Modelling and Optimal Design of a Shunt Active Power Filter

by

Mokgatla Abram Lefawane

Dissertation submitted in partial fulfilment of
the requirements for the
Bachelor of Engineering (Hons)
(Electrical and Electronic Engineering)

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
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Approved by,

(Assoc. Prof. Dr Konapalli Siva Rama Rao)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

May 2011

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Mokgatla Abram Lefawane

ABSTRACT

Power electronic converters are widely being used to mitigate harmonics in power systems. Active power filters have been proven to be effective in voltage and current harmonic compensations in the power systems. A shunt active power filter that uses low voltage components can be used in a medium or high voltage system to compensate for the distortions that affect power quality. This project investigates the optimal designs of a shunt active power filter and static compensator. The investigation is performed on the system with non-linear load and a bus network power system, respectively. The shunt active power filter provides the current harmonic compensation for a nonlinear load on a single bus network while static compensator provides voltage harmonic compensation to the load bus in a network. A p-q theory controller is implemented to compensate current harmonics. This is achieved by keeping the source current as a fundamental while injecting current to neutralise the load current harmonics. This injected current is equal in magnitude but phase shifted by 180° to the current harmonics. The simulated results of this project proved that a shunt active power is suitable for use in current harmonic compensation and static compensator is suitable for use in voltage harmonic compensation.

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LIST OF ABBREVIATIONS

AC	Alternating Current
ACO	Ant Colony Optimisation
APF	Active Power Filter
ASD	Adjustable Drive
DC	Direct Current
IEEE	Institute of Electrical and Electronics Engineers
FACTS	Flexible Alternating Current Transmission System
GTO	Gate Turn-Off Thyristor
PQ	Power Quality
PSAT	Power System Analysis Toolbox
SAPF	Shunt Active Power Filter
SMPS	Switch Mode Power Supply
StatCom	Static Compensator
UPS	Uninterruptible Power Supply
VFD	Variable Frequency Drive
VSC	Voltage Source Converter

CHAPTER 1: INTRODUCTION

1.1.Background Study

Distributed power system is a converse technique whereby the power requirements of the power systems are given to a number of minute power processing units. Power is usually taken to the consumption points via different units in the power system. The main advantage of Distributed Power Systems is the possibility of locating and isolating faults much easier than in other conventional systems. However, just like in any other power system, distributed power systems have harmonic problems.

It is anticipated of the voltage and current waveforms in AC power circuits to be sinusoidal with constant amplitude and frequency [1]. All power plant components have a tendency of introducing distortion into the AC power circuit. This is not really good for the power circuit because the voltage and current waveforms deviate from their expected sinusoidal waveforms. The root cause of today's harmonics problems is the power electronics equipment. It is, however, paradoxical that this power electronics equipment can be used effectively to alleviate the system of harmonics and help in making sure that the desired voltage and current sinusoidal waveforms are delivered in a power system [1].

There are two approaches to alleviate harmonics in a power system, passive and active filtering [3]. Though passive filters are simple, they do not always respond accurately to the harmonics in power systems. The active power filters (APFs) have a number of advantages over passive filters, among them the ability to suppress current harmonics and reactive currents. Today APFs are intended for compensating harmonic currents of nonlinear loads in the power system. Different types of APFs are specifically designed for specific applications. Their fundamental objective is to control the current that goes into the power system so that the harmonic signal can be compensated to result in a stable and sinusoidal signal.

1.2.Problem Statement

Power quality (PQ) is generally defined as the physical characteristic of the electrical supply provided under normal operating conditions. These conditions should be in such a way that they do not disturb the usage by the consumer. There will then be a problem with the PQ if the harmonics in the power system result in the failure or malpractice of the consumer's equipment. Lightning is a known common source of PQ problem. When non-linear loads are connected to the power system, they do have a tendency to cause disturbances in the PQ because they create current and voltage harmonic components. Active power filters are being designed to solve the problems with PQ. It is desirable to interface a low-voltage SAPF in the medium voltage power system to solve this problem.

1.2.1. Problem Identification

In this report modelling and optimal design of the shunt active power filter (SAPF) is attempted by using MATLAB software. Prior to doing any designing and modelling, it was imperative that the fundamental principles of an active power filter be well understood. Here an example will be used to test the operational capabilities of the compensation technique. To further make the project more practicable, the static compensation technique on a practical power system would be implemented. Subsequently, SAPF would be modelled using MATLAB/SIMULINK.

1.2.2. Significance of Project

The main idea of this project was to design a SAPF that is capable of operating at low voltage in a medium voltage power system. It is achieved by developing a state-space model and by deriving the optimal parameters using MATLAB/SIMULINK. This modelling is significant in the power systems industry, especially in distribution, because PQ problem is a big problem in this industry. The success of this project can go a long way in bridging a gap in harmonics elimination in the distributed power systems by using low voltage power electronics equipment.

1.3.Objective

The objective of this research project is to evaluate the performance of a SAPF converter which could operate at low voltage in a medium voltage power system. A four-leg topology of SAPF is increasingly required in Distributed Power Systems. In addition, the modelling of a StatCom in a real power system will be performed to evaluate its effect on the critical system parameters.

1.4.Scope of Study

This project revolves mostly around the modelling and optimal designing in MATLAB of the Shunt Active Power Filter in a power system to optimise the power flow. Critical insight on the mathematical models involved in this modelling come in handy in understanding the real parameters of the power system. The main component of this project is a filter, so the understanding of the fundamental principles and applications of a filter was required to help in carrying out the project. The scope of the project also included the modelling of a static compensator influence on a power system, thus literature review on the APFs and FACTS devices was highly beneficial.

1.4.1. The Relevance of Project

A number of optimisation techniques are used to alleviate the harmonics in power systems and help improve the power flow. However, the need to get better and more effective and efficient schemes is still there. The industry is still in need of the improvement in the current methods used to compensate for the harmonics in the power systems. This project is relevant to the industry because the usage of low voltage power electronics equipment to compensate the harmonics in a medium/high voltage power system is highly required.

1.4.2. Feasibility of the Project within Scope and Time frame

The early stages of this project required the collection of books, journals and technical papers to perform a study on the APFs and MATLAB applications of the SAPF. Research continued until the end to get a better and improved understanding of the subject matter. The latter stages of the project were channelled into the modelling and designing of the SAPF using MATLAB. The simulation was to be performed to investigate and illustrate the performance of SAPF in compensating the harmonics of a power system. The author feels that the project was reasonably allocated enough time as regards to the time frame, however, ineffectiveness of some of the tried tools made it difficult to achieve the primary objective of the project timeously.

CHAPTER 2: LITERATURE REVIEW

2.1. Active Power Filter

Active Power Filter (APF) is a type of analogue electronic filter, which is used in mitigation of harmonic distortion in voltage or current supply signal [17]. Unlike passive filter, APF actually generates specific current components that can cancel out the harmonic current component caused by the non-linear load by simply utilizing the power electronics technologies for the control unit [4].

The information regarding the harmonic currents and other system variables are passed onto the compensation current or voltage reference signal estimator. From this, the current compensation signal will be generated thus driving the overall system controller which in turn provides the control over the gating signal generator [3].

Beside the fact that APF is able to suppress the supply current harmonics, APF can also suppress the reactive current. Another advantage of using APF is that they do not cause harmful resonances with the power distribution systems thus making them independent on the power distribution properties [3]. However, the main setback with APF is that the switching of high currents in the power circuit is slow and in modern technology fast switching is required. This generally results in high frequency noise that causes electromagnetic interference in the power system [3] [17].

2.2. Series Active Power Filter

The series APF is normally connected to the system through a matching transformer. The voltage source inverter is used as the controlled source. The most obvious difference between the SAPF and series APF is that the series APF does not have the interfacing inductor, but an interfacing transformer. The series APF works to isolate the harmonics between the non-linear load and the source. To achieve this, the harmonic voltages are injected across the interfacing transformer. Depending on the nature of the disturbance, the injected harmonic voltages will either be added or subtracted to or from the source voltage so that the pure sinusoidal voltage waveform can be maintained across the non-linear load [2].

2.3. Shunt Active Power Filter

There exist different topology constructions of the active power filters. To fulfil the mandate of this project, SAPF will be designed. This is the type of an APF that compensates the current harmonics by injecting equal, but opposite, harmonic compensating current. It is widely used in the active power filtering applications of its ability to suppress both the current harmonics and reactive currents [6]. The harmonic components the SAPF injects are phase shifted by 180° [3]. The voltage source inverters are used to shape the compensating current waveform. Table 2.1 illustrates the difference in operation between SAPF and series active power filter [3]. Figure 2.3.1 shows a structure of SAPF.

Table 2.1.: Comparison between SAPF and series active power filter in solving PQ problems

Active Power Filter	Load on AC Supply	AC supply on load
Shunt	• Current harmonic filtering • Reactive current compensation • Current unbalance • Voltage flicker	
Series	• Current harmonic filtering • Reactive current compensation • Current unbalance • Voltage flicker • Voltage unbalance	• Voltage sag • Voltage unbalance • Voltage distortion • Voltage interruption • Voltage flicker • Voltage notching

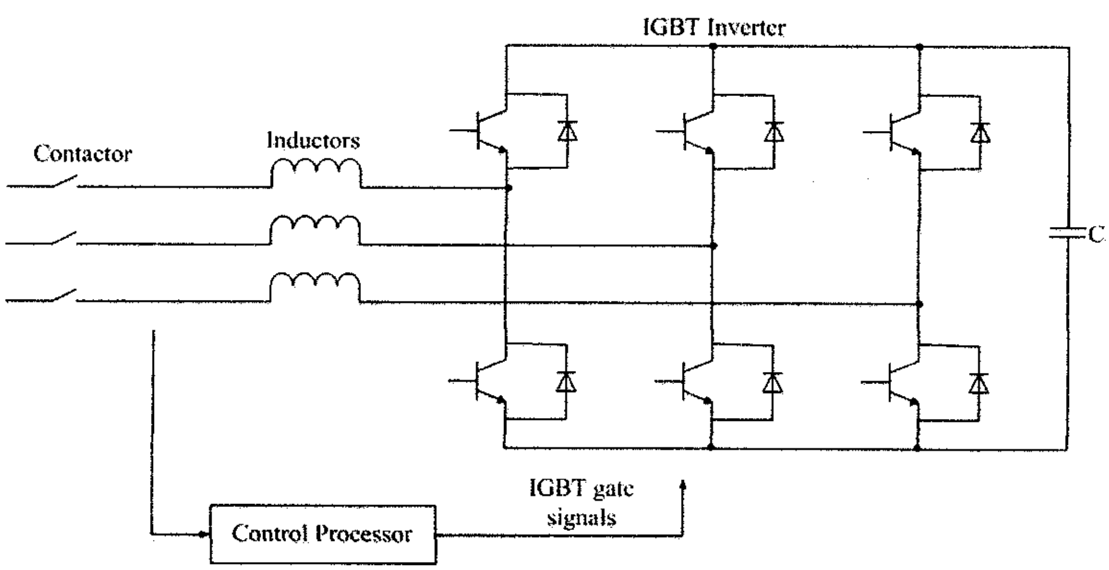

Figure 2.3.1: Structure of SAPF

2.4. Non-linear Load

A system load is characterised as non-linear if its impedance changes with applied voltage. Due to this change in the load impedance, the current drawn by the non-linear load would not be sinusoidal even if the applied voltage is sinusoidal. The resultant current, which is non-sinusoidal, has harmonic currents that will interact with the impedance and lead to voltage distortion that affect both the power system and loads connected to it. In the industry today, the non-linear loads include the uninterruptible power supply (UPS), variable frequency drives (VFD), and adjustable speed drives (ASD) and switched mode power supplies (SMPS) [7].

2.5. Power System Load Flow Analysis

The study of power flow (or load-flow) in power engineering is of critical importance and involves the numerical analysis of the power system. The study is based mostly on the various forms of AC power and not solely on the voltage and current. These power forms can be reactive, real or apparent power or a combination thereof. The simpler one-line diagrams and per-unit systems are used to analyse the power system in normal steady-state operation [15]. The principal information that can be obtained from the power study is the magnitude and phase angle of the voltage at each bus and the real and reactive powers flowing in each line. The voltage angle and magnitude are to be obtained in each bus in a power system and this power system must possess the specified load and generator real power and voltage conditions [14] [15]. From the obtained information, real and reactive power flow and generator reactive power – if any – can be determined analytically by different iteration methods. In the results section of this report, the Newton-Raphson method is used to simulate the StatCom in a bus system. This method is the most widely used in solving simultaneous nonlinear algebraic equations. Newton-Raphson method performs the successive approximation based on the initial estimates of the unknown [15].

The load flow study involves different types of buses; generator bus, load bus and swing bus. The load bus is a bus where the real and reactive powers are specified and it is known as the PQ (P for real power and Q for reactive power) bus. Normally the system will also have a generator bus, which is where the magnitude of the voltage is kept constant by the adjustments to the field current tied to the bus. The generator bus is also known as the PV (P for real power and V for bus voltage) bus. The reference bus to the power system is referred to as the slack or swing bus. It is accepted to be 1 per unit with angle of zero degree. The real and reactive powers of this bus cannot be controlled. They are only available to make the power flows in the system balanced [15]. An admittance bus system should then be constructed so that initial estimation in the bus system can be made.

It is simpler to study the power flow system by use of iterative computations. The solution to power flow problem can be obtained with the following steps [14]:

- Making an initial guess of all known voltage magnitudes and angles. Preferably, voltage angles are set to zero and all the voltage magnitudes are set to 1.0 per unit.
- The most recent voltage angle and magnitude values are used to solve the power balance equations.
- The system around the next recent voltage angle and magnitude values is linearised.
- Solve for the change in voltage angle and magnitude.
- Update the voltage magnitude and angle.
- Check the stopping conditions and terminate.

2.5.1. Mathematical Analysis

To demonstrate the theory given above, a practical system in Figure 2.5.1 is used to give an idea. The system is without the quantitative parameters but can show how the power flow analysis is performed. Figure 2.5.1 system is a 3-bus network showing the admittances:

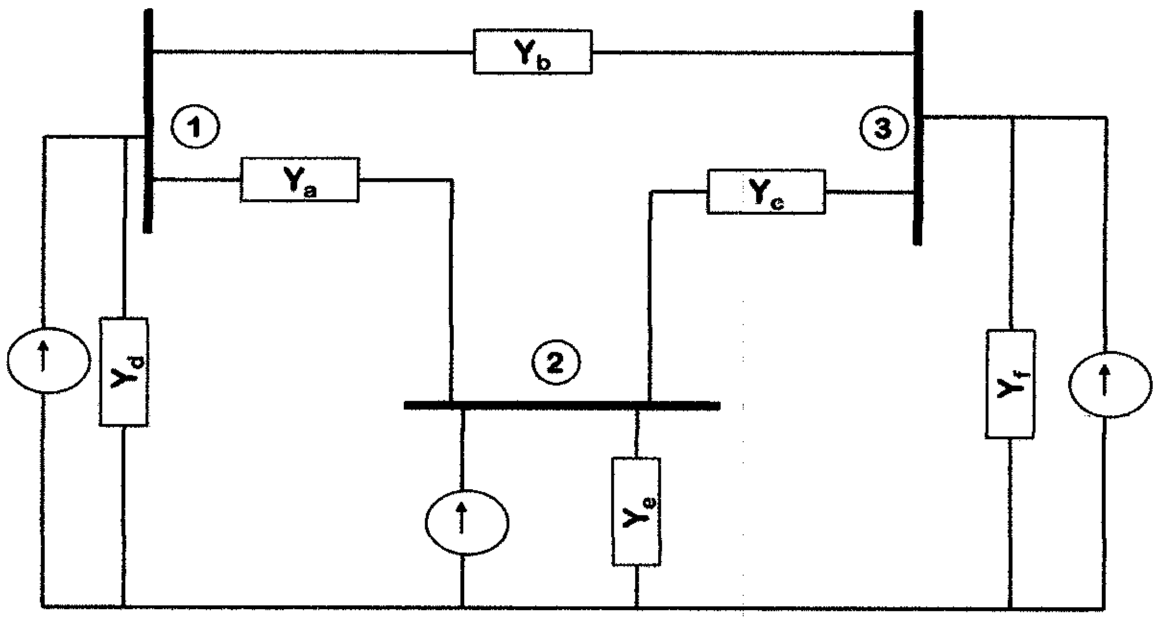

Figure 2.5.1: Three Bus system

From Figure 2.5.1, the power flow equations can be derived. The fundamental Kirchhoff's voltage and current laws aid in deriving the following.

At node 1: $(V_1 - V_2)Y_a + (V_1 - V_3)Y_b + V_1Y_d = I_1$

At node 2: $(V_2 - V_1)Y_a + (V_2 - V_3)Y_c + V_2Y_e = I_2$

At node 3: $(V_3 - V_1)Y_b + (V_3 - V_2)Y_c + V_3Y_f = I_3$

The above equations can be rearranged to find:

$$(Y_a + Y_b + Y_d)V_1 - Y_a V_2 - Y_b V_3 = I_1$$
$$-Y_a V_1 + (Y_a + Y_c + Y_e)V_2 - Y_c V_3 = I_2$$
$$-Y_b V_1 - Y_c V_2 + (Y_b + Y_c + Y_f)V_3 = I_3$$

Representing in the matrix form:

$$\begin{bmatrix} Y_a+Y_b+Y_d & -Y_a & -Y_b \\ -Y_a & Y_a+Y_c+Y_e & -Y_c \\ -Y_b & -Y_c & Y_b+Y_c+Y_f \end{bmatrix}\begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix}=\begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix}$$

The matrix can be solved to determine the node currents as follows, using the apparent power equation (where n represents a node):

$$S = VI^* = P + jQ$$

$$V_n I_n^* = P + jQ$$
$$I_n^* = \frac{P_n + jQ_n}{V_n}$$
$$I_n = \frac{P_n - jQ_n}{V_n^*}$$

To solve for the parameters in the system, it is important that two of the parameters (P, Q, V or θ) be known. This will make it easier to solve for the other unknown variables per bus. The iterative algorithm is important in solving the power flow problem. However, one first needs to start with a guess at the anticipated parameters [14]. This method will prove how close the guess is to the right parameter value and if not, it will update in a direction that will yield relevant results. The subsequent solutions will have to converge towards the previously set parameters to be regarded as accurate; otherwise the power flow analysis will not be yield desired results.

2.6. Static Compensation (StatCom) [10]

StatCom is a regulating device belonging to the Flexible Alternating Current Transmission System (FACTS) family of devices. StatCom comprises of a step-down transformer with leakage reactance, a three-phase GTO voltage source converter and a DC capacitor. It is utilized on the AC transmission systems and it is based on a power electronics voltage-source converter and acts as either a source or sink of reactive power in the network. This is achieved depending on the system voltage. If the system voltage is low, the StatCom generates reactive power and when the system voltage is high, it absorbs reactive power. It is essential that the voltage be regulated at the reference voltage and this can be attained by having the reactive current staying within the constant maximum and minimum current values dictated by the converter rating. Therefore, this can lead to relevant V-I characteristic of StatCom defined by the following equation:

$$V = V_{ref} + X_s I$$

V – positive sequence voltage (in per unit)

Vref – reference voltage

Xs – reactance

I – reactive current ($I > 0$ indicates an inductive current while $I < 0$ shows capacitive current)

The single line diagram of a test system for StatCom is shown in Appendix F. Figure 2.6.1 shows a basic circuit diagram of a three-phase StatCom.

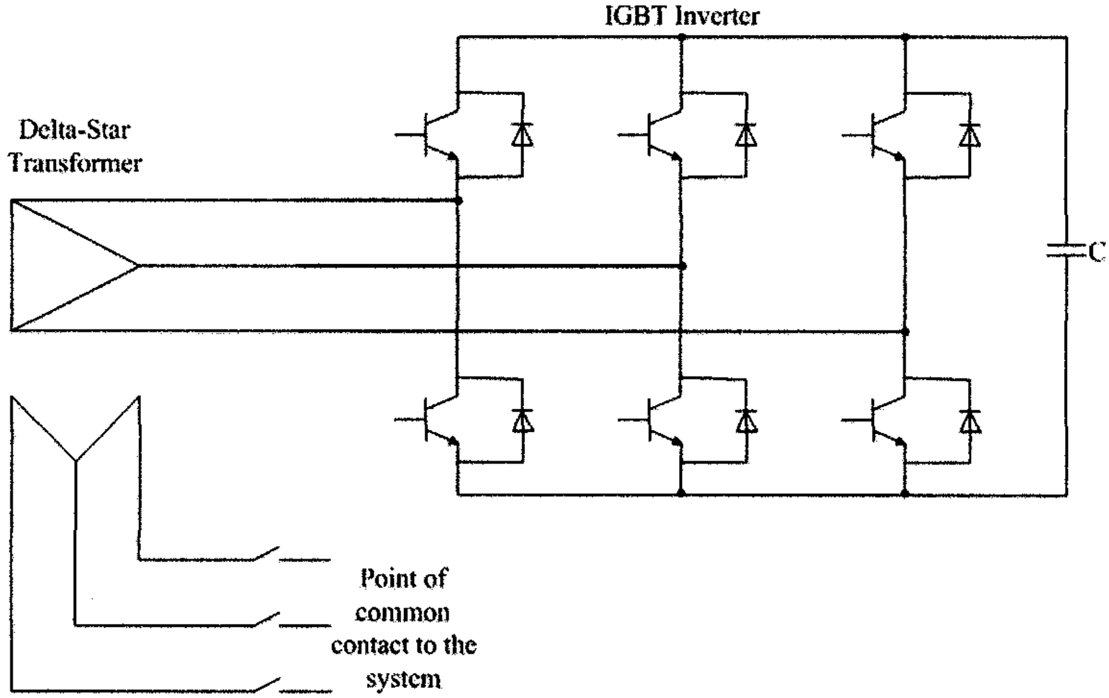

Figure 2.6.1: Basic StatCom circuit

2.7. Voltage Source Converter (VSC)

This is a power electronic device used to source a sinusoidal voltage. This generated voltage can have any required parameters; magnitude, frequency and phase angle. The VSC can be effectively used to mitigate voltage dips. Due to the harmonics, there tend to be a difference between the nominal and actual voltages and VSC can be used to replace this voltage difference. If connected in shunt with the AC system, the VSC can be used for voltage regulation and compensation of reactive power, correction of power factor and elimination of current harmonics.

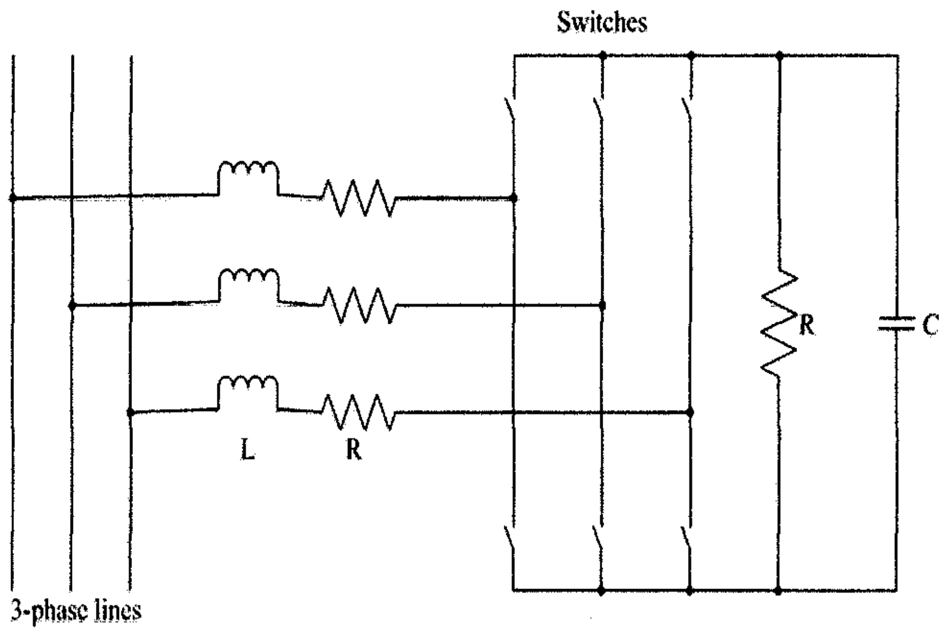

Figure 2.7.1: Basic VSC circuit

2.8. The p-q Theory [11] [12] [13]

p-q theory is developed based on a set of instantaneous powers that are defined in time domain. The theory can be applied to the three-phase power systems with three-wire or four-wire (fourth wire being the neutral wire) configurations. In these configurations, the voltage and current waveforms have no limitations. There non-existence of restrictions on the waveforms makes this theory valid in both steady and transient states. The objective of the p-q theory is to define the instantaneous powers by first transforming the voltages and currents from the *abc* to $\alpha\beta0$ coordinates using what is called the Clarke Transformation [12].

2.8.1. The Clarke Transformation

v_a, v_b and v_c – the three-phase instantaneous voltages in the *abc* phases – are mapped into the instantaneous voltage v_α, v_β and v_0 on the $\alpha\beta 0$-axes. The Clarke Transformation and its inverse voltages are given by:

$$\begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & \frac{-1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{-1}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix}$$

Using the same transformation, the three-phase line currents i_a, i_b and i_c can be transformed in the $\alpha\beta 0$

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & \frac{-1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{-1}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix}$$

In a three-phase, three-wire system, the zero sequence current does not exist, meaning i_0 can be eliminated from the above matrices. On the other hand, in a balanced four-wire system, the zero sequence voltage component is not present, thus v_0 can be eliminated.

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ \frac{-1}{2} & \frac{\sqrt{3}}{2} \\ \frac{-1}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix}$$

As with preceding matrices, the line currents matrices can be obtained as above.

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ \frac{-1}{2} & \frac{\sqrt{3}}{2} \\ \frac{-1}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}$$

2.8.2. Powers of the p-q Theory [12] [13]

Using the matrices in the preceding subsection, the instantaneous zero sequence, real and imaginary powers can be obtained.

$$p_0 = v_0 \times i_0$$

$$p = v_\alpha \times i_\alpha + v_\beta \times i_\beta$$

$$q = v_\alpha \times i_\beta - v_\beta \times i_\alpha$$

p_0 refers to the power that is transferred from the power supply to the load through the zero sequence components of voltage and current.

p is the energy per unit time that is transferred from the power supply to the load. It is the normal real power that is sourced from the power supply.

q is the instantaneous imaginary (reactive) power. This is the power that is transferred between the load phases and it is not the desired power component in the system since it is responsible for the current that circulate between system phases. The reactive power does not transfer power from the supply to the load and it also does not exchange power.

Based on the three-phase three-wire system, the zero sequence voltage and current components can be eliminated to have the following power matrix:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}$$

The positive value of the instantaneous imaginary power q is due to the product of the positive sequence voltage and an inductive (lagging) positive sequence current. The only power components obtained through the p-q theory that are desirable and constructive are the average real power and the average zero sequence power. As stated earlier, this is when the power is transferred from the power supply to the load. All the other undesirable power components can be compensated using the methods proposed in this project.

2.8.3. p-q Theory for Shunt Current Compensation [11]

Of all the applications of the p-q theory, perhaps the compensation of undesirable currents in a power system is the most important and significant. A normal system to show this compensation basic principle is shown in Appendix G. The shunt compensator behaves like a three-phase, controlled current source that can draw any chosen current reference.

Figure 2.8.1 shows a general control method implemented in compensation using the p-q theory. The real (p) and reactive (q) load powers will have their undesired properties compensated, these powers are p* and q* as shown in Figure 2.8.1. The negative signs associated with these components signifies the basic operation of the SAPF, where the compensating current to be drawn by the compensator will be the inverse of the undesired components of the powers drawn from the non-linear load. In actual fact, as can be seen in Appendix G, the source current is the sum of the load and compensating currents. The i^*_{Ca}, i^*_{Cb} and i^*_{Cc} are the compensating reference currents that are acquired from the inverse transformation.

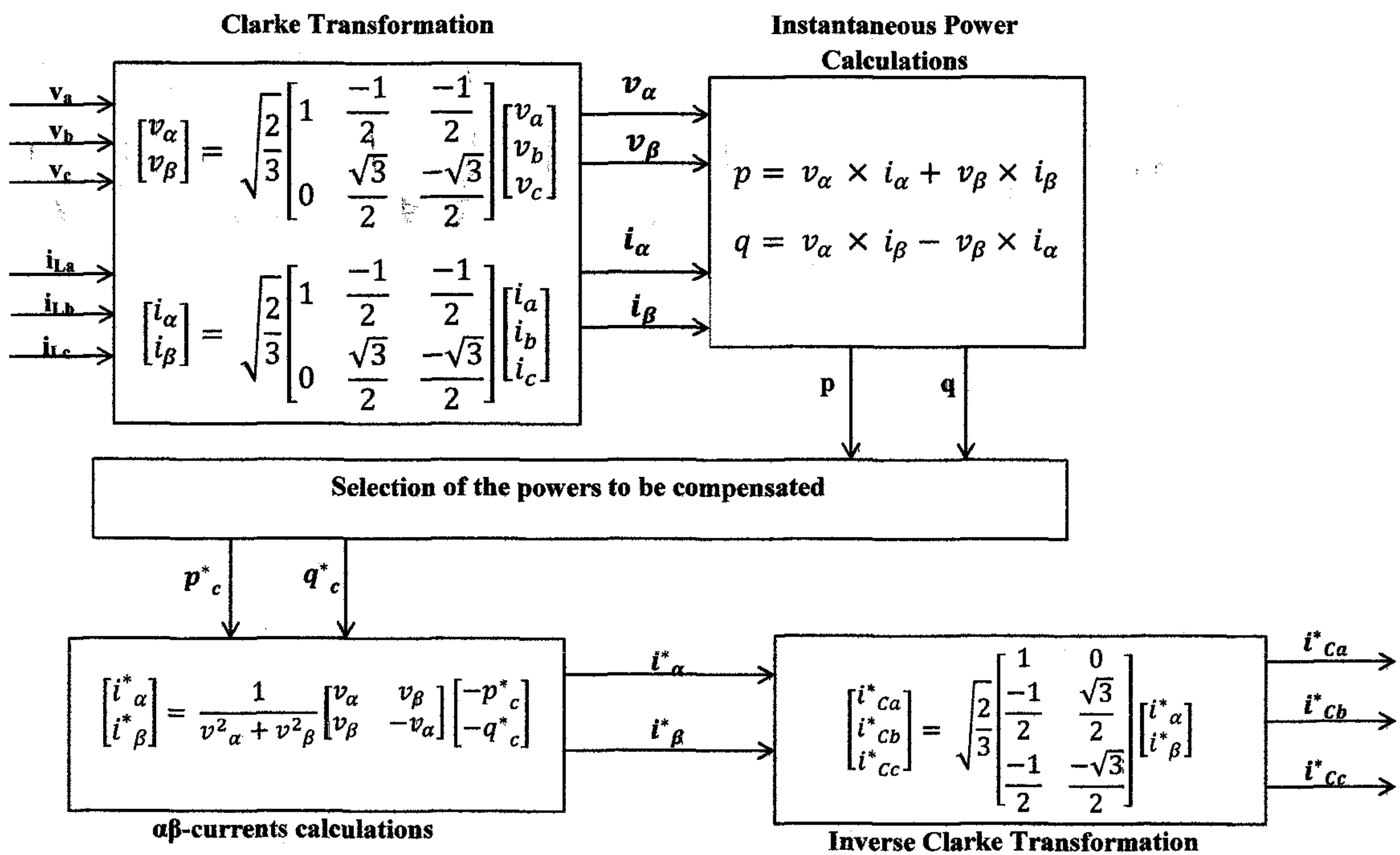

Figure 2.8.1: Control Method for shunt current compensation based on the p-q theory

2.9. MATLAB

MATLAB is a numerical computing environment and fourth generation programming language. It allows matrix manipulation, plotting of function and data, implementation of algorithms, creation of user interfaces and interfacing with program in other languages. Although it is only numerical, it also has optional toolbox that uses MuPAD symbolic engine which allows access to computer algebra capabilities. An additional package, SIMULINK adds graphical multi-domain simulation and Model-Based Design for dynamic and embedded systems [16]. SIMULINK software is used to model, simulate and analyze dynamic systems. Models can be built from scratch or already existing models can be modified accordingly by using SIMULINK. MATLAB commands or SIMULINK menus may be used to define and simulate a model. Scopes and other display blocks are used to view the simulation results as the simulation runs.

CHAPTER 3: METHODOLOGY

3.1. Procedure Identification

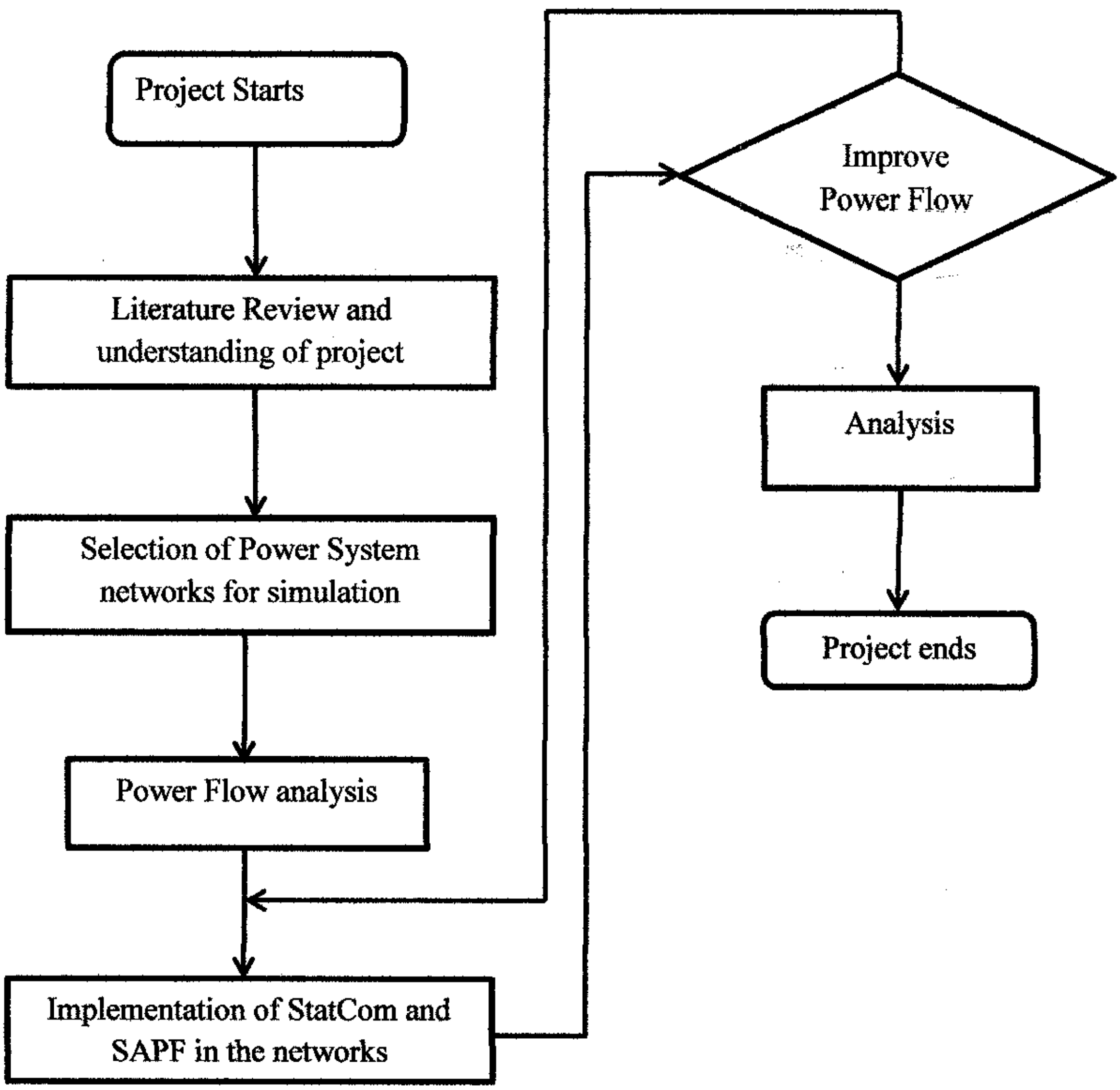

Figure 3.1: Flowchart of the project

3.2. Research Methodology

For the successful accomplishment of this project's objective, literature-oriented research was carried out using technical and research papers, relevant books and World Wide Web. Continuous research was needed as the area related to this project has drawn so much interest in recent times. This meant that new concepts were always meant to surface at regular intervals as more and more researches were conducted in this area. The information gathered is based more on the Distributed Power Systems, Power Quality, Power Systems Harmonics, Active Power Filters, StatCom, ant colony systems and Power Electronics in Power Systems and related topics. Subsequent to the literature study, the latter stages of the project required performing the simulation using MATLAB/SIMULINK. This was initiated to model the static compensator in a power system and also try to model SAPF in a small power system. The aim was to investigate and demonstrate their ability to alleviate harmonics in a power system. Thorough understanding of the MATLAB tools came in handy, especially when a dead-end was reached due to the inefficiencies of SIMULINK. This is when the use of PSAT was included in the project, but it being a fairly new and independent toolbox, extensive research on its usage was also required. To gain more information to help in carrying out of the project, physical consultation with the technicians, post graduate students and other undergraduate students was done throughout the project.

3.3. Tools Required

To fully accomplish the objective of this research project, modelling and simulation are required. These processes will be performed using the MATLAB software and its secondary software, SIMULINK.

CHAPTER 4: RESULTS AND DISCUSSION

This part covers the research findings and the simulation of the implementation of the STATCOM in a real power system. The simulation work aided in vividly explaining the project's scope and the results that could be expected when the implementation of SAPF is done. Through the research work done, one expects the simulation results to show a high level of harmonic compensation when a STATCOM is connected to the system. The same can be expected with the use of SAPF. The simulated system was designed randomly by taking into consideration the possible conditions as set out by IEEE. Appendix I shows how the StatCom is connected to the system. The system parameter values were chosen randomly but also kept within the practical ranges. Most of the values were settled after trial and error method and after being deemed good enough to give relevant and desired results. The use of different kind of buses; slack, load and generator buses, was implemented so that there can be variation in the simulation.

Subsequently, the results of the modelling of SAPF are outlined. This model was constructed using the p-q theory in the controller of the active filter. The analysis of the results shows that the current compensation anticipated of the SAPF took place and within the set boundaries.

4.1. Simulation of StatCom in an IEEE 30-bus system

The following results (as copied MATLAB command window) were obtained from the simulation of STATCOM using MATLAB. The M-file codes that were used in the project are provided in the accompanying compact disc. The STATCOM connection to the system was varied by connecting to one bus incrementally until 30 buses at a time. Figure 4.1.1 shows the system that was used to perform this simulation. But the results shown below are only when it was connected to one bus, two and three buses at a time. The program fragment code is attached in Appendix J.

The following single line diagram of IEEE 30-bus system is used in the project for simulations using STATCOM

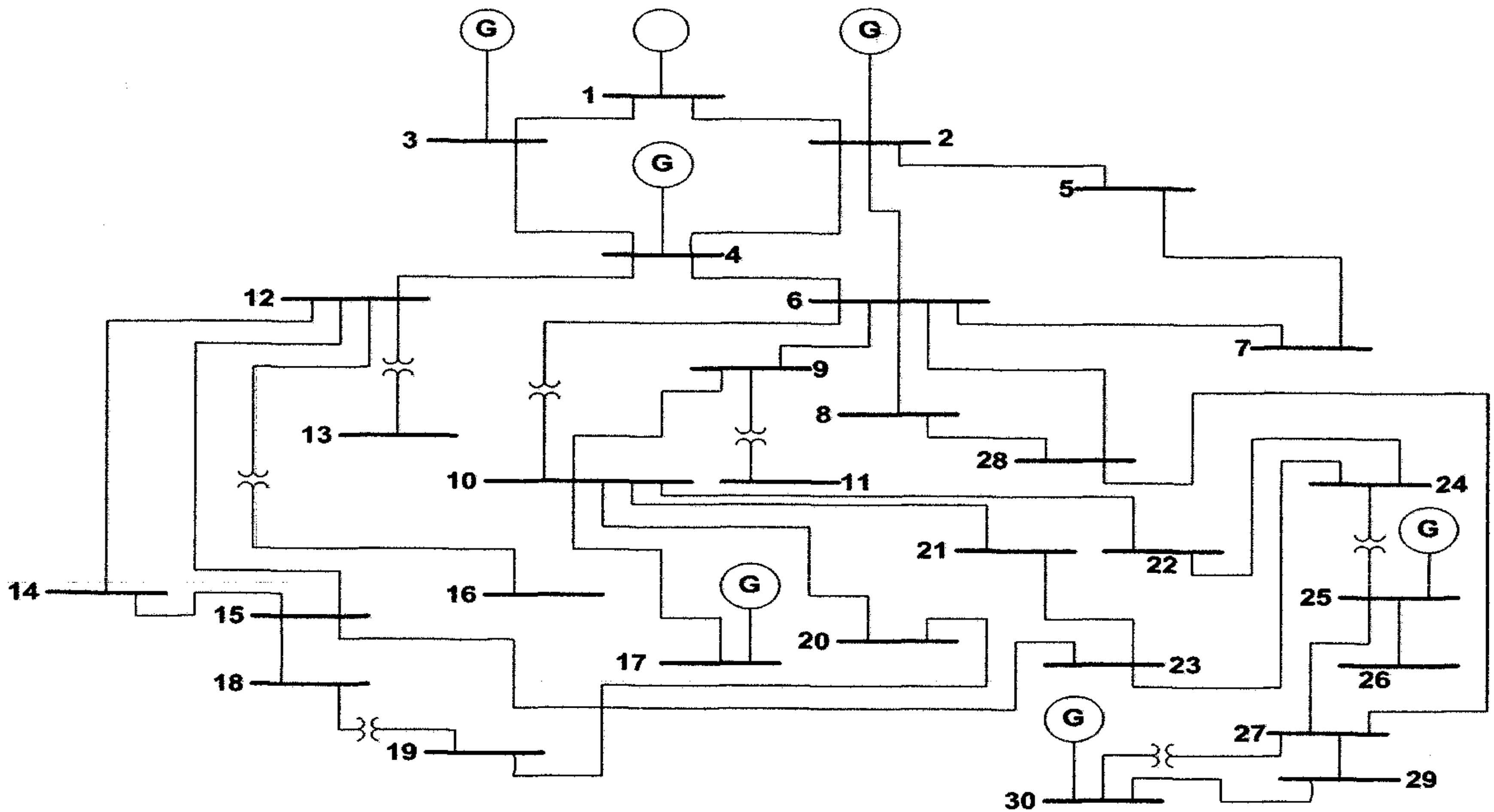

Figure 4.1.1: Single Line Diagram of IEEE 30-Bus System

4.1.1. Connecting STATCOM to one bus at a time

Table 4.1.: Simulation results when StatCom is connected to one bus at a time

Bus	Without StatCom		With StatCom	
	Voltage (p.u.)	Angle	Voltage (p.u.)	Angle
5	1	0	1.0233	-12.9768
6	1	0	1.0195	-10.5641
7	1	0	1.0166	-11.8519
8	1	0	1.0105	-10.8495
9	1	0	1.0110	-14.3683
10	1	0	1.0048	-14.8018
11	1	0	1.0037	-16.3737
12	1	0	0.9991	-14.3698
13	1	0	0.9996	-14.7965
14	1	0	1.0035	-15.8019
15	1	0	1.0050	-15.6763
16	1	0	0.9995	-15.1372
18	1	0	1.0055	-16.2660
19	1	0	1.0053	-16.1154
20	1	0	1.0051	-15.8807
21	1	0	1.0029	-15.1827
22	1	0	1.0054	-16.6755
23	1	0	1.0042	-15.8055
24	1	0	1.0072	-16.8038
26	1	0	1.0009	-17.2730
27	1	0	0.9992	-14.7835
28	1	0	1.0074	-11.0883
29	1	0	0.9998	-15.1427

The above results show that the system used required reactive power generation from the StatCom at most of the buses. Only a few buses required voltage suppression. The slack and generator buses were not used during simulation; this is because practically it would not be a good exercise to perform on these buses. Proper protection and other stability techniques are expected to be well-implemented in them.

4.1.2. Connecting STATCOM to two buses at a time

Table 4.2.: Results with StatCom connected to buses 20 and 26

Bus	Without StatCom		With StatCom	
	Voltage (p.u.)	Angle	Voltage (p.u.)	Angle
20	1	0	1.0051	-15.8807
26	1	0	1.0009	-17.2732

There is no physical connection between buses 20 and 26, but we can still witness some compensation. The compensation seems to be almost equal to when one bus at a time had a StatCom connected to it.

Table 4.3.: Results with StatCom connected to buses 20 and 28

Bus	Without StatCom		With StatCom	
	Voltage (p.u.)	Angle	Voltage (p.u.)	Angle
20	1	0	1.0049	-15.8799
28	1	0	1.0069	-11.0858

There is no physical connection between buses 20 and 28, but we can still witness some compensation. The compensation seems to be almost equal to when one bus at a time had a StatCom connected to it.

Table 4.4.: Results with StatCom connected to buses 26 and 28

Bus	Without StatCom		With StatCom	
	Voltage (p.u.)	Angle	Voltage (p.u.)	Angle
26	1	0	1.0009	-17.2734
28	1	0	1.0074	-11.0883

There is no physical connection between buses 26 and 28, but we can still witness some compensation. The difference here is that the buses used are the same ones used in the previous two simulations. We can also see compensation with similar changes as above. This proves the fact that in a stable system, the coordination of compensation should not change much when the sequence of compensated buses changes.

Table 4.5.: Results with StatCom connected to buses 10 and 22

Bus	Without StatCom		With StatCom	
	Voltage (p.u.)	Angle	Voltage (p.u.)	Angle
10	1	0	1.0031	-14.7919
22	1	0	1.0053	-16.6749

Different to the previous simulations is that buses 10 and 22 have a line between them. The presence of line 10-22 does not halt compensation. The voltage magnitudes and angles of individual buses still changed. This can be owing to the fact that compensation does not see the buses in isolation, but as a system.

Table 4.6.: Results with StatCom connected to buses 18 and 19

Bus	Without StatCom		With StatCom	
	Voltage (p.u.)	Angle	Voltage (p.u.)	Angle
18	1	0	1.0027	-16.2501
19	1	0	1.0032	-16.1032

There is a transformer between buses 18 and 19. Compared to previous results, we find that here the compensation is almost the same at each bus. The voltage ratio around a transformer is determined by the turns ratio, hence the compensation yields closer results.

4.1.3. Connecting StatCom to three buses at a time

Table 4.7.: Results with StatCom connected to buses 6, 9 and 11

Bus	Without StatCom		With StatCom	
	Voltage (p.u.)	Angle	Voltage (p.u.)	Angle
6	1	0	1.0152	-10.5385
9	1	0	1.0089	-14.3567
11	1	0	0.9996	-16.3525

There is a transformer between buses 9 and 11 and a line between buses 6 and 9. This system configuration seems to still allow for compensation. Under normal circumstances, harmonics would be more expected in this kind of configuration, thus the way the compensation results appear.

Table 4.8.: Results with StatCom connected to buses 6, 8 and 28

Bus	Without StatCom		With StatCom	
	Voltage (p.u.)	Angle	Voltage (p.u.)	Angle
6	1	0	1.0185	-10.5578
8	1	0	1.0025	-10.8051
28	1	0	0.9984	-11.0386

There exist two lines in the above simulation, lines 6-8 and 8-28. The presence of these lines does not influence compensation negatively. The voltage magnitudes and angles of individual buses still changed. This can be owing to the fact that compensation does not see the buses in isolation, but as a system.

Table 4.9.: Results with StatCom connected to buses 10, 12 and 26

Bus	Without StatCom		With StatCom	
	Voltage (p.u.)	Angle	Voltage (p.u.)	Angle
10	1	0	1.0051	-14.8036
12	1	0	0.9985	-14.3667
26	1	0	1.0009	-17.2731

There is no physical connection between buses 10 and 12 nor between buses 12 and 26, but we still witness some compensation. The compensation seems to be almost equal to when one bus at a time had a StatCom connected to it.

Table 4.10.: Results with StatCom connected to buses 18, 19 and 27

Bus	Without StatCom		With StatCom	
	Voltage (p.u.)	Angle	Voltage (p.u.)	Angle
18	1	0	1.0027	-16.2501
19	1	0	1.0032	-16.1032
27	1	0	0.9991	-14.7833

Unlike in table 4.7, there is a transformer between buses 18 and 19 but bus 27 does not have any direct connection the other two buses. Compensation is fairly similar to when the buses where compensated separately.

Table 4.11.: Results with StatCom connected to buses 15, 16 and 18

Bus	Without StatCom		With StatCom	
	Voltage (p.u.)	Angle	Voltage (p.u.)	Angle
15	1	0	1.0028	-15.6636
16	1	0	0.9976	-15.1265
18	1	0	1.0046	-16.2611

The difference of the above results to those in table 4.8 is not really visible even though there is only one line here, between buses 15 and 18. Similar to the above, compensation is not deviated away from the anticipated outcome regardless of the bus configuration to the compensated buses.

4.2. SIMULINK Model of SAPF in Medium Voltage System

Figure 4.2.1 shows the SAPF model simulated in SIMULINK. The model was simulated in both low voltage and medium voltage. The low voltage model and its results are shown in Appendix H. The p-q theory was implemented to estimate the parameters needed for current compensation. As outlined in section 2.8, the distortions in the source currents are compensated by the injected currents. The sum of the injected currents and load currents is equal to the source currents. The system parameters of this model are shown in Appendix I.

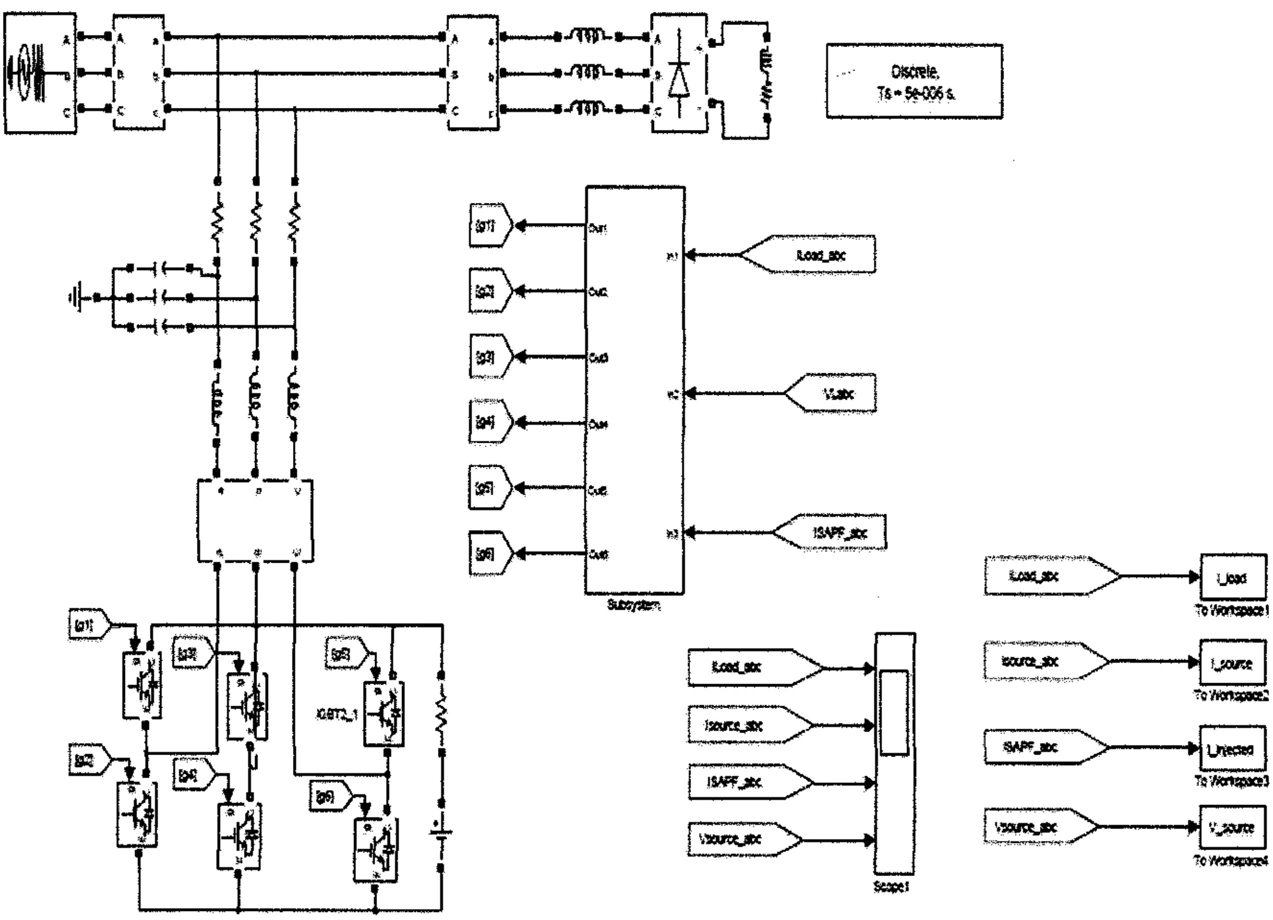

Figure 4.2.1: SAPF SIMULINK model

4.2.1. SAPF Model Results

The following graphs were obtained from the model simulation. Figure 4.2.2 shows the source voltages. These are the voltages supplied by the power source to the system. It can be noticed from Figure 4.2.2 that there is a clear distortion of the signals at the beginning. Since the system is assumed to be balanced, supplying a non-linear load, it is evident that the source voltages, even with distortion, seem to be trying to mitigate the distortion. Before steady-state, phase *a* seems to be more negative than phases *b* and *c*. However, the difference between the negative and positive distortion will later cancel out for steady state.

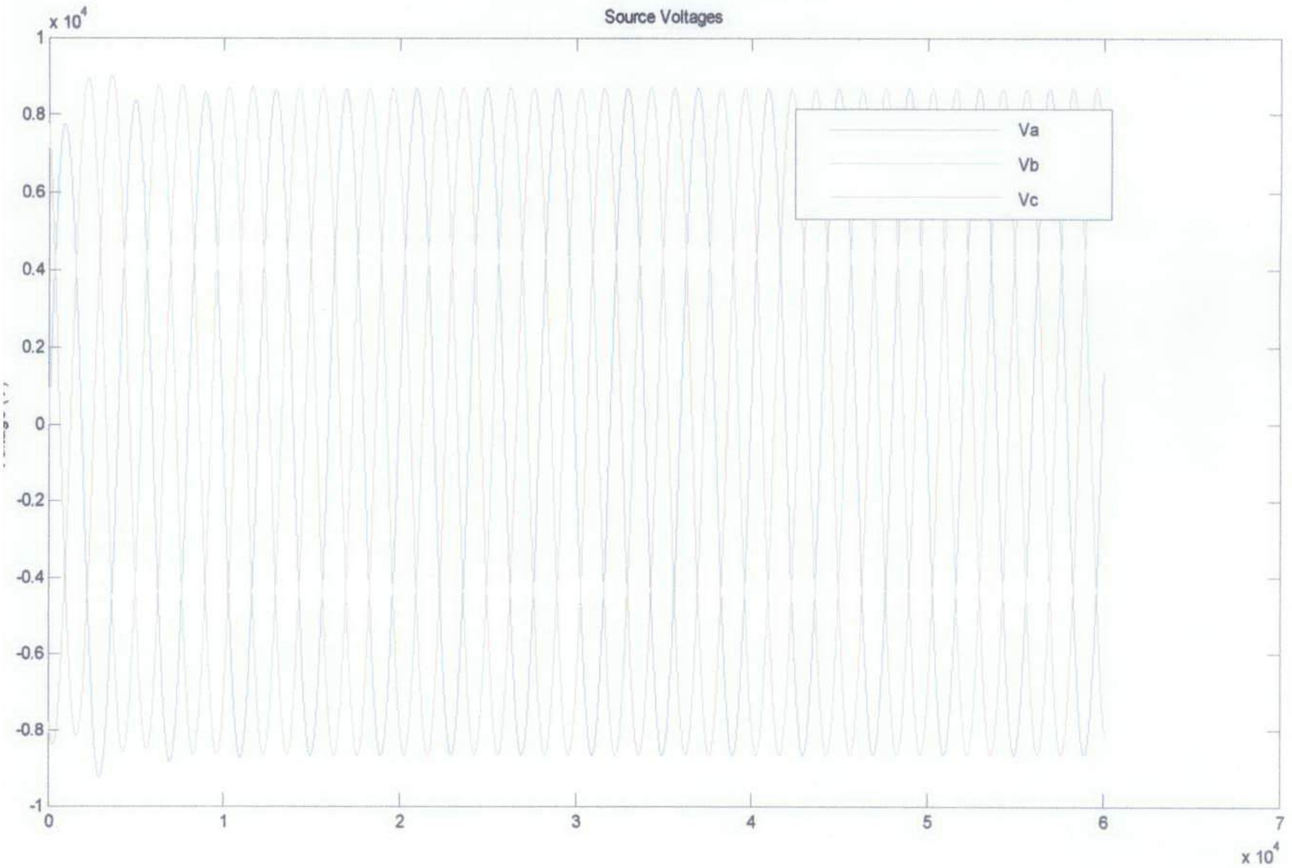

Figure 4.2.2: Source Voltages

Figure 4.2.3 shows the source currents of the system and Figure 4.2.4 the injecting currents. These injecting currents are in fact the compensating currents to mitigate the harmonics in the source currents. It can be observed that the compensating current signal is equal in magnitude to the source signal, but phase shifted by 180°. This is true for all the three phases. As expected of a balanced three-phase system, one phase could be used for analysis as the other two phases will prove similar. Compared to Figure 4.2.2, phase *a* is still the one with more distortion.

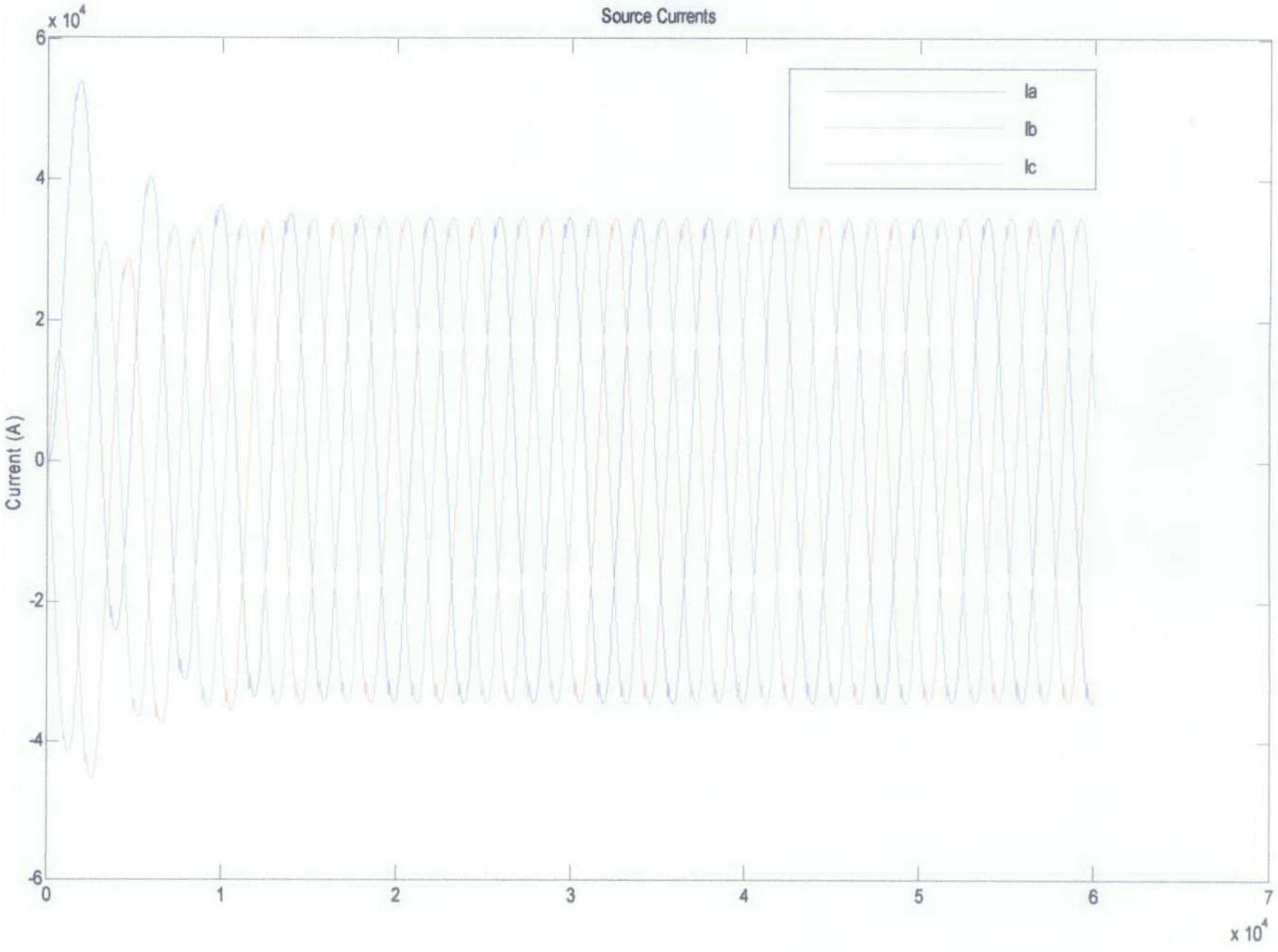

Figure 4.2.3: Source Currents

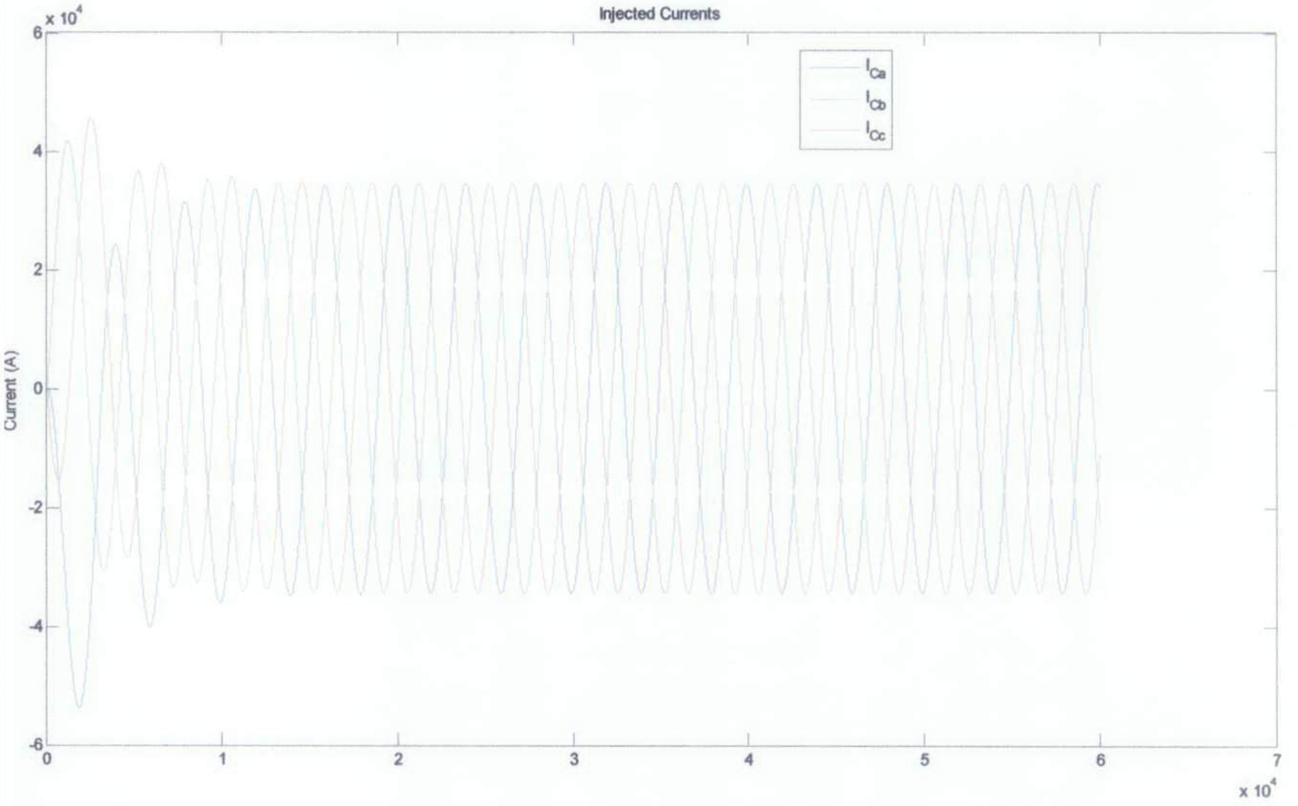

Figure 4.2.4: Injected Currents

Figure 4.2.5 shows the load currents of the system. These load currents can be obtained by the following equation:

$$i_{load} = i_{Source} - i_{injected}$$

The above equation satisfies the compensation principle that is shown in Appendix G. This gives a clearer impression that in a system with only desired parameters, the load will be supplied with only the desired power without any distortion.

Figure 4.2.5: Load Currents

4.3. Discussion

From the above results in section 4.1, it can be deduced that the StatCom connected to the system buses acted as both voltage source and sink. In the simulation results, the voltage at a concerned bus has increased in magnitude and the angle becoming smaller while on the other buses the voltage magnitude decrease and the angle still became smaller. The StatCom is generating reactive power into the system at most of the buses. The voltage magnitudes were regulated at reference voltage of 1.0 pu. Though there has not been any mention of current, we assume that it has been kept within the constant maximum and minimum limits.

Simulation at slack and generator buses was not taken into consideration in the above results. This due to the presumption that these buses will not have much of the reactive power to cause major disturbances as stability is assumed. Some of the obtained results might have deviated a bit from the expected values since the determination of parameters was based mostly on practical values that have been tried before. The other factor that might cause the deviation of the results is the number of iterations needed before the simulation can terminate. Using Newton-Raphson iteration method, this implies that if the maximum number of iterations can be reached before proper compensation, then it would be difficult to acquire proper results. The values used are in per unit and thus very small. This makes the values susceptible to random deviations since they might tend to diverge instead of converging. The power flow analysis is carried out with anticipation that the results will diverge. This can be corrected by adjusting some of the values to the system. Nonetheless, this does not affect a lot of buses in this particular system, which means the results obtained are desirable and can be trusted.

From the results in section 4.2, it is observed that there were distortions at the source currents. The currents of the same magnitude, phase shifted by 180°, were thus injected to compensate for the distortions. The load current waveform is shaped by the voltage source inverter used. This inverter estimates the flow of current and then supplies the required power to shape the load currents. This shaping is made possible by the DC capacitor connected to the inverter. Poor selection of this capacitor can hamper the compensation. The non-linear load, a three-phase diode bridge, is connected across a balanced three-phase system, thus the total harmonic distortion should be the same across a particular phase over the whole system.

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.1. Conclusion

As desired, the simulation of a StatCom in a power system proved to produce the results that prove its impact on the system. An IEEE 30-bus system used with practical parameters reacted swiftly to the compensation of StatCom. The results of the SAPF modelling show that the SAPF performed the current harmonic compensation well. There is no really high concern in compensating voltage harmonics since the power supplies have considerably low impedances. However, it is highly critical to ensure pure sinusoidal supply to the power system protection devices and other voltage sensitive devices. The reduction of current harmonics is critical to avoid device heating and shorter device lifespan, as well as for the designs of power system equipment. Root mean square values of load current include the sum of squares of individual harmonics, therefore proper current harmonic compensation can aid designers in approaching proper power rating of equipment.

5.2. Recommendations

The following recommendations are made for future work in the project, or any similar problems that may require harmonic compensation:

- Model a StatCom as SAPF. This can be done by modifying the StatCom parameters to suit those of SAPF.
- Develop an M-file for SAPF. This will require extensive use of MATLAB commands to satisfy the basic building blocks of SAPF. Similar M-file to that of StatCom can be implemented.
- Track the improvement of Power System Analysis Toolbox in MATLAB to perform power flow analysis using both StatCom and SAPF.
- Perform simulation with StatCom and SAPF connected to the system at the same time.
- Implement the power system optimisation techniques to a modelled system.
- Design and implementation of a predictive control scheme for SAPF.

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APPENDIX A: Project Gantt Chart

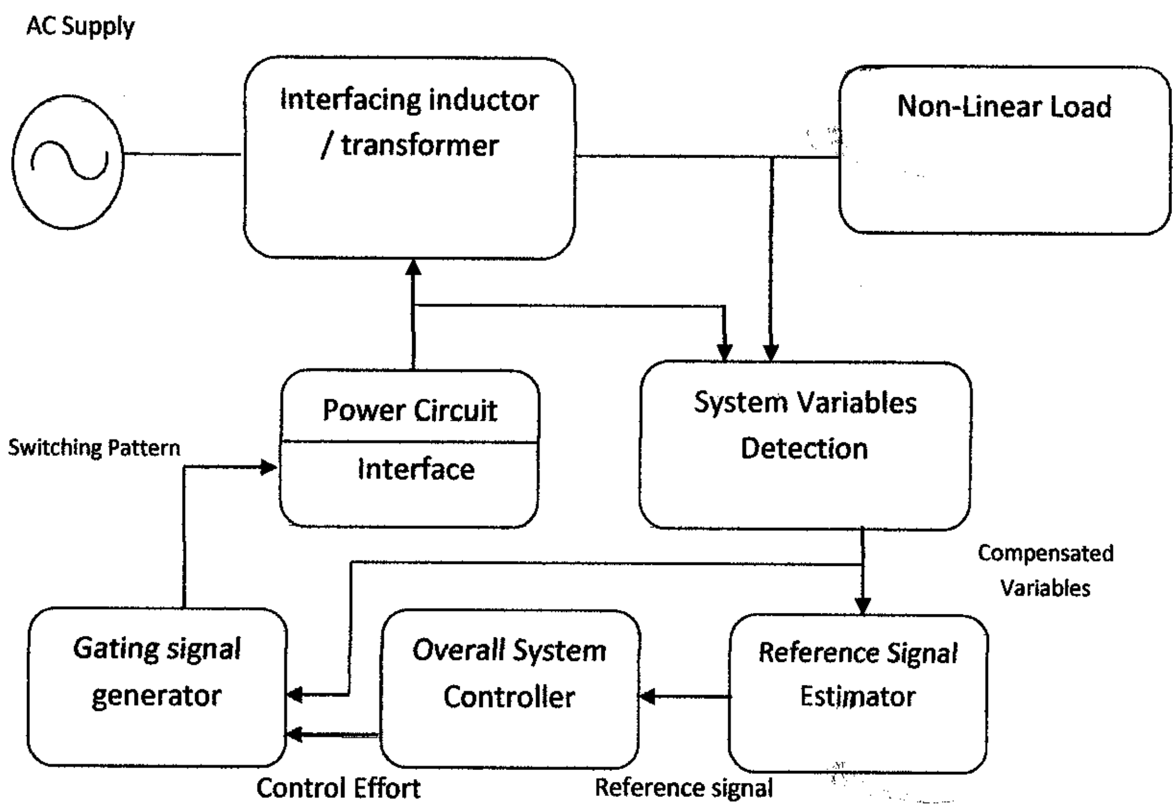
		WEEK																	
	TASK	1	2	3	4	5	6	7		8	9	10	11	12	13	14	15	EXACT DATE
1	SELECTION OF PROJECT TOPIC								MID-SEM BREAK									
2	PRELIMINARY RESEARCH WORK																	
3	SUBMISSION OF PRELIMINARY REPORT																	19/08/2010
4	PROJECT WORK																	
5	SUBMISSION OF PROGRESS REPCRT																	22/09/2010
6	SEMINAR																	
7	PROJECT WORK																	
8	SUBMISSION OF DRAFT REPORT																	18/10/2010
9	CORRECTIONS ON THE REPORT																	
10	SUBMISSION OF INTERIM REPORT																	02/11/2010
11	ORAL PRESENTATION																	08/11 - 10/11/2010

Figure A.1: FYP1 Gantt Chart

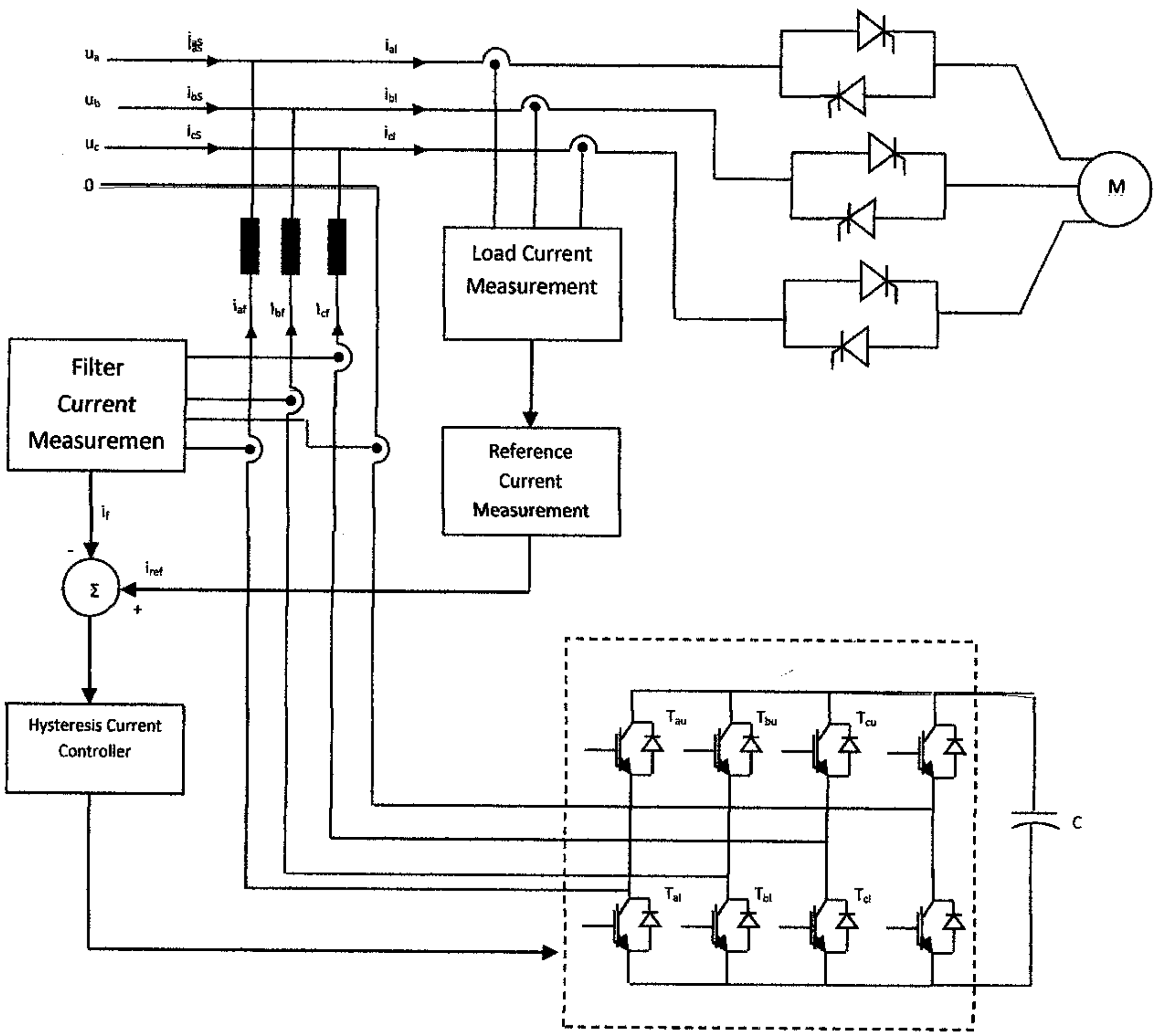
		WEEK																
	TASK	1	2	3	4	5	6	7	8	9	10	11	12	13	14			EXACT DATE
1	PROJECT WORK																	
2	SUBMISSION OF PROGRESS REPORT																	14/03/2011
3	PROJECT WORK																	
4	SUBMISSION OF DRAFT REPORT																	18/04/2011
5	SUBMISSION OF FINAL REPORT (SOFT COVER)																	28/04/2011
6	SUBMISSION OF TECHNICAL PAPER																	28/04/2011
7	VIVA																	03/05 - 04/05/2011
8	SUBMISSION OF FINAL REPORT (HARD COVER)																	20/05/2011

Figure A.2: FYP2 Gantt Chart

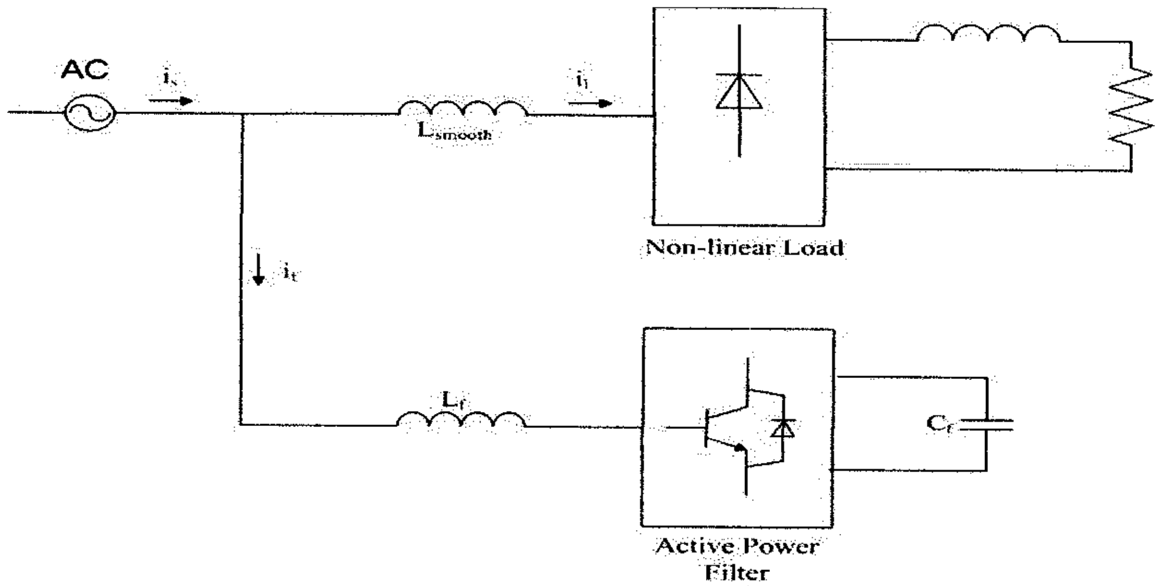
APPENDIX B: Generalized block diagram of APF [2]



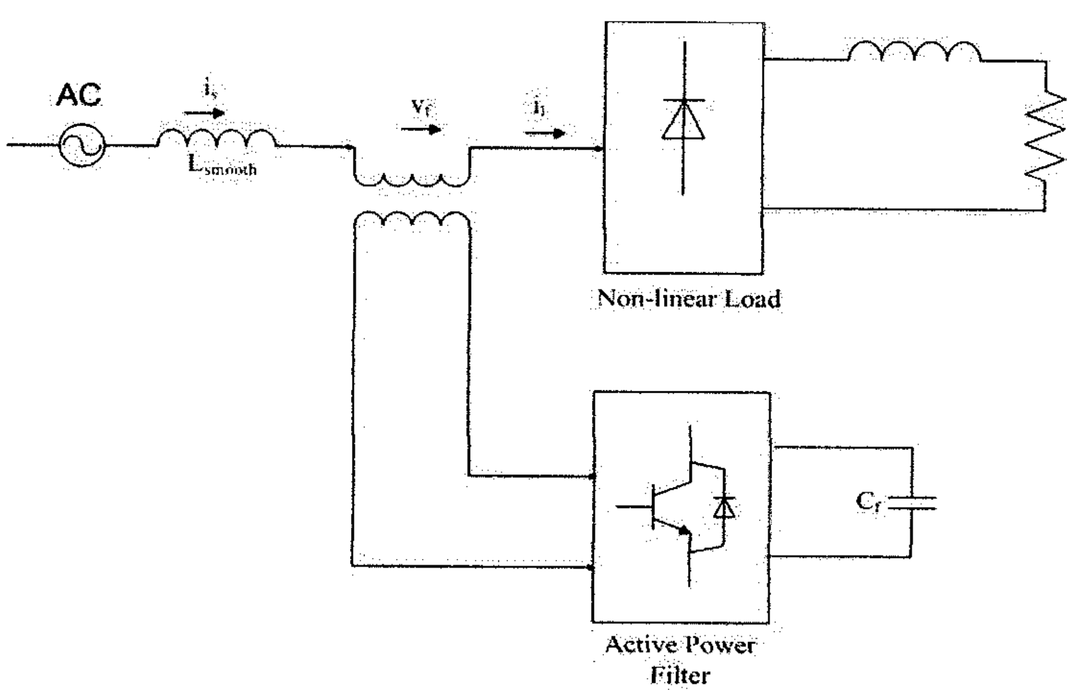
APPENDIX C: Block Diagram of SAPF [4]



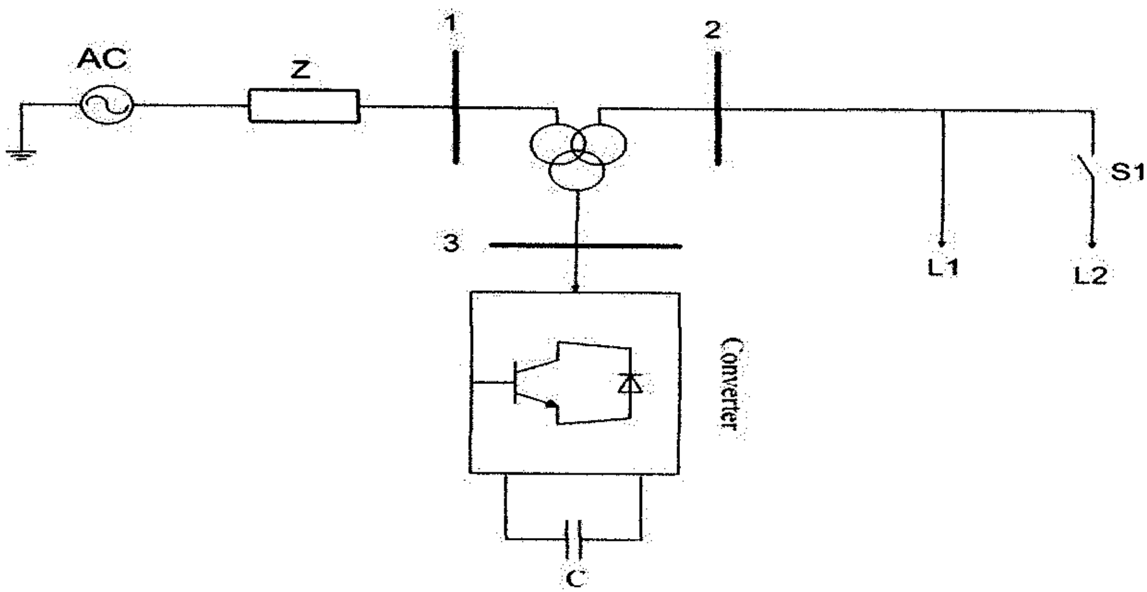
APPENDIX D: Configuration of the voltage source SAPF [8]



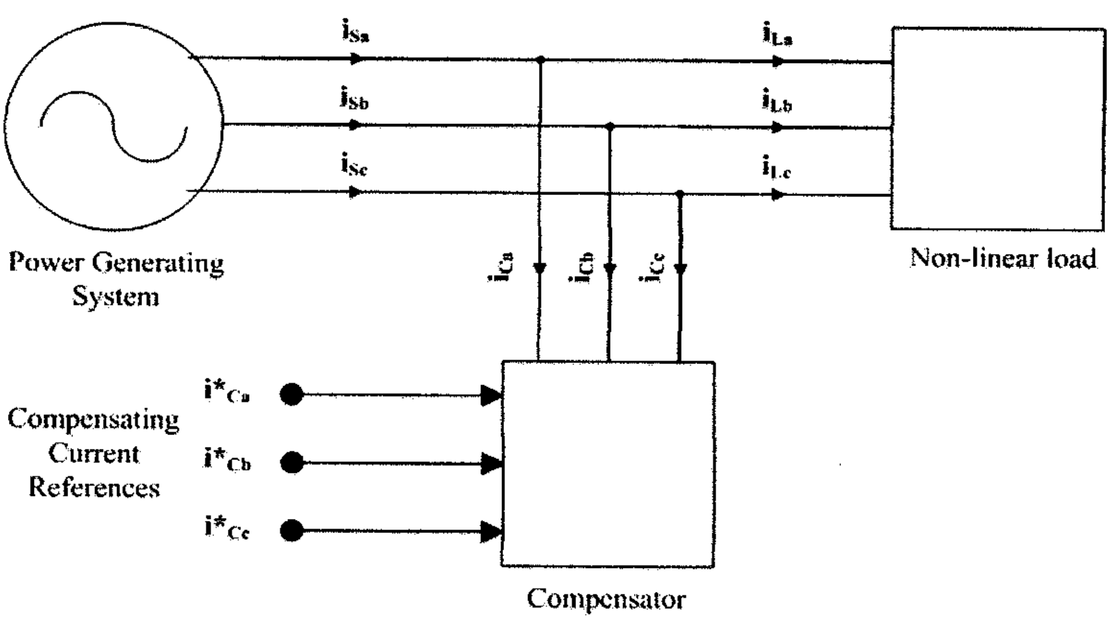
APPENDIX E: Configuration of the voltage source Series APF [2]



APPENDIX F: Single Line diagram of a test system for StatCom



APPENDIX G: Compensation Strategy of Instantaneous Power Theory [11]



APPENDIX H: SAPF Model in Low Voltage System, its results and system parameters

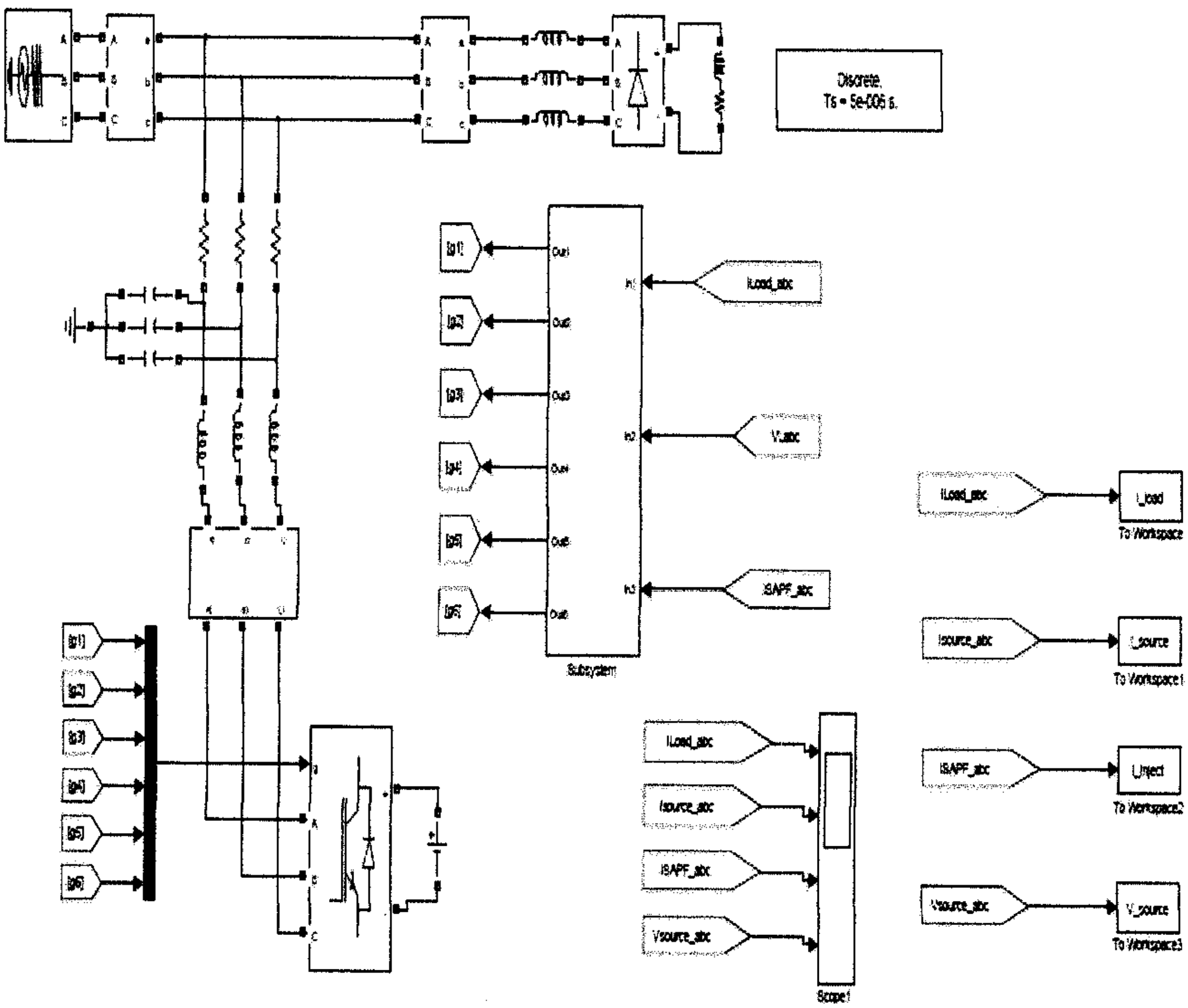


Figure H.1: SAPF model in LOW Voltage System

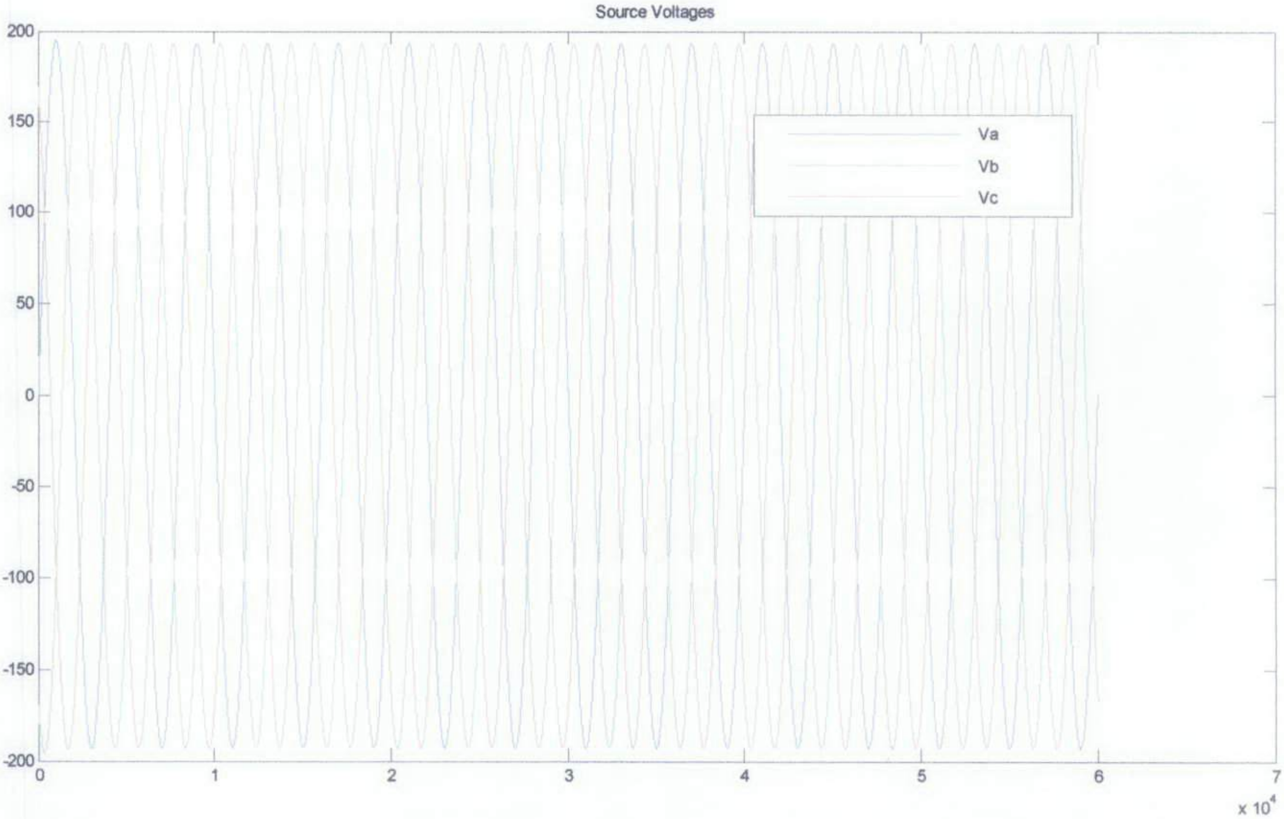


Figure H.2: Source Voltages

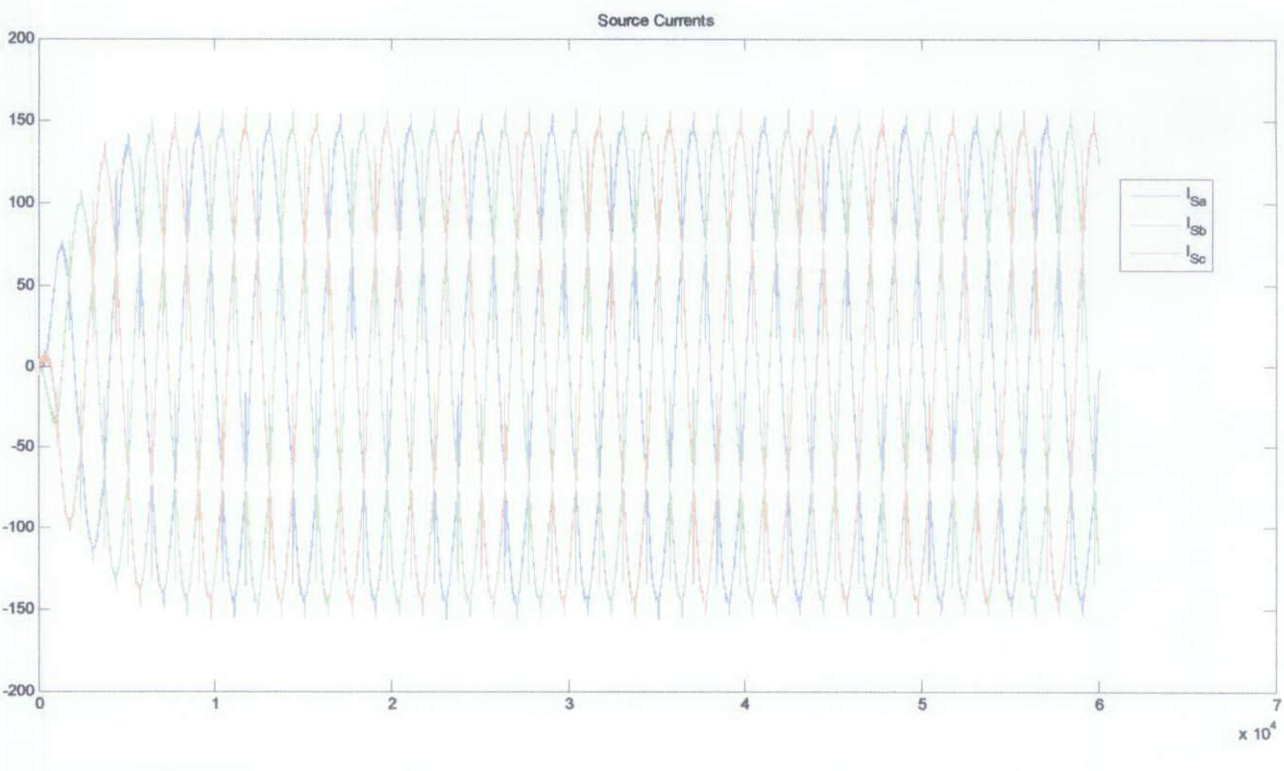


Figure H.3: Source Currents

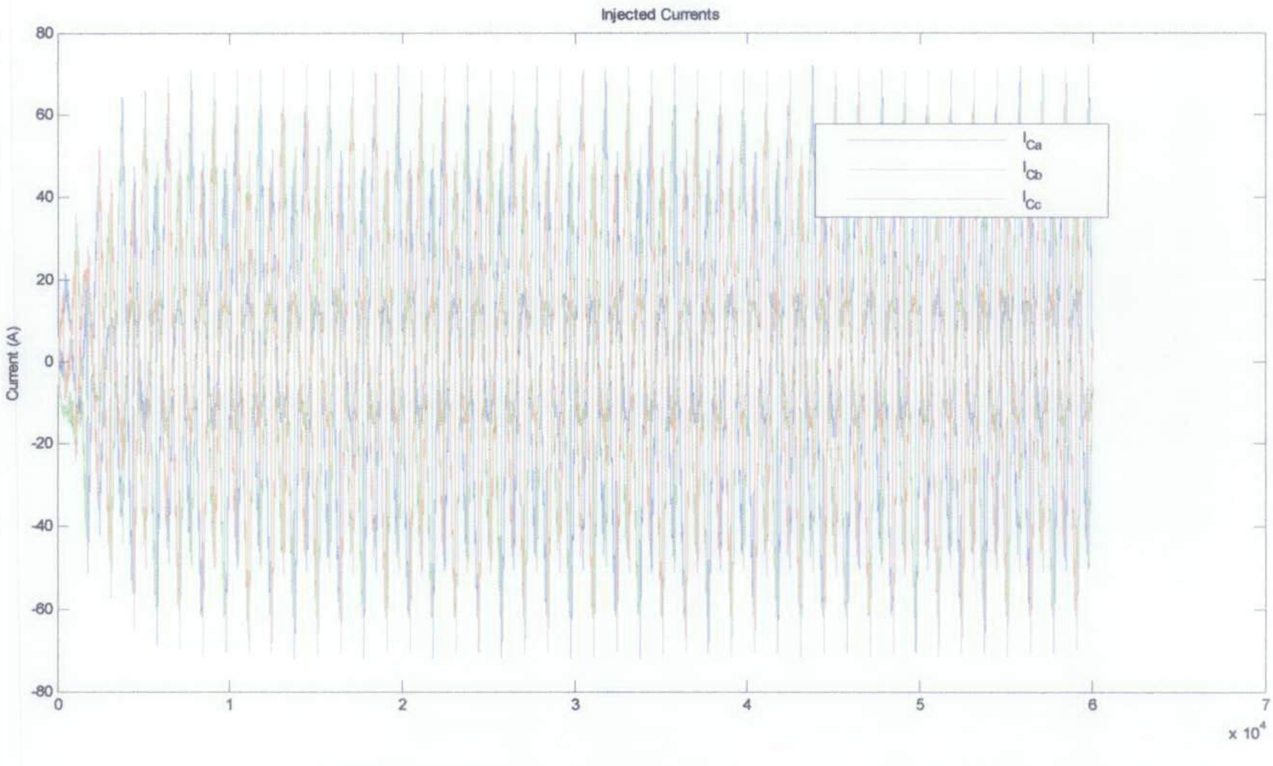


Figure H.4: Injected Currents

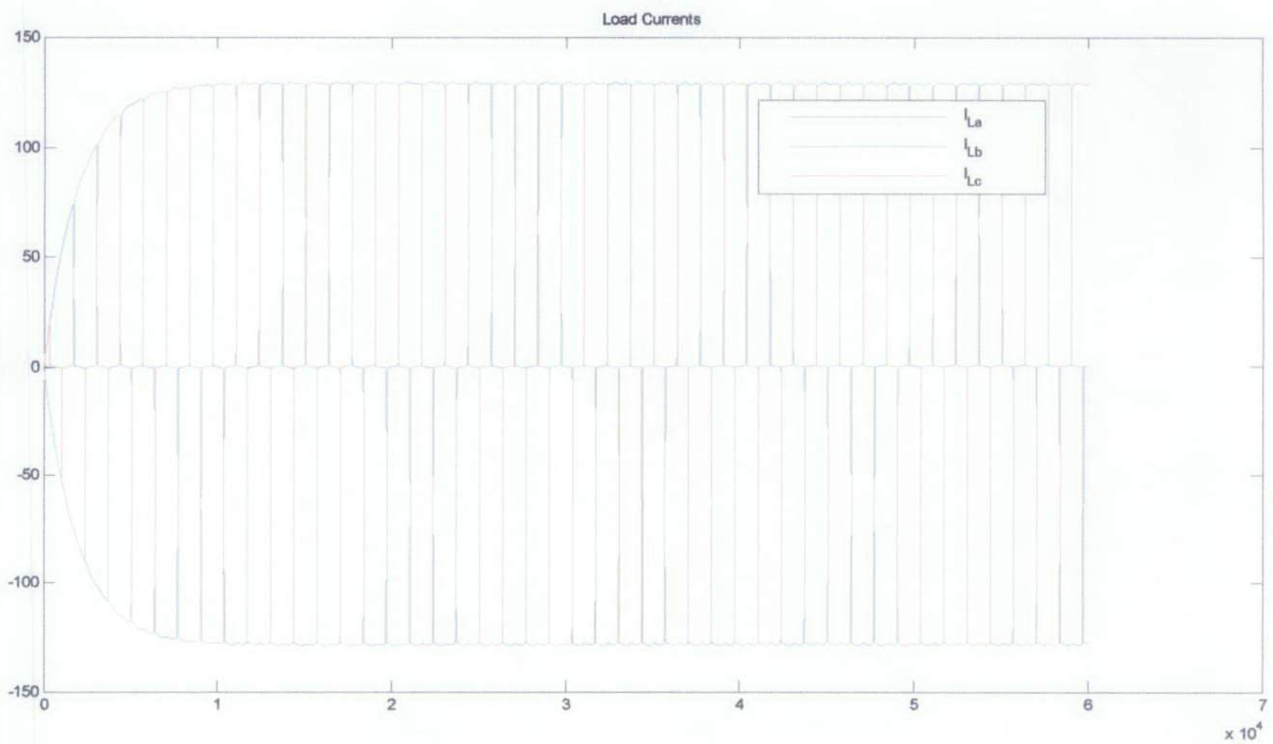


Figure H.5: Load Currents

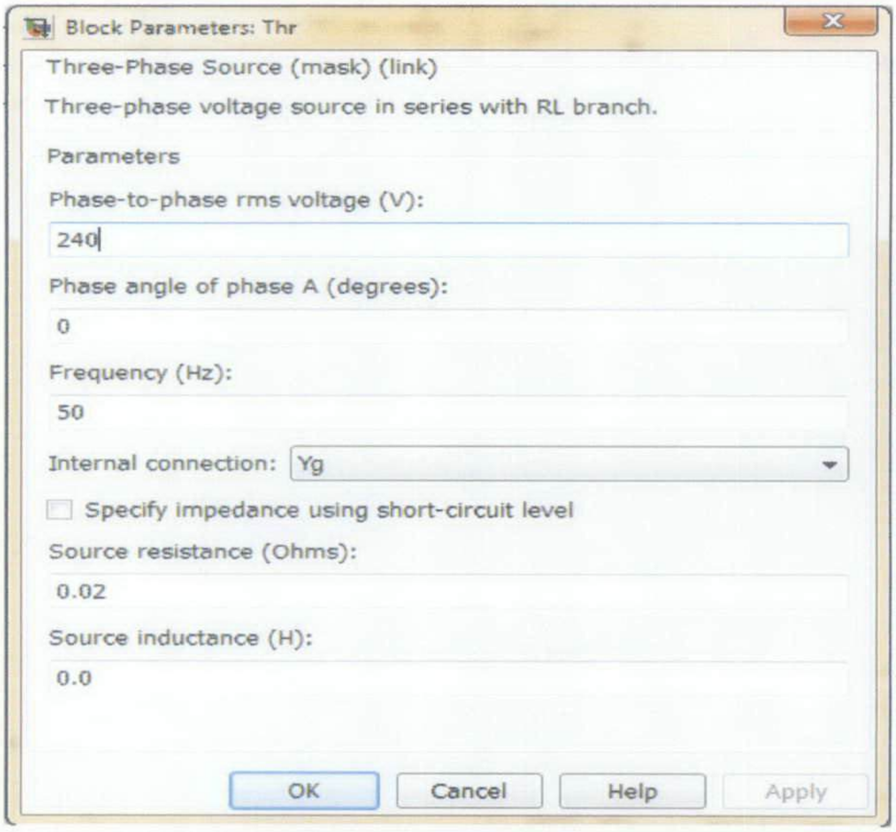


Figure H.6: Three-phase voltage source

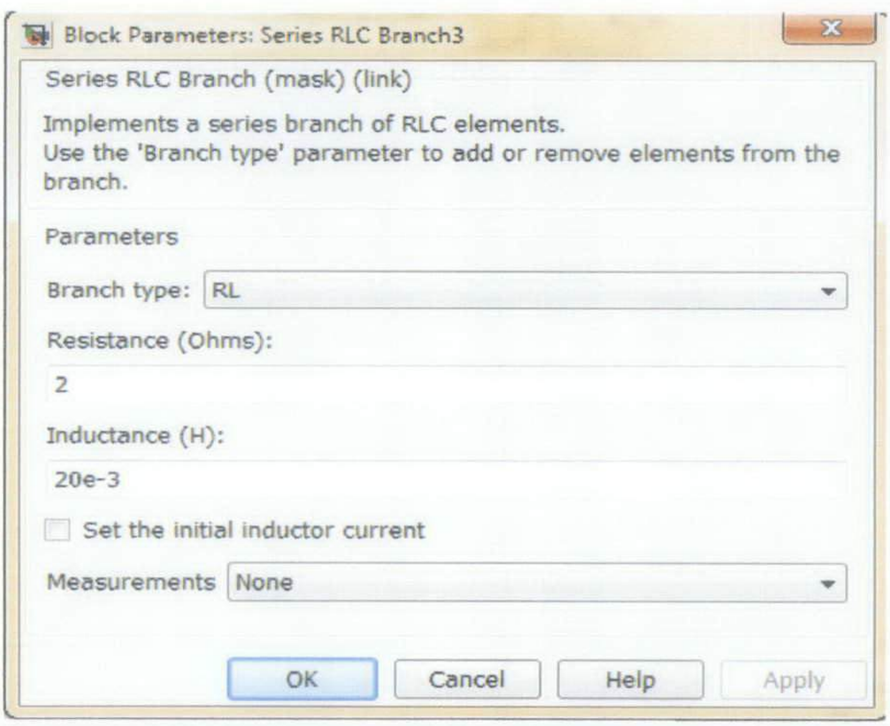


Figure H.7: RL branch of nonlinear load

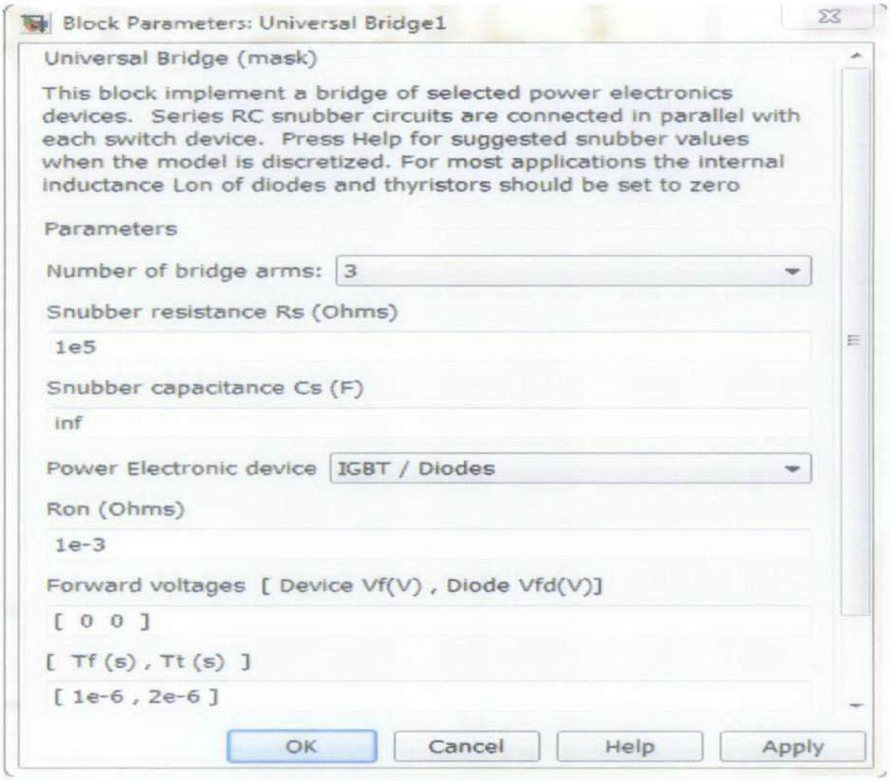


Figure H.8: Three-phase IGBT Bridge

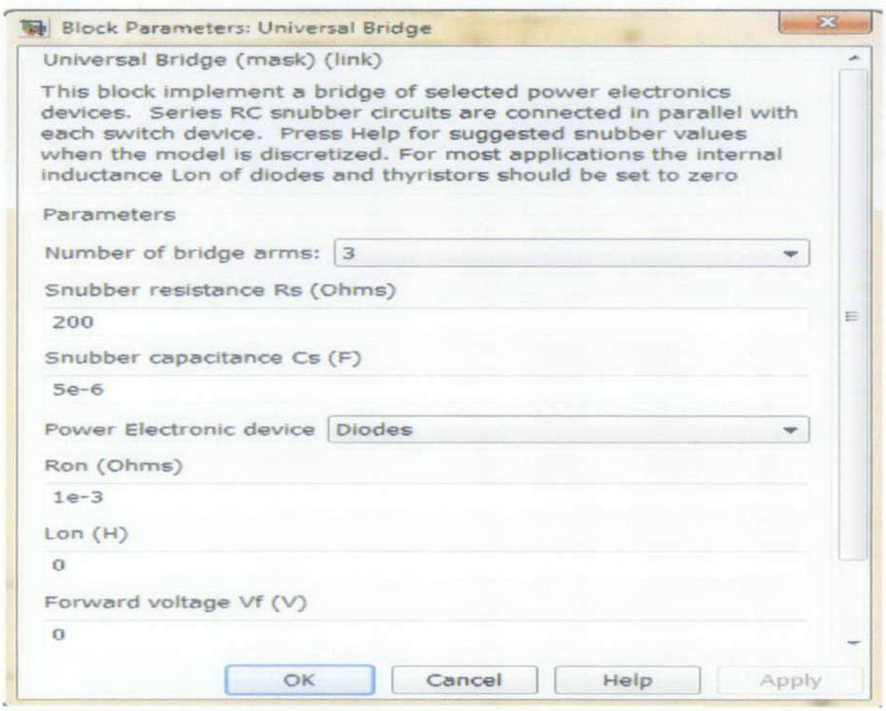


Figure H.9: Three-phase Diode Bridge

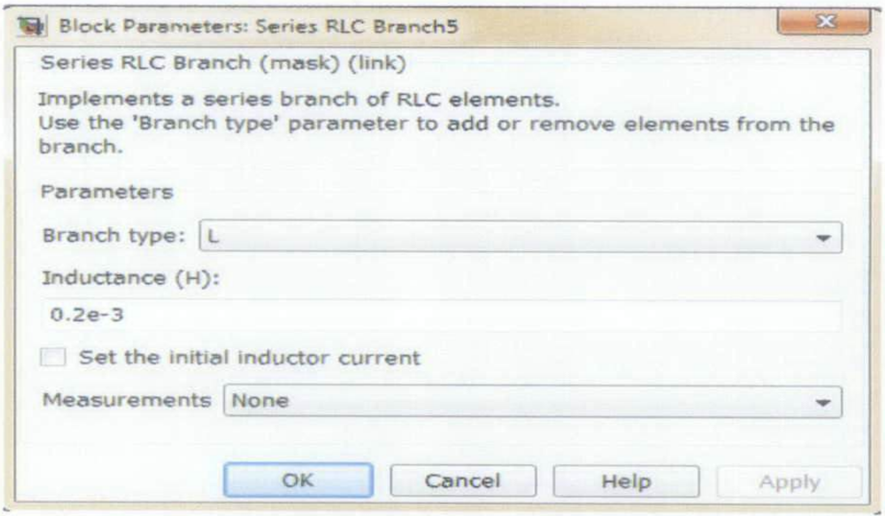


Figure H.10: SAPF Inductance

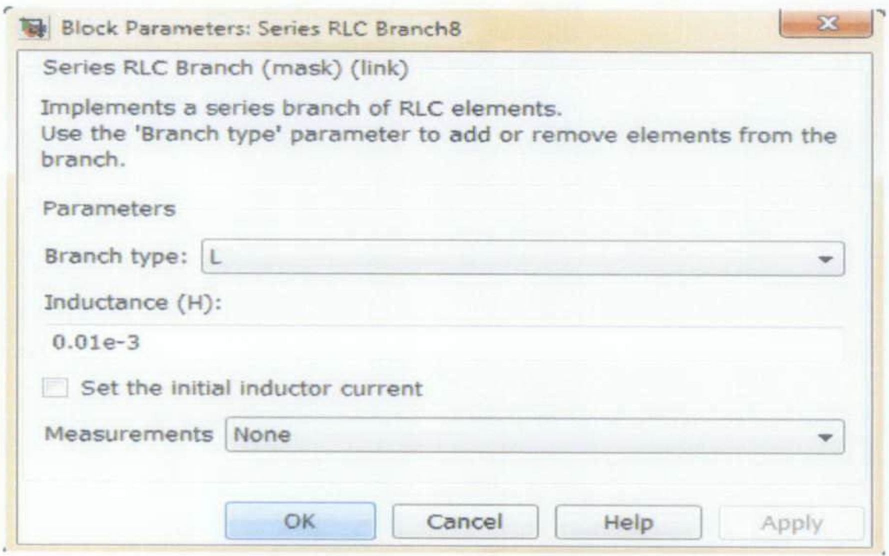


Figure H.11: Load Inductance

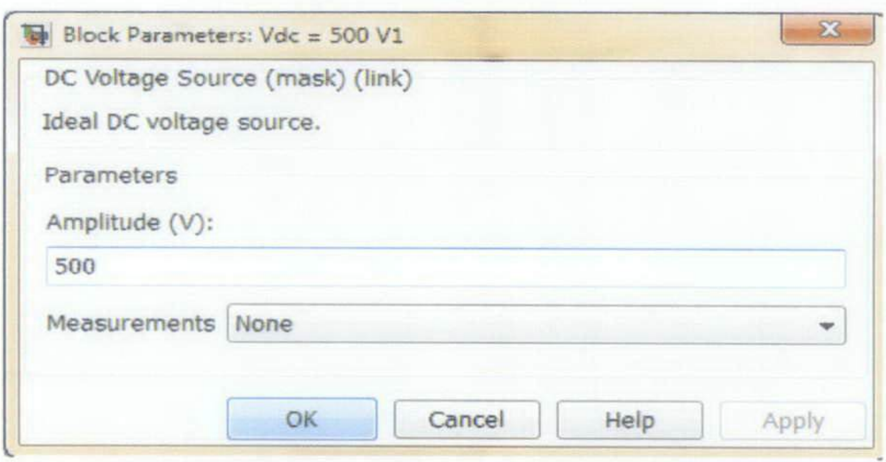


Figure H.12: VSC Capacitance

APPENDIX I: System Parameters of SAPF model in Medium Voltage System

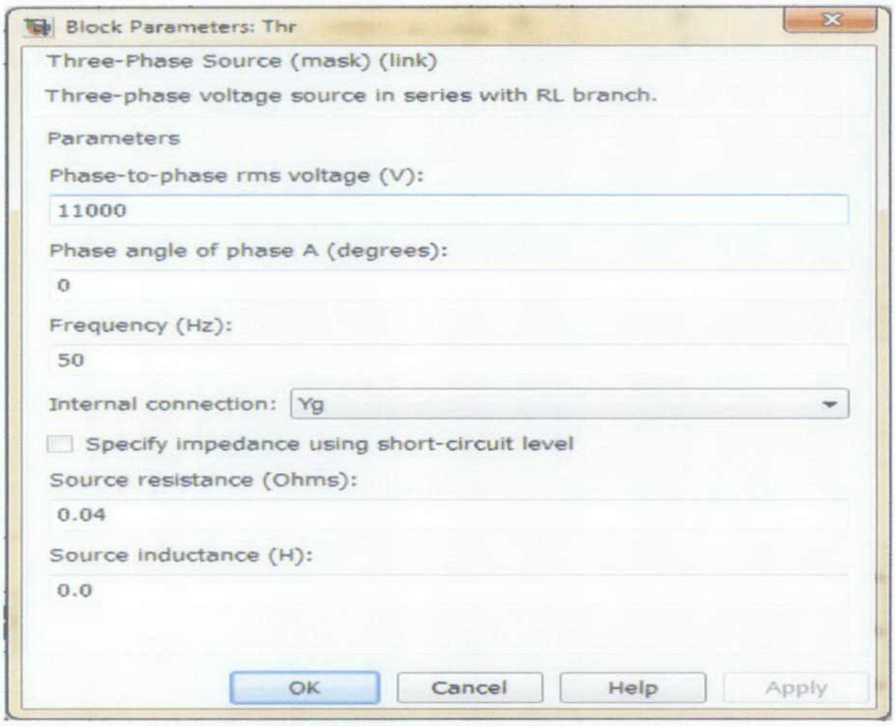


Figure I.1: Three-phase voltage source

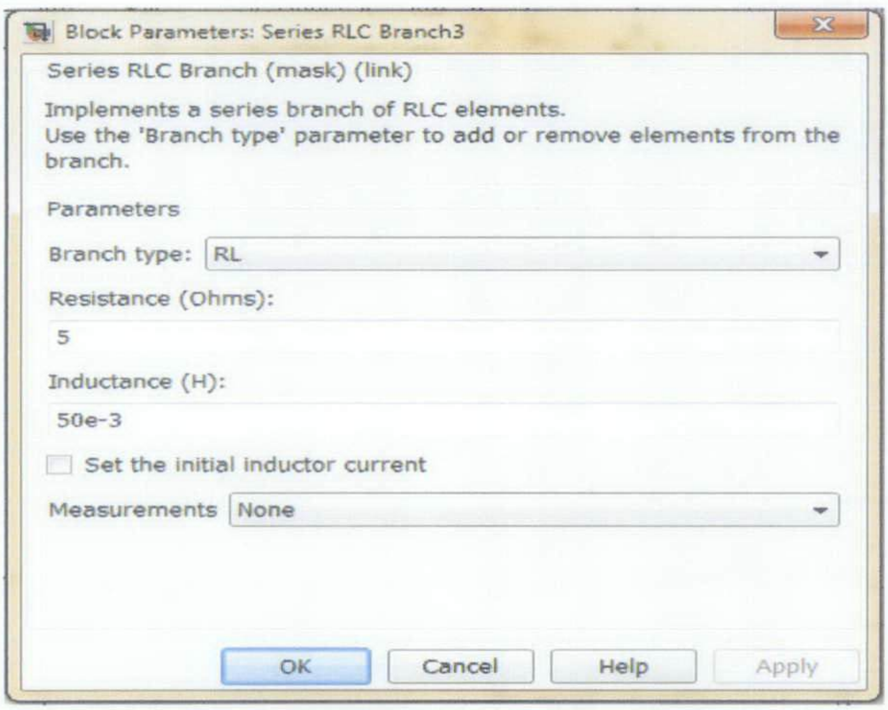


Figure I.2: RL branch of nonlinear load

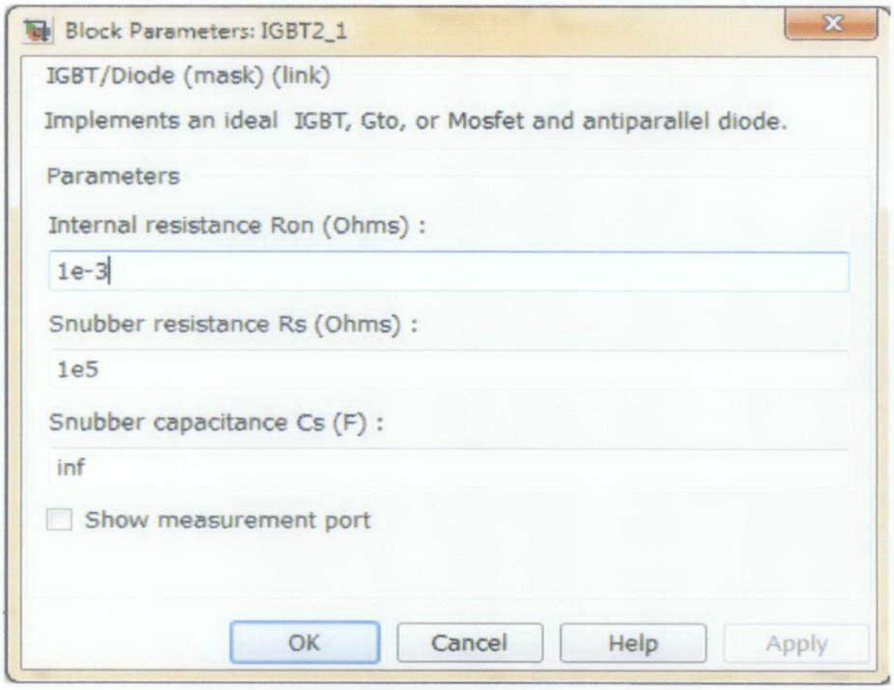


Figure I.3: Three-phase IGBT bridge

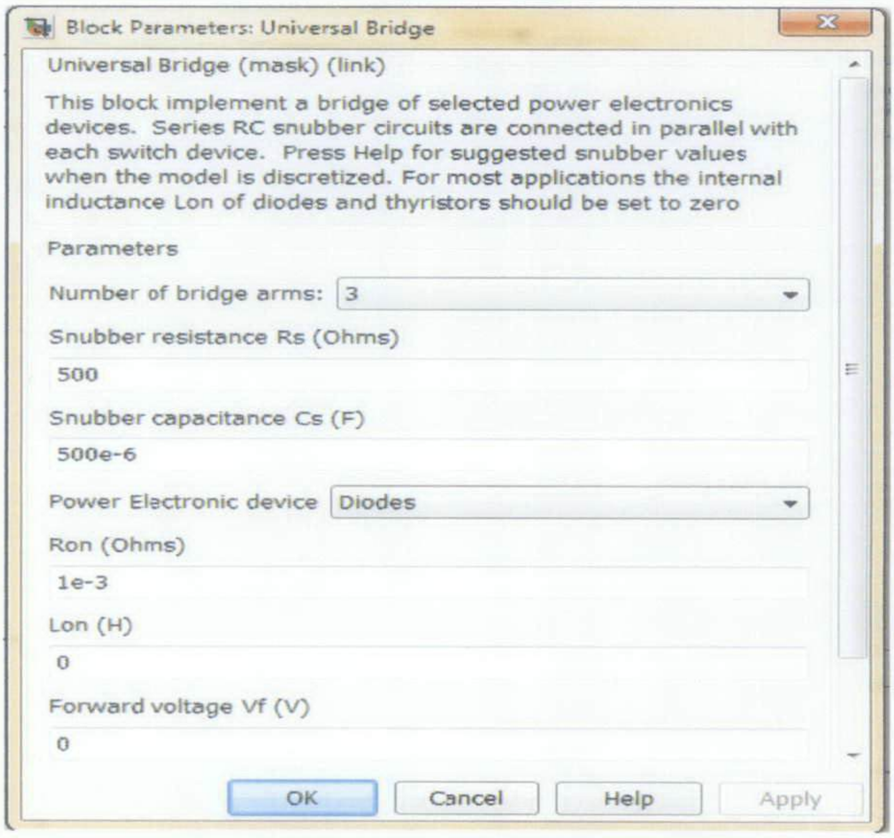


Figure I.4: Three-phase diode bridge of nonlinear load

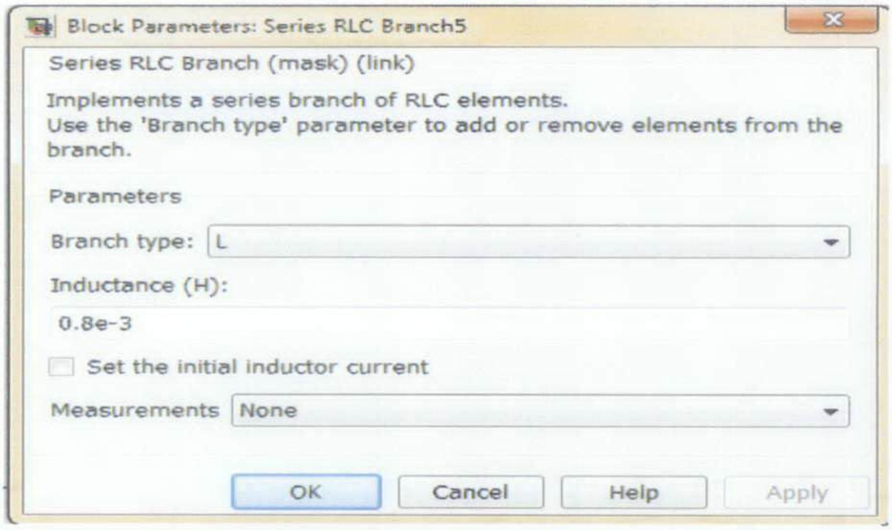


Figure I.5: SAPF inductance

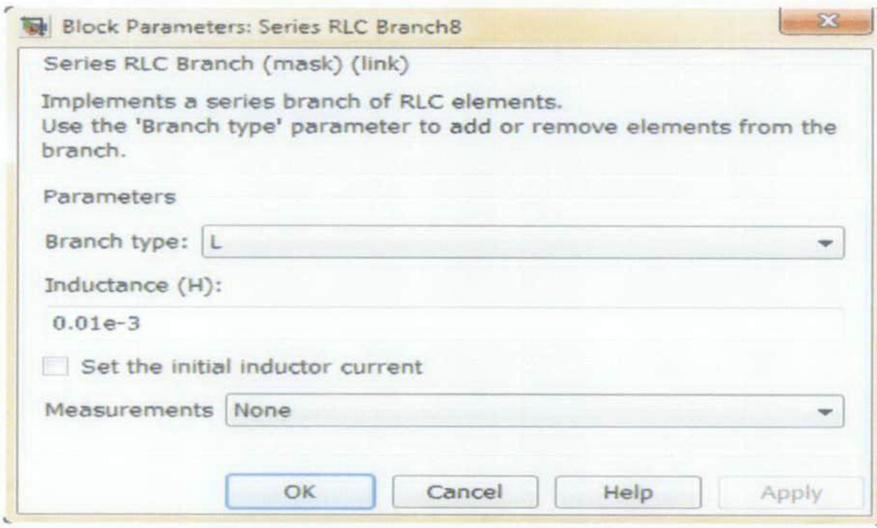


Figure I.6: Load inductance

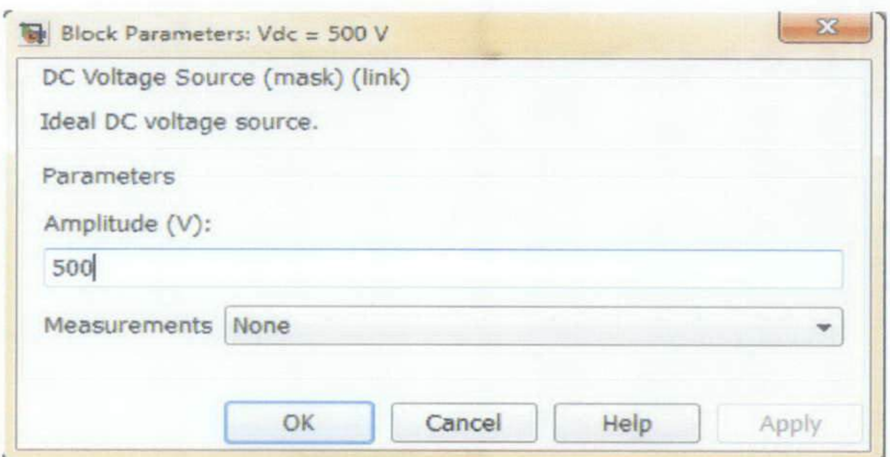


Figure I.7: VSC capacitance

APPENDIX J: M-file showing how StatCom is introduced to a power flow of a system

```
% connecting the STATCOM to bus

function statcom = stat_com()

%       |Bus||Vmag||Angle||Qmin||Qmax|

statcom = [ 15   1.000  0  -0.5   0.5

            16   1.000  0  -0.5   0.5

            18   1.000  0  -0.5   0.5 ];
```