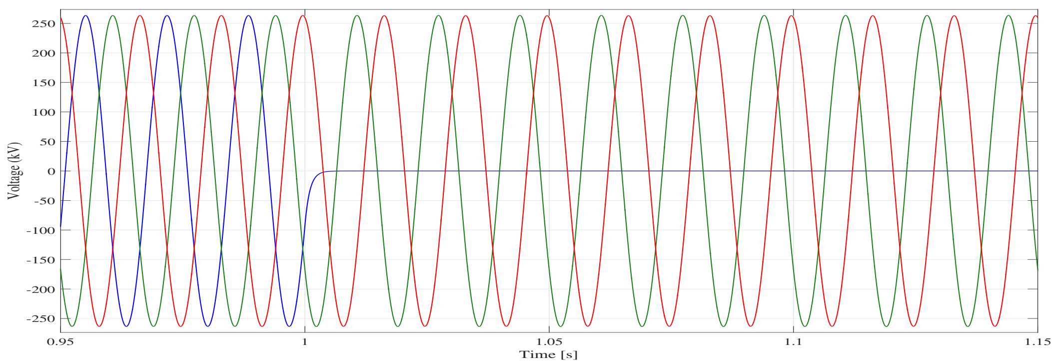

Figure A.4: Voltage, Solid to ground fault (SLG Fault) Grid without STATCOM

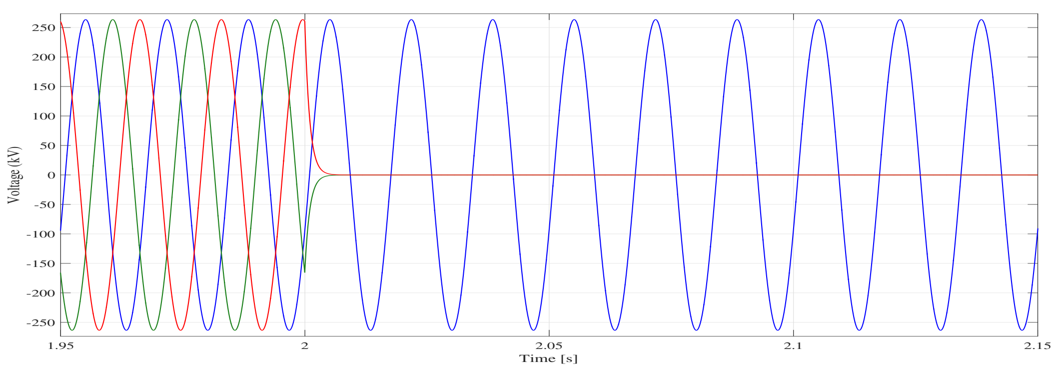

Figure A.5: Voltage, Solid to ground fault (DLG Fault) Grid without STATCOM

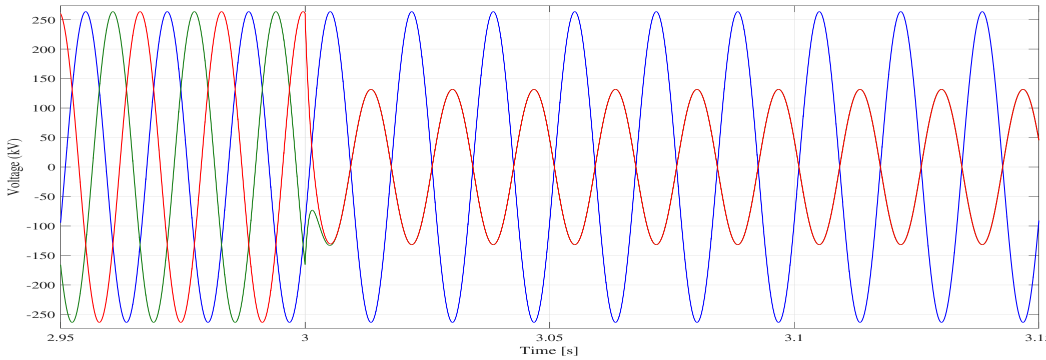

Figure A.6: Voltage, Solid to ground fault (DL Fault) Grid without STATCOM

A.1 Case Study 1

A.1.1 Single line to ground fault

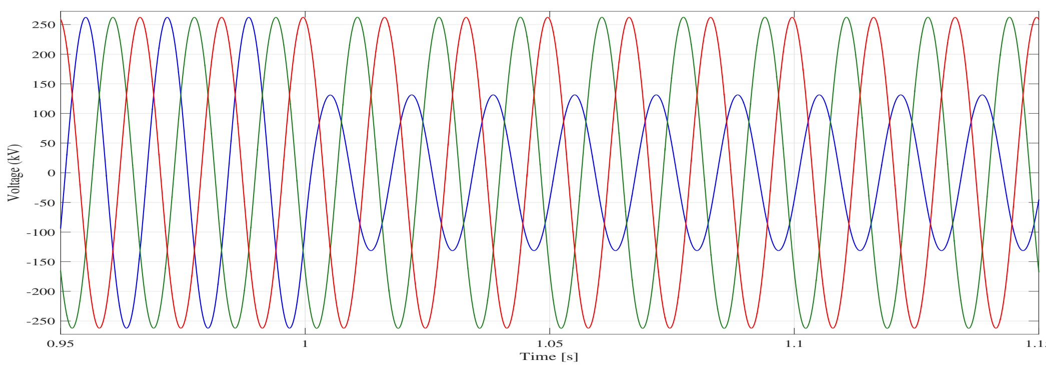

Figure A.7: Voltage, 50% voltage drop (SLG Fault) Grid with ungrounded transformer

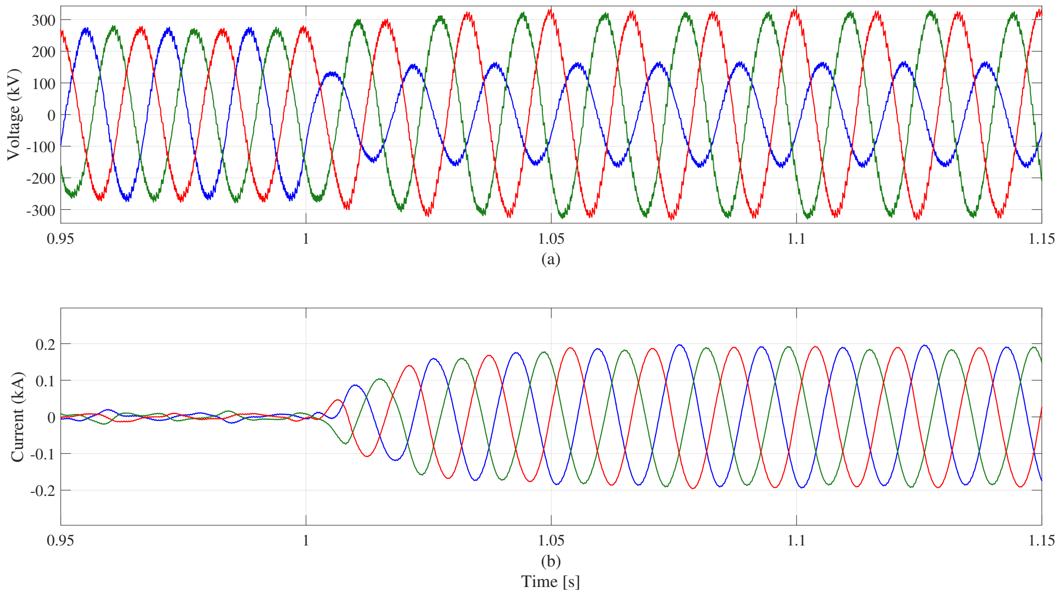

Figure A.8: (A)Voltage (B)Current, 50% voltage drop (SLG Fault) during STATCOM with only positive sequence control while transformer is ungrounded

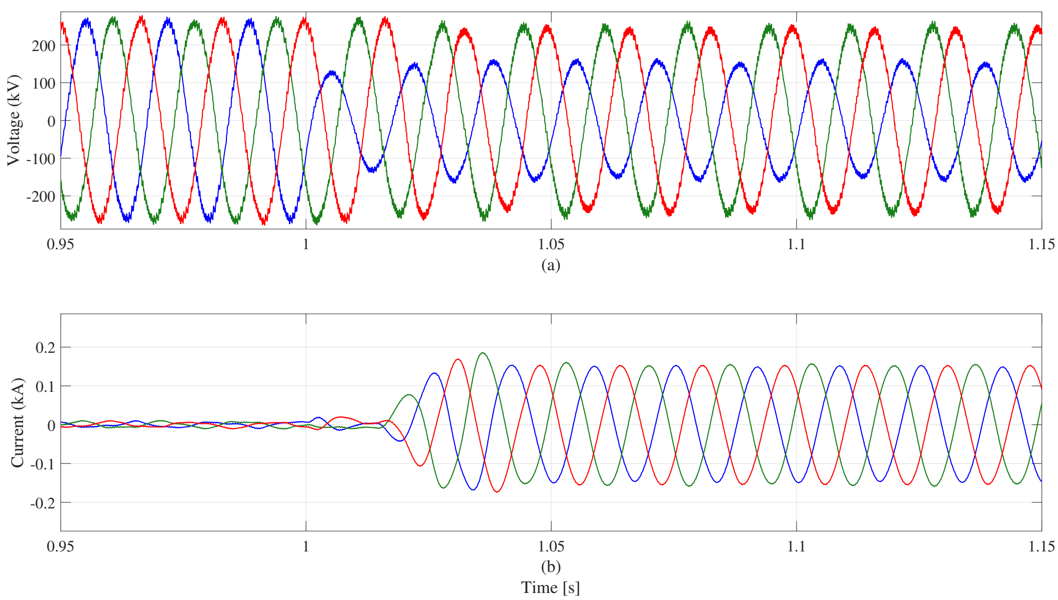

Figure A.9: (A)Voltage (B)Current, 50% voltage drop (SLG Fault) during STATCOM with only negative sequence control while transformer is ungrounded

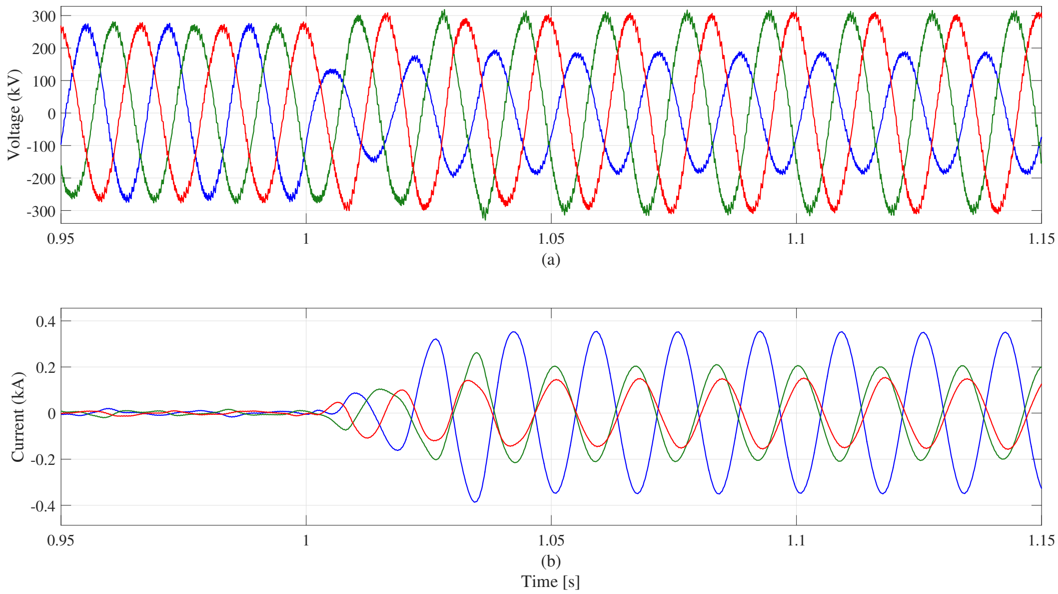

Figure A.10: (A)Voltage (B)Current, 50% voltage drop (SLG Fault) during STATCOM with both positive and negative control while transformer is ungrounded

A.1.2 Double line to ground fault

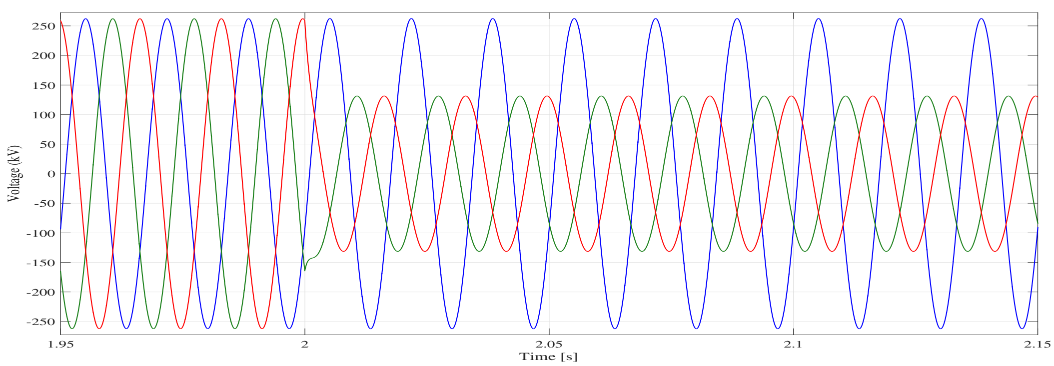

Figure A.11: Voltage, 50% voltage drop (DLG Fault) Grid with ungrounded transformer

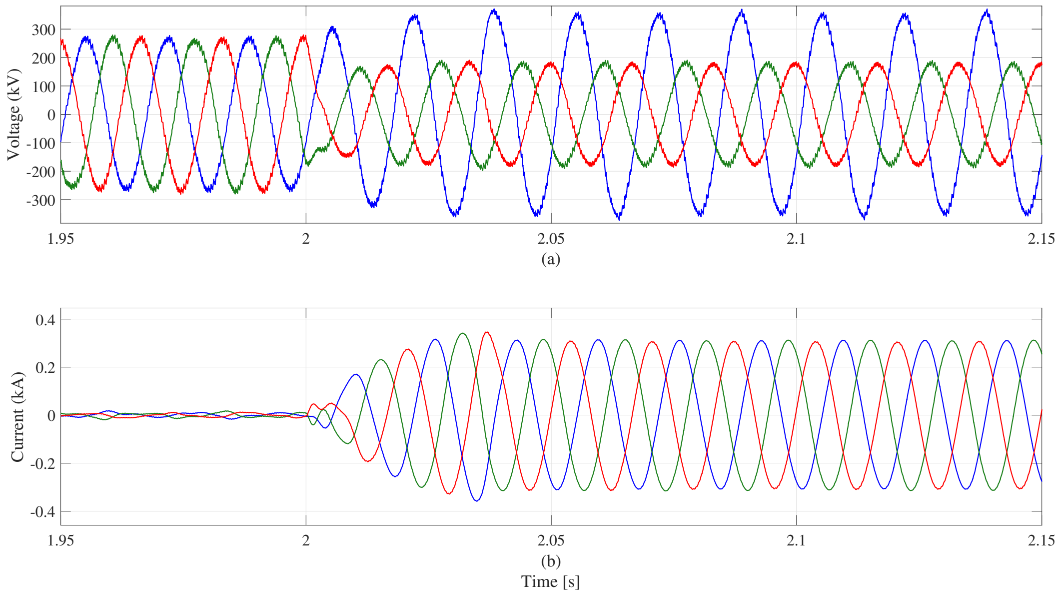

Figure A.12: (A)Voltage (B)Current, 50% voltage drop (DLG Fault) during STATCOM with only positive sequence control while transformer is ungrounded

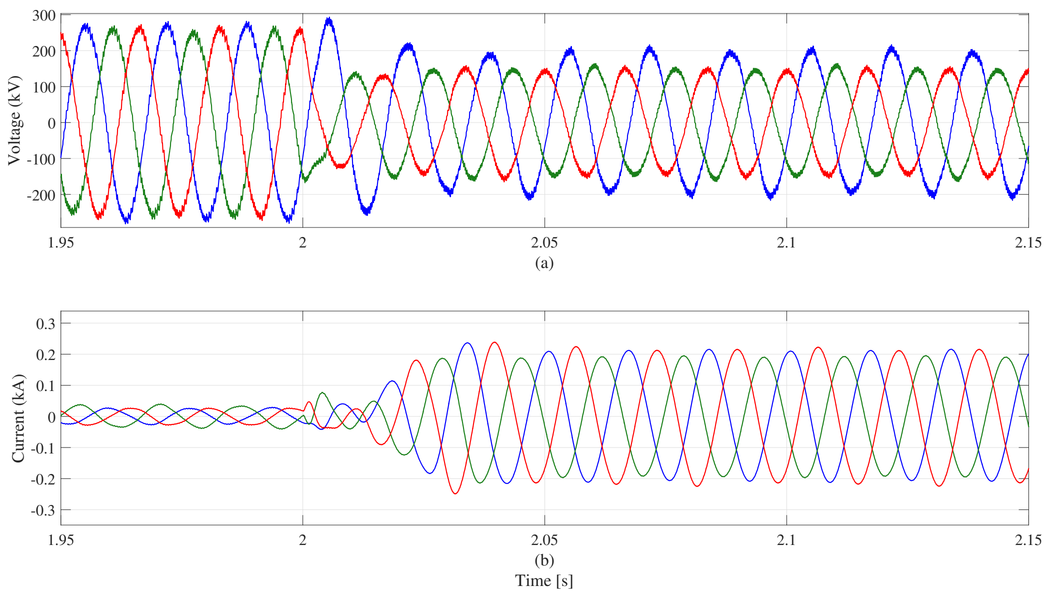

Figure A.13: (A)Voltage (B)Current, 50% voltage drop (DLG Fault) during STATCOM with only negative sequence control while transformer is ungrounded

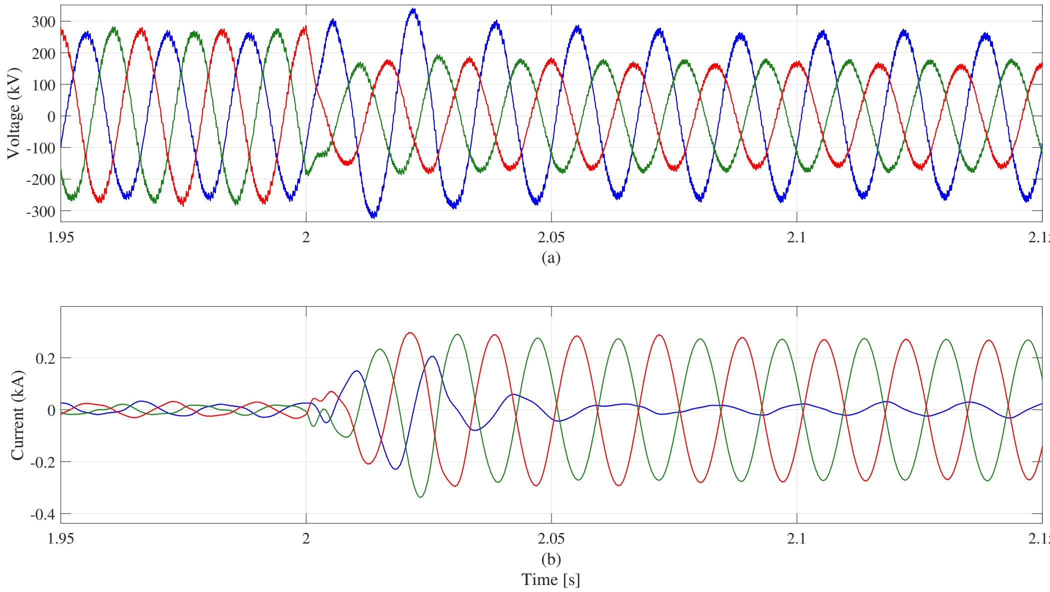

Figure A.14: (A)Voltage (B)Current, 50% voltage drop (DLG Fault) during STATCOM with both positive and negative control while transformer is ungrounded

A.1.3 Double line fault

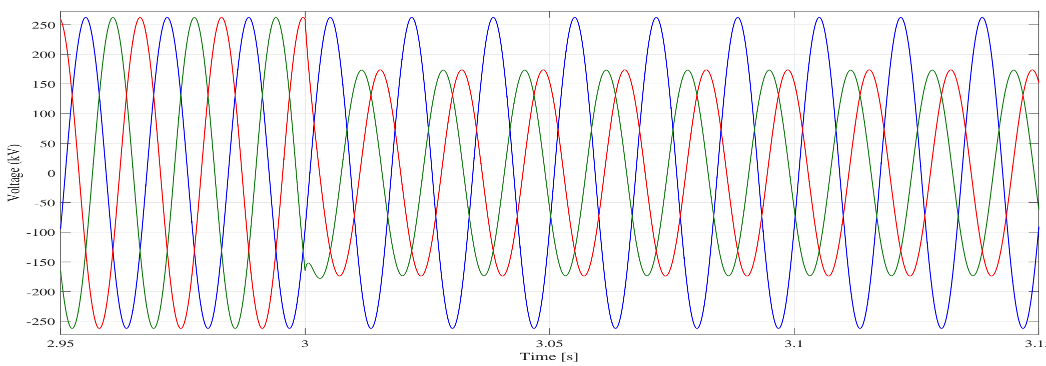

Figure A.15: Voltage, 50% voltage drop (DL Fault) Grid with ungrounded transformer

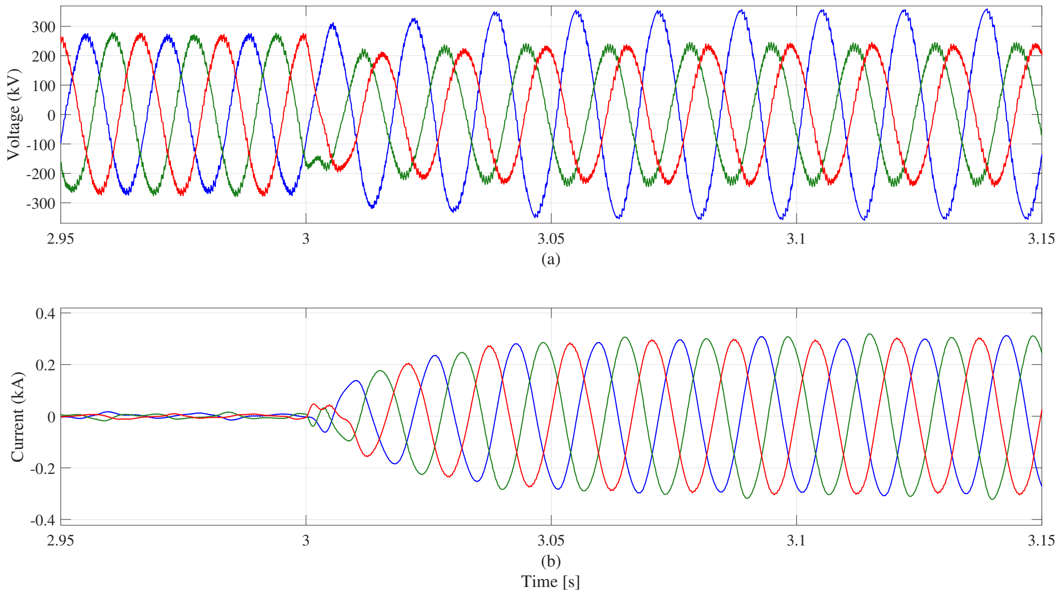

Figure A.16: (A)Voltage (B)Current, 50% voltage drop (DL Fault) STATCOM with only positive sequence control while transformer is ungrounded

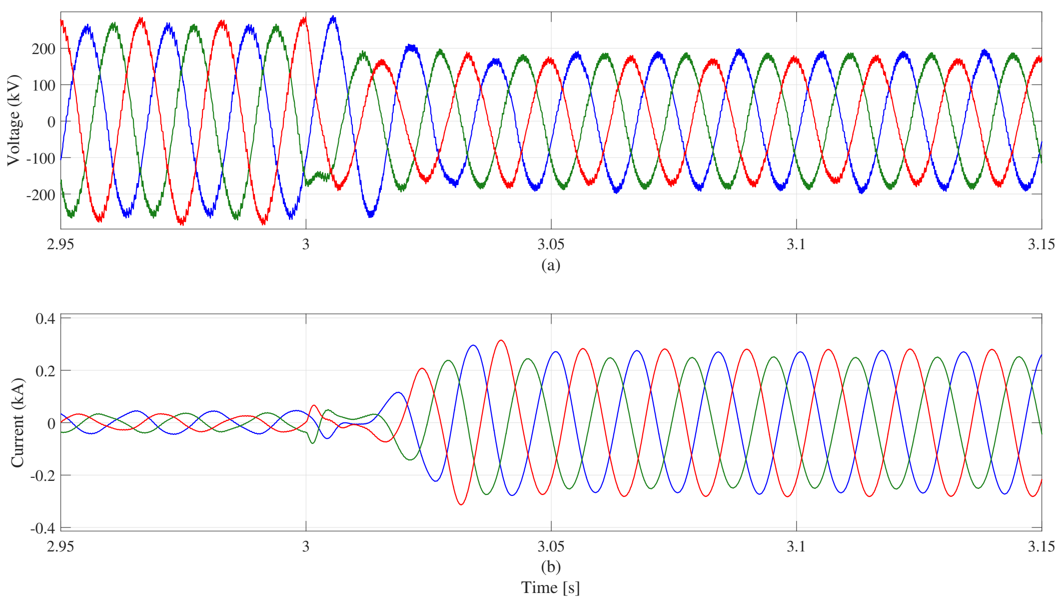

Figure A.17: (A)Voltage (B)Current, 50% voltage drop (DL Fault) during STATCOM with only negative sequence control while transformer is ungrounded

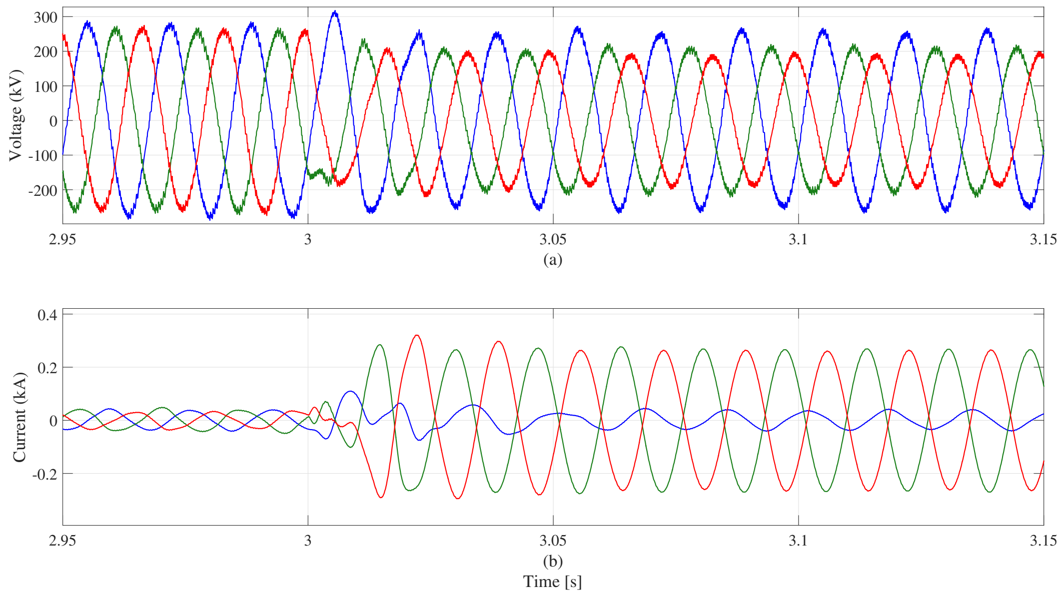

Figure A.18: (A)Voltage (B)Current, 50% voltage drop (DL Fault) during STATCOM with both positive and negative control while transformer is ungrounded

A.2 Case Study 2

A.2.1 Single line to ground fault

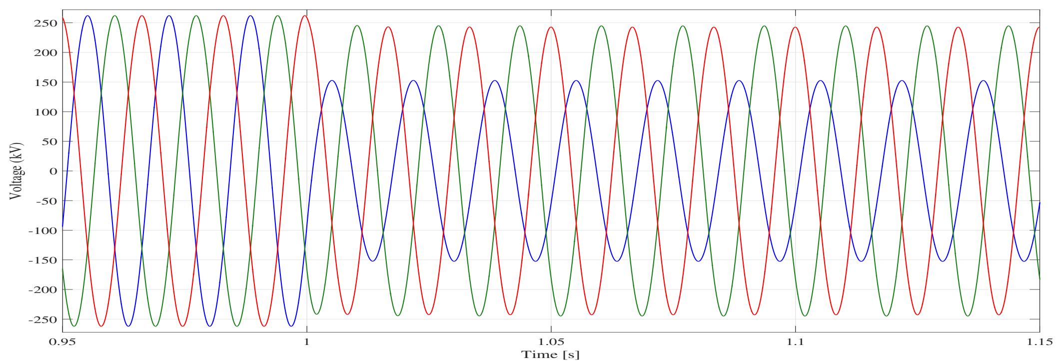

Figure A.19: Voltage, 50% voltage drop (SLG Fault) Grid with directly grounded transformer

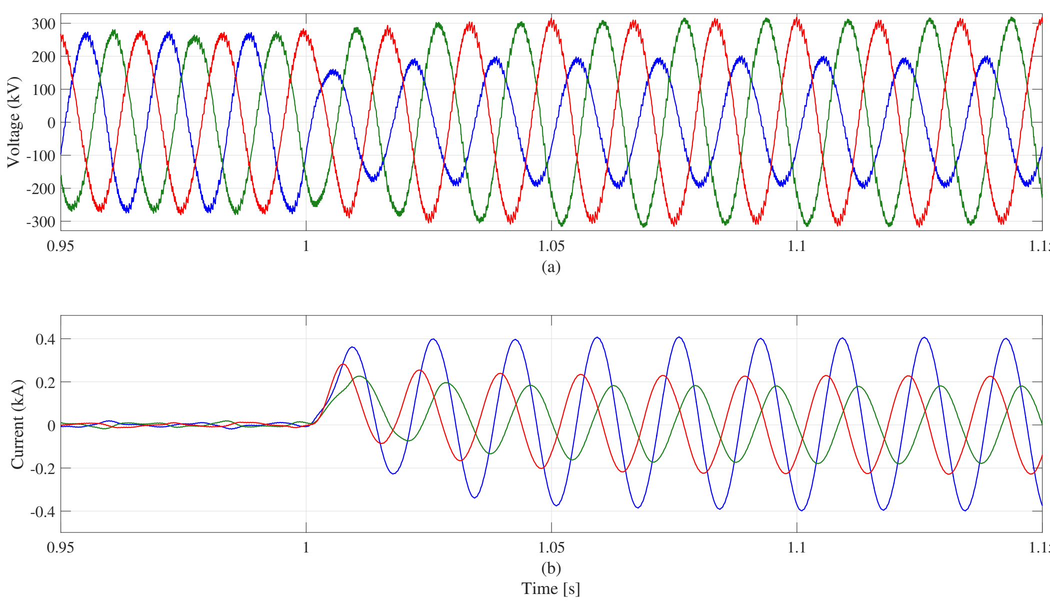

Figure A.20: (A)Voltage (B)Current, 50% voltage drop (SLG Fault) during STATCOM with only positive sequence control while transformer is directly grounded

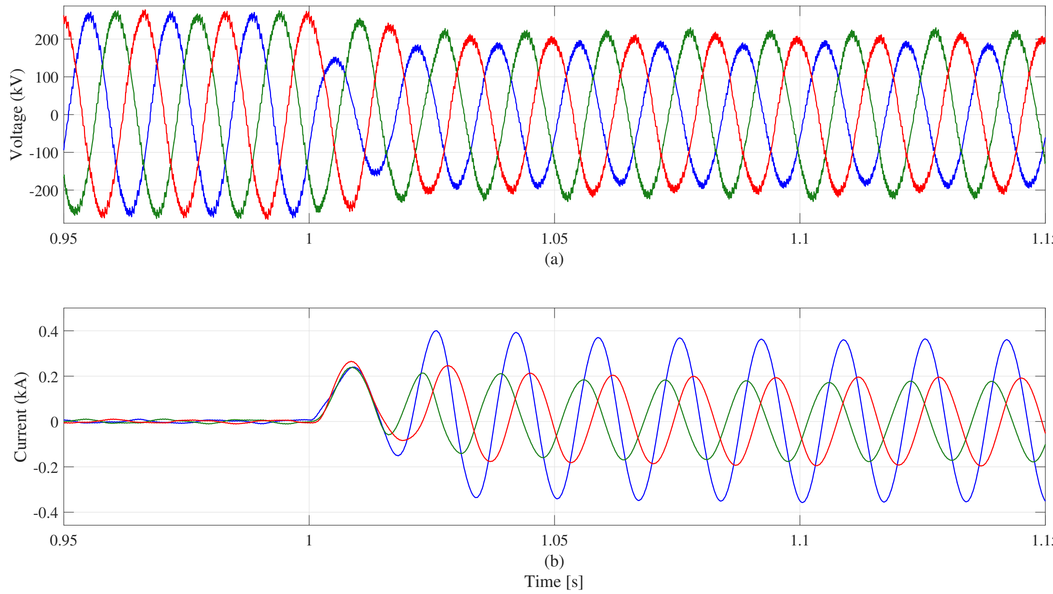

Figure A.21: (A)Voltage (B)Current, 50% voltage drop (SLG Fault) during STATCOM with only negative sequence control while transformer is directly grounded

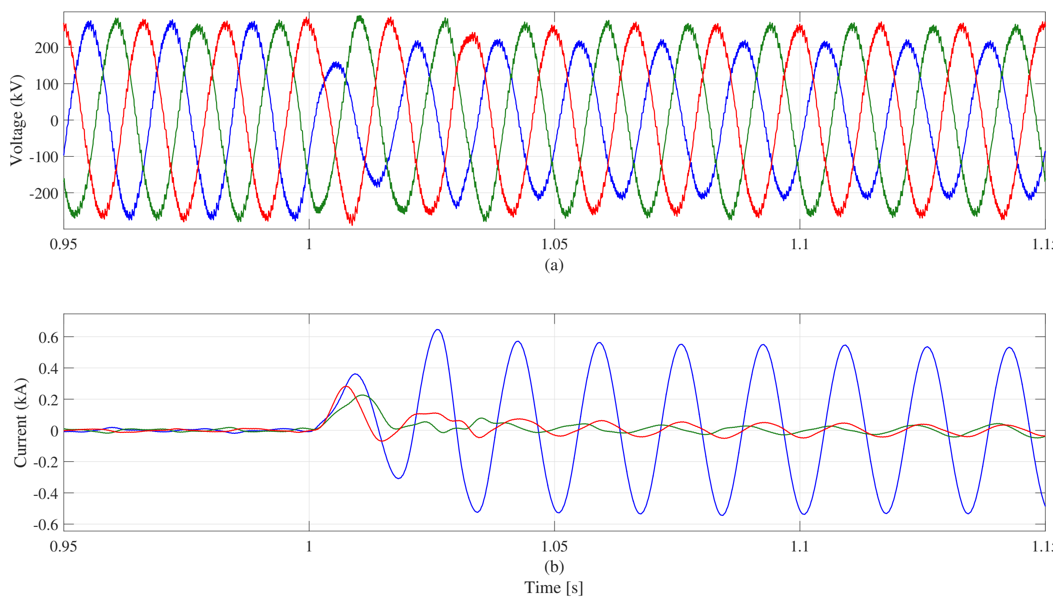

Figure A.22: (A)Voltage (B)Current, 50% voltage drop (SLG Fault) during STATCOM with both positive and negative control while transformer is directly grounded

A.2.2 Double line to ground fault

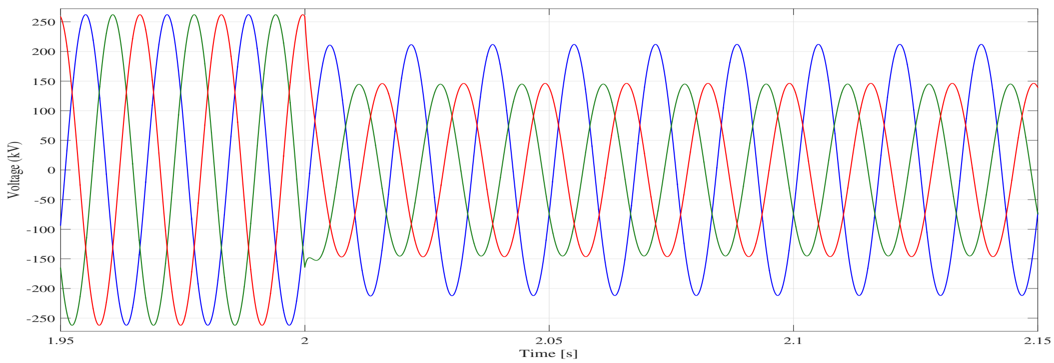

Figure A.23: Voltage, 50% voltage drop (DLG Fault) Grid with directly grounded transformer

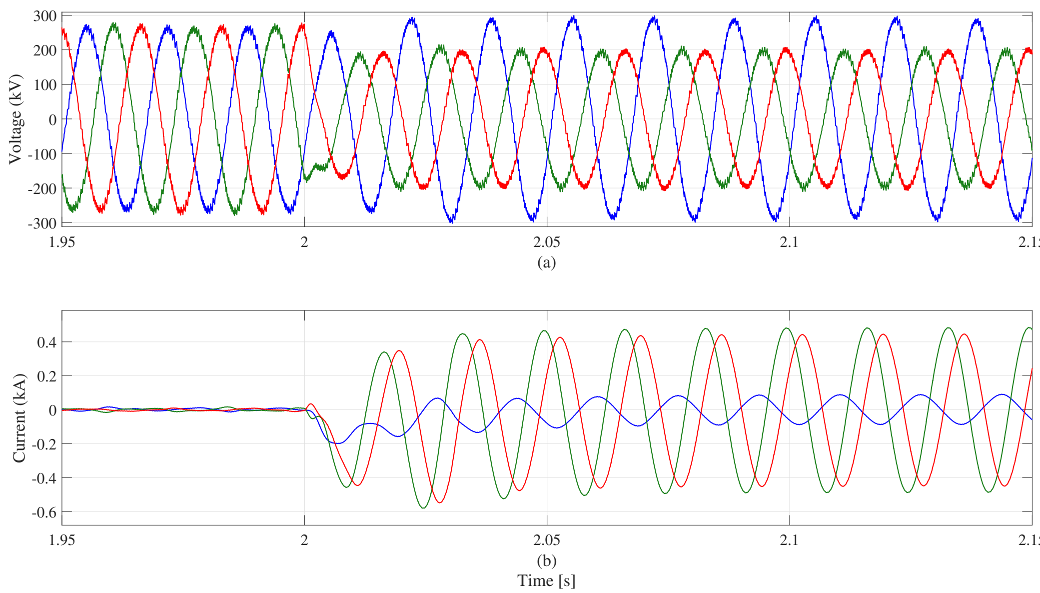

Figure A.24: (A)Voltage (B)Current, 50% voltage drop (DLG Fault) during STATCOM with only positive sequence control while transformer is directly grounded

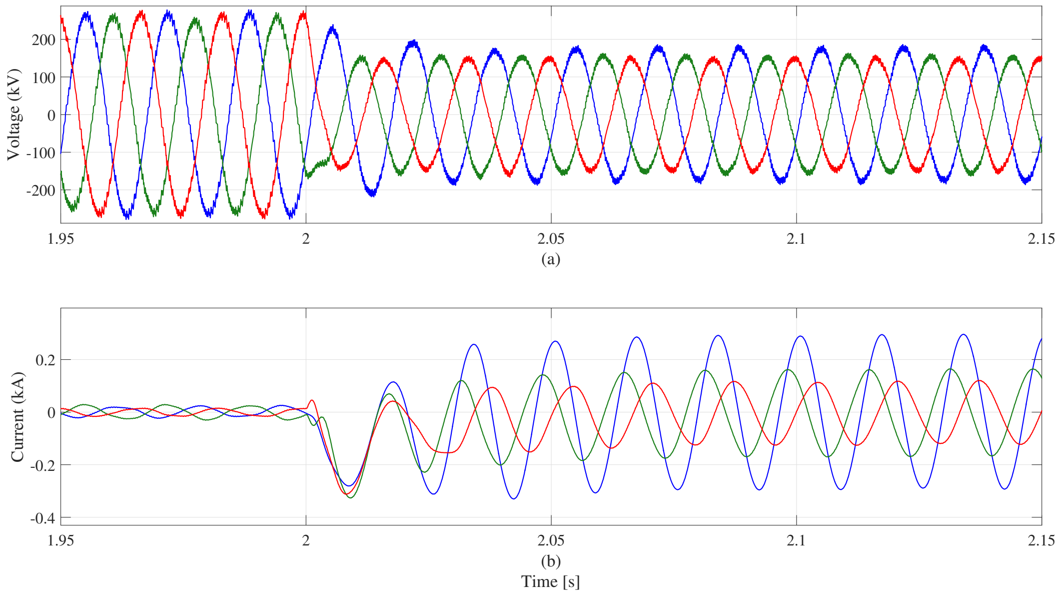

Figure A.25: (A)Voltage (B)Current, 50% voltage drop (DLG Fault) during STATCOM with only negative sequence control while transformer is directly grounded

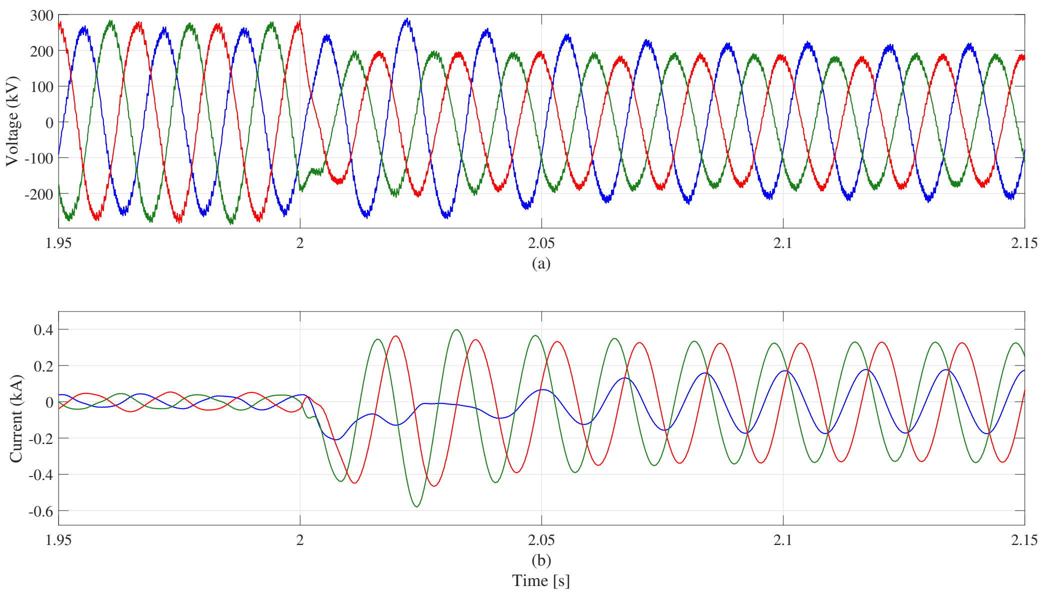

Figure A.26: (A)Voltage (B)Current, 50% voltage drop (DLG Fault) during STATCOM with both positive and negative control while transformer is directly grounded

A.2.3 Double line fault

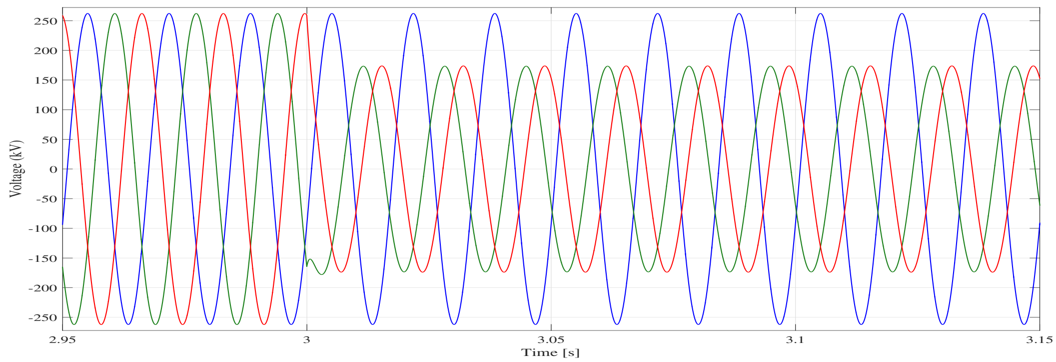

Figure A.27: Voltage, 50% voltage drop (DL Fault) Grid with directly grounded transformer

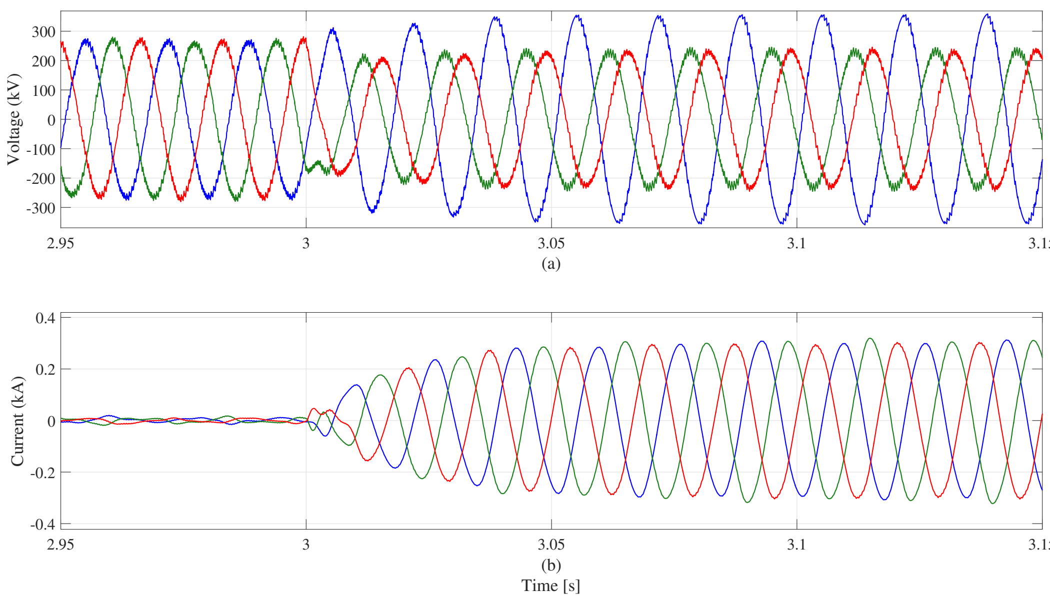

Figure A.28: (A)Voltage (B)Current, 50% voltage drop (DL Fault) STATCOM with only positive sequence control while transformer is directly grounded

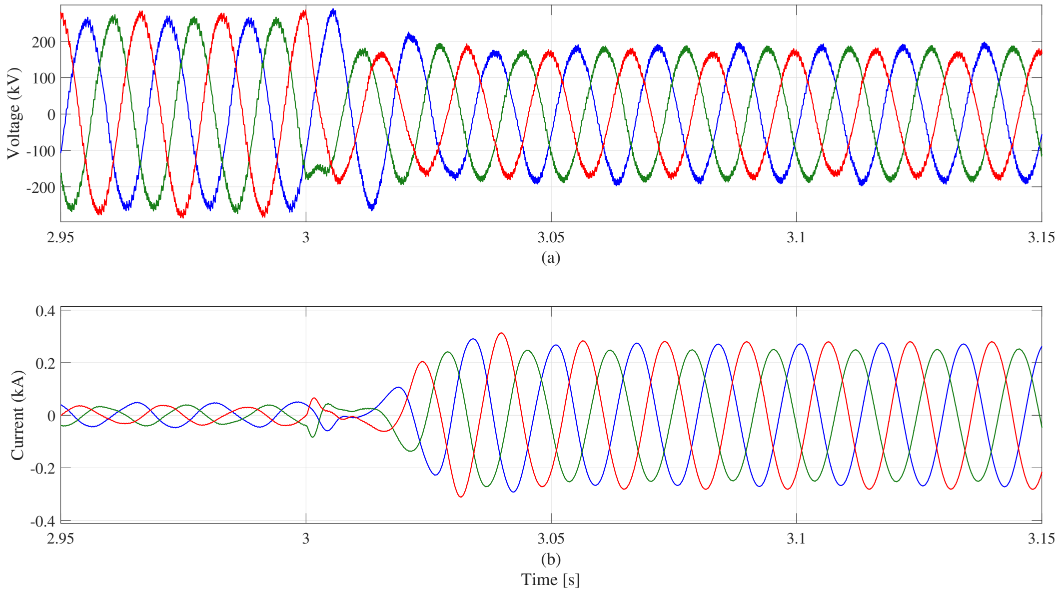

Figure A.29: (A)Voltage (B)Current, 50% voltage drop (DL Fault) during STATCOM with only negative sequence control while transformer is directly grounded

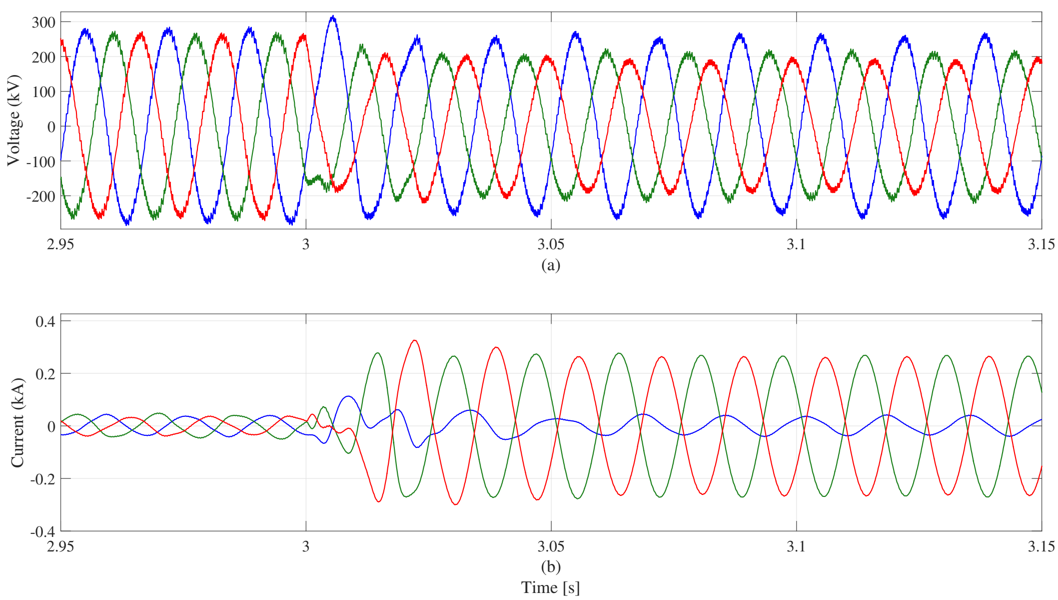

Figure A.30: (A)Voltage (B)Current, 50% voltage drop (DL Fault) during STATCOM with both positive and negative control while transformer is directly grounded

A.3 Case Study 3

A.3.1 Single line to ground fault

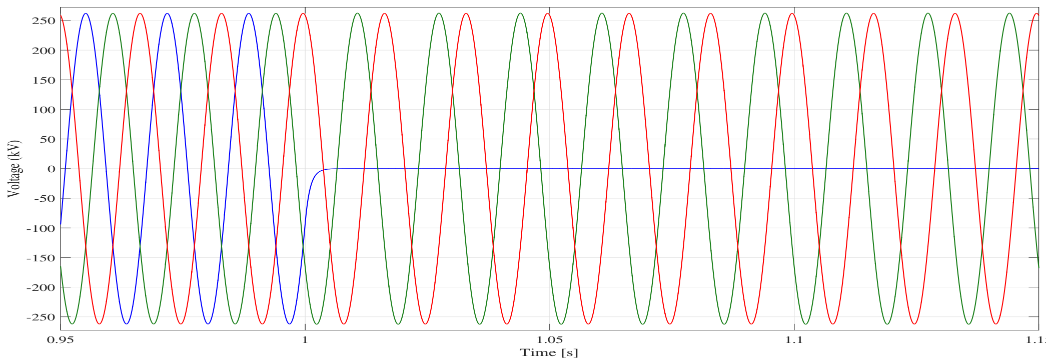

Figure A.31: Voltage, Solid to ground fault (SLG Fault) Grid with ungrounded transformer

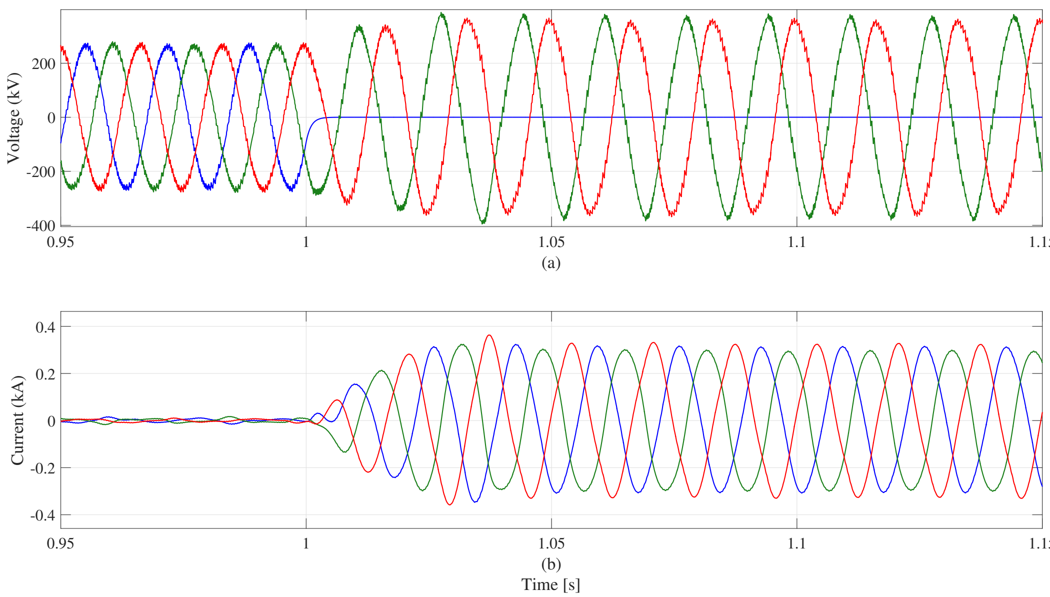

Figure A.32: (A)Voltage (B)Current, Solid to ground fault (SLG Fault) during STATCOM with only positive sequence control while transformer is ungrounded

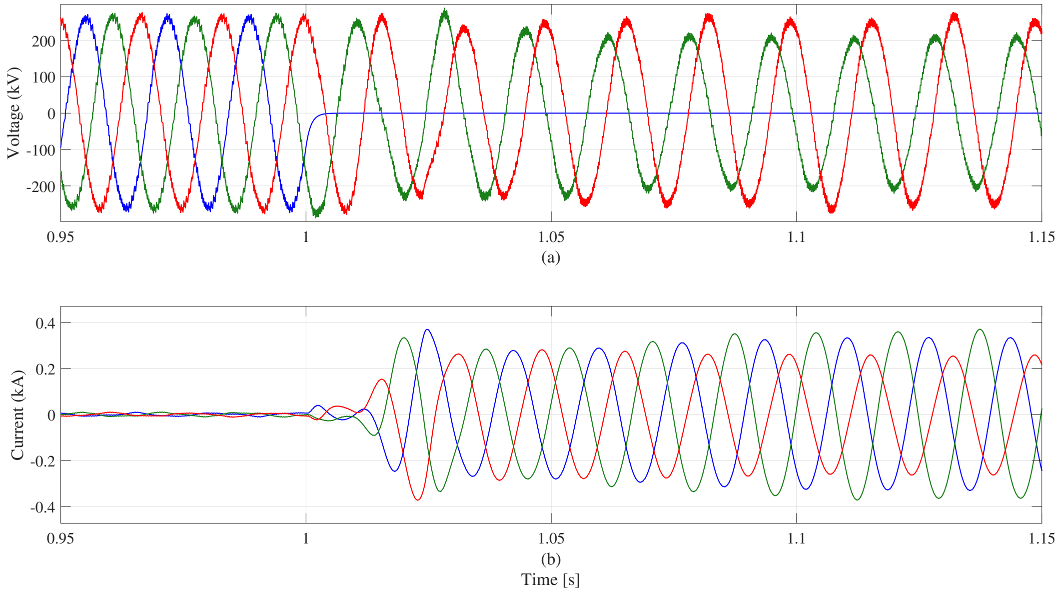

Figure A.33: (A)Voltage (B)Current, Solid to ground fault (SLG Fault) during STATCOM with only negative sequence control while transformer is ungrounded

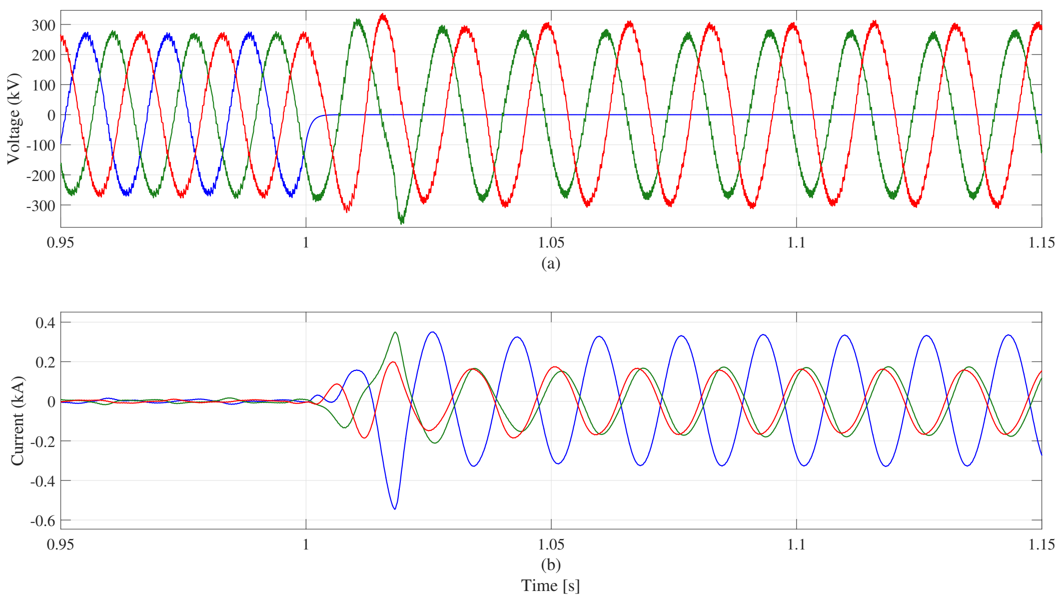

Figure A.34: (A)Voltage (B)Current, Solid to ground fault (SLG Fault) during STATCOM with both positive and negative control while transformer is ungrounded

A.3.2 Double line to ground fault

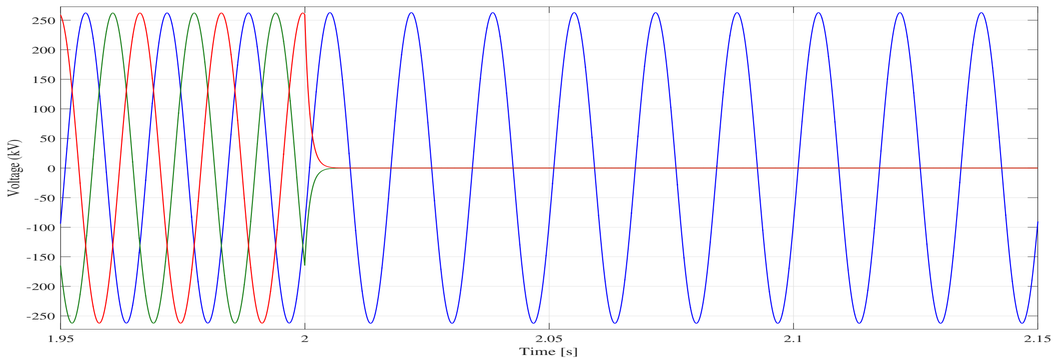

Figure A.35: Voltage, Solid to ground fault (DLG Fault) Grid with ungrounded transformer

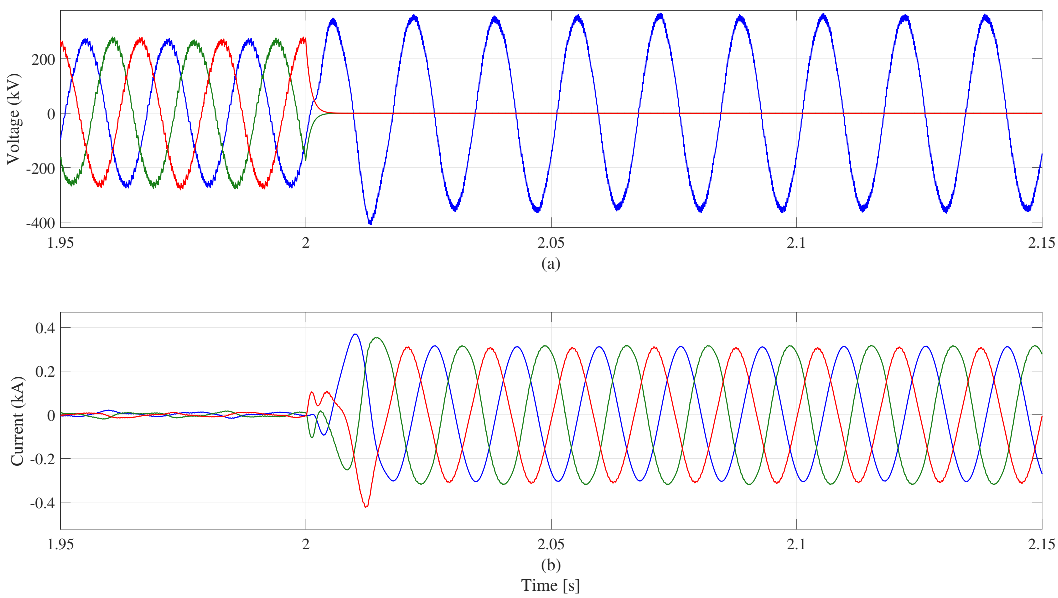

Figure A.36: (A)Voltage (B)Current, Solid to ground fault (DLG Fault) during STATCOM with only positive sequence control while transformer is ungrounded

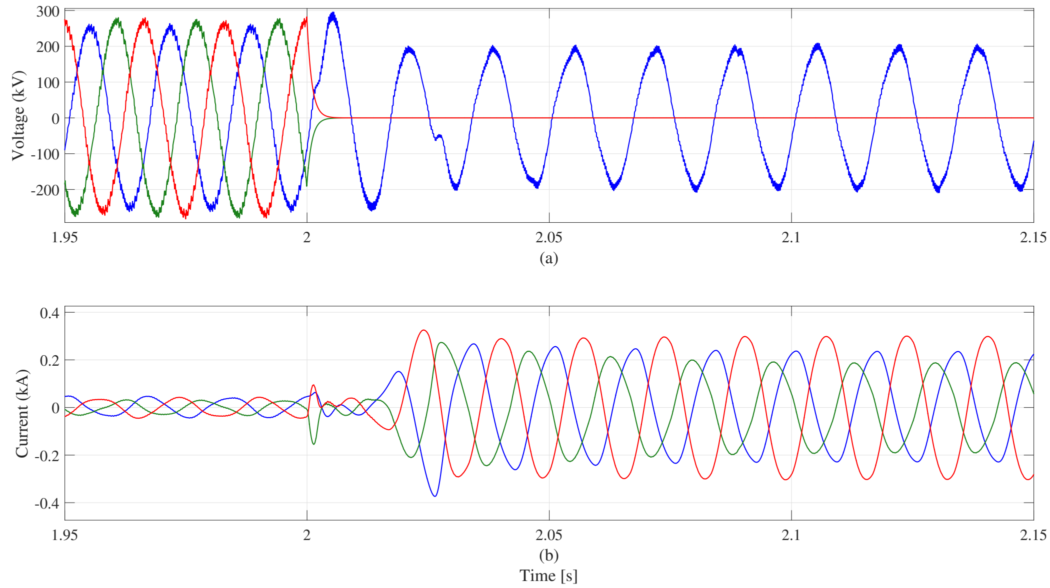

Figure A.37: (A)Voltage (B)Current, Solid to ground fault (DLG Fault) during STATCOM with only negative sequence control while transformer is ungrounded

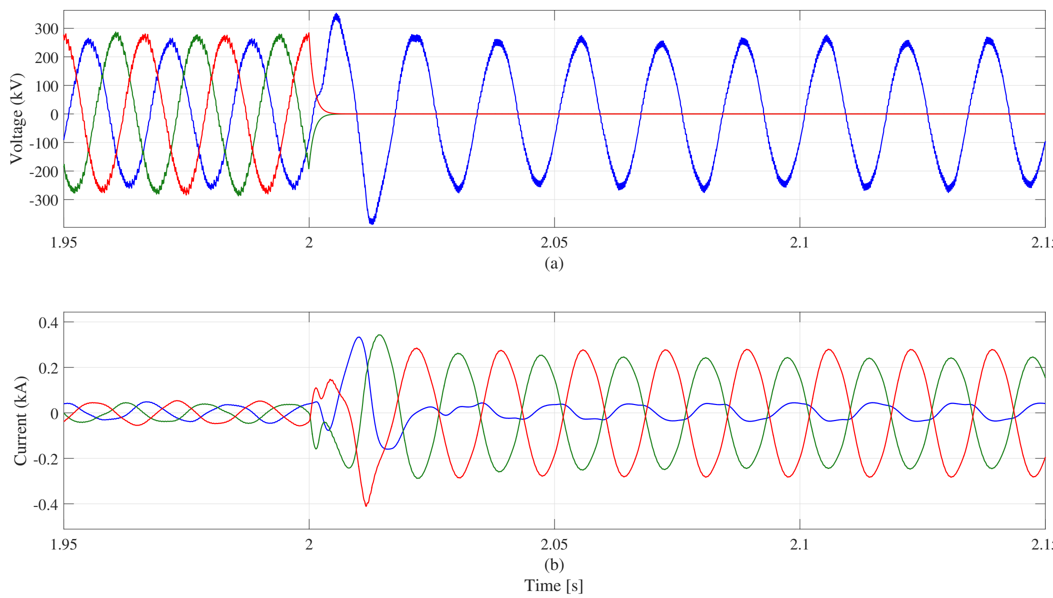

Figure A.38: (A)Voltage (B)Current, Solid to ground fault (DLG Fault) during STATCOM with both positive and negative control while transformer is ungrounded

A.3.3 Double line fault

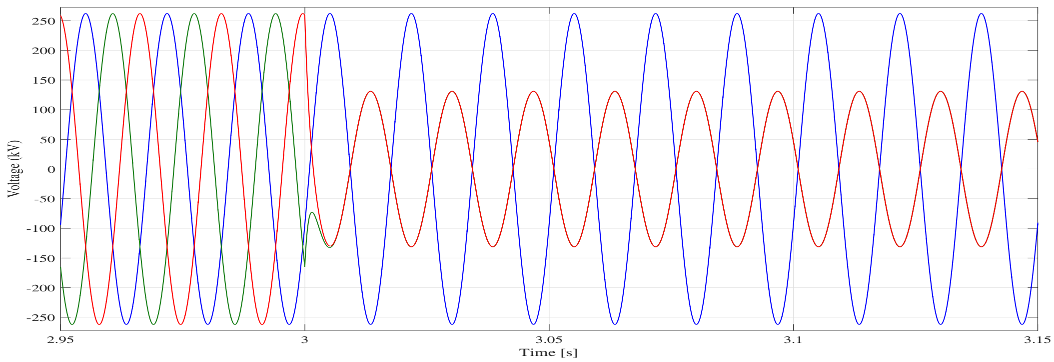

Figure A.39: Voltage, Solid to ground fault (DL Fault) Grid with ungrounded transformer

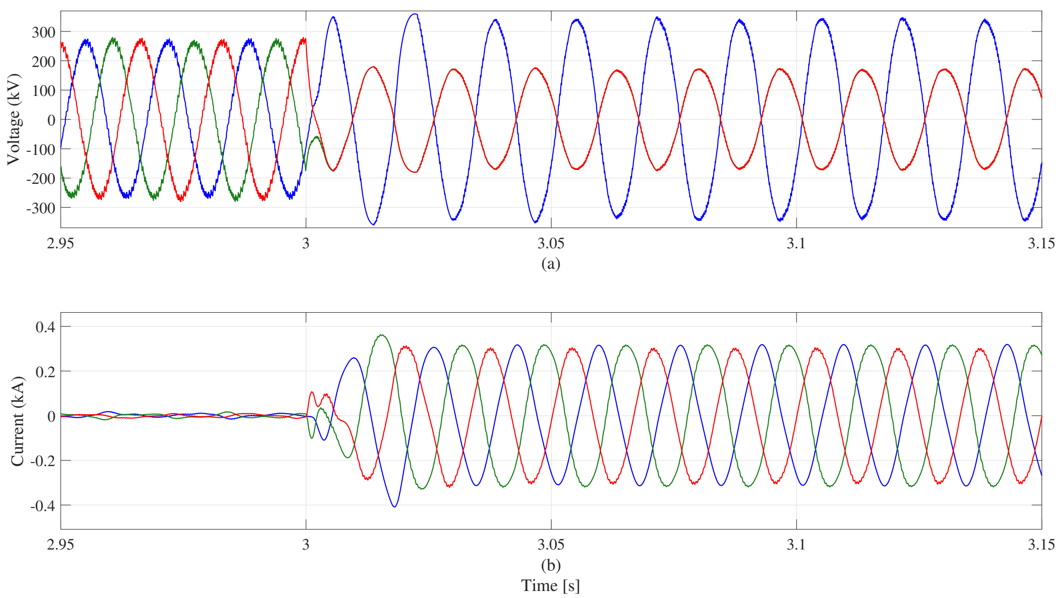

Figure A.40: (A)Voltage (B)Current, Solid to ground fault (DL Fault) STATCOM with only positive sequence control while transformer is ungrounded

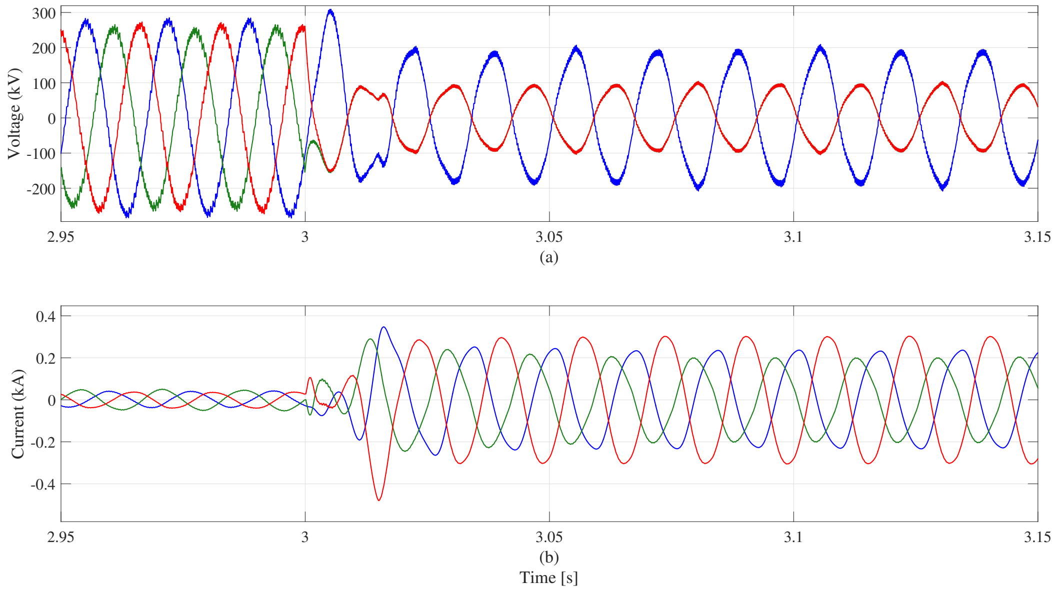

Figure A.41: (A)Voltage (B)Current, Solid to ground fault (DL Fault) during STATCOM with only negative sequence control while transformer is ungrounded

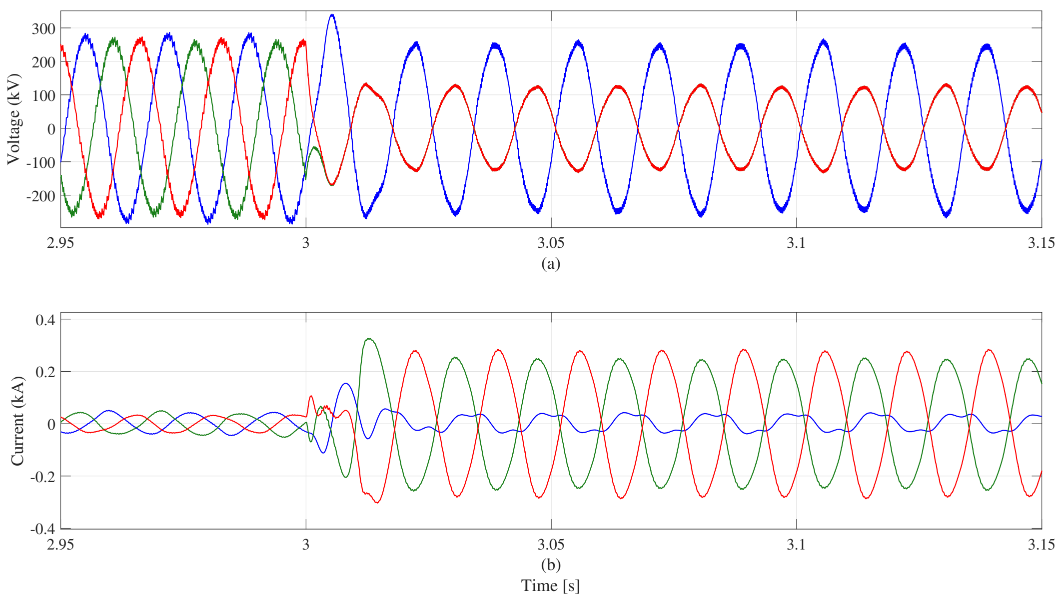

Figure A.42: (A)Voltage (B)Current, Solid to ground fault (DL Fault) during STATCOM with both positive and negative control while transformer is ungrounded

A.4 Case Study 4

A.4.1 Single line to ground fault

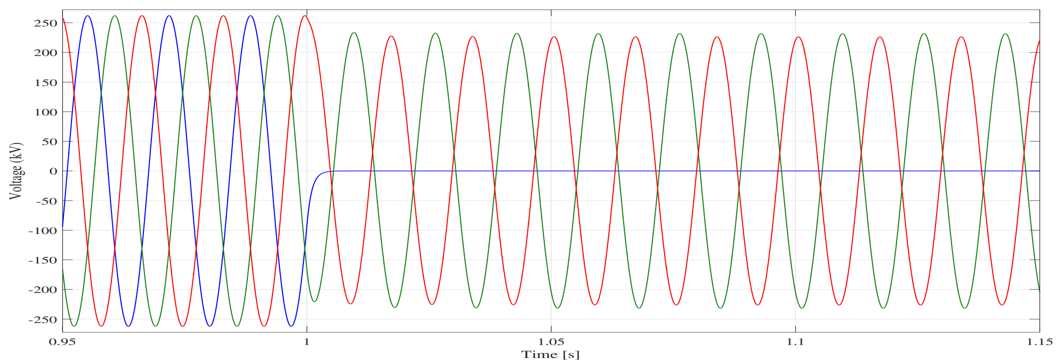

Figure A.43: Voltage, Solid to ground fault (SLG Fault) Grid with directly grounded transformer

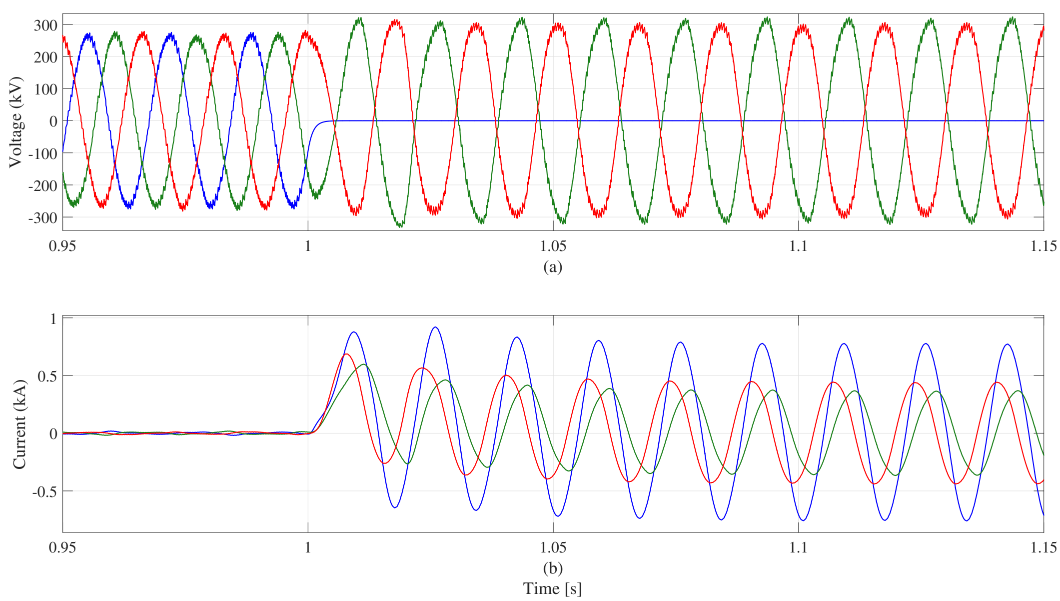

Figure A.44: (A)Voltage (B)Current, Solid to ground fault (SLG Fault) during STATCOM with only positive sequence control while transformer is directly grounded

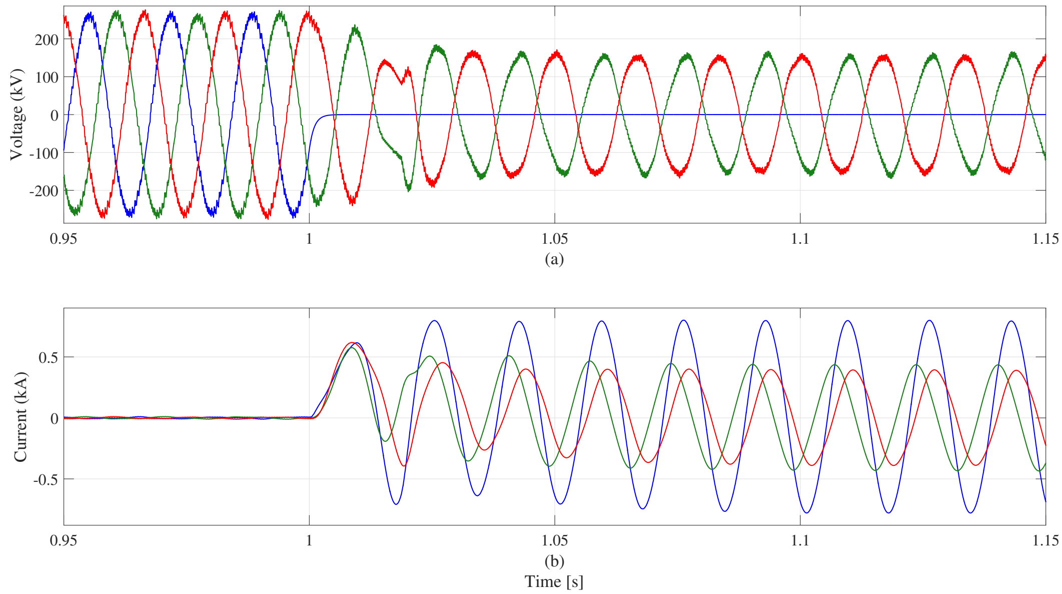

Figure A.45: (A)Voltage (B)Current, Solid to ground fault (SLG Fault) during STATCOM with only negative sequence control while transformer is directly grounded

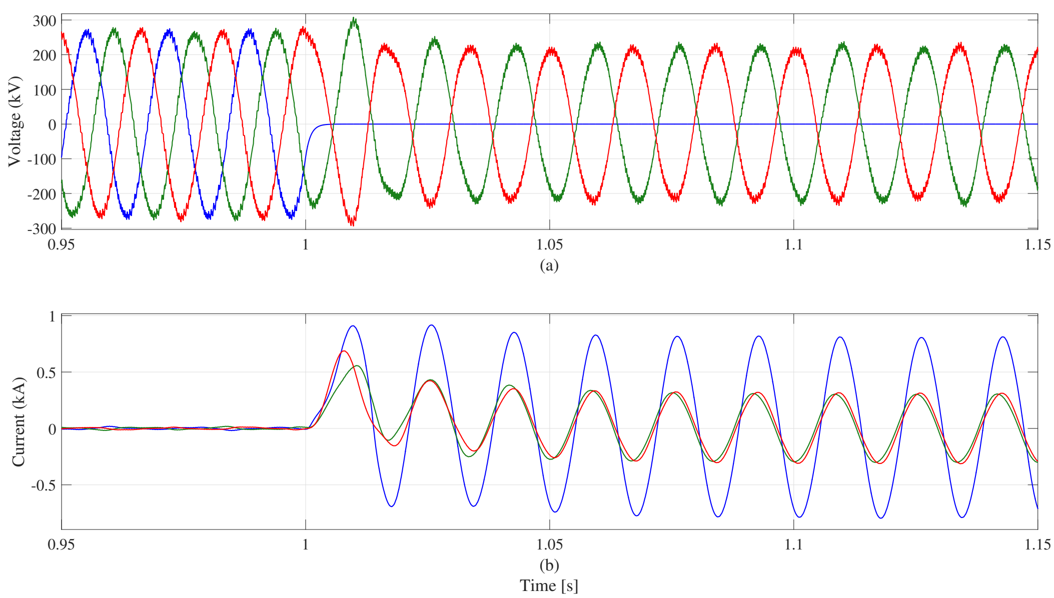

Figure A.46: (A)Voltage (B)Current, Solid to ground fault (SLG Fault) during STATCOM with both positive and negative control while transformer is directly grounded

A.4.2 Double line to ground fault

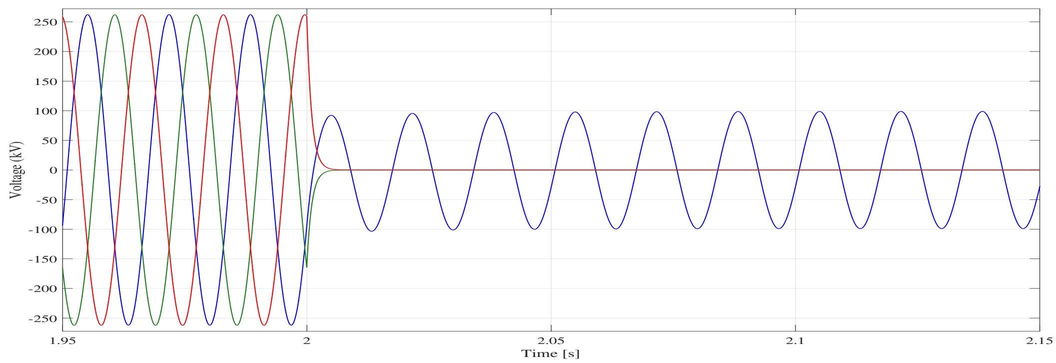

Figure A.47: Voltage, Solid to ground fault (DLG Fault) Grid with directly grounded transformer

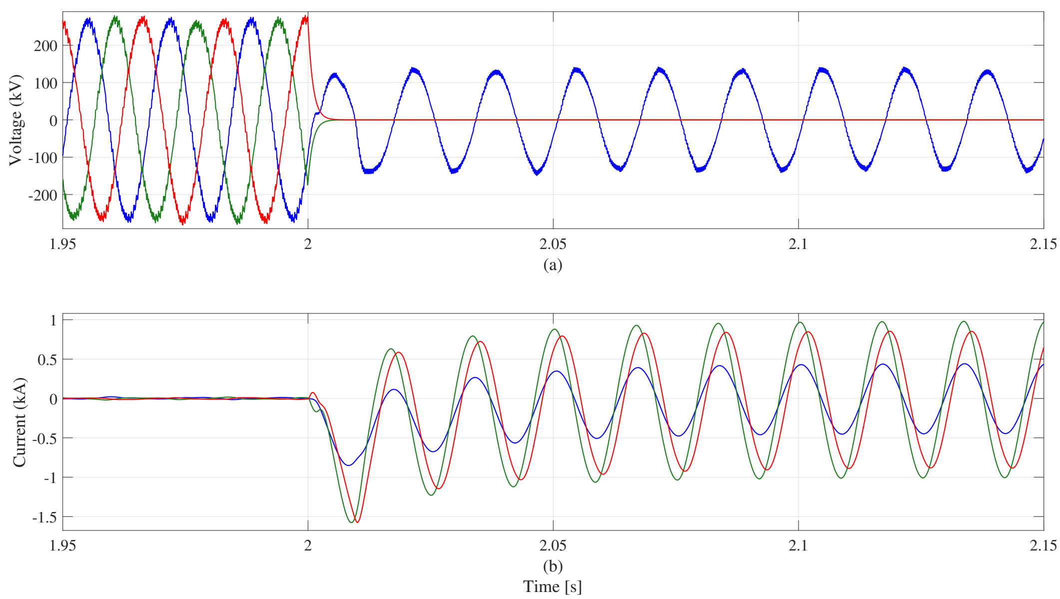

Figure A.48: (A)Voltage (B)Current, Solid to ground fault (DLG Fault) during STATCOM with only positive sequence control while transformer is directly grounded

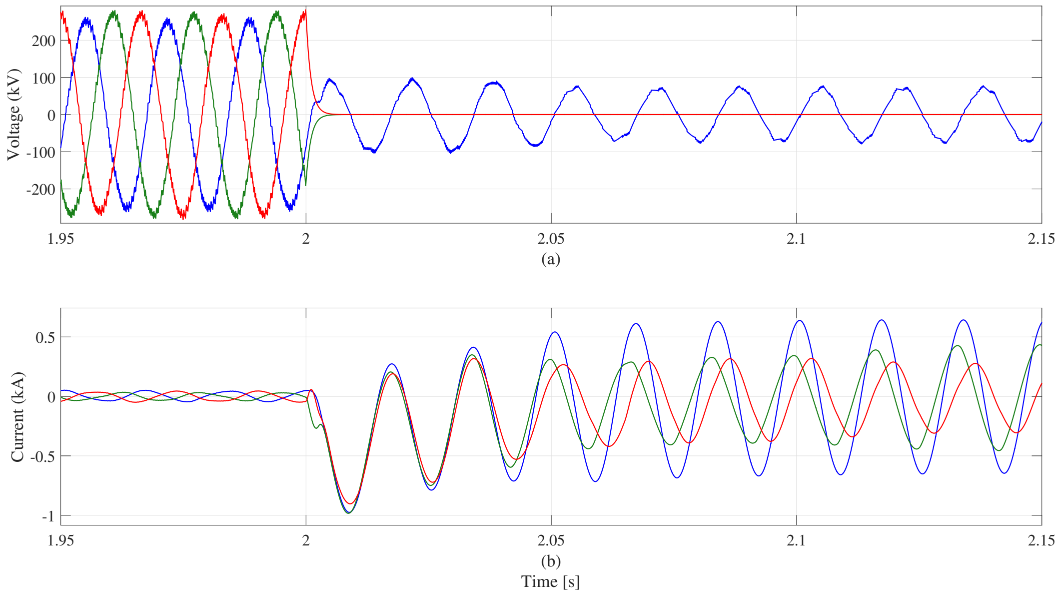

Figure A.49: (A)Voltage (B)Current, Solid to ground fault (DLG Fault) during STATCOM with only negative sequence control while transformer is directly grounded

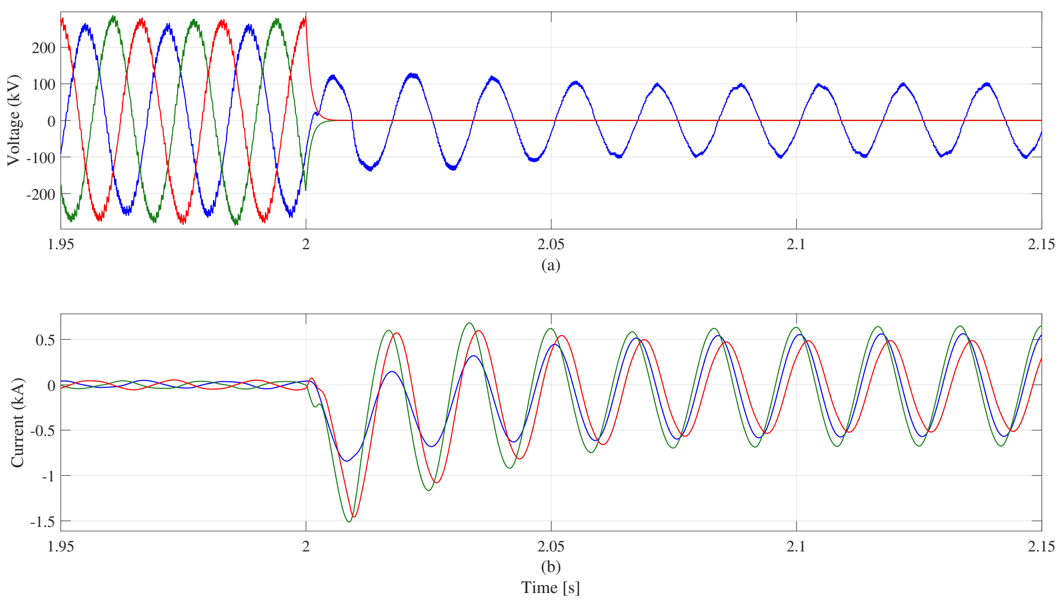

Figure A.50: (A)Voltage (B)Current, Solid to ground fault (DLG Fault) during STATCOM with both positive and negative control while transformer is directly grounded

A.4.3 Double line fault

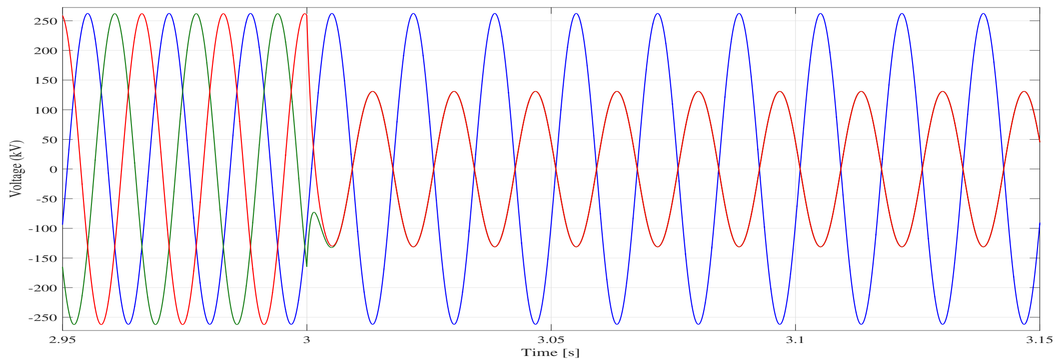

Figure A.51: Voltage, Solid to ground fault (DL Fault) Grid with directly grounded transformer

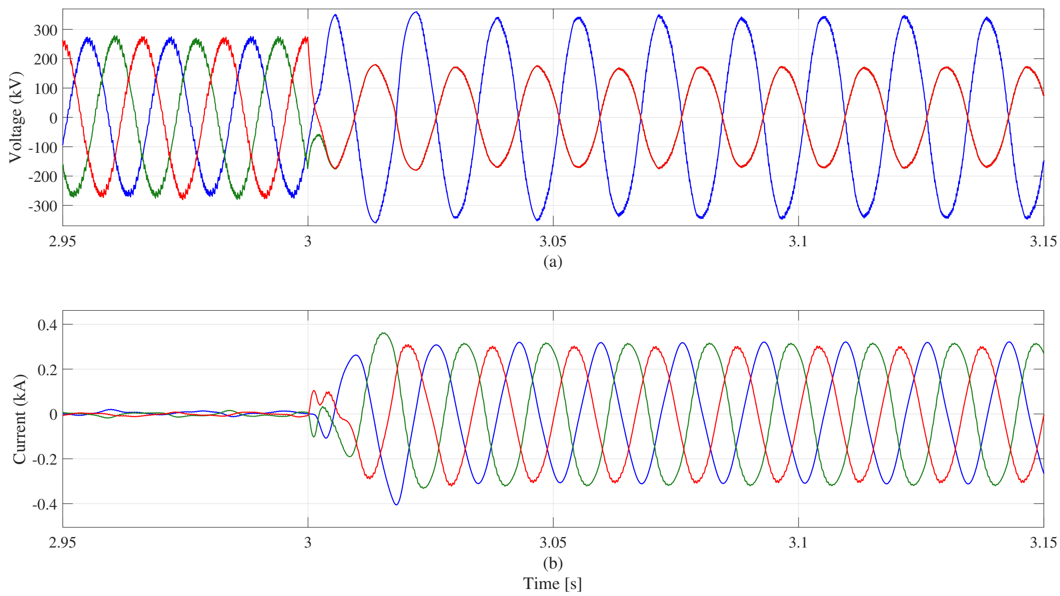

Figure A.52: (A)Voltage (B)Current, Solid to ground fault (DL Fault) STATCOM with only positive sequence control while transformer is directly grounded

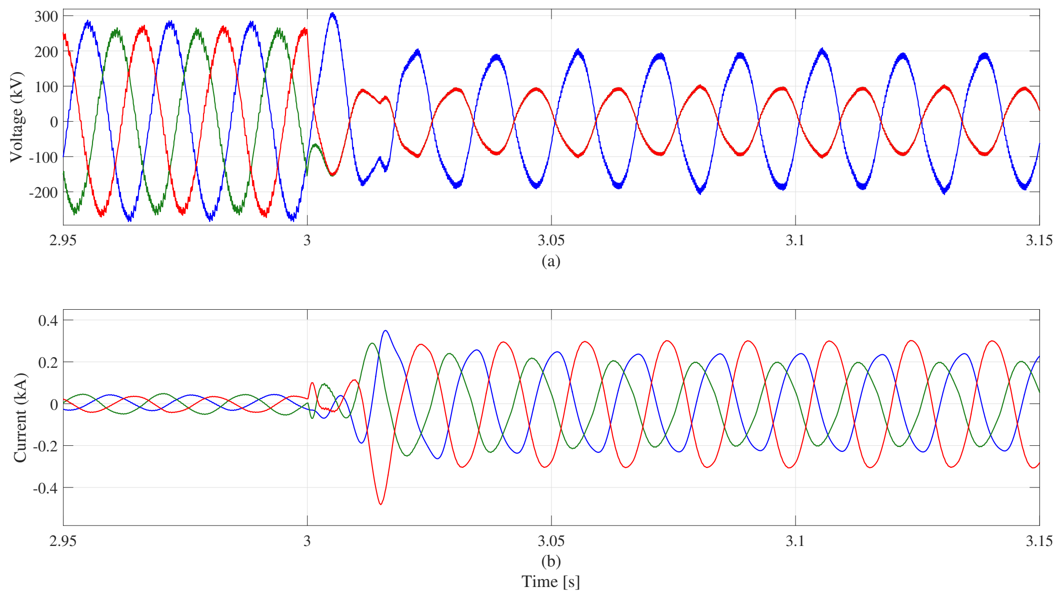

Figure A.53: (A)Voltage (B)Current, Solid to ground fault (DL Fault) during STATCOM with only negative sequence control while transformer is directly grounded

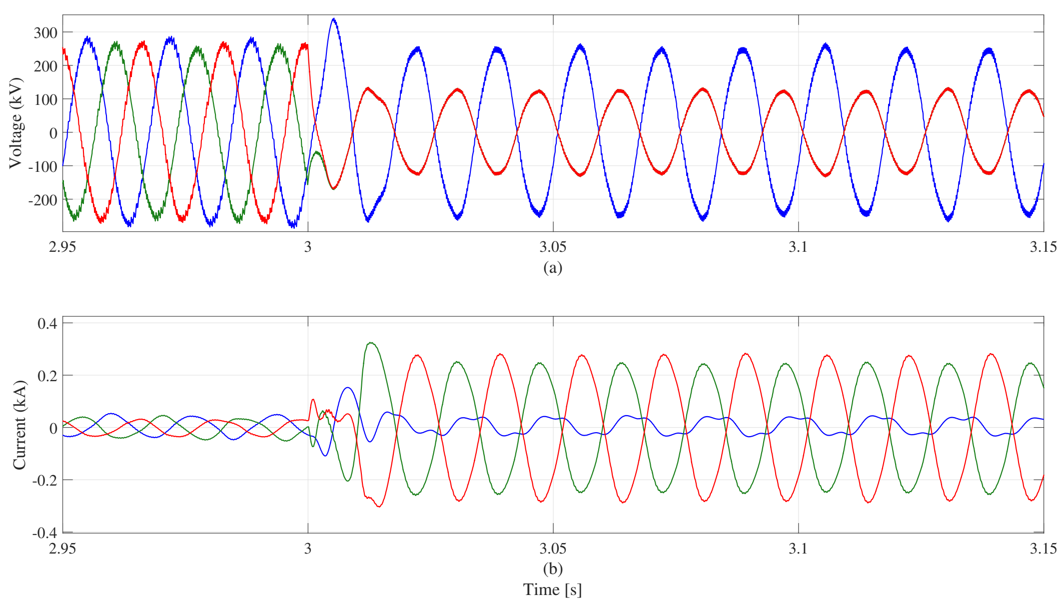

Figure A.54: (A)Voltage (B)Current, Solid to ground fault (DL Fault) during STATCOM with both positive and negative control while transformer is directly grounded

Appendix B

Strong Network

Appendix B tables is the result of examining a weak network of 1000 MVA. The network has experience Solid line to ground fault. During the examination, the transformer, which link the STATCOM to the network, has been directly grounded and grounded with high impedance to observe the impact of the transformer to the network.

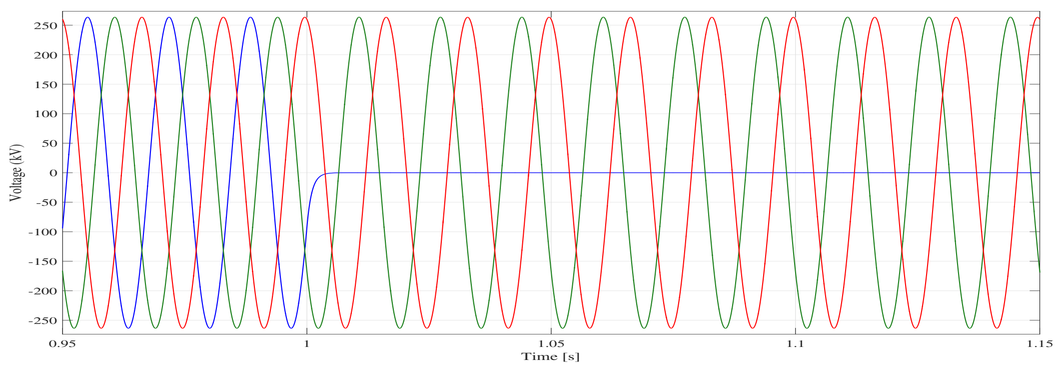

Figure B.1: Voltage, Solid to ground fault (SLG Fault) Grid without STATCOM

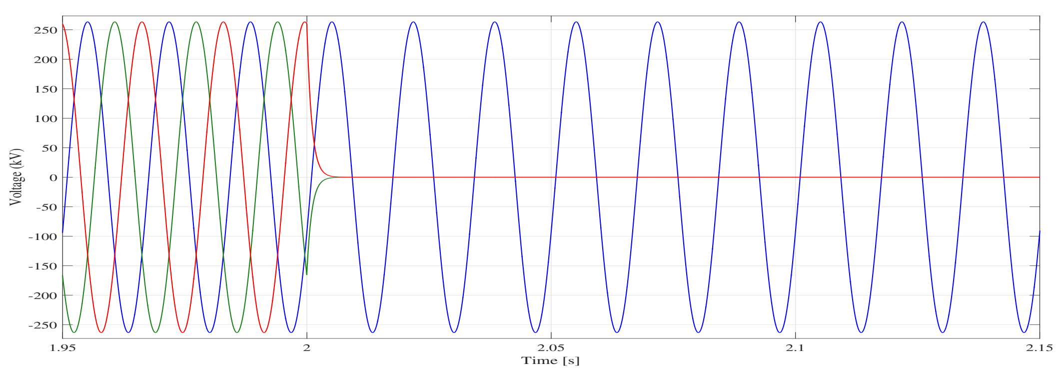

Figure B.2: Voltage, Solid to ground fault (DLG Fault) Grid without STATCOM

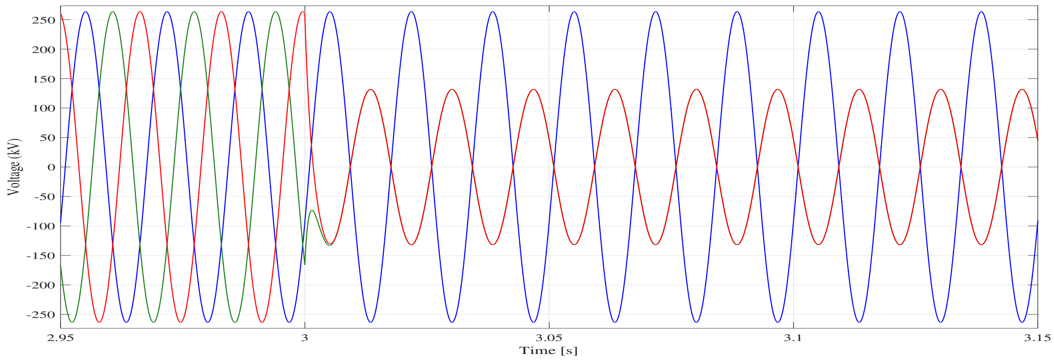

Figure B.3: Voltage, Solid to ground fault (DL Fault) Grid without STATCOM

B.1 Case Study 5

B.1.1 Single line to ground fault

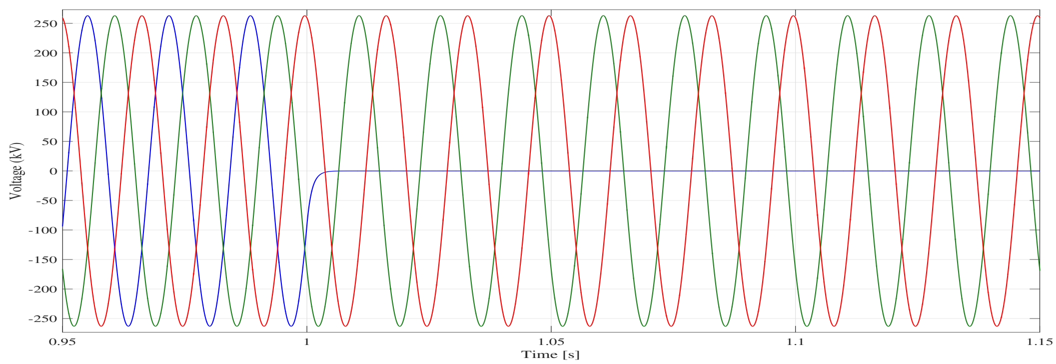

Figure B.4: Voltage, Solid to ground fault (SLG Fault) Grid with ungrounded transformer

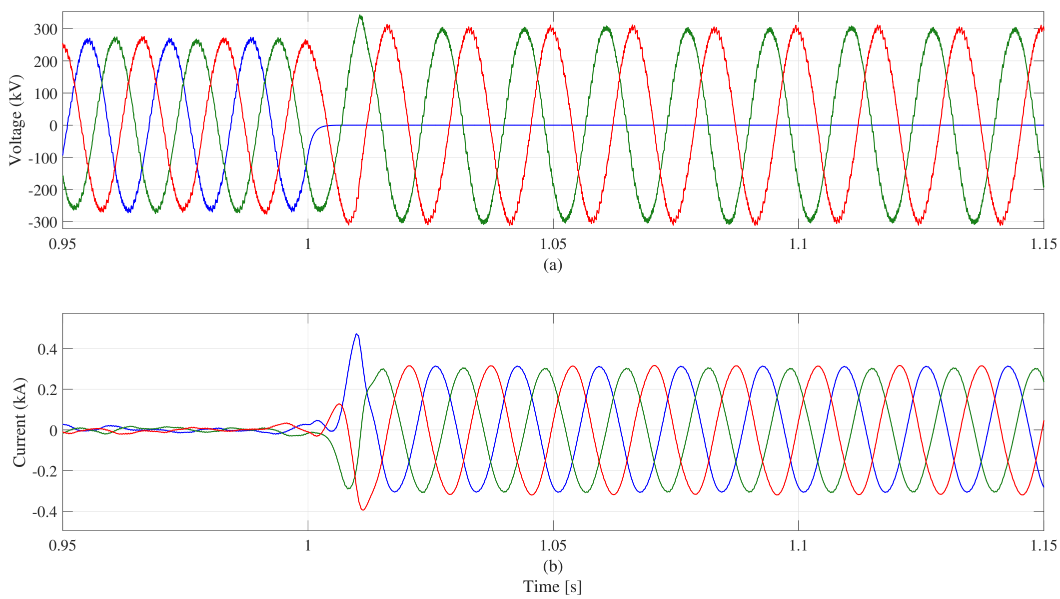

Figure B.5: (A)Voltage (B)Current, Solid to ground fault (SLG Fault) during STATCOM with only positive sequence control

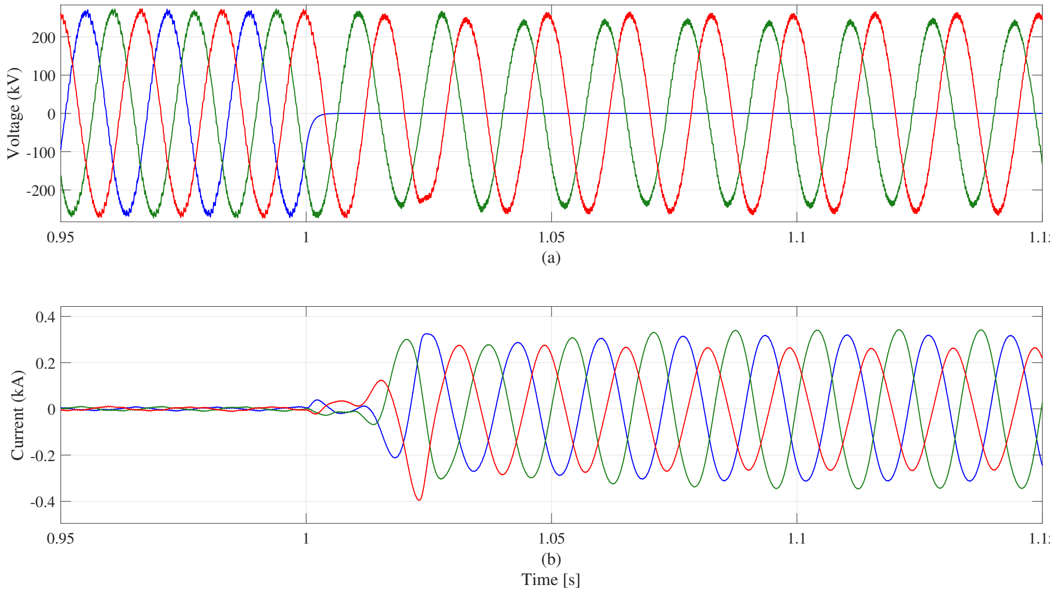

Figure B.6: (A)Voltage (B)Current, Solid to ground fault (SLG Fault) during STATCOM with only negative sequence control

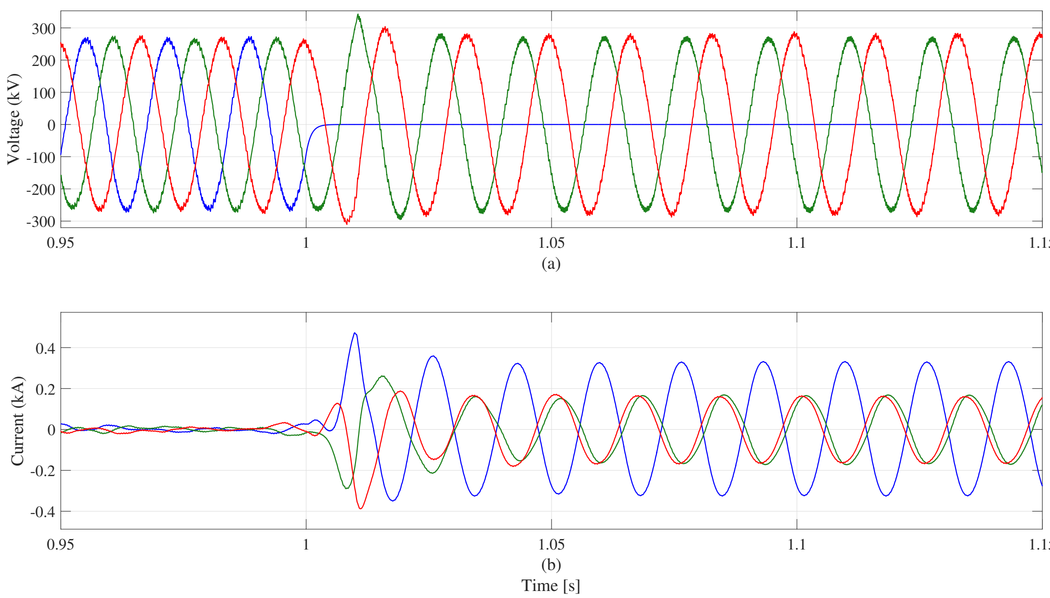

Figure B.7: (A)Voltage (B)Current, Solid to ground fault (SLG Fault) during STATCOM with both positive and negative control

B.1.2 Double line to ground fault

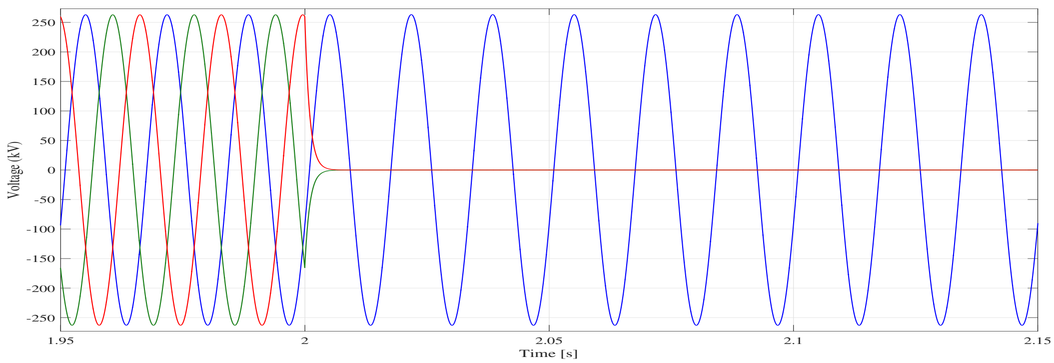

Figure B.8: Voltage, Solid to ground fault (DLG Fault) Grid with ungrounded transformer

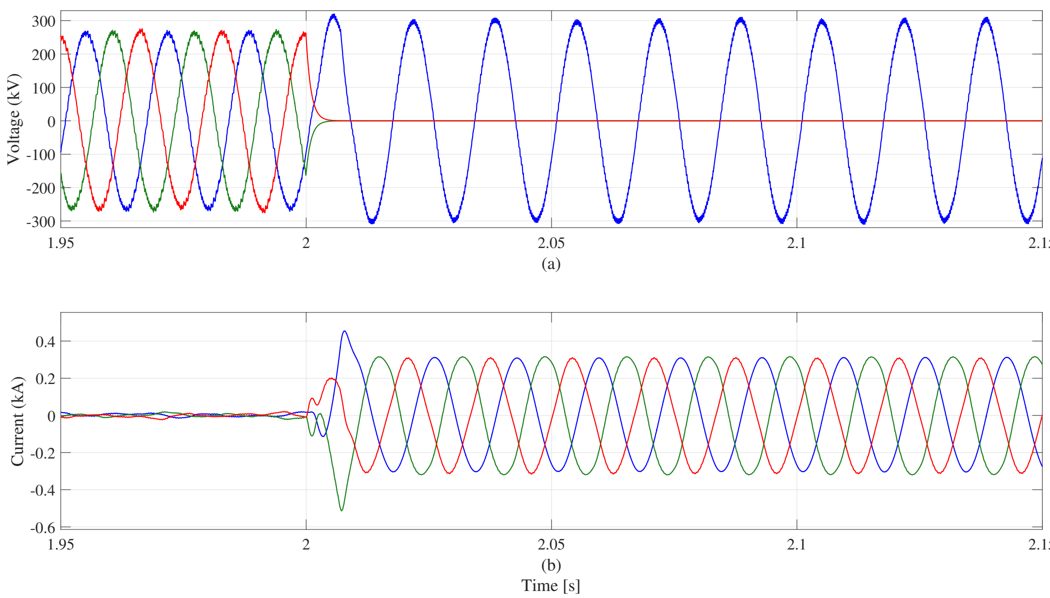

Figure B.9: (A)Voltage (B)Current, Solid to ground fault (DLG Fault) during STATCOM with only positive sequence control while transformer is ungrounded

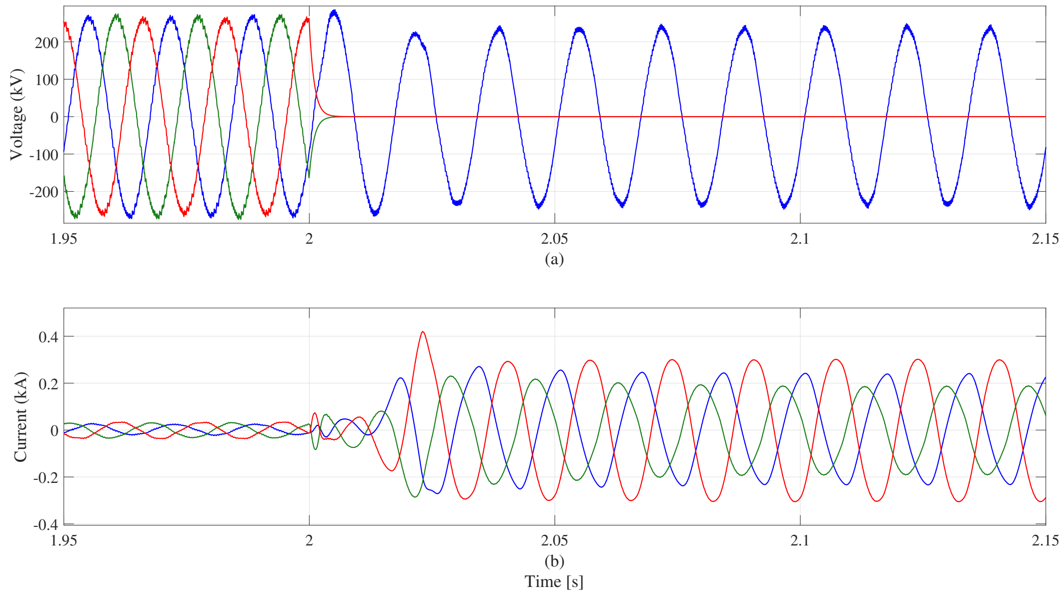

Figure B.10: (A)Voltage (B)Current, Solid to ground fault (DLG Fault) during STATCOM with only negative sequence control while transformer is ungrounded

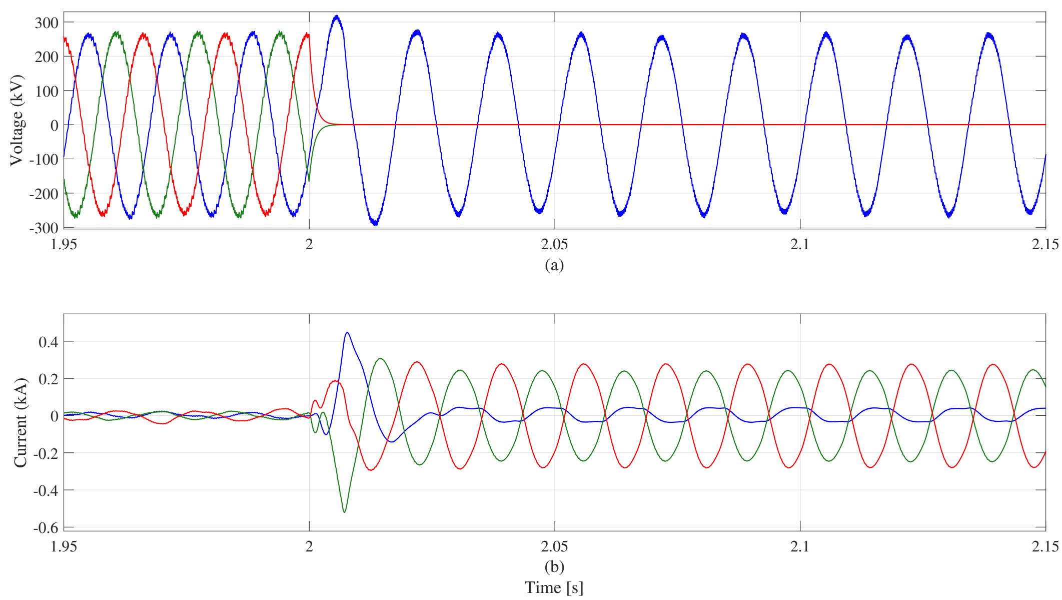

Figure B.11: (A)Voltage (B)Current, Solid to ground fault (DLG Fault) during STATCOM with both positive and negative control while transformer is ungrounded

B.1.3 Double line fault

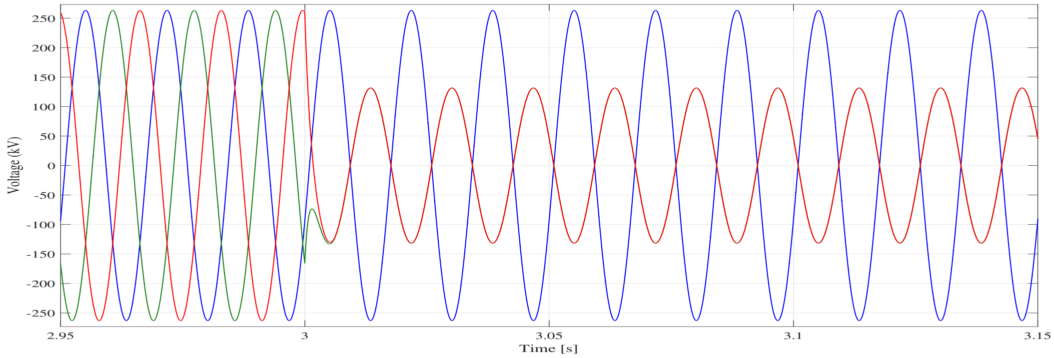

Figure B.12: Voltage, Solid to ground fault (DL Fault) Grid with ungrounded transformer

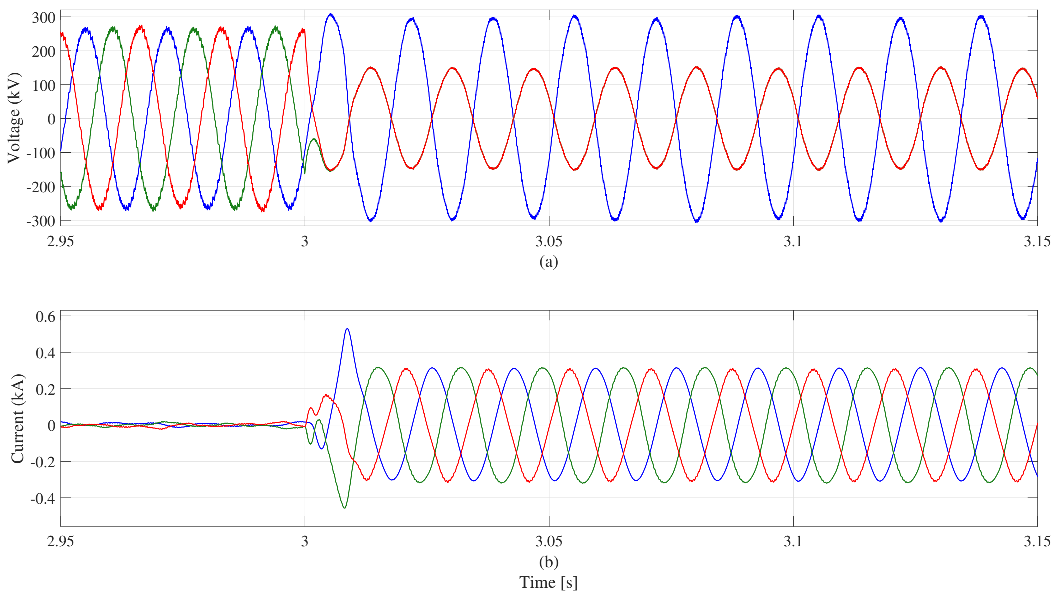

Figure B.13: (A)Voltage (B)Current, Solid to ground fault (DL Fault) STATCOM with only positive sequence control while transformer is ungrounded

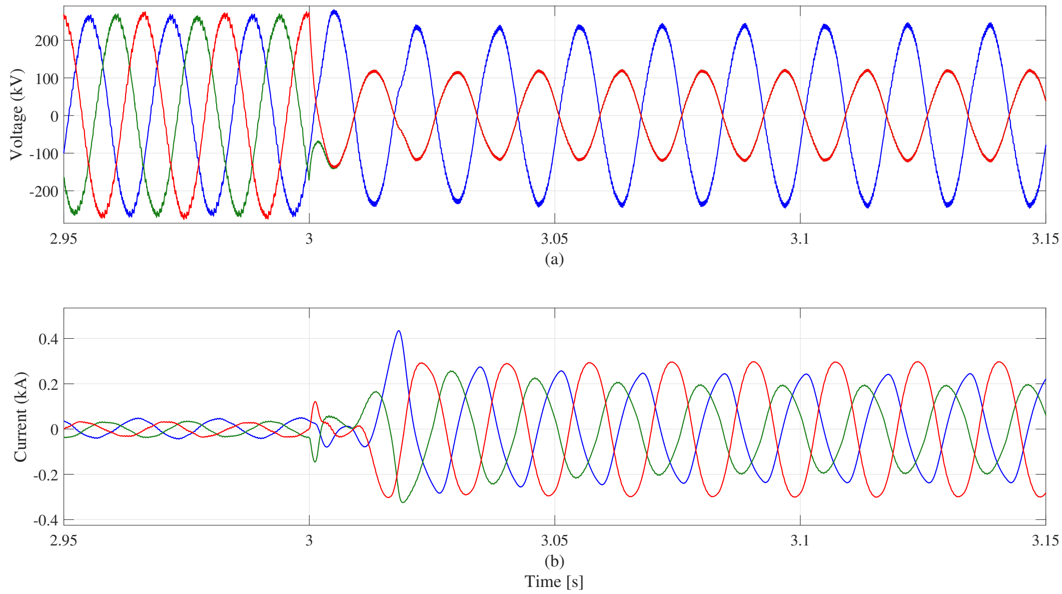

Figure B.14: (A)Voltage (B)Current, Solid to ground fault (DL Fault) during STATCOM with only negative sequence control while transformer is ungrounded

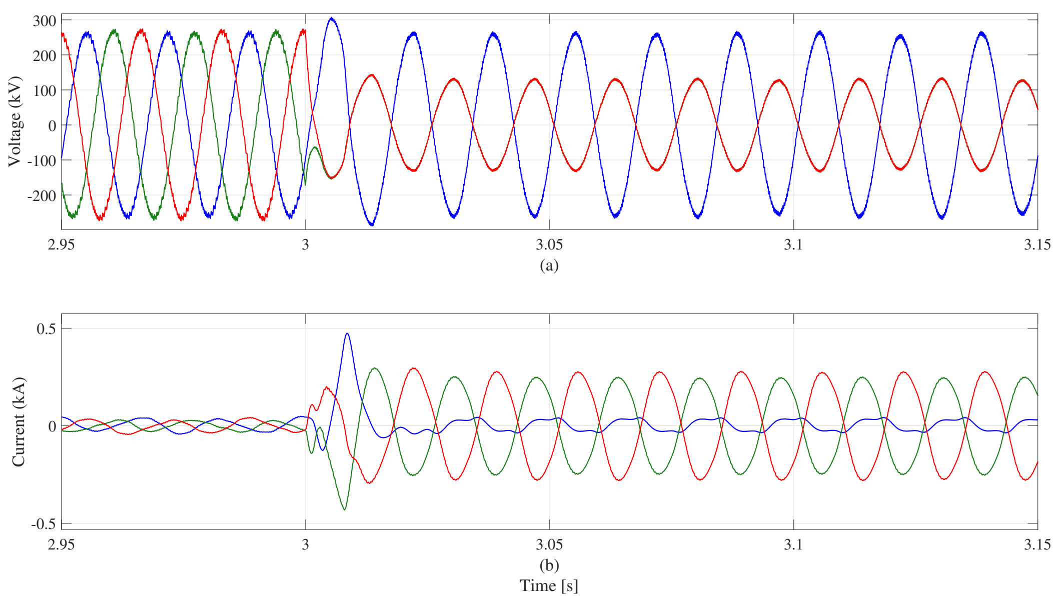

Figure B.15: (A)Voltage (B)Current, Solid to ground fault (DL Fault) during STATCOM with both positive and negative control while transformer is ungrounded

B.2 Case Study 6

B.2.1 Single line to ground fault

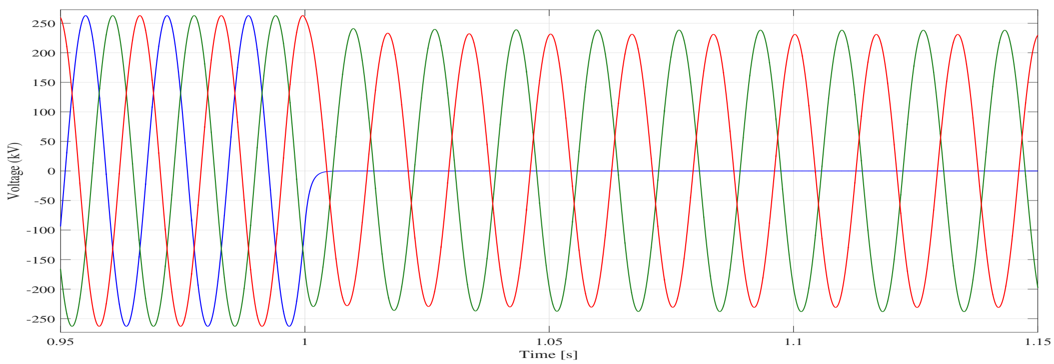

Figure B.16: Voltage, Solid to ground fault (SLG Fault) Grid with directly grounded transformer

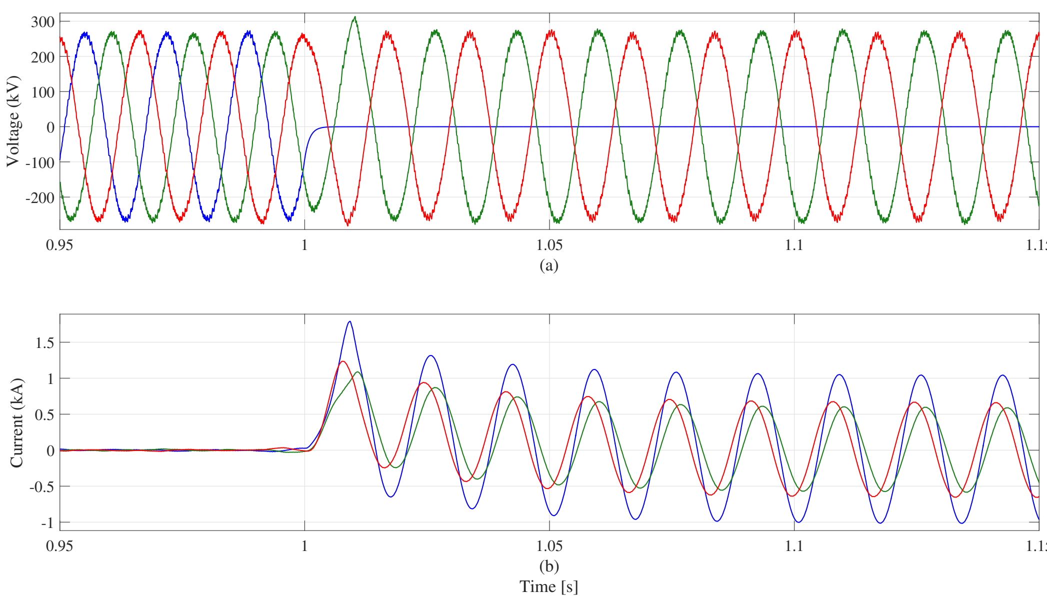

Figure B.17: (A)Voltage (B)Current, Solid to ground fault (SLG Fault) during STATCOM with only positive sequence control while transformer is directly grounded

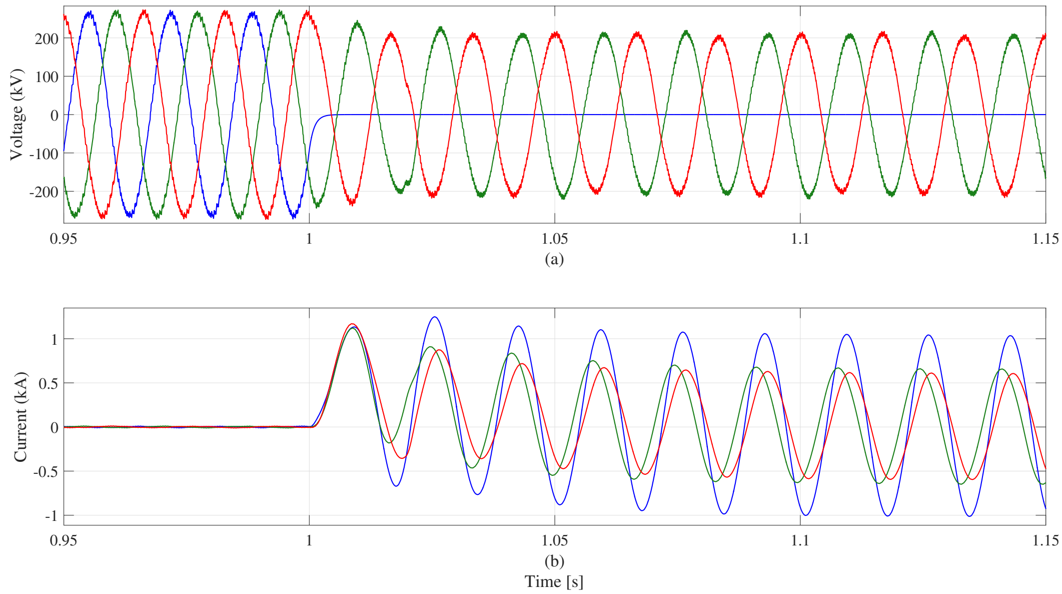

Figure B.18: (A)Voltage (B)Current, Solid to ground fault (SLG Fault) during STATCOM with only negative sequence control while transformer is directly grounded

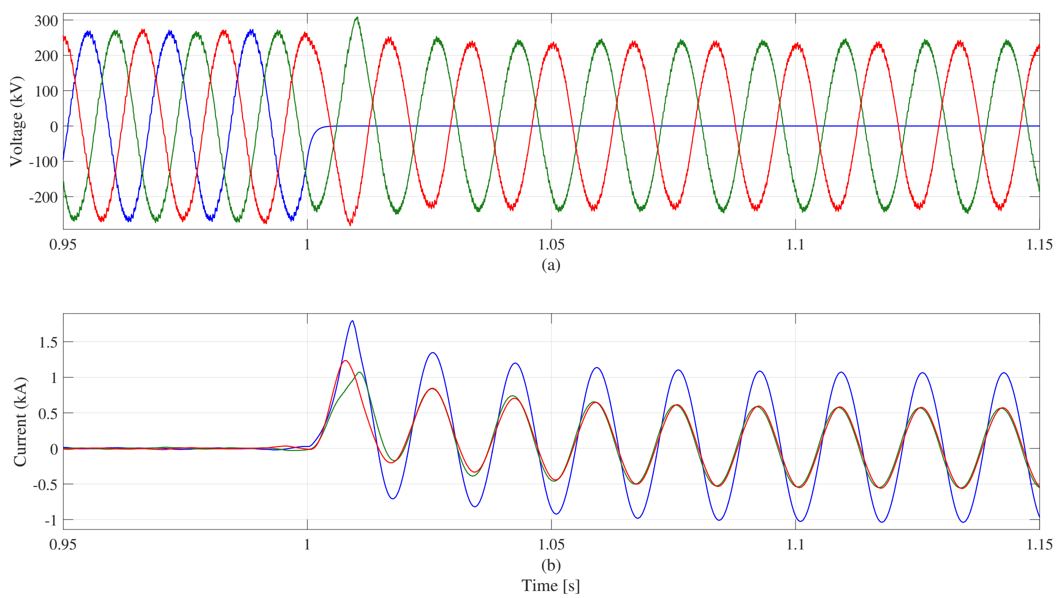

Figure B.19: (A)Voltage (B)Current, Solid to ground fault (SLG Fault) during STATCOM with both positive and negative control while transformer is directly grounded

B.2.2 Double line to ground fault

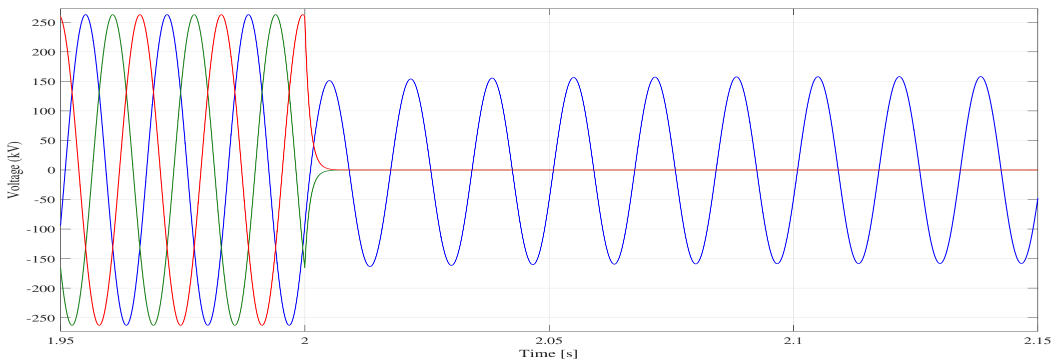

Figure B.20: Voltage, Solid to ground fault (DLG Fault) Grid with directly grounded transformer

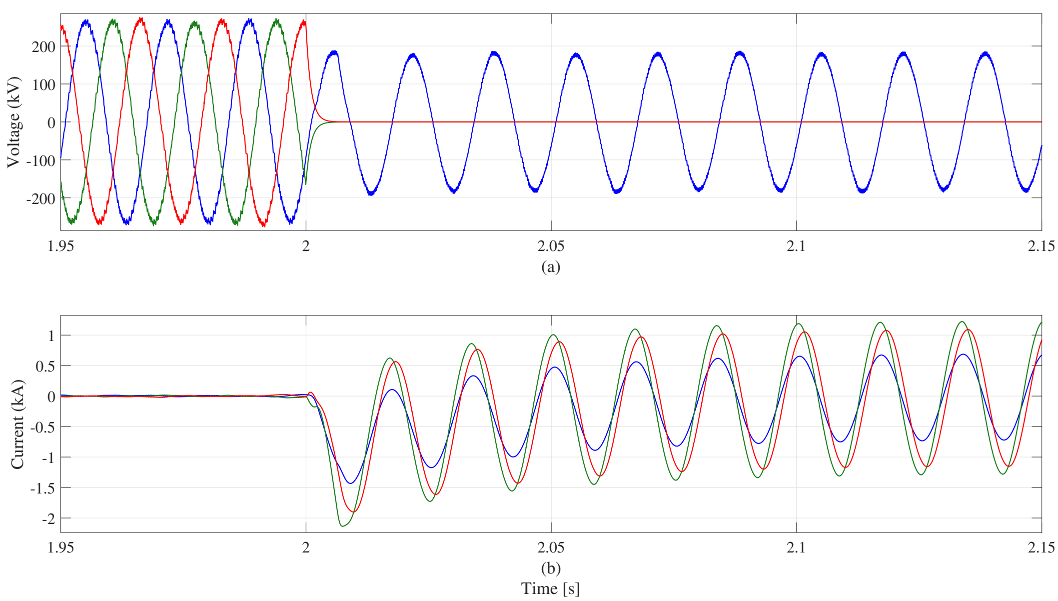

Figure B.21: (A)Voltage (B)Current, Solid to ground fault (DLG Fault) during STATCOM with only positive sequence control while transformer is directly grounded

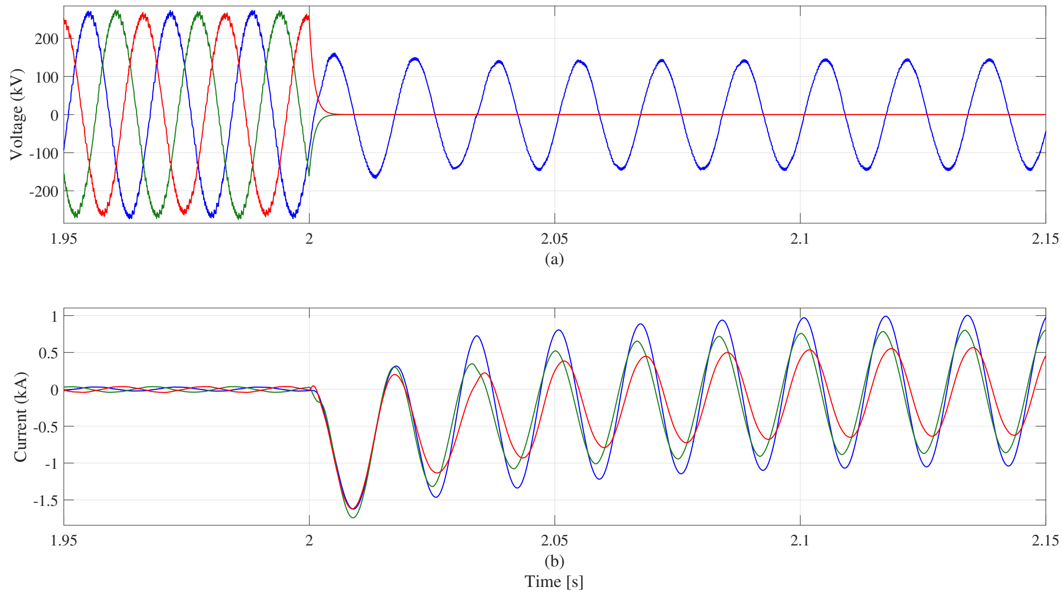

Figure B.22: (A)Voltage (B)Current, Solid to ground fault (DLG Fault) during STATCOM with only negative sequence control while transformer is directly grounded

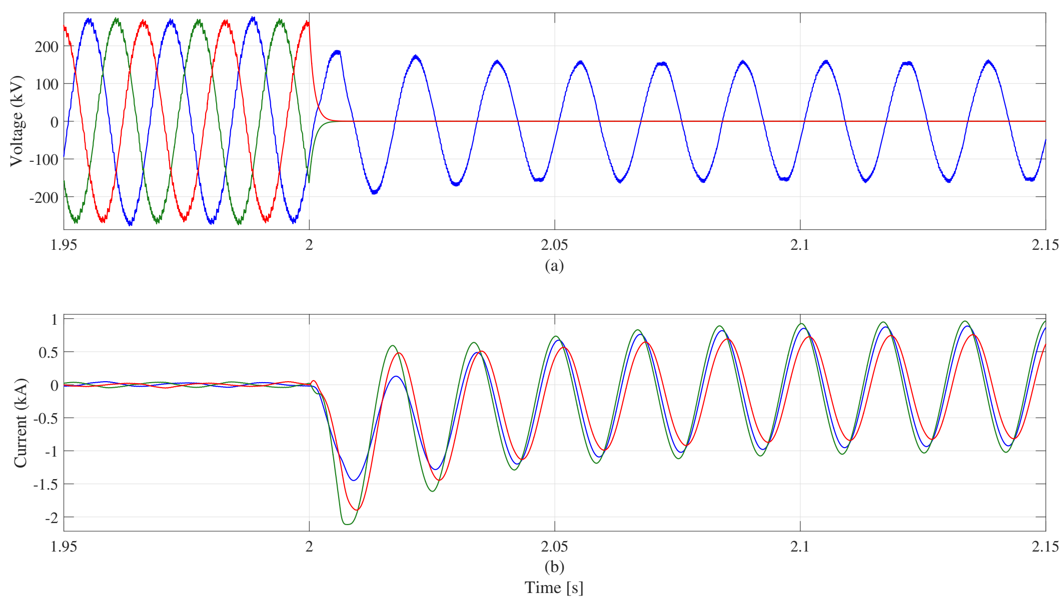

Figure B.23: (A)Voltage (B)Current, Solid to ground fault (DLG Fault) during STATCOM with both positive and negative control while transformer is directly grounded

B.2.3 Double line fault

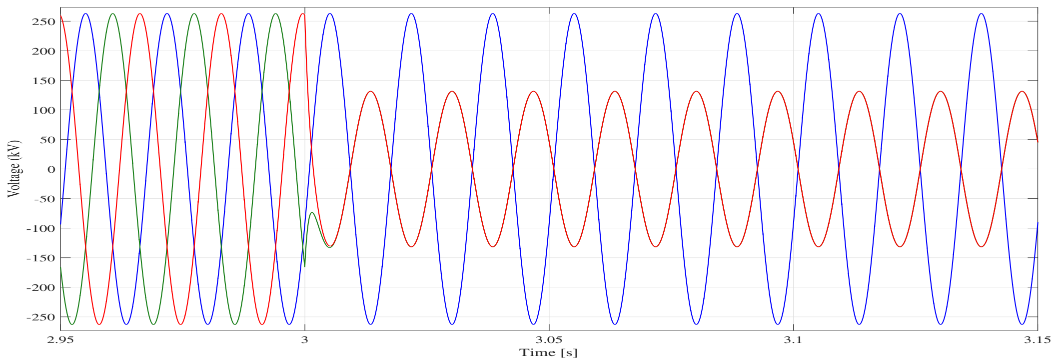

Figure B.24: Voltage, Solid to ground fault (DL Fault) Grid with directly grounded transformer

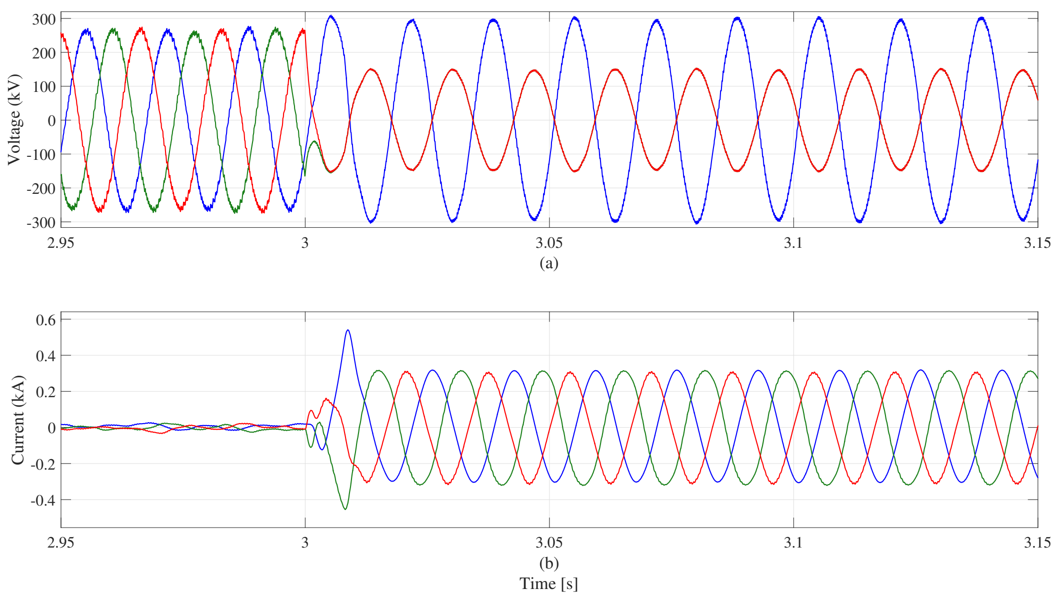

Figure B.25: (A)Voltage (B)Current, Solid to ground fault (DL Fault) STATCOM with only positive sequence control while transformer is directly grounded

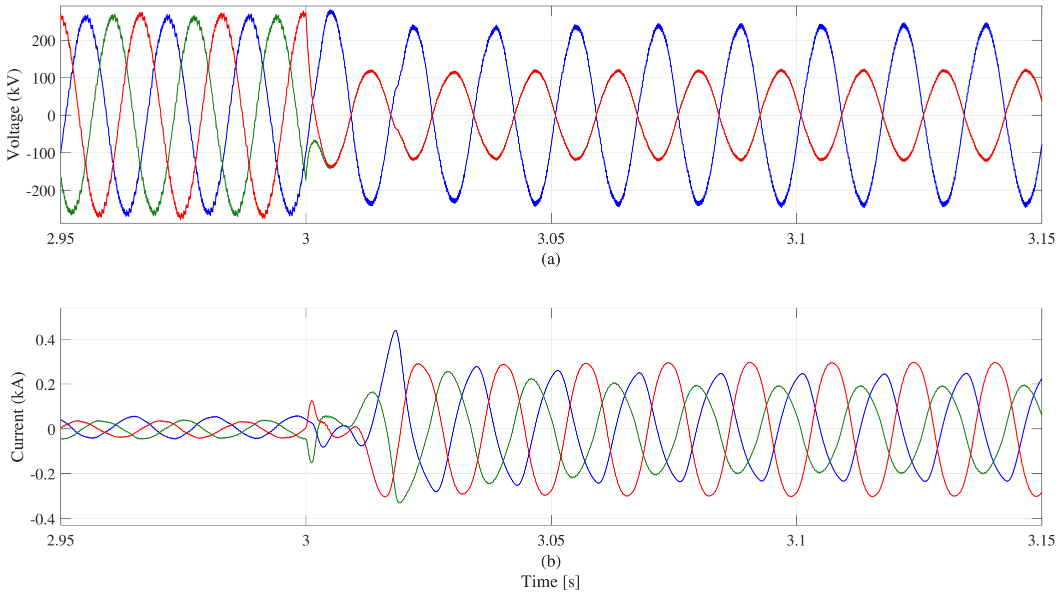

Figure B.26: (A)Voltage (B)Current, Solid to ground fault (DL Fault) during STATCOM with only negative sequence control while transformer is directly grounded

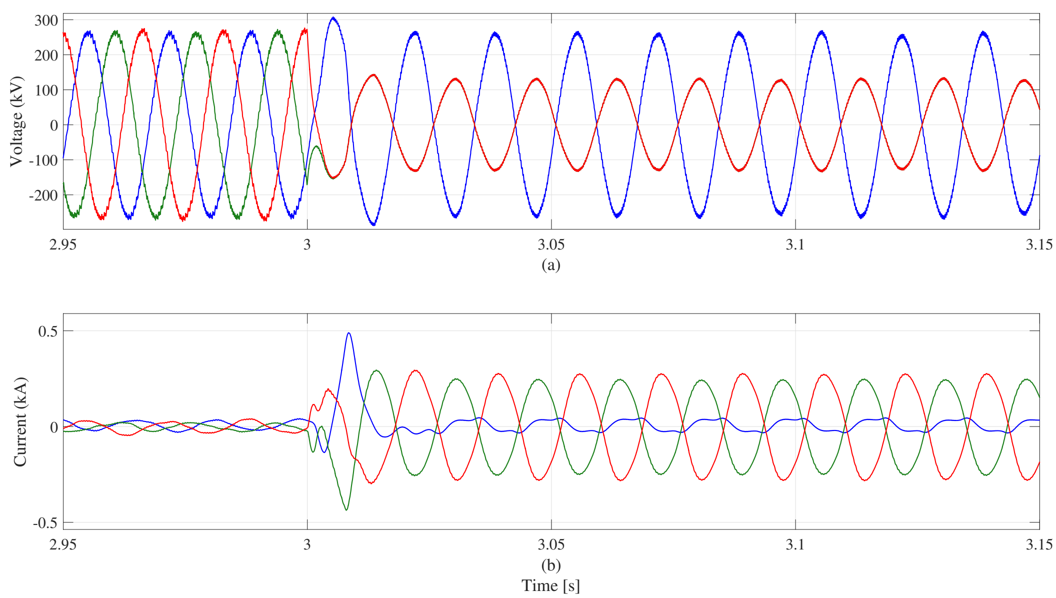

Figure B.27: (A)Voltage (B)Current, Solid to ground fault (DL Fault) during STATCOM with both positive and negative control while transformer is directly grounded

Appendix C

SCC contribution

C.1 Case Study 1: Ungrounded Transformer

Table C.1: Case 1: Total short circuit current

Case 1: Iscc_rms (kA)									
Scenario	Single line to ground			Double line to ground			Double line		
	A	B	C	A	B	C	A	B	C
Grid Only	0.33	-	-	-	0.33	0.33	-	0.29	0.29
Ungrounded Transformer	0.33	-	-	-	0.33	0.33	-	0.29	0.29
Only Positive	0.41	-	-	-	0.45	0.45	-	0.39	0.39
Only Negative	0.39	-	-	-	0.38	0.37	-	0.38	0.38
Both	0.46	-	-	-	0.43	0.40	-	0.39	0.38

C.2 Case Study 2: Grounded Transformer

Table C.2: Case 2: Total short circuit current

Case 2: Iscc_rms (kA)									
Scenario	Single line to ground			Double line to ground			Double line		
	A	B	C	A	B	C	A	B	C
Grid Only	0.33	-	-	-	0.29	0.29	-	0.29	0.29
Grounded Transformer	0.39	-	-	-	0.37	0.37	-	0.29	0.29
Only Positive	0.48	-	-	-	0.50	0.50	-	0.39	0.39
Only Negative	0.47	-	-	-	0.40	0.38	-	0.38	0.38
Both	0.53	-	-	-	0.46	0.46	-	0.38	0.38

C.3 Case Study 3: Ungrounded Transformer

Table C.3: Case 3: Total short circuit current

Case 3: Iscc_rms (kA)									
Scenario	Single line to ground			Double line to ground			Double line		
	A	B	C	A	B	C	A	B	C
Grid Only	0.67	-	-	-	0.67	0.67	-	0.58	0.58
Ungrounded Transformer	0.67	-	-	-	0.67	0.67	-	0.58	0.58
Only Positive	0.89	-	-	-	0.91	0.89	-	0.78	0.78
Only Negative	0.89	-	-	-	0.81	0.74	-	0.74	0.74
Both	0.91	-	-	-	0.86	0.80	-	0.77	0.77

C.4 Case Study 4: Grounded Transformer

Table C.4: Case 4: Total short circuit current

Case 4: Iscc_rms (kA)									
Scenario	Single line to ground			Double line to ground			Double line		
	A	B	C	A	B	C	A	B	C
Grid Only	0.67	-	-	-	0.67	0.67	-	0.58	0.58
Grounded Transformer	0.93	-	-	-	0.94	0.96	-	0.58	0.58
Only Positive	1.24	-	-	-	1.27	1.17	-	0.78	0.78
Only Negative	1.25	-	-	-	0.95	0.89	-	0.74	0.74
Both	1.26	-	-	-	1.07	1.03	-	0.77	0.77

C.5 Case Study 5: Ungrounded Transformer

Table C.5: Case 5: Total short circuit current

Case 5: Iscc_rms (kA)									
Scenario	Single line to ground			Double line to ground			Double line		
	A	B	C	A	B	C	A	B	C
Grid Only	1.67	-	-	-	1.67	1.67	-	1.45	1.45
Ungrounded Transformer	1.67	-	-	-	1.67	1.67	-	1.45	1.45
Only Positive	1.90	-	-	-	1.91	1.90	-	1.65	1.65
Only Negative	1.90	-	-	-	1.80	1.72	-	1.60	1.60
Both	1.90	-	-	-	1.86	1.80	-	1.63	1.63

C.6 Case Study 6: Grounded Transformer

Table C.6: Case 6: Total short circuit current

Case 6: Iscc_rms (kA)									
Scenario	Single line to ground			Double line to ground			Double line		
	A	B	C	A	B	C	A	B	C
Grid Only	1.67	-	-	-	1.67	1.67	-	1.45	1.45
Grounded Transformer	2.15	-	-	-	2.06	2.12	-	1.45	1.45
Only Positive	2.45	-	-	-	2.35	2.40	-	1.65	1.65
Only Negative	2.43	-	-	-	2.12	2.06	-	1.60	1.60
Both	2.46	-	-	-	2.22	2.20	-	1.63	1.63