Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Information Technology and Electrical Engineering
Department of Electric Power Engineering

Hanna Authen

Impact of Combining a STATCOM and an Active Filter on the Modular Multilevel Converter Controller

Master's thesis in Energy and Environmental Engineering
Supervisor: Kjetil Uhlen
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Summary

A STATCOM improves the voltage level in a transmission system. Improving the voltage level enhances the power quality, which in turn improves the security of supply. Installing a STATCOM has proved to be beneficial in different power systems all over the world. The STATCOM is believed to be even more favorable in the future, as more energy will be produced by unreliable renewable energy sources.

The active filter components and configuration are similar to the STATCOM. These similarities suggest that a STATCOM also can perform active filtering. However, the STATCOM controller must be altered to enable this feature. A device like this is referred to as a developed STATCOM.

This thesis presents a STATCOM MMC controller that combines reactive and harmonic compensation. The proposed controller combines the traditional control methods of the STATCOM and the active filter. Moreover, the controller has been altered and adapted so that both features are optimized. The proposed controller is named a combined controller. Compared to the traditional STATCOM controller, additional PI controllers must be included to obtain the harmonic compensation current. The combined controller is slower since the controller is more complex.

The combined controller is modeled in PSCAD. Simulations show promising results. The developed STATCOM is tested in both a simple and a more complex system. The results confirm that the developed STATCOM improves the voltage level while reducing the harmonic content. This is the case for all the simulated cases and different system configurations. This suggests that the controller is working.

Sammendrag

Spenningen i et transmisjonsnett kan forbedres ved å installere en STATCOM. Ved å forbedre spenningsnivået øker effektkvaliteten og forsyningssikkerheten blir bedret. Å installere en STATCOM har vist seg å være fordelaktig ved flere tilfeller rundt om i hele verden. I fremtiden vil STATCOMen kunne være avgjørende for å håndrere den varierende produksjonen av fornybar energi som vind og solkraft.

En STATCOM og det avtive filteret består av like komponenter. Derfor er det rimelig å anta at en STATCOM også kan utføre aktive filtrering. Regulatoren må tilpasses for å

kunne muliggjøre dette. En slik innretning er omtalt som en videreutviklet STATCOM.

Masteroppgaven presenterer en MMC regulator som kombinerer den tradisjonelle kontrollen av en STATCOM og et aktivt filter. Videre må regulatoren tilpasses slik at den både utfører reaktiv og harmonisk kompensasjon optimalt. Regulatoren er kalt "a combined controller". Sammenlignet med en tradisjonell STATCOM regulator er flere PI regulatorer brukt for å oppnå aktiv filtrering. Den foreslåtte regulatoren reagerer derfor saktere.

Regulatoren er modellert i PSCAD. Simuleringer av regulatoren viser lovende resultater. Et enkelt og mer komplekst system er brukt for å teste den videreutviklede STATCOMen. Resultatene bekrefter at den videreutviklede STATCOMen forbedrer spenningen samtidig som harmoniske strømmer er nøytralisert. Dette er tilfeller for samtlige simuleringer. STATCOMen fobedrer alle målte spenning og strøm parametre. Dette viser at regulatoren fungerer.

Preface

The thesis is submitted for the degree of Master of Technology. It concludes a five-year study of energy and environmental engineering. The topic of the master thesis is in line with my interests and field of specialization; electrical power systems.

Before starting on the master thesis, I had serveral expectations. I expected to both make use of previously acquired knowledge and learn more. The topic of this master thesis was not given much attention and was only briefly introduced throughout the study. Thus, I anticipated spending much time reading unknown material. Writing the thesis was believed to be a rite of passage - many of these expectations where met.

The extensive literature study facilitated the simulations. Still, implementing the model in PSCAD was time-consuming. The model and simulation compose a significant part of this thesis. I reached some dead ends and overcame multiple obstacles throughout the process. The PSCAD support team has been supportive and helpful along the way. I wish to thank them for all the helpful advice.

Moreover, I would like to thank my supervisor, Kjetil Uhlen, for useful input throughout this process. The project description is provided by Statnett and their contact Jarle Eek. Jarle has provided guidance and pushed the process forward. Both have helped broaden my point of view. My fellow students have provided moral support throughout this period. This especially applies to my fellow students at F313. We have shared ups and downs the last five mounts. Thank you all.

I hereby declare that the content of this thesis is original. However, parts of it have previously been submitted as a specialization project in the course TET4520 at NTNU. The TET4520 course description states ”The specialisation project typically forms the basis for the Master’s project”. This is true for my thesis. Which parts that are reused are stated in the introduction.

Hanna Authen Trondheim, June 2019

Table of Contents

List of Tables

List of Figures

Abbreviations

AC	Alternating Current
AF	Active Filter
CSC	Current Source Converter
DC	Direct Current
DSO	Distribution System Operator
FACTS	Flexible Alternating Current Transmission System
IGBT	Insulated Gate Bipolar Transistor
ICC	Inner Current Control
KCL	Kirchhoff's Current Law
KVL	Kirchhoff's Voltage Law
LPF	Low Pass Filter
MMC	Modular Multilevel Converter
PCC	Point of Common Coupling
PI	Proportional Integrator
PLL	Phase-Locked Loop
PSCAD	Power System Computer- Aided Design
PSC	Phase Shift Carrier
PWM	Pulse Width Modulation
STATCOM	Static Synchronous Compensator

SVC Static Var Compensator

TDD Total Demand Distortion

THD Total Harmonic Distortion

TSO Transmission System Operator

VSC Voltage Source Converter

Project Description

"Harmonic distortion is an increasing concern for secure and reliable operation of the power system due to implementation of more power electronics. Harmonic sources may interact with the grid dependent on the grid operating state. The STATCOM may have the ability to provide active filtering of harmonics compared to the traditional SVC. The STATCOMs may change the active filtering based on operational state of the grid to which its connects, which would be a benefit compared to the passive filtering where the filter resonance is fixed. The master's thesis should explore how this active filtering can be implemented and how it will influence the overall design and control of the STATCOM."

Chapter 1

Introduction

1.1 Background

The power system can be viewed as one of the critical infrastructures of modern society. Everyone from large industrial clients to individual members of the public is relying on and is often highly dependent on a functioning power grid.

The evolutionary development of the power system has lasted more than a century. Nevertheless, there are changes on the horizon. The power production and consumption habits are changing rapidly due to changes in power access and demand. The increased awareness and effects of climate change have and will become a greater concern. A desire to operate more sustainably may motivate radical business decisions, which in turn affect the power system.

It is the transmission and distribution system operator's (TSO's and DSO's) responsibility to operate and maintain the grid to meet the ever-changing demand. The operators must also plan and build for the future power consumption. Investing in further development and research is crucial to take on current and future challenges. The stately owned enterprise Statnett is the TSO of Norway. This implies that Statnett is responsible for all of the mentioned concerns when it comes to the Norwegian transmission system. Also, Statnett must fulfill the requirement - security of supply. This requirement covers, not only the total power demand but also the power quality. Today, Statnett provides high security of supply. However, this may be challenged as power production and consumer habits will change.

Security of supply means the ability of the power system to provide end users with an uninterrupted supply of electricity and a specified quality of supply, and includes energy *security, adequacy and operational security.*

- A quotation from Energy Facts Norway [1]

The security of supply can be improved by installing a static synchronous compensator (STATCOM). A STATCOM is a flexible AC transmission system (FACTS) device. The primary task of a shunt connected STATCOM is to regulate the transmission system's voltage level at the point of common coupling (PCC). The voltage level and the quality are enhanced by means of reactive power. The enhanced voltage quality improves the power quality, which in turn enhances the security of supply.

Installing a STATCOM is an alternative measure compared with the more traditional compensation device, the static VAr compensator (SVC). Both devices can be installed to regulate the voltage level and improve the power quality. The SVC utilizes traditional mechanical switches and thyristors to offer reactive compensation. While the transistor based voltage source converter (VSC) is the key element of the STATCOM, enabling continuous reactive compensation. The VSC of the STATCOM enables better characteristics compared with the SVC. One of the main advantages of the STATCOM is that it produces less harmonic currents. Harmonic currents pollute the power and bring the power quality down. Furthermore, the STATCOM configuration allows for it to be operated as an active filter (AF). A shunt connected AF filters out undesirable harmonic currents in the grid, reducing the overall harmonic content and its dissipation. By recreating and injecting the harmonic currents, only phase shifted, the AF cancel harmonic currents. AFs are an alternative to traditional passive filters.

The STATCOM has been an object of research for some time. The latest STATCOMs utilize the relativly new modular multilevel converter (MMC). The MMC has gained much attention, which has accelerated the development of the STATCOM. The MMC enables the combination of a STATCOM and an AF. The device combining the traditional STATCOM and AF is henceforth referred to as a developed STATCOM. The leading manufacturers of STATCOMs, such as Siemens AG and ABB, have explored this opportunity to some extent. However, limited research and simulations of the developed STATCOM are published.

1.2 Project Outline and Limitations of Scope

The master thesis is written in collaborating with Statnett. Statnett has provided the project outline. As already presented, the harmonic content is an increasing concern. As the TSO in Norway, Statnett is obliged to reduce harmonics as well as maintain the desired voltage levels within the transmission system. A developed STATCOM aims to do just this.

The overall aim of the thesis was to acquire in-depth knowledge and conduct simulation of the STATCOM with active filtering. However, limitations of the scope were necessary due to the thesis's time frame. The chosen focus area of the thesis is the VSC controller. The thesis discusses how the traditional STATCOM's VSC controller must be altered to enable active filtering. Such a controller is proposed and simulated.

The STATCOM has only in recent times become a commercial device. However, much research has been published on both the STATCOM and the AF. Some have also proposed a STATCOM with active filtering. Nevertheless, few have investigated the developed STATCOM's VSC controller performance. By focusing on the VSC controller and simulation of it, I hope to make a contribution.

First, the STATCOM is presented. This is necessary in order to explore the possibility of adding active filtering. Harmonic pollution is reviewed and the most common measures are discussed. This leads to the developed STATCOM. A combined controller is proposed to obtain the desired functioning. To support the presented theory and review the controller performance, the developed STATCOM and its controller are simulated in PSCAD.

A chapter-wise overview of the report is shown below.

- Chapter 2 and 3 introduce the STATCOM and filters. The technologies are reviewed and examples are presented.
- Chapter 4 and 5 focus on the VSC. The MMC is presented. A combined controller suited for the developed STATCOM is proposed.
- Chapter 6 covers the PSCAD model and description.
- Chapter 7 and 8 reviews and discusses the results. These chapter poses an important part of the paper. The results are used to verify the presented theory and the controller performance is evaluated. Simulation findings are used to support the installment of the developed STATCOM.

1.2.1 Relation to the Specialization Project

The master thesis is based on a specialization project. The specialization project was submitted by the author (Hanna Authen) as the final assessment in the course TET4520 in December 2018. It was not published, but graded. The research topic of the specialization project was chosen to complement the master thesis.

The objective of the specialization project was to give a state of the art description of the STATCOM. A literature study was conducted. Much of the findings are just as relevant and valid for the master thesis. Chapter 2, 4 and partly Chapter 5 present much of the findings. These sections cover the traditional STATCOM and the VSC technology. Parts of the text is rewritten and altered to fit with the master thesis project outline.

1.3 Simulation

The simulation and discussion of the results comprise a significant part of this thesis. PSCAD is used to simulated the behavior and performance of the developed STATCOM and its controller. A STATCOM model was provided on request by PSCAD. Values, model elements and so forth which are referred to as ”original” are set or implemented by the PSCAD team, not the author. However, extensive alterations are made in order to enable active filtering. Changes implemented by the author are referred to as alterations. PSCAD has also provided a model of the IEEE39 power system - ”The New England Power System”. Changes are made to simplify the system and keep the number of nodes within the given node limitation. The alterations will be listed. This is mentioned here and later to underline that the developed STATCOM model is a result of work conducted not only by the author.

Chapter 2

STATCOM

Installing a STATCOM is presented as a measure to improve the power quality and the voltage level of a power system. The STATCOM provides balancing of reactive power. Fundamental electric power correlations explains the basic principle of the STATCOM. However, the STATCOM has only become a commercial device in fairly recent times. The latest development of the device is a result of the inceasing use of power electronics. This chapter presents the STATCOM and covers its fundamentals. Firstly, some background information and fundamental electrical power concepts are reviewed to facilitate the STATCOM description section. To obtain insight into the STATCOM functioning, the working principle and examples are described.

2.1 Background

2.1.1 Power Quality and Voltage Stability

The power demand in a power system must be covered at all times. The production must, therefore, cover both the power demand and losses throughout the transmission and distribution system. Furthermore, there are also strict constraints on power quality. The power must fulfill the given requirements. An especially important power quality parameter is the voltage level. The voltage level is constantly prone to minor voltage deviations or more significant voltage depressions. An accepted voltage deviation is defined as $\Delta V > 0.1$ pu [2]. One measure to improve the power quality, or keep the quality within the given limits, is to install a FACTS compensation device. Compensation devices improve the power quality of a system and increase the capacity by improving the current or voltage quality. A shunt connected compensation device improves the voltage quality.

IEEE/CIGRE defines voltage stability ”as the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition. It depends on the ability to maintain/restore equilibrium between load demand and load supply from the power system" [3].

Too large voltage deviations are undesirable as they cause short term voltage instability or long term voltage depression. The time frame of short voltage instabilities varies from seconds to tens of minutes [3]. Both short and long term voltage deviations can cause sustained interruptions. The system will suffer a voltage collapse if it is not able to obtain a voltage level in compliance with the given limits within an acceptable time frame. During a voltage collapse, components and equipment can be broken beyond repair. Such events must, therefore, be avoided to guarantee security of supply.

During steady state, there can be sufficient time to react and prevent a sustained interruption. During contingency cases, the drop of voltage can be sudden and no adequate action can be taken immediately after the fault [4]. Typical reasons for a voltage collapse can be [5] [3]:

- Reactive power imbalance
- A sudden short circuit fault in a line
- Overloading
- Too high penetration of asynchronous generators
- Exceeded field or armature current time-overload capacity limits

The most common cause of a voltage collapse is a voltage drop. Another more rare case is whenever the voltage increases beyond the accepted limits.

Voltage stability problems have received more attention from researches and system operators in recent times [6]. As the power system has been developed, it has become more and more complex. Many dynamic variables must be accounted for. Examples of this are maximum possible production, demand, scheduled maintenance, energy storage and weather, which all affect the voltage of a system. At the same time, the consumers are more than ever dependent on sufficient power supply. These tendencies will be just as profound in the future. Severe faults in such a system will induce huge repercussions and costs. These concerns, as well as major blackouts in the past, have in the latest years increased the investment in voltage stability research and the installation of FACTS devices.

Install a synchronous condenser or an SVC has been the traditional measure to improve the reactive power balance of a grid. The STATCOM has been introduced as an alternative due to the rapidly increasing performance of power electronics. A STATCOM does cost more, but it has many favorable features. The advantages of the STATCOM makes it superior, especially during low voltages [7].

2.1.2 Power Flow Equations

The power flow equation is reviewed to provide some insight into the coupling of voltage and power. The apparent power can be expressed as

$$\mathbf{S}_R = P_R + jQ_R = \frac{V_S V_R cos(\delta_{SR} - \theta)}{Z} - \frac{V_R^2 cos(-\theta)}{Z} + j(\frac{V_S V_R sin(\delta SR - \theta)}{Z} - \frac{V_R^2 sin(-\theta)}{Z}) \tag{2.1}$$

The power flows between a sending (S) and a receiving (R) end. The full derivation is added to Appendix A.1.

The following assumptions simplify the power flow equation:

- δ close to 0, so that $\sin\delta \approx \delta$ and $\cos\delta \approx 1$
- $R_{Line} << X_{Line}$, so that $Z_{Line} \approx X_{Line}$ and $\theta \approx 90$ degrees
- The shunt conductance of the line is neglected

Thus, the apparent power can be expressed as

$$\mathbf{S}_R = P + jQ \approx \frac{V_S V_R \delta_{SR}}{X} + j\frac{V_R(V_S - V_R)}{X} \tag{2.2}$$

Equation 2.2 shows the coupling of the voltage and reactive power. To fulfill the steady state condition, the voltage at the receiving end must be more than half of the sending end [8]. If so, the received reactive power decreases as the voltage at the receiving end increases, assuming a constant sending end voltage. For a decreasing receiving end voltage, the received reactive power increases.

The power flow equation and the assumptions are in line with the theory presented by the book ”Power System Dynamics Stability and Control” [8].

2.2 Operation

A shunt connected STATCOM stabilizes the voltage, which in turn enhances the power quality. As the name suggests, reactive power compensates voltage changes. The voltage and reactive power are closely coupled, as shown in Equation 2.2. By either acting as a source or sink of reactive power, the STATCOM counteracts the continuous variations of voltage or more significant voltage deviations, such as voltage depressions.

The STATCOM offers two modes of operation; voltage regulation and VAR control. In line with the project outline, the master thesis only discusses the voltage regulation mode. In this mode, the system voltage can be controlled by regulating the received end reactive power. The STATCOM produces or consumes reactive power, whichever is desirable, to match the desired voltage level.

The voltage level at the STATCOM terminals, V_C, is controlled by a VSC. The reactive power flows in the direction of decreasing voltage magnitude. How much is dependent on the V_C magnitude. Figure 6.7 shows the simplified equivalent circuit of the STATCOM.

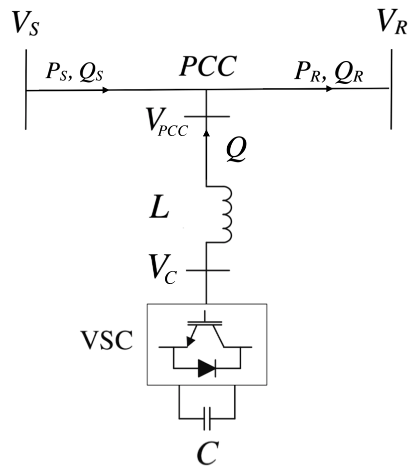


Figure 2.1: Shunt connected STATCOM

The STATCOM produces reactive power whenever the receiving end voltage is lower than the nominal value. To produce reative power, the converter voltage is set to be larger than the PCC voltage, $V_C > V_{PCC}$. The reactive power improves the reactive power balance and enhances voltage stability. Moreover, the STATCOM consumes reactive power whenever the receiving end voltage exceeds the nominal value. During such times, the converter voltage is set to be lower than the PCC voltage, $V_C < V_{PCC}$. Chapter 4 and 5 are dedicated to the VSC technology and control.

Figure 2.2 illustrates the mentioned operating states. The capacitive and inductive states are equivalent to the STATCOM acting like a source or sink of reactive power. A capacitor is considered a source of reactive power, while an inductor consumes it. As already explaied, the state of operation is determined by the converter voltage.

The STATCOM rating limits and reduces the possible dynamic voltage regulation. However, the compensation current is still constant whenever the voltage deviation exceeds the voltage regulation range. A crucial drawback of the more traditional compensation device, the SVC, is the reduction of current during low voltage. The thyristors in an SVC cannot alter the terminal voltage as the VSC of the STATCOM does. The VSC sets its terminal voltage regardless of the grid voltage.

The improved voltage stability obtained by a shunt connected compensation device increases the possible power transfer. Regarding the STATCOM, this is studied and confirmed in another paper written by the author (Hanna Authen) [10]. The relevant part of

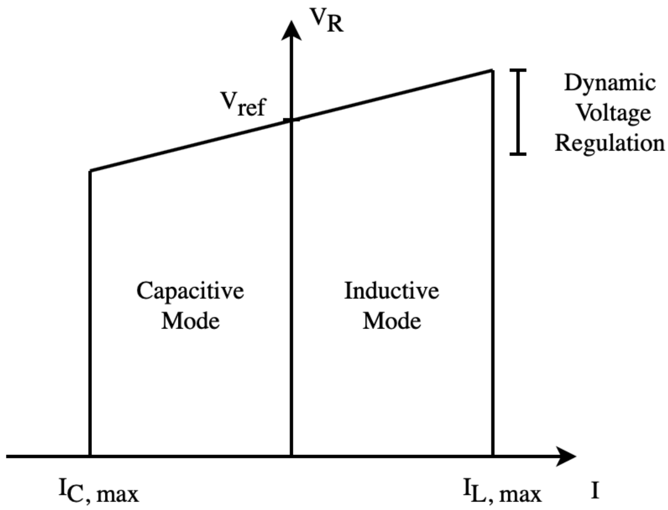


Figure 2.2: Operating range of a STATCOM [9]

the paper is added to Appendix F.1, as it is not published.

The operation of the STATCOM can be extended to include active filtering. The AF and the combination of the AF and STATCOM are discussed in depth in later chapters.

2.3 Equivalent Circuit

Figure 2.3 shows the elemental equivalent circuit diagram of an ideal STATCOM. The main components are the coupling circuit inductance, the VSC and the DC link. A more realistic equivalent circuit includes series and shunt connected resistances to incorporate active power losses. The subscript "S" refers henceforth to the system not the sending end.

The STATCOM is connected to the grid at the PCC, which is placed along a power line or at a power station. The grid sees the STATCOM as a rotating synchronous condenser without inertia. Unlike the condenser, the STATCOM offers static compensation by means of power electronics. The STATCOM acts faster as it does not have any moving parts. The STATCOM equivalent circuit does not include a step-up transformer. This is a common feature as the STATCOM is installed in a transmission system. A transformer reduces the required voltage rating. Some STATCOMs include a battery energy storage system that provides active power. This paper does not focus on or discuss this feature.

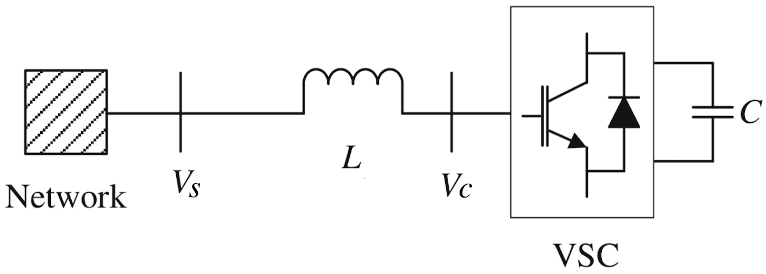


Figure 2.3: Simplified equivalent circuit [2]

2.4 Application

Statnett, as the TSO in Norway, is in charge of the maintenance, present and future operations of the transmission system. Norway has a widespread population with a lot of remote and rural areas. Such places are often prone to problems considering the voltage stability due to a shortage of installed capacity [11]. This was the case at the Lofoten Islands. The specific circumstances at Lofoten made it ideal to install the first STATCOM at transmission level in Norway. Reducing the area required and the fast installation were key advantages when installing the STATCOM. A STATCOM eliminates the need for large attachments and passive filters, and therefore, the area required. The STATCOM is generally more expensive than the SVC due to the cost of the converter components [12]. Nevertheless, the increased cost is, to some extent, offset by the reduction of costs related to the required area and size of the device. Prefabricated modules shortened the project and the delivering time. Figure 2.4 shows the installation at Sortland, Lofoten. Siemens has named its STATCOM SVC PLUS. The components are placed inside a container to protect against the harsh climate and reduce noise.

STATCOMs are installed all over the world [13]. Siemens AG and the ABB Group are leading suppliers of STATCOMs. The motivation behind installing such devices is not the same for all cases. Similar to the case at Sortland, many STATCOMs are installed in remote areas to improve the steady state voltage and capacity. But not only remote grids are exposed to challenges concerning voltage stability. Siemens has also provided the city of Long Island, New York, with a STATCOM. The grid had a returning problem concerning low voltage. Each summer, the hot weather leads to increased use of air condition. The peak loads during the season caused under-voltages for longer periods.

Other application areas are grids with or close to rapidly changing and disturbing loads, such as heavy industrial loads. Arc furnaces are known for causing voltage flickering and producing harmonic currents. STATCOMs can reduce the flickering by a factor of 6-8 [13]. The amount of power produced by renewable energy sources such as wind power is increasing fast. High penetration of renewable energy presents new challenges. The STAT-

Figure 2.4: STATCOM installed at Sortland [11]

COM can be installed close to these plants to compensate for a varying power production [5]. A STATCOM was recently installed close to the wind farm Westermost Rough. The installation of the STATCOM was a significant measure to keep the operation in line with grid codes [5].

2.5 Mathematical Model

The following mathematical representation of the STATCOM and VSC is in line with the theory presented by the book "Static Compensators (STATCOMs) in Power Systems" [2]. The complete derivation is not shown, but added to Appendix A.3. Figure 2.5 shows a more detailed equivalent circuit of the STATCOM. The serie and shunt connected resistance, R and R_C, are added to include internal losses.

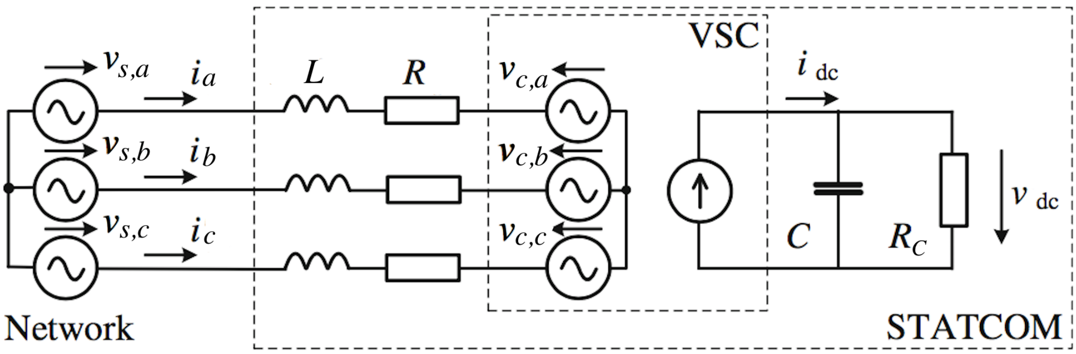


Figure 2.5: STATCOM equivalent circuit diagram

Kirchhoff's voltage law (KVL) states that the sum of voltages in a closed loop is zero. KVL applied to the AC side of the STATCOM gives

$$L\frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = -R\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} (v_{s,a} - v_{c,a}) \\ (v_{s,b} - v_{c,b}) \\ (v_{s,c} - v_{c,c}) \end{bmatrix} \tag{2.3}$$

The system voltage is given as v_s and is equal to the voltage at the PCC. The converter voltage is given as v_c.

Kirchhoff's current law (KCL) states that the sum of currents entering and leaving a node is zero. Applying KCL to the DC side gives

$$i_{dc} = C\frac{dv_{dc}}{dt} + \frac{v_{dc}}{R_C} \tag{2.4}$$

The instantaneous power at both terminals of the converter must be equal at all times. The energy balance of the converter must be intact. As a result, the instantaneous power equation becomes

$$\left[v_{dc}i_{dc} = v_{c,a}i_a + v_{c,b}i_b + v_{c,c}i_c\right] \tag{2.5}$$

The modulation index is dependent on the converter AC and DC voltage and given as

$$v_i = m_i(t)\frac{v_{dc}}{2} \tag{2.6}$$

The modulation index states the ratio between the AC and DC side voltages. The modulation index is feed into a modulation generator which produces the switching function. Given the converter switching function, the AC voltage is expressed as

$$\begin{bmatrix} v_{c,a} \\ v_{c,b} \\ v_{c,c} \end{bmatrix} = k_p \begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} v_{dc} \tag{2.7}$$

The switching is covered and discussed in Chapter 4. The factor k_p is dependent on the converter type [2].

Combining Equation 2.5 and 2.7 gives a second expression for the DC side current

$$i_{dc} = k_pS_ai_a + k_pS_bi_b + k_pS_ci_c \tag{2.8}$$

Substituting i_{dc} into Equation 2.4 gives DC side voltage equation. Combining the AC current and the DC voltage equation gives the complete mathematical model

$$\frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \\ v_{dc} \end{bmatrix} = \begin{bmatrix} \frac{-R}{L} & 0 & 0 & \frac{-k_p}{L}S_a \\ 0 & \frac{-R}{L} & 0 & \frac{-k_p}{L}S_b \\ 0 & 0 & \frac{-R}{L} & \frac{-k_p}{L}S_c \\ \frac{k_p S_a}{C} & \frac{k_p S_b}{C} & \frac{k_p S_c}{C} & \frac{-1}{R_C C} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \\ v_{dc} \end{bmatrix} + \frac{1}{L}\begin{bmatrix} v_{s,a} \\ v_{s,b} \\ v_{s,c} \\ 0 \end{bmatrix} \tag{2.9}$$

To simplify the mathematical calculations and correlations, such models are often transformed into the direct-quadrature (dq) coordinate system. The reference frame of dq coordinate system rotates with the same speed as the fundamental AC phase voltage. For an ideal system, this transformation removes the time-varying variables. The complete transformation is added to Appendix A.2. Transforming Equation 2.9 into the dq reference frame gives

$$\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \\ v_{dc} \end{bmatrix} = \begin{bmatrix} \frac{-R}{L} & \omega & \frac{-k_p}{L}S_d \\ -\omega & \frac{-R}{L} & \frac{-k_p}{L}S_q \\ \frac{3k_p S_d}{2C} & \frac{3k_p S_q}{2C} & \frac{-1}{R_C C} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ v_{dc} \end{bmatrix} + \frac{1}{L}\begin{bmatrix} v_{s,d} \\ v_{s,q} \\ 0 \end{bmatrix} \tag{2.10}$$

Figure 2.6 shows the block diagram of Equation 2.10. If unbalanced currents are present, additional equations describing the negative sequence currents must be added to the equation set. A STATCOM does not produce zero sequence currents. These currents can, therefore, be neglected from the model.

The model with unbalanced conditions is added to Appendix A.3. Unbalanced conditions introduce multiple new challenges. One challenge is the introduction of harmonics. Negative sequence currents on the AC side introduce harmonics of the second order at the DC side. This must be avoided to prevent the presence of even higher order harmonics on the AC side. The second order harmonics can be eliminated by increasing the capacitor rating or use $V_{dc,ref}$, not the measured v_{dc}, when obtaining the switching function.

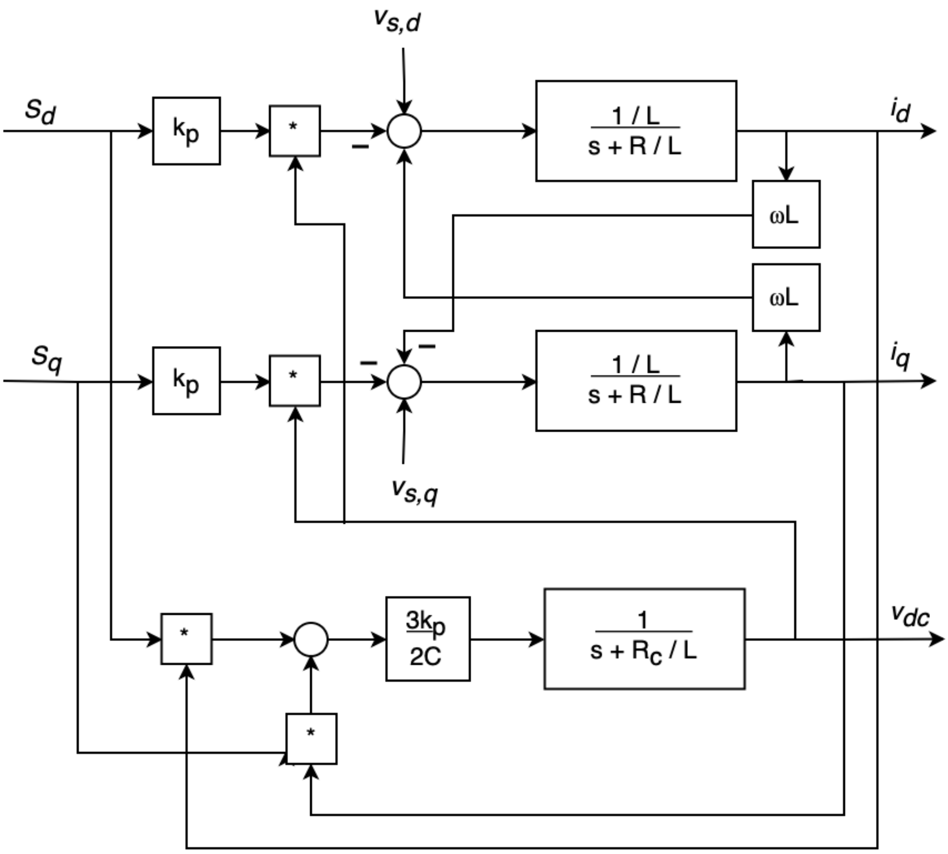


Figure 2.6: STATCOM block diagram

Chapter 3

Harmonic Content and Filters

Filters are installed to reduce polluting harmonic content of a power system. This is necessary as the impact and the dissipation of harmonic content can be damaging. Thus, standard limits for the total demand distortion (TDD) of an electrical power system are provided. Measures, such as installing filters, must be taken to keep the TDD within these limits. Filters, can by reducing the harmonic pollution, improve the power factor and reduce loading, which increases the efficiency [14]. Reducing the origin of harmonics is desirable, but not feasible in most cases. Power electronics, which produce harmonics, are and will be an essential part of the grid and common everyday applications.

The traditional STATCOM does not reduce the TDD of a power system. Installing passive filters is the traditional measure for reducing the harmonic content. With the increasing research and development of power electronics, alternative filters have been introduced. Active filters (AFs), also called overall harmonic compensation, overcome some of the drawbacks of passive filters. Also, devices combining the STATCOM and AF have been proposed.

This chapter describes harmonic content and presents the most common measures for reducing the harmonic content. Filters can be connected to a grid both in shunt and series. However, shunt connected filters do not need to be rated for the full load. Such filters do not need overcurrent protection devices, reducing the overall cost [15]. Only shunt connected filters are considered in this report.

Usually, 50 or 60 Hz is considered the fundamental frequency. Complying with Norwegian and Statnett grid codes, 50 Hz is treated as the fundamental frequency throughout this paper.

3.1 Harmonic Pollution

Harmonic content pollutes and distorts the power. Thus, the power quality of a system is reduced by the presence of harmonics. Harmonics are defined as quantities of a frequency that is not equal the fundamental frequency. Both voltage and current harmonics affect the power quality in a negative manner. However, harmonics refer to current harmonics by default. Voltage harmonics are often considered a result of current harmonics.

Non-linear loads draw currents of varying frequencies. The impedance of such loads changes with the applied voltage. The total current drawn by non-linear loads will not be sinusoidal, the desirable waveform. The load current is rather a sum of multiple sinusoidal currents. All of the currents of a frequency not equal to fundamental frequency are considered harmonic currents. Converters, electrical drives, non-ideal transformers are examples of such non-linear loads. A major contributor of harmonics is power electronics. Both large industrial and common home equipment utilize power electronics such as transistors and diodes.

Power electronics have become a vital part, of not only industrial and later common household devices, but also of the power system sector. Power electronics support and enable the implementation of the increasing renewable energy production [16]. Power conversion devices, converters, are necessary for transmitting power and operate the grid efficiently. A major drawback of the power electronic devices is the induced harmonic currents. Today, most power electronics are semiconductor switching devices. The harmonics produced by each switch during operation can be transmitted throughout the grid. In spite of this, power electronics are essential elements of devices that reduces the harmonic content.

The probability for significant power system problems to occur due to harmonic pollution is low [17]. However, harmonics are generally undesired for several reasons. Harmonic currents give rise to the total amount of current. As a consequence, the harmonics increase loading and stress, which in turn reduces the power transfer capacity. Many electrical components and devices are not designed and constructed to handle additional currents. Such devices could suffer, resulting in damaging malfunctions. Excessive heating and motor torque problems are examples of possible malfunctions [18]. Currents of higher frequencies do also give rise to frequency dependent losses such as hysteresis and eddy current losses. Another aspect is that higher frequencies can interfere with other independent electrical systems. Other unwanted outcomes due to high levels of harmonic currents can be increased heating, miss-operations and meter malfunctions [15].

3.1.1 Mathematical Description

Phase currents in an ideal balanced three phase system are commonly expressed as

$$i_a = \hat{I}_a sin(\omega_1 t + \varphi_a)$$

$$i_b = \hat{I}_b sin(\omega_1 t - 2\pi/3 + \varphi_b) \tag{3.1}$$

$$i_c = \hat{I}_c sin(\omega_1 t - 4\pi/3 + \varphi_c)$$

The quantity, in this case the phase current, is described by a single sinusoidal signal of the fundamental frequency. ω represent the angular frequency and φ represents the phase shift.

Few implemented systems are ideal if any. Harmonic currents are examples of non-ideal and unwanted quantities. Such quantities alter the expressions describing the system. A non-ideal current can be expressed as a sum of multiple sinusoidal signals, a Fourier series. A general description of balanced non-ideal phase current is

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \sum_{h=1,3,5,...} \begin{bmatrix} \hat{I}_h sin[h\omega_1 t + \varphi_h] \\ \hat{I}_h sin[h\omega_1 t - 2\pi/3 + \varphi_h] \\ \hat{I}_h sin[h\omega_1 t - 4\pi/3 + \varphi_h] \end{bmatrix} \tag{3.2}$$

Non-ideal phase voltages can be expressed in the same manner.

The order of each current is given by the parameter "h". The first order, h = 1, represent currents of the fundamental frequency which are not considered harmonic currents. Currents of the following orders are considered harmonics. The frequency of each harmonic is equal the integer h multiplied with the fundamental frequency. Harmonics of frequencies in the range second to 19th order are the most common ones in electrical power systems [18]. Moreover, the harmonics of lower order are considered more harmful. Electrical circuits are mostly inductive. The inductive reactance acts like a low pass filter, reducing the amplitude of higher order harmonics. Harmonics of orders up to 13th are therefore often more prominent [19]. Even harmonics, h = 2,4,6.. are not included in Equation 3.2 due to intrinsic cancellation.

The triplen harmonics, harmonics with orders that are multiples of 3, are all zero-sequence components. Due to the additive effect, triplen harmonics are considered the most damaging. Neutral current cancellation does not take place, as the order multiplied with the 120 degree phase shift is an integer multiple of 360 degrees. Thus, the different phase currents become in phase in the neutral [20]. The fifth harmonic is a negative-sequence component. The next odd harmonics alter between positive, zero and negative-sequence currents.

$$h = 1, 3, (-)5, 7, 9, (-)11, 13, 15, (-)17, ... \quad (3.3)$$

Inter harmonics are harmonics that do not fit the traditional definition as the frequency may not be integers of the fundamental frequency. Such harmonics can be averted by an optimal DC link design [17].

3.1.2 Total Demand Distortion

The TDD of a line is defined as the ratio of the root sum square value of the harmonic currents to the root mean square value of the fundamental full load current. At full load, total harmonic distortion (THD) is equal the TDD. The THD is calculated in similar manner as the TDD. However, the THD divisor is equal the actual fundamental current. The current TDD of a system is calculated by

$$TDD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + I_5^2 + ...}}{I_{1,FL}} \times 100\% \quad (3.4)$$

Power quality problems may be unavoidable if the TDD is too high. IEEE STD 519 provided by Institute of Electrical and Electronics Engineers offers distortion limits to avert such problems. The standard provides both voltage and current TDD limits. Only current TDD and THD are considered in this thesis.

The maximum TDD is determined after considering the system characteristics. The limits are set based on the short circuit strength or system capacity (I_{sc}) and full load current (I_{FL}) at the PCC. Harmonic currents are limited by the system impedance [21]. Thus, the short circuit strength parameter incorporates the system impedance. The system voltage level does also affect the maximum allowed current TDD. Some system information may be unavailable. Individual devices or equipment are then considered [22].

Table 3.1 shows the maximum harmonic current distortion for each odd harmonic order at voltages higher than 161 kV. The limits are higher than the ones for lower voltage levels. The limits of even harmonics are set to be 25% of the odd harmonic limits. The distortion limits are of the range 0.1-3 %.

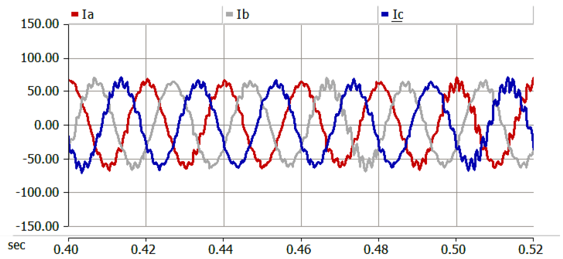
I_{sc}/I_L	$3 \leqslant$ h < 11	11$\leqslant$ h < 17	17$\leqslant$ h < 23	23$\leqslant$ h < 35	35$\leqslant$ h < 50	TDD
< 25	1.0	0.5	0.58	0.15	0.1	1.5
25 $<$ 50	2.0	1.0	0.75	0.3	0.15	2.5
$\geqslant$ 50	3.0	1.5	1.15	0.45	0.22	3.75

Table 3.1: Total demand distortion limits [%], V $>$ 161 kV [23]

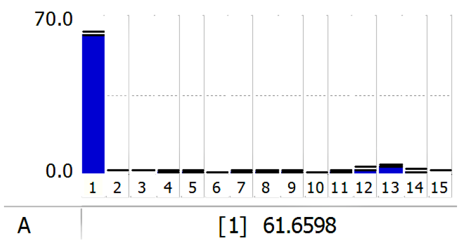
IEC 61000-3-2 is another standard that provides TDD limits. The standard is provided by International Electrotechnical Commission. These limits are determined more rigorously based on system characteristics [24].

3.1.3 Illustration

A simple system is considered to illustrate the effect of harmonics. Figure 3.1a shows the line current during base case. The system produces some harmonic currents. Still, the magnitude of these currents are small. Thus, the fundamental sinusoidal waveform is prominent. The harmonic current magnitude overview, shown in Figure 3.1b, confirms a low amount of harmonic pollution. As a result, only small current ripples are visible. The current waveform is close to ideal.



(a) Line current



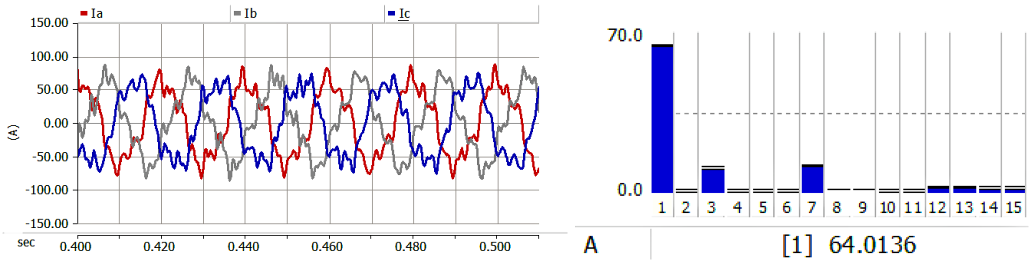
(b) Magnitude of harmonic currents

Figure 3.1: Harmonic content overview of a simple system

Neglecting the presence of all harmonics except the 13th order, the phase current, i_a, can be expressed as

$$i_a = 60sin(2\pi 50t + \varphi_1) + 2.8sin(13 \times 2\pi 50t + \varphi_{13}) \tag{3.5}$$

To illustrate the damaging effect, additional harmonic currents are injected. Note that the load current is not equal to the full load current. If it was, the TDD would be way beyond the given limit. Figure 3.2a shows how the line current is affected by a 3rd and 7th order harmonic current injection. The harmonic currents alter and disrupt the sinusoidal waveform. The harmonic currents are clearly of a higher order of magnitude, as can be confirmed by Figure 3.2b.



(a) Line current

(b) Magnitude of harmonic currents

Figure 3.2: Harmonic content overview of a simple system with harmonic current injections

Neglecting the presence of all harmonics except the 3rd, 7th and the 13th order, the phase current, i_a, can be expressed as

$$\begin{aligned} i_a = 64sin(2\pi 50t + \varphi_1) + 10.2sin(3 \times 2\pi 50t + \varphi_3) + \\ 11.4sin(7 \times 2\pi 50t + \varphi_7) + 2.2sin(13 \times 2\pi 50t + \varphi_{13}) \end{aligned} \tag{3.6}$$

3.2 Passive Filter

For decades, passive filters have been installed to reduce harmonic currents. Passive filters filter out quantities of specific frequencies. Series connected passive filters increase the system impedance for currents of unwanted frequencies. The alternative to series connected filters is shunt connected ones. Such filters provides a low impedance path to ground for unwanted currents. Passive filters have a simple structure and are composed by different combinations of the components; resistors, inductors and capacitors, all passive elements. These filters do not have an external power source. Common passive filters are high pass, low pass, band pass and band stop filters. As the name suggests, the passive filter does not operate dynamically. The filter is tuned once with the one option to be connected or disconnected from the grid. The reactive elements of the shunt connected filters may offer reactive compensation.

An SVC is a common source of harmonic currents. Passive filter arms are therefore included to reduce harmonic dissipation. STATCOMs do not need additional passive filters. The enhanced performance of the MMC and pulse width modulation (PWM), used in most STATCOMs, eliminates the need for additional filters.

To illustrate the general behavior and function of a passive filter is illustrated.

3.2.1 Passive Filter Example: C-Type Filters

C-type filters are second order filters and considered a broadband filter. Characteristics for such filters include a broad bandwidth. The filter can eliminate higher order harmonics and inter-harmonics efficiently [25]. The C-type filter reduces resonance by damping, it does not just shifting the harmonics to a lower frequency.

Figure 3.3 shows the topology of the C-type filter. The L-C2 branch is tuned to match the fundamental frequency, reducing the active power losses on the damping resistor. At the fundamental frequency, the L-C2 branch is short-circuited, offering a current path with low active power losses. As a result, the C-type filter acts as a single stand-alone capacitor bypassing the damping resistor at 50 Hz. This minimizes the power loss. As the frequency increases, the filter first acts as a single tuned filter then a first-order tuned filter. The L-C2-C1 branch is tuned to match the desired harmonic frequency [26].

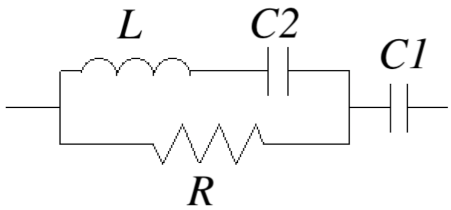


Figure 3.3: C-type filter topology

The frequency dependent impedance of a C-type filter is expressed by Equation 3.7. By tuning the filter parameters, the filter optimizes the grid quantities.

$$Z(j\omega) = \frac{R(j\omega L + \frac{1}{j\omega C2})}{R + j\omega L + \frac{1}{j\omega C2}} + \frac{1}{j\omega C1} \tag{3.7}$$

Figure 3.4 shows the bode plot of the C-type filter. The L-C2-C1 branch is in this case tuned to the 3rd order harmonic. As can be seen, the magnitude of the impedance transfer function is at a low point at 150 Hz. The filter offers a low-impedance path to ground for signals of 150 Hz. Multiple C-type filters must be connected in parallel to reduce harmonic quantities of different frequencies. As a result of these filters, the current waveform becomes closer to the optimal sinusoidal waveform. The impact of C-type filters, like any others, are limited by the component ratings, possible reactive power flow and quality factor.

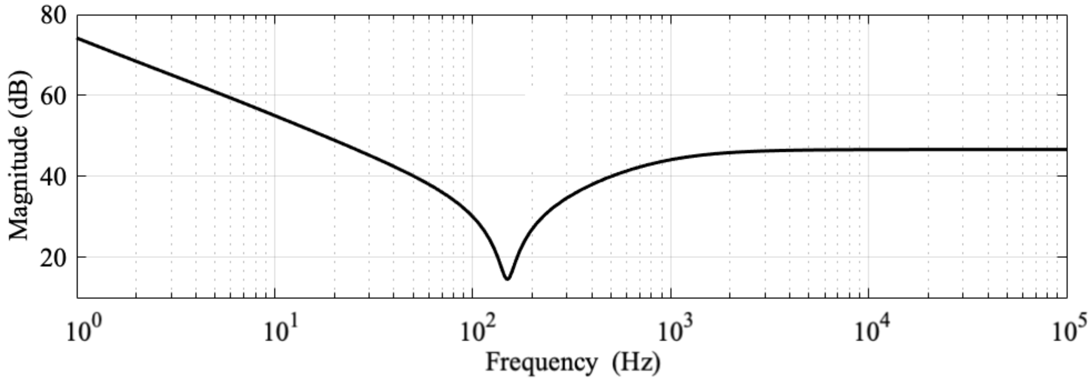


Figure 3.4: Bode plot c-type filter

The static behavior of the passive filters makes them unsuitable for varying system operating conditions. In spite of the broad bandwidth, this is true for the C-type filter as well. Parallel resonance is also a concern regarding passive filters. In order to filter out currents of different frequencies, many series or parallel connected filters are needed.

3.3 Active Filter

AFs overcome some of the problems concerning passive filters. The presence of harmonic pollution is dependent on the ever-changing system configuration. The frequency of the harmonic content change too. The tuned passive filters may become ineffective. As described, C-type filters only filter out quantities of a specified frequency span. Other passive filters have an even more narrow frequency span. Due to the increasing research and development of power electronics, alternative solutions such as the AF have been introduced. The more advanced and dynamic AF adapts to the changing need of harmonic filtering. Also, an AF is considered to be more efficient and have a simple design [15].

AFs eliminate harmonic content continuously by means of an external power source. The power source produces and injects quantities of the same frequency and amplitude as the harmonics content, only of the opposite phase. An opposite phase implies a phase shift of 180 degrees. The current will cancel out the harmonics content. This is called harmonic compensation. Figure 3.5 illustrates the principle of a shunt connected AF. The shunt connected AF is considered to be a current source, reducing harmonic currents. The compensating currents are added to the grid at the PCC. The AF isolates the harmonic content at the receiving end, protecting the sending end and avoiding further dissipation.

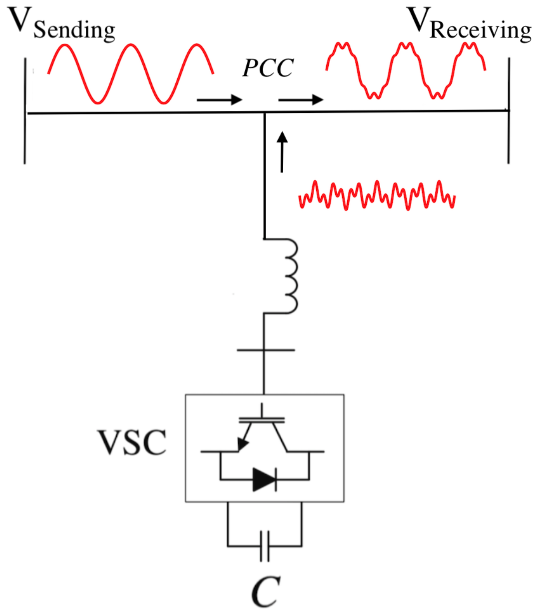


Figure 3.5: Active power filter

The AF configuration is similar to the STATCOM configuration and topology. Likewise, the main component is usually the current controlled VSC. The mathematical model of the VSC is identical for the AF and STATCOM. Power electronics, which generally produce harmonic currents, are key elements of the VSC. However, this is not a great concern for devices using the MMC. The MMC and the PWM technology reduce the production of harmonic pollution compared with traditional converters. Hence, an AF or a STATCOM is not considered a large source of harmonics. In fact, the MMC enables harmonic compensation. The STATCOM equivalent circuit diagram and block diagram are just as valid for the AF.

3.3.1 Reactive Power Compensation

Researchers have proposed to combine the STATCOM and the AF [27]. This device is referred to as a developed STATCOM. The fast and precise performance of the STATCOM suggests that it is possible and beneficial to operate it as an AF. ABB has investigated this opportunity. Today, they offer STATCOMs that perform active filtering [28]. Likewise, as the traditional AF, the shunt connected developed STATCOM reproduces the harmonic content in phase opposition to the measured harmonic currents. These currents are injected into the grid, eliminating the original harmonic currents [5]. The VSC control must be altered in order to combined the AF and STATCOM.

Chapter 4

Voltage Source Converter

VSC technology enables continuous reactive power compensation by a STATCOM. Compensation by a VSC eliminates the need for large banks of capacitors and inductors, reducing the requirement area and land costs. The VSC represents the main difference between the STATCOM and SVC. Moreover, MMCs are considered the state of the art technology. The fast and precise performance of the MMC supports harmonic compensation, which reduces the harmonic dissipation. This chapter covers the description and control of the MMC. PWM is the most commonly used modulation method and is briefly presented.

4.1 Background

The interest in VSCs has increased with the increasing amount of bulk transmission and renewable energy production. The change in production and demand patterns has challenged the traditional way of building and expanding the grid. Also, HVDC systems have proven more beneficial due to the improved performance of the VSC.

The ”gate turn off” feature of semiconductors has been pivotal for the development of the VSC. The semiconductors enabled better control, produce fewer harmonics and offer finer reactive power control [29]. This is especially favorable for weak AC systems, AC/DC interconnections and when integrating renewable energy production. Still, the transistors used in semiconductors withstand much less voltage than thyristors. Nevertheless, the performance of the semiconductors is rapidly improving, which enable the use at higher voltage levels. As a result, ”Voltage-source-converters have become the most suitable and universal topology [...].” [30].

The VSC was introduced as an alternative to the more traditional current source converter (CSC) in the late 1990s. The CSC is also known as a line-commutated converter

(LCC). The CSC performs well whenever high capacity and efficiency are needed. Also, the thyristors used in the converter withstand higher voltages than the transistors. However, the control of the CSC switching devices is limited. The CSC can be equipped with semiconductors too. Nevertheless, many challenges are introduced by combining the CSC and semiconductors [30]. As a result, new and efficient technologies like the VSC have been introduced in fairly recent times.

4.2 Modular Multilevel Converter

The very first modular multilevel converter was patented by MIT in 1975 [31]. The application was predicted to be beneficial for HVDC systems. The first ”modern” multilevel converter was presented by Alstom in 1998 [32]. The most significant development of the MMC took place after Lesnicar and Marquardt presented their research on HVDC MMC, in 2003 [33]. However, the increased research of MMC in HVDC transmission system has been beneficial to the development of the STATCOM as well. STATCOMs are now presented as a more area effective and a better choice for dealing with low voltage compared with an SVC. In addition to this, the STACOM produces less harmonic and does not need additional filters.

The MMC has become the preferred choice for high voltage applications [34]. Statnett commissioned their first STATCOM, which utilizes the MMC-technology, in 2010 [11]. In Norway, the transmission systems usually operate at a voltage level between 300 and 420 kV [35]. Each semiconductor cannot handle higher voltage than a couple of kilovolts, limiting most VSCs [36]. The MMC withstands higher voltage due to its advanced semiconductors and topology. Operating at higher levels reduces the current as well as conduction losses. Applications such as FACTS and HVDC transmission depend on such characteristics.

4.2.1 Fundamentals and Working Principle

The MMC is a bidirectional converter; it works as both a rectifier and an inverter. The converter shares a lot of characteristics and benefits with the more traditional 2 and 3 level VSCs. Power electronics are used to convert AC and DC signals. The MMC uses semiconductors. Insulated gate bipolar transistor (IGBT) is the most commonly used semiconductor for MMCs. ABB states that ”the IGBT gives it [the STATCOM] unequalled performance in terms of effective rating and response speed” [5]. The semiconductors are considered superior due to its three states; inserted, bypassed and blocked. Three states enable better control and improve the converter performance.

An MMC produces an output with fewer harmonics, compared with traditional converters. Multiple levels can produce quantities with a more prominent sinusoidal waveform. The many advantages of the MMC are the direct consequence of the MMC topology [36]. The topology reduces the switching frequency of each semiconductor. Smaller switching frequencies shift the harmonic content towards higher frequencies. Smaller voltage steps, rather than pole to pole voltage changes, reduce the stress on the components and the stray capacitance. The MMC is a compact converter with short commutation paths, which reduce stray inductance. This assures that switching losses and voltage overshoots are further reduced.

As for the STATCOM, earlier AF utilized either the 2 and 3 level converters. Likewise, the development of the MMC has been beneficial for the AF. The advantages of the MMC are just as lucrative for active filtering. However, the desired current output waveform is not equal to the sinusoidal waveform as for the STATCOM. With multiple levels, recreating the harmonic content is possible. The harmonic compensation current is phase shifted by 180 degrees to cancel out the unwanted currents.

4.2.2 Topology

The MMC is build up by multiple series connected submodules. A submodule, also called cell or chain link, consists of semiconductors, anti-parallel-connected diodes and dc link capacitors. Capacitors are used as constant short term energy storage supplied by either the AC or DC terminal. The STATCOM and AF do not have a DC terminal. Each added submodule adds another possible output level. This topology represents the fundamental difference between the MMC and the traditional converters. The modular construction has given the converter a second name, cascaded multilevel converter. Figure 4.1 shows the topology of a star connected full-bridge STATCOM with MMC.

There are multiple advantages to the modular topology. The most apparent benefit is the ease of installation and manufacturing. The submodules are identical, and adding one increases the voltage level. These converters can be manufactured without the system specification and configured at a later stage. More important, the MMC performs better at higher ratings. The output becomes closer to the desired waveform. Series connected submodules gives an increased blocking capacity. Each semiconductor does only need to block the parallel connected capacitor, not the rated converter voltage.

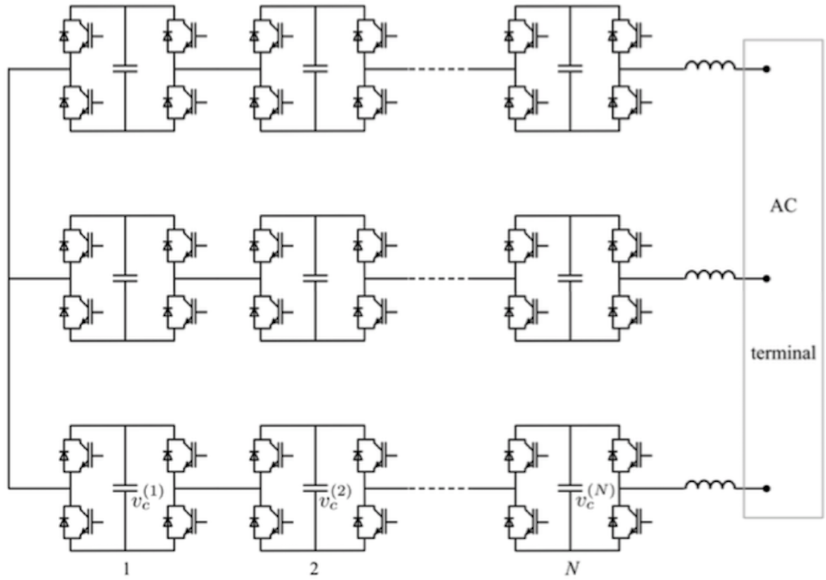


Figure 4.1: Star connected full-bridge STATCOM [36]

A submodule is similar to a 2 level converter phase leg. Semiconductor valves and DC link capacitors form either a half-bride or a full-bridge (also called H-bridge). These two configurations have different advantages and application areas. The main difference is the possible output. Figure 4.2 illustrates the output calculated by Equation 4.1 for the half bridge and Equation 4.2 for the full bridge. The total capacitor voltage, ${V_{cap}}^{\Sigma}$, is normally equal to the DC voltage with a modulation index equal to one. There exist other configurations, such as a semi-full bridge. These alternatives are not discussed any further.

$$\hat{v_c} = 0.5({V_{cap}}^{\Sigma} - (2V_{dc} - {V_{cap}}^{\Sigma})) \tag{4.1}$$

$$\hat{v_c} = ({V_{cap}}^{\Sigma} - V_{dc})) \tag{4.2}$$

The converter output is dependent on the modulation index. The modulation index givens the ratio of the AC and DC terminal voltage. Equation 4.3 states the correlation between the voltage and modulation index.

$$\hat{v_c} = m\frac{V_{dc}}{2} \tag{4.3}$$

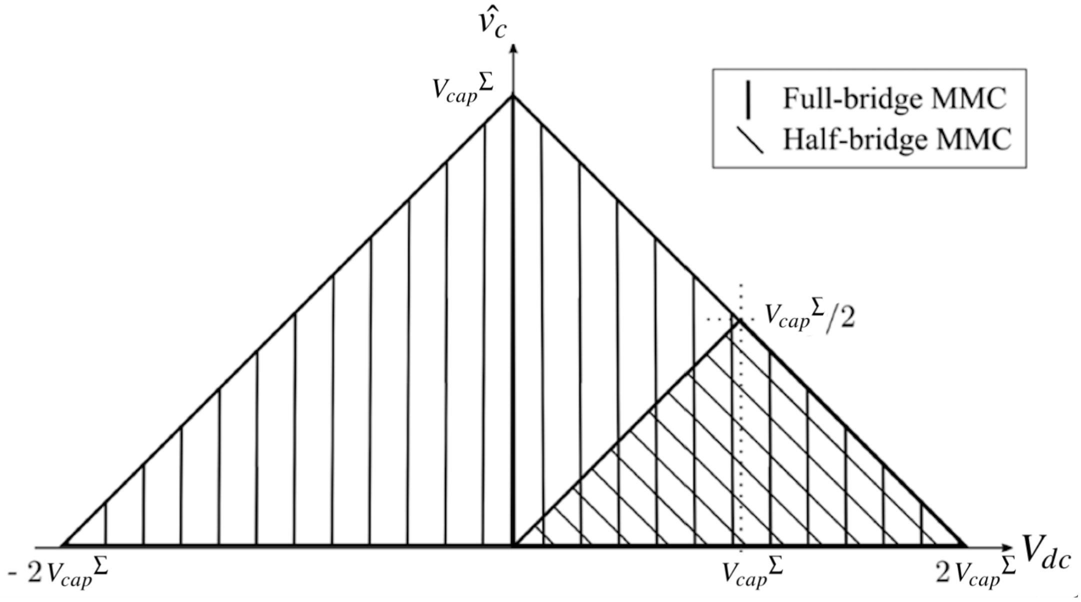


Figure 4.2: Possible MMC output at a given number of submodules [36]

The half-bridge MMC is the most commonly used converter technology for HVDC applications [36]. These submodules have the lowest power loss and cost. Half-bridge submodules are especially preferred for underground and submarine transmission [37].

For a modulation index equal or below 1 and $V_{dc} > V_{cap}{}^{\Sigma}$, a half-bridge MMC is the most area and cost-effective one compared with the full-bridge submodule. Under these conditions, the same number of submodules is required for both the half-bridge and the full-bridge MMC. Choosing half-bridge MMC reduces the number of semiconductors by half, in addition to the reduced switching loss, area and cost. Operating at $V_{dc} < V_{cap}{}^{\Sigma}$ is not reasonable as the same output could be achieved by a lower rated $V_{cap}{}^{\Sigma}$.

However, the half-bridge submodule is inferior to the full-bridge submodule under short circuit faults [36]. The half-bridge submodule does not provide decoupling of the AC and DC side, isolating the fault. Without current control, the whole system or components can be damaged as current still flows during a short circuit fault. Protective measures can be taken, e. g. limit the current by increasing series inductance or adding diodes, but either active or reactive power can be exchanged during a fault. Installing breakers or combinations of other mentioned measures increases the total cost.

Figure 4.2 shows the half-bridge MMC's shortcomings at a given number of modules and rated capacity voltage. A half-bridge MMC cannot produce an output voltage, *Vac*, greater than half of *Vdc*, i. e. modulation index exceeding 1 pu. Increasing the voltage output requires a larger number of components compared with full-bridge converters. The number of capacitors which act like energy storages must be increased. The total rated capacitor voltage is a key expense and increasing it will reduce or even eliminate some of the mentioned advantages of the half-bridge submodule. Losses and cost of semiconductors increase as more submodules are added as well.

Given the arguments above, the half-bridge MMC is not an alternative for the STATCOM. The modulation index is greater than 1 pu when producing reactive power. As this paper focuses on the STATCOM, half-bridge converters are not considered further.

4.3 Pulse Width Modulation

The semiconductor states are controlled by modulation. PWM is presented in this report as the majority of STATCOM VSCs utilize this method [5].

The PWM generator produces the output by means of switching. The desired waveform is usually sinusoidal. The sinusoidal signal is obtained by altering the width of each pulse optimally. In contrast to squared modulation, the PWM has a high switching frequency. For the squared signal, all pulses are of the same width and equal half of the wavelength. As a result, the squared modulation method recreates the sinusoidal waveform poorly and induces a high amount of harmonics. Increasing the switching and optimizing the pulse width reduces the harmonic content and improve the converter performance [2]. Figure 4.3 shows this correlation.

Increasing the switching frequency has drawbacks, such as increased losses and stress on components. The control does also become more complex. However, this correlation is not as strong for MMC [36]. Pole to pole voltage switching is avoided with multiple voltage levels. Switching will only impact one submodule each time. Making use of the multiple voltage levels improves performance and reduces the production of harmonic currents further. Figure 4.4 confirms this.

Multiple different carriers can be used in combination with the PWM. The switching of a carrier-based PWM is dependent on and set by the intersection of a chosen carrier and the voltage reference. Phase-shifted carrier (PSC) is claimed to be the most used carrier [38]. Using the PSC produces a low amount of harmonic current. Moreover, the PSC provides an excellent power balancing of the capacitors [38].

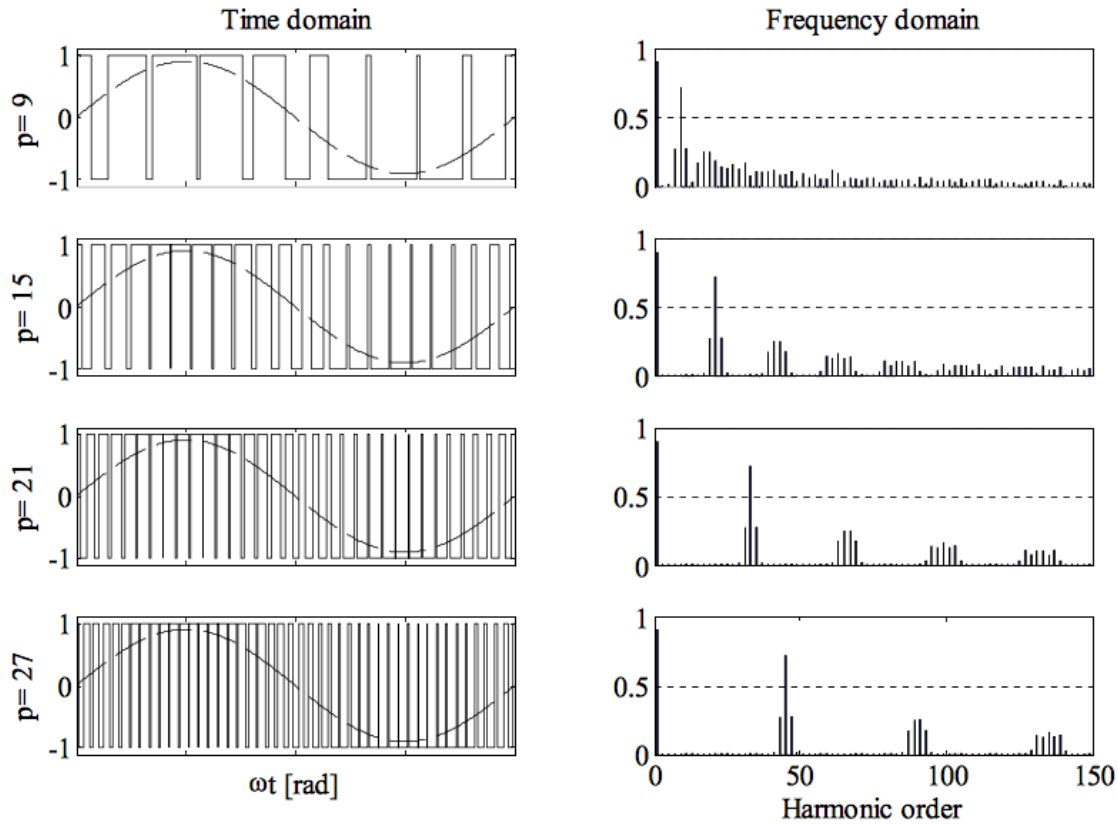


Figure 4.3: Two level PWM [36]

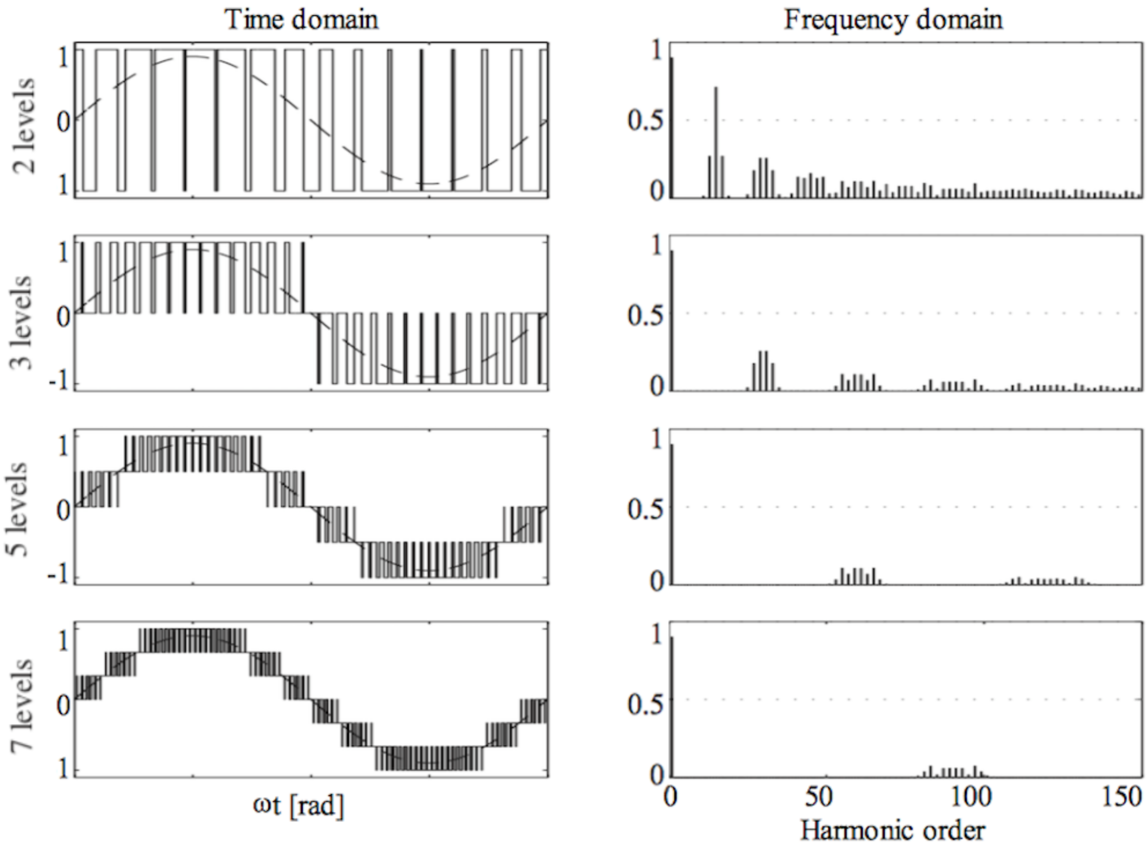


Figure 4.4: Multiple level PWM [36]

Chapter 5

Modular Multilevel Converter Control

Various control methods can be implemented to obtain control of the MMC output. A much used MMC control method is vector control [39]. It is a common choice for both the STATCOM and the AF. It assures that the instantaneous active and reactive power are controlled independently of each other. This characteristic is desirable for the developed STATCOM controller as well. However, the controller must be adapted in order to fulfilled the specific output requirements of both the STATCOM and the AF.

This chapter presents the developed STATCOM controller. The controller is simple while combining the two features; reactive and harmonic compensation. The developed STATCOM MMC controller is henceforth referred to as a combined controller. To the author's knowledge, no identical controller has previously been proposed. However, the idea and principle are widely known and similar controllers have been proposed by others.

5.1 Proportional Integral Controller

There exist multiple control algorithms. A conventional proportional integrator (PI) controller is considered to be the most commonly used controller for VSC control [40]. It is simple and has a good performance during steady state as well during dynamic conditions. There exist no universal design for PI controllers. A good performance is conditional on a well tuning. Empirical tuning is a common strategy [41] and used throughout this thesis.

All of the presented control loops utilize the PI controller. The PI transfer function is given by Equation 5.1.

$$H_{PI} = K_p + \frac{K_i}{s} \tag{5.1}$$

5.2 The Combined Controller

Figure 5.2 shows the vector control scheme of the combined controller. The controller combines traditional STATCOM and AF control. Full control is achieved by combining an inner current control loop, a phase-locked loop (PLL) and an outer control loop. The next subsections reviews the inner structure of each subcontroller. The inner structure of the PWM Generator block and VSC are not considered but assumed ideal. The inner current controller and PLL loop are designed in the same manner as for the traditional STATCOM and AF controller. The main changes imposed by the combined controller are located in the outer control loop. All of the controller transfer functions are added to Appendix C.1.

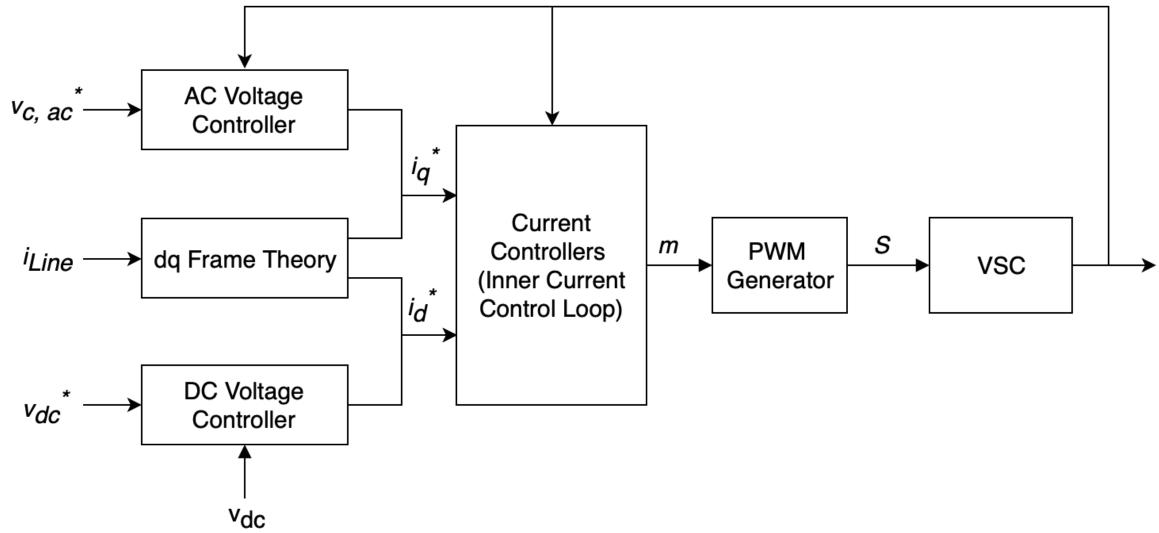


Figure 5.1: Vector control scheme

5.2.1 Inner Current Control Loop

The main controller is described as the heart of the control system [36]. The main controller of the current vector controller is the inner current control loop. The inner current controller (ICC) sets the system input. The output of the ICC is then fed into the system. For the developed STATCOM, the PWM generator and VSC make up the system.

Figure 5.2 shows the inner structure of the subsystem ”Inner Current Control Loop”. It shows the calculation of error and how the voltage control signal is obtained by means of PI

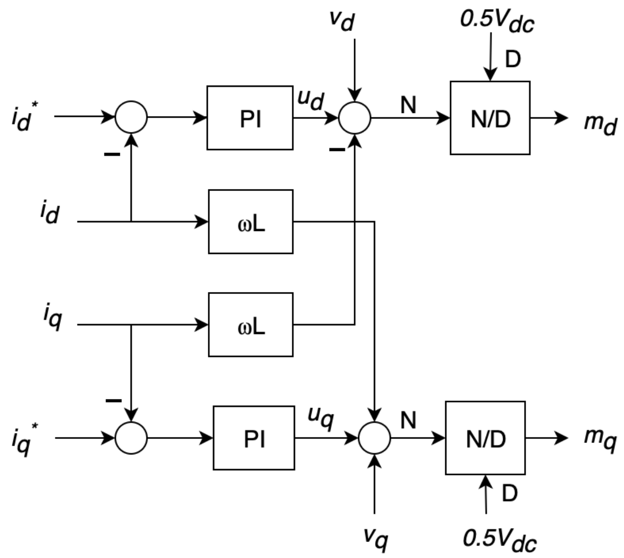


Figure 5.2: Inner current controller block diagram

controllers. Decoupling is included to cancel the natural coupling of the VSC, presented in Chapter 2.6. It is necessary to transform the voltage control signal into a modulation signal. The modulation signal is generated by the voltage control signal and DC voltage, as shown in Figure 4.3. A modulation unit, the ”PWM Generator”, transforms the voltage control signal into a switching function, the desired MMC input. Modulation and switching are discussed in Section 4.3. In turn, the switching function controls the power electronics, which enables and generates the MMC output.

The input variables are measured at the converter terminals and abc-dq0 transformed. The required voltage angle θ is obtained by the PLL.

5.2.2 Phase-Locked Loop

The PLL detects the phase angle and frequency of a system. In addition and just as important, the PPL maintains the synchronization of the devices and the grid. The PPL does this by aligning the dq reference frame and the actual system voltage. Thus, the direct voltage component is aligned with the system voltage and the quadrature voltage component equal to zero. As a result, the fundamental dq voltage components become DC value. The dq reference frame and the system voltage rotates at the same angular speed, eliminating the time dependencies. The angular speed and frequency are linked. Due to constant changes in system conditions, the angle and frequency will change and deviate from the initial condition. A feedback loop is, therefore, necessary to force alignment and keep the error close to zero at all times.

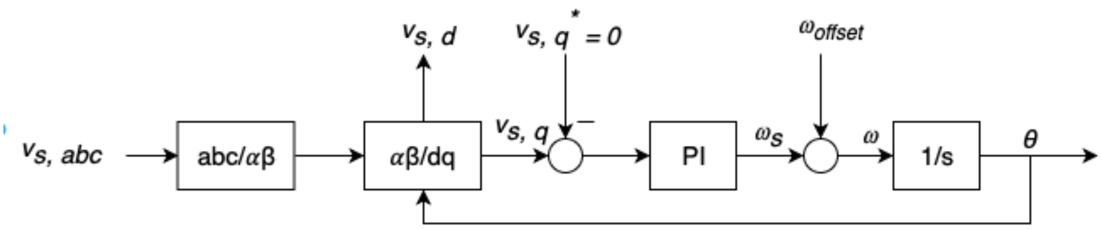


Figure 5.3: Phase-locked loop block diagram

Figure 5.3 shows the block diagram of the PLL. A PI controller is used to calculate the system angular speed, ω_s. ω_{offset} is added to improve system performance during the transient state by reducing the settling time. The ω_{offset} is equal to the expected system angular speed. The reference angle, θ, is obtained by integrating the angular speed, as the angular speed is the time derivative of the angle [2].

A PLL is one of the multiple ways of maintaining synchronization [2].

5.2.3 Outer Control Loop

The outer control loop sets the current control signal, the input of the inner current controller. Essentially, the current control signal controls the AC voltage, DC link voltage and current waveform. Several different outer control loop control strategies can be implemented. Both voltage and power control are common choices [42]. Moreover, implementing harmonic compensation will alter the outer control loop compared with the traditional voltage control.

A device combining the AF and STATCOM must regulate the voltage level in addition to controlling the current waveform. Firstly, the traditional STATCOM voltage controllers are presented. Then a typical AF dq frame controller is reviewed. Finally, an altered combination of the voltage control and dq frame theory controllers is proposed.

5.2.3.1 Reactive Compensation

Regarding this thresis, the main motivation for studying the STATCOM is the possibility of voltage regulation. This is enabled by voltage control. Figure 5.4 shows the block diagram of the outer control loop with voltage control. The inner structure of the DC and AC voltage control are shown respectively by Figure 5.5 and 5.6.

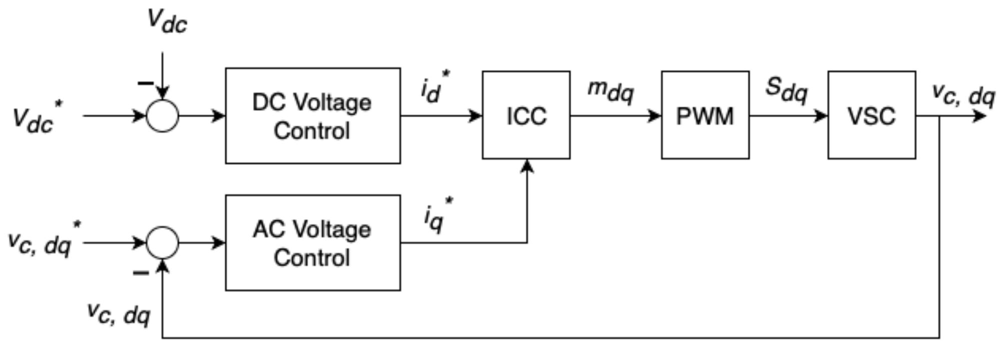


Figure 5.4: Outer control loop block diagram

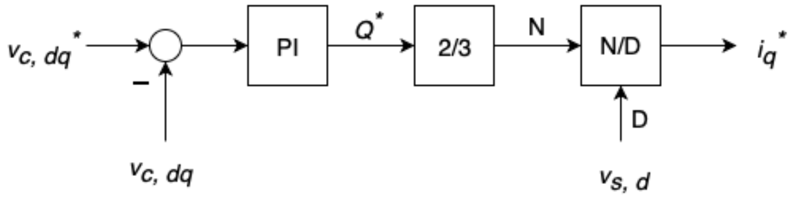


Figure 5.5: AC voltage control block diagram

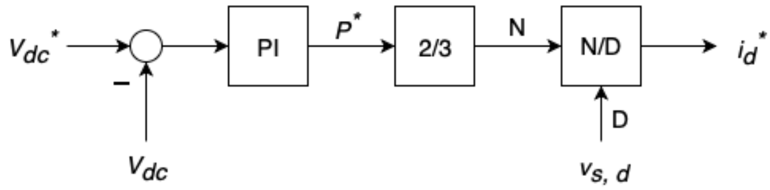


Figure 5.6: DC voltage control block diagram

The alignment of the direct axis and the voltage vector allows independent active and reactive power control. The constant $\sqrt{2/3}$ assures power invariance. The power expressed by quantities in the dq reference frame can be expressed as

$$P = \frac{3}{2} V_d I_d \tag{5.2}$$

$$Q = -\frac{3}{2} V_d I_q \tag{5.3}$$

The full derivation of the power equation in the dq reference frame is added to Appendix A.3.

The reactive power transferred between the PCC and STATCOM is calculated by the AC voltage controller. The optimal reactive power transfer assures that the desired voltage is obtained at the PCC. However, the system rating may limit possible transfer. Still, the controller aims to minimize output error. This is achieved by a feedback loop. A feedback loop considers and incorporates the system output and control performance.

An ideal STATCOM delivers only reactive power. The voltage at each submodule capacitor is constant after the initial charging. No active power is required to maintain the charging of capacitors or other losses. During such conditions, the direct current component is equal to zero. However, this is not the case. The presence of a direct current component suggests an active power flow between the grid and the STATCOM. The active power maintains the desired capacitor voltage level and counteracts additional active power losses within the system. The power loss can be reduced by higher capacitor rating. This entails higher costs. The DC voltage control provides the direct current component much in the same way as the AC voltage controller.

The DC link voltage reference, V_{dc}^*, can be controlled by a voltage droop controller [42]. A voltage droop controller limits the voltage drop during loading. The reference DC voltage can be obtained by Equation 5.4. k_g represents the droop constant.

$$V_{dc}^* = V_s + K_g(P - P^*) \tag{5.4}$$

5.2.3.2 Harmonic Compensation

The control of an AF differs from the STATCOM. The objective of the control unit is to control the current waveform. The controller objective is to generate an optimal reference current. Unlike the STATCOM, the optimal current waveform produced by AF controller is not sinusoidal. Common control strategies for the traditional AF include the synchronous reference (dq) frame theory and instantaneous power (pq) theory.

Figure 5.7 shows a block diagram of the dq frame theory controller. In dq frame theory, quantities of the fundamental frequency are expressed as DC component. Quantities of a non-fundamental frequency are expressed as time-dependent AC components. This characteristic simplifies the calculation of the reference current.

The current control signal is generated by recreating line current. The line current, AC and DC voltage must be tracked to achieve this. The optimal current control signal is equal the line current, only phase shifted by 180 degrees and without the fundamental frequency component. The direct fundamental current component is filtered by means of a low pass filter (LPF). The quadratic fundamental current component is often included to provide some reactive power compensation. However, the possible reactive compensation does not automatically retain the desired voltage level. The traditional control unit of the AF does not consider the grid voltage when providing reactive compensation. As for the STATCOM, the capacitor voltage is controlled by a DC voltage controller. Likewise, the rotating angle, theta, is calculated by the PLL. The derivation of the dq frame theory is added to Appendix A.3.

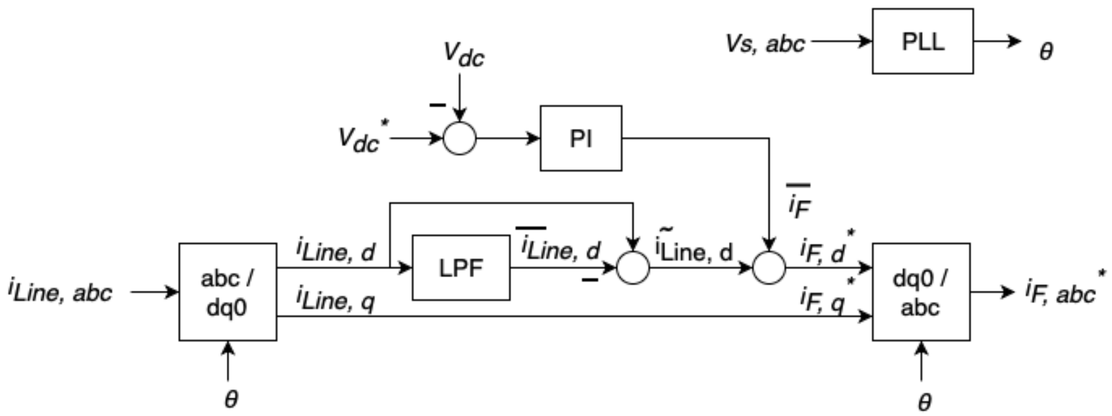


Figure 5.7: Control scheme dq frame theory

The alternative, pq theory, can be implemented much in the same way. The reference currents are calculated based on the instantaneous power constraint. Nonetheless, operating in the dq reference frame facilitates the calculations.

5.2.4 Complete Block Diagram

Figure 5.8 shows the complete block diagram of the proposed controller. As for the traditional STATCOM, reactive compensation is provided by the AC voltage controller. The DC link voltage is controlled and maintained by a DC voltage. A control loop similar to the dq frame theory is added to provide harmonic compensation. However, a second DC voltage controller is not necessary. Also, the quadratic fundamental current component is filtered out as reactive compensation is already provided. The final current control signal components are obtained by adding the outputs of the voltage controller and the harmonic compensation loop.

Likewise, as the traditional STATCOM and AF, the developed STATCOM and the combined controller is dependent on a PLL. The PLL provides the necessary system voltage angle. The abc-dq0 transformation is required for both the reactive and harmonic compensation loop.

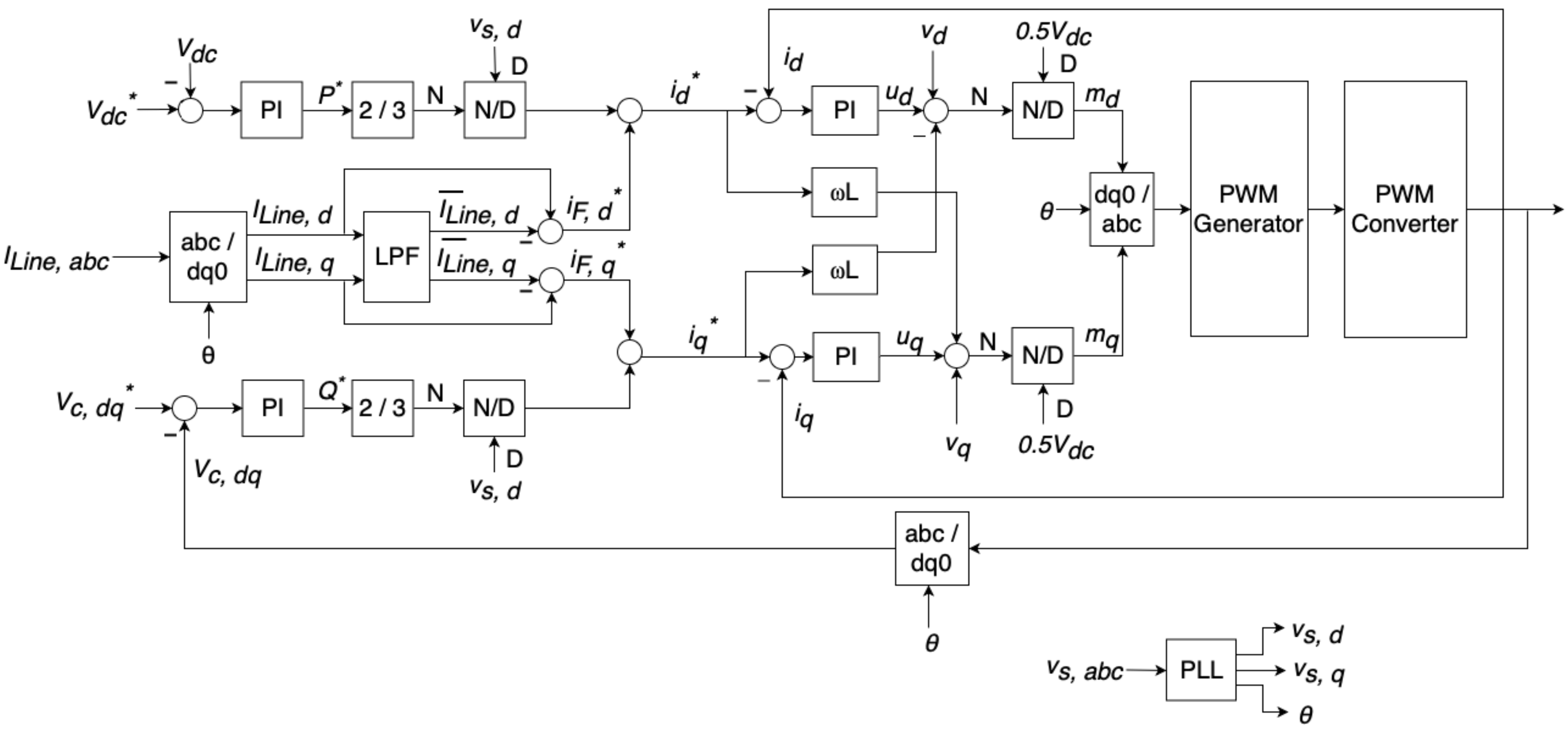


Figure 5.8: Complete combined controller block diagram

Chapter 6

PSCAD Model Description

Modeling and simulations provide insight into the performance and behavior of the developed STATCOM. Multiple programs can be used to achieve this. According to Statnett's wish, the develoeped STATCOM is modeled in PSCAD (Power System Computer-Aided Design). PSCAD is described as an "electromagnetic transient simulation engine" [43], which offers detailed models for most components. A comprehensive and accurate way of modeling components and devices is essential for obtaining results of meaning and use.

This chapter covers the implementation of the developed STATCOM and the combined controller. The controller is reviewed and the simulated cases are presented.

6.1 System Model and Properties

The PSCAD standard library offers many example models, including several STATCOM models. As mentioned, the latest development of the MMC has taken place in recent times. All of the existing example STATCOM models utilize traditional converters, such as the 2 level converter. On request, an updated model of a STATCOM with full bridge MMC was provided by PSCAD. Figure 6.1 shows the original STATCOM model, while model properties are listed in Table 6.1 and 6.2. The component characteristics and tuning are set by the PSCAD development team. All further alterations are implemented by the author. To enhance the effect of the developed STATCOM, the original grid is weakened. To enforce a weaker grid, the system impedance is increased by an RL impedance. The combined controller is implemented. The implemented fault is not triggered during the simulations.

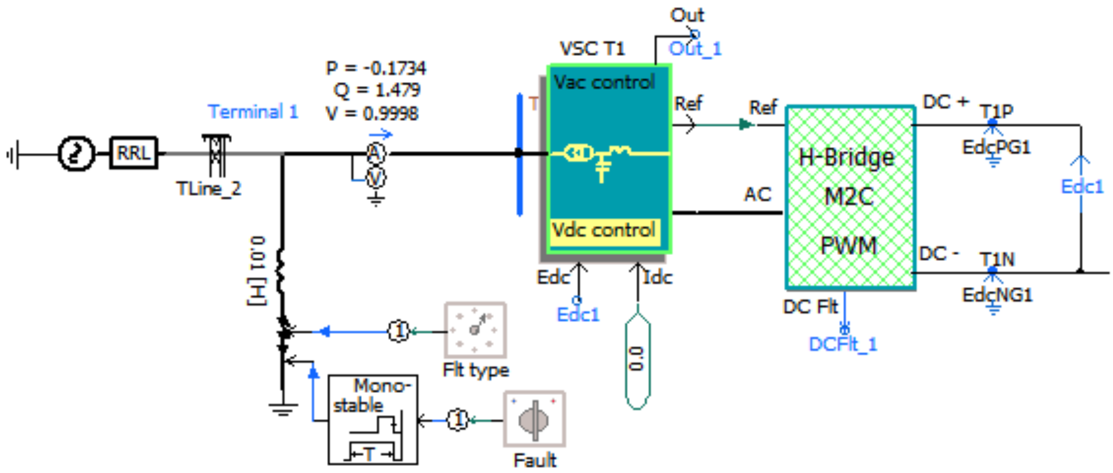


Figure 6.1: STATCOM model scheme

Component	Caption	Data
Voltage Source	Rated apparent power	100 MVA
	Vbase (L-L, RMS)	400 kV
	Frequency	50 Hz
	Phase Shift	0 deg
Transformer	Rated MVA	100 MVA
	Winding 1 Voltage (L-L, RMS)	400 kV
	Winding 2 Voltage (L-L, RMS)	37 kV
	Winding Type 1-2	Y-Δ
MMC	Rated MVA	200 MVA
	Rated AC Voltage (L-L, RMS)	37 kV
	Rated DC Voltage	52.53 kV
	Number of cells, each phase arm	60
	Cell DC capacitor	17600 μF
	Capacitor leakage resistance	100 MΩ
	Smoothing inductance	0.45 mH
	Type of carrier	Phase-shifted carrier
	Carrier frequency as multiple of fundamental frequency	75

Table 6.1: System properties

Controller	Caption	Data
Inner Current Controller	Kpd	1
	Tid	0.001
	Kpq	0.65
	Tiq	0.01
AC Voltage Controller	KpAC	1
	TiAC	0.002
DC Voltage Controller	KpDC	1
	TiDC	0.5

Table 6.2: Controller properties

6.2 Combined Controller - Sources of Disruption

The original model does only offer reactive compensation. Thus, the controller must be altered to enable harmonic compensation. The combined controller should be implemented as proposed by Figure 5.8. The main alterations and changes will be located in the controller block of Figure 6.1. In addition to the control unit, the control block includes a step-up transformer and circuit breaker.

The combined controller and the developed STATCOM itself are not ideal, and non-ideal components connect the developed STATCOM to the grid. Losses and time delays disrupt the compensating current. Necessary measures must be taken to account for significant disruptions. If not, the harmonic compensation may become not only ineffective but aggravate the TDD. Imagine the harmonic compensating current having the same phase as the original harmonic current. This would double up the harmonic content. To successfully control the harmonic compensation current, the controller must account for disruptions. The next section identifies some of the most obvious sources of disruption. Measures reducing the impact or removing the source of disruption to obtain an acceptable performance are presented. Implementing these measures will alter the block diagram in Figure 5.8.

6.2.1 Transformer Behavior

The combined controller measures the STATCOM current at the converter terminal. The converter terminal is located at the secondary side of the transformer (Δ), close to the MMC. Moreover, the Y-Δ transformer inflicts a phase shift of 30 degrees on the fundamental current and acts like a low pass filter affecting currents of higher frequencies. This distortion must be accounted for to avoid the mentioned destructive outcomes. A possible solution is to quantify the effect of the transformer and implementing an additional compensation control loop. This alternative is error-prone and adds to the controller's complexity. An alternative is to measure the converter current directly at the transformer's primary side (Y). This method assures that the transformer phase shift and filter effects are accounted for. However, the base values must be replaced to match the primary side values. These base values correspond to the high voltage side and using them provides the right scaling.

Figure 6.2 shows how a current on the secondary side of a transformer, *I2a*, lags the primary side current, *Ita*. By inspection, the secondary side current lags the primary side current by approximately 30 degrees. The transformer leakage inductance provides some filtering of the harmonic content [44], altering the phase shift. By measuring at the primary side, one can neglect the transformer inflicted phase shift and filtering.

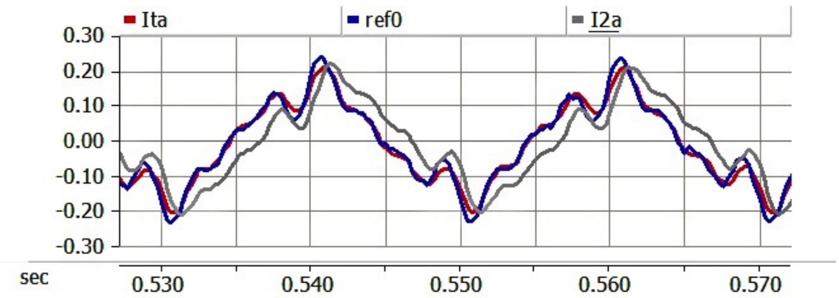


Figure 6.2: Primary and secondary transformer current

6.2.2 Frequency Dependent Distortion

The system impedance inflicts frequency dependent distortion. The controller must account for such behavior to enhance the developed STATCOM performance. If not, the compensation current may have a less than optimal amplitude and phase angle. The RL impedance connecting the developed STATCOM and the grid is such a source of distortion. The inductive part acts as a low pass filter. Such a filter reduces the current amplitude and alters the phase angle. Note that, measuring the current on the primary side of the transformer already accounts for all the frequency dependent impedance on the secondary side of the transformer.

The impact of the RL impedance is illustrated by bode plots, as shown in Figure 6.3. The bode plots are obtained by using the RL transfer function, $Z = R + j\omega L$. The PSCAD frequency scanner meter verifies the results and is in line with the bode plots. The transfer function and frequency scanner meter output are added to Appendix B.4. The figure illustrates how both the impedance magnitude and phase are frequency dependent. For low frequencies, the R component of the RL impedance is prominent and the phase shift insignificant. For higher frequencies, the reactance becomes more prominent and the phase shift settles at 90 degrees due to the inductor characteristics. Thus, the impedance is greater for currents of higher frequencies. For a given voltage level, the current amplitude and phase decrease with higher frequency. This suggests that the amplitude and phase of the harmonic compensation current components decreases with increasing order.

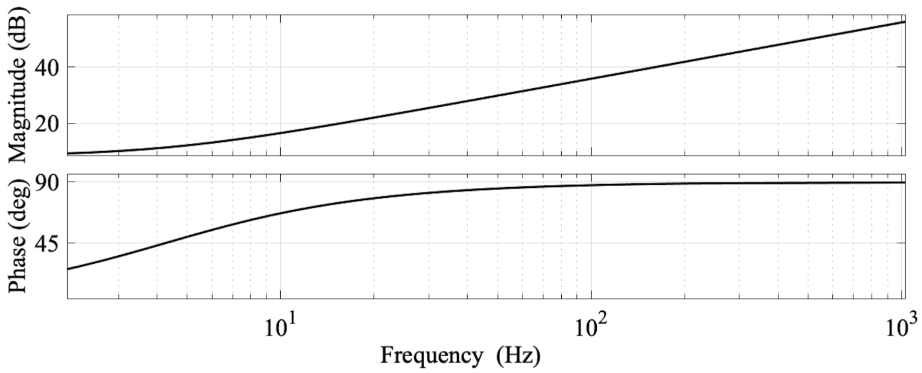


Figure 6.3: Bode plot RL impedance

Phase shifts can be accounted for by adding time delays. The time delays neutralize the time delays inflicted by the passive elements. Frequency-dependent gains can counteract the amplitude variations. The optimal time constants and gains can be obtained by quantifying the disruption of all components causing the non-ideal behavior. However, this is not believed to be feasible and will be challenging for most cases as the transfer function of most components causing non-ideal behavior are unknown. The RL impedance is just one of many non-linear components. Hence, the behavior must be incorporated in another way.

The optimal time delays and gains can be obtained by simple and efficient PI controllers. Such controllers ensure that time delays and gains are adapted to each system configuration. The optimal time delay and gain vary for each harmonic order. Hence, the parameters must be calculated individually.

6.2.2.1 Frequency Dependent Phase Shift

The phase angle error for each harmonic is used to obtain the optimal corresponding time delay. The original idea was to use PI controller to do this efficiently. However, the time delay block in PSCAD does not accept a varying time delay. Using a feedback loop to alter the time delay is therefore not as simple as first predicted. The PI controller is shown in Appendix C.1 should work fine if this was not a problem. Using a Z domain component is an alternative. Instead of using the PI controller or Z-domain components, the optimal time delay for each harmonic order is calculated ”by hand” and implemented as a constant. This method should provide the same results as long as the harmonic currents have a constant phase angle. The optimal time delays are dependent on the system configuration.

6.2.2.2 Frequency Dependent Amplitude

PI controllers are implemented to obtain the frequency dependent gains that account for the amplitude variations. This way, the gain is set in line with the system configuration. The proportional tuning constant of each PI controller is set to be dependent on the amplitude of the harmonic currents. Poor controller performance is avoided with dynamic tuning. The ideal gain is also provided much faster. The integral tuning constant is constant for each simulated case and system configuration.

6.2.3 Controller Tuning

Another obvious source of error is the non-ideal tuning of the controllers. Tuning a controller can be challenging. Poor tuning may not just lead to less optimal behavior, but also damage the STATCOM and system. The original tuning constants are used as they are believed to be sufficient for the combined controller as well. By inspection, it is evident that the steady state error is minimal and considered acceptable. The controller performance is further evaluated when discussing the simulation results.

The current of the transformer's primary side is almost identical to the reference current shown in Figure 6.2. The current is slightly less and lagging compared with the desired reference current. Still, the error is considered insignificant.

6.2.4 Constant Filter Characteristic Frequency

The PLL assures the alignment of the dq0 reference frame and the frequency. Rather than the reference frequency of 50 Hz, the instantaneous frequency is used during transformation. This way, minor frequency variations are not a concern when performing the dq0 transformation. However, the characteristic frequency of the band pass filters is constant. These filters let currents of the characteristic frequency pass. In order to include minor frequency variations, the filters are tuned so that they obtain a sufficient bandwidth. A too large bandwidth would be disruptive as it allows currents of unwanted frequencies to pass. Figure 6.4 shows the bode plot of the bandpass filter with a characteristic frequency of 250 Hz. The same filter constants, expect the filter characteristic frequency, are used in all filters.

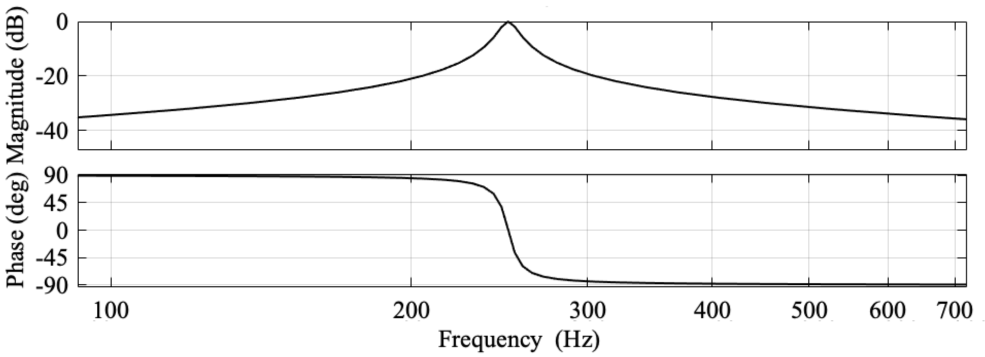


Figure 6.4: Bode plot band pass filter, characteristic frequency 250 Hz

The filter phase shift is only zero at the characteristic frequency. However, the possible frequency deviation is limited and measures that counteract the unwanted phase shift is previously described and implemented.

6.3 Modified Combined Controller Scheme

Figure 6.5 shows a modified combined controller. This controller accounts for some of the mentioned non-ideal behavior by incorporating appropriate measures. The controller is implemented as shown by the figure. The only exception being a limited number of harmonic addends. Also, as mentioned the time constants are calculated ”by hand” and the additional PI controllers set the gains.

Snapshots of the PSCAD model can be viewed in Appendix C.1.

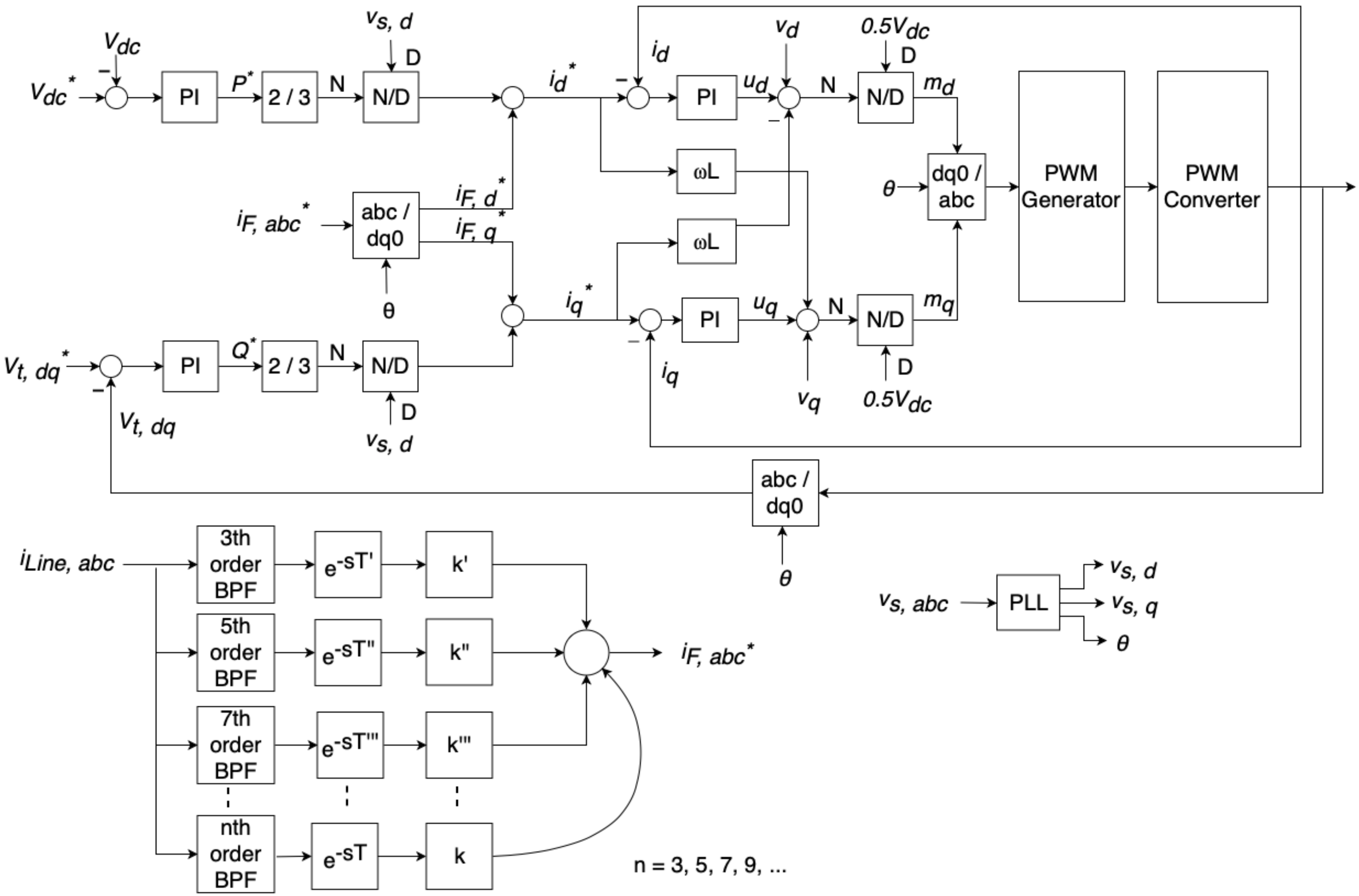


Figure 6.5: Complete modified combined controller block diagram

6.4 Case Descriptions

Multiple cases are simulated. This way, multiple aspects of the control response are shown. The cases are presented in increasing order of complexity.

6.4.1 Case 1: Base Case - No Added Harmonic Content

The proposed combined controller should be able to provide reactive compensation with and without the presence of harmonic content. Before introducing harmonic pollution, the base case without added harmonic content is simulated. The performance of the developed STATCOM is considered during a varying system voltage level. Figure 6.6 shows the developed STATCOM model connected to a single voltage source. The single voltage source represents the grid. The system includes a harmonic current injection component. During this case, the harmonic current injection component does not produce any currents. This should disable the harmonic compensation loop.

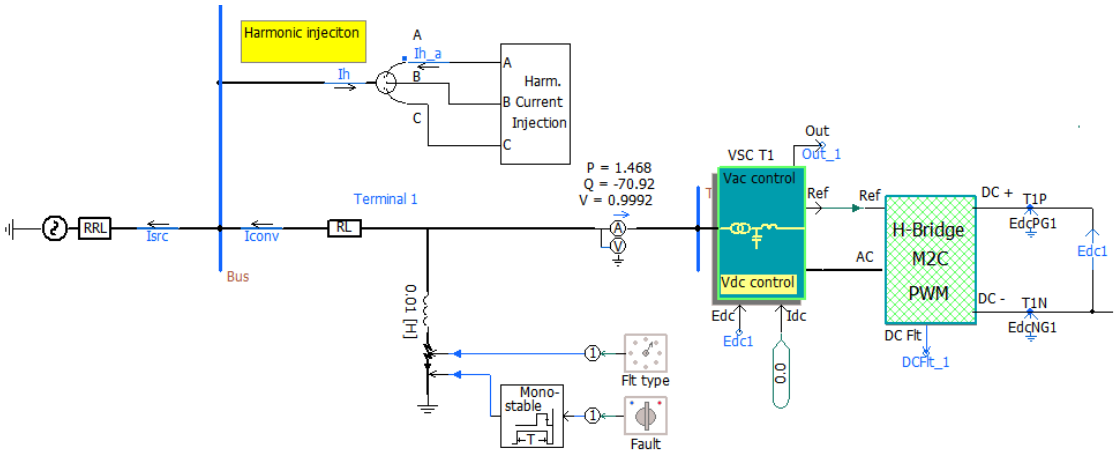


Figure 6.6: Case 1 & 2 system model

It is assumed that the harmonic content generated by the developed STATCOM and system is insignificant. As argued in the theory, the MMC with PWM produces less harmonic currents than the alternatives. The low amount of harmonics is one of the primary reasons for installing a STATCOM. Harmonic compensation should, therefore, not be necessary. However, the controller must still supply reactive compensation.

6.4.2 Case 2: Harmonic Currents Injection

Harmonic currents are injected into the same system as Case 1. Currents of the fundamental, 3rd, 5th and 7th order are injected into the system. The amplitude of these currents is set to be 0.01 kA. The system should perform active filtering of the injected harmonic currents. Reactive compensation should take place as for Case 1.

6.4.3 Case 3: New England Power System

A larger grid is considered to show the effect of installing a developed STATCOM in a more complex grid. A well established and much-researched grid, the New England Power System, is used. PSCAD offers a complete model of the New England Power system [45]. Most of the parameters are kept as they are given. However, the following alterations are implemented

- A developed STATCOM is connected to bus 24
- A varying voltage source is connected to bus 6
- An arc furnace is connected to the grid
- The fundamental frequency is changed to 50 Hz
- Bus 1, 8, 9 and 39 are removed (including Generator 10)
- The capacitor banks at bus 4 & 5 are removed
- Current through transmission line T16_24 (I1), from generator 6 (I2), from generator 7 (I3), through transmission line T13_14 (I4), though transmission line T16_21 (I5) and through transmission line T23_24 (I6) are measured.

The developed STATCOM is connected to bus 24 in order to improve the bus voltage. A varying voltage source is included to enable a dynamic behavior. The original system does not have any major source of harmonic content. So an arc furnace is added to increase the harmonic content. The placement of the arc furnace is not fixed. The system is simplified to keep the number of nodes below 200. As a result, multiple buses are removed including Generator 10. The overall goal of a STATCOM is to improve the system voltage level. Large capacitors bank offers additional reactive compensation. To weaken the system, the two capacitor banks are removed. The currents are measured to keep track of the THD through the system. Figure 6.7 shows the updated PSCAD model. In addition to the mentioned alterations, the AC voltage reference of the STATCOM transformer is set to 0.98 pu.

In addition to these changes, the nominal voltage at the grid side of the STATCOM transformer is changed to match the grid voltage of 230 kV.

The arc furnace is included instead of having a ”perfect” harmonic current injection component. The arc furnace causes both voltage flickers and inflicts harmonic currents. Harmonics of the 5th and 7th order are the most significant ones. The amplitude of the harmonic currents is time-varying. It is set to vary in a sinusoidal manner, the alternative is a Gaussian manner.

Multiple scenarios of Case 3 are simulated. These are

- 3a - The base case: the arc furnace is connected to bus 24
- 3b - The arc furnace is connected to bus 16
- 3c - The arc furnace is connected to bus 23
- 3d - The transmission line T16_24 is open while the arc furnace is connected to bus 24

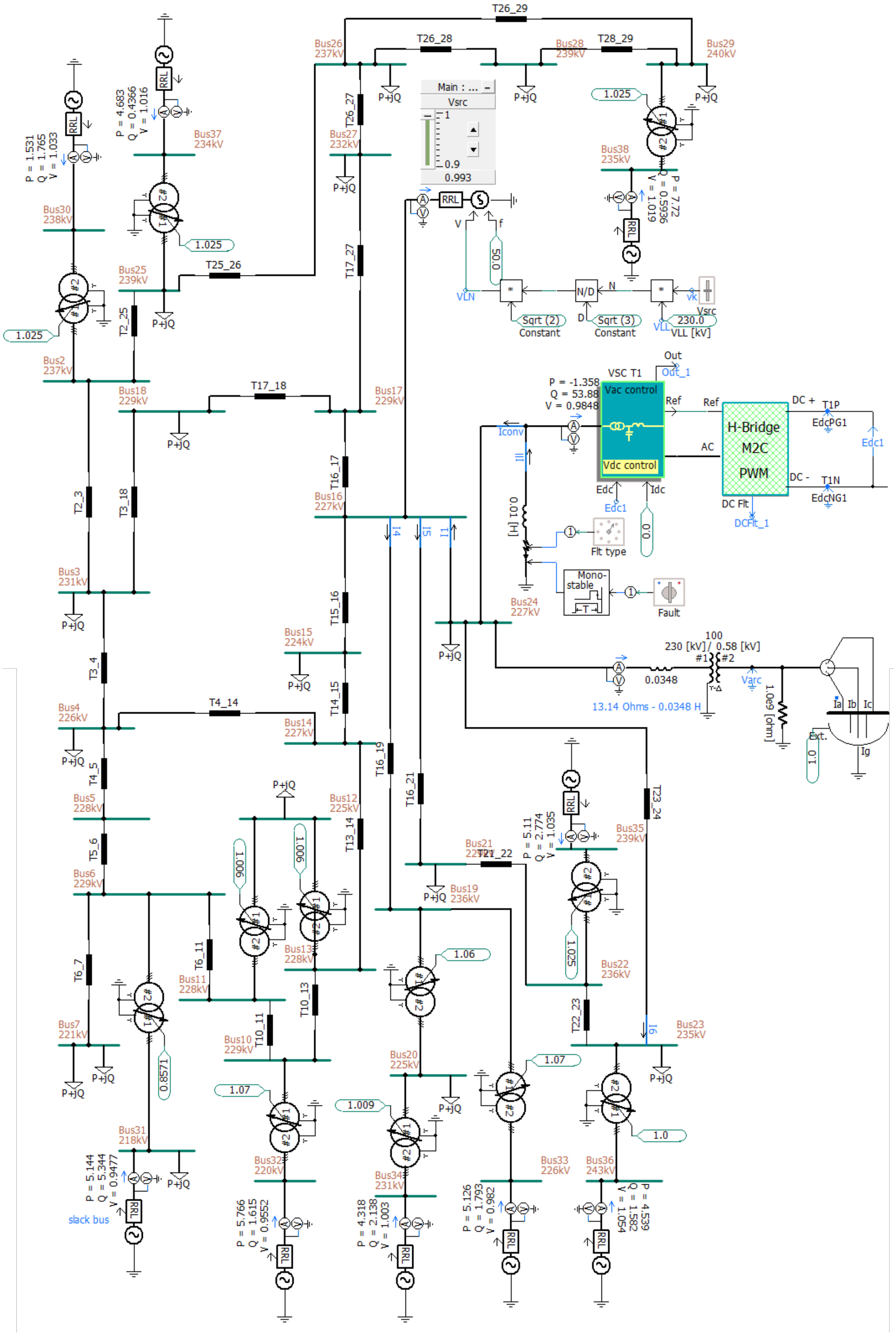


Figure 6.7: Case 3 system model - altered New England power system

Chapter 7

Simulation Results and Evaluation

The main results of the simulation are shown and evaluated in this chapter. The presented results are chosen to highlight the main findings. Further detailed results can be found in Appendix C.1. Common for all cases; the AC breaker is first closed at 0.1 seconds, de-blocking of the converter takes place at 0.2 seconds and active filtering is enabled after 0.75 seconds. The voltage of the varying voltage source is set to be 0.985-0.993-0.96-0.92-0.993 [pu]. These voltage steps take place at 1, 1.25, 1.5 and 1.75 seconds. The initial stages are not considered or shown as the system has not reached steady state. The developed STATCOM is meant to improve the steady state behavior.

7.1 Case 1

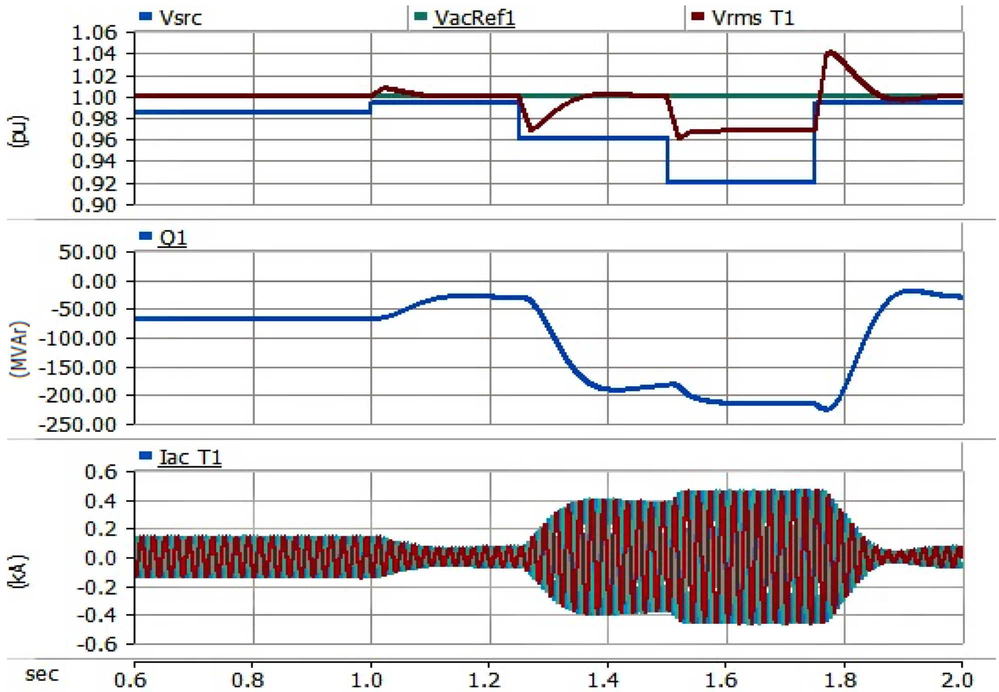


Figure 7.1: Case 1: STATCOM output

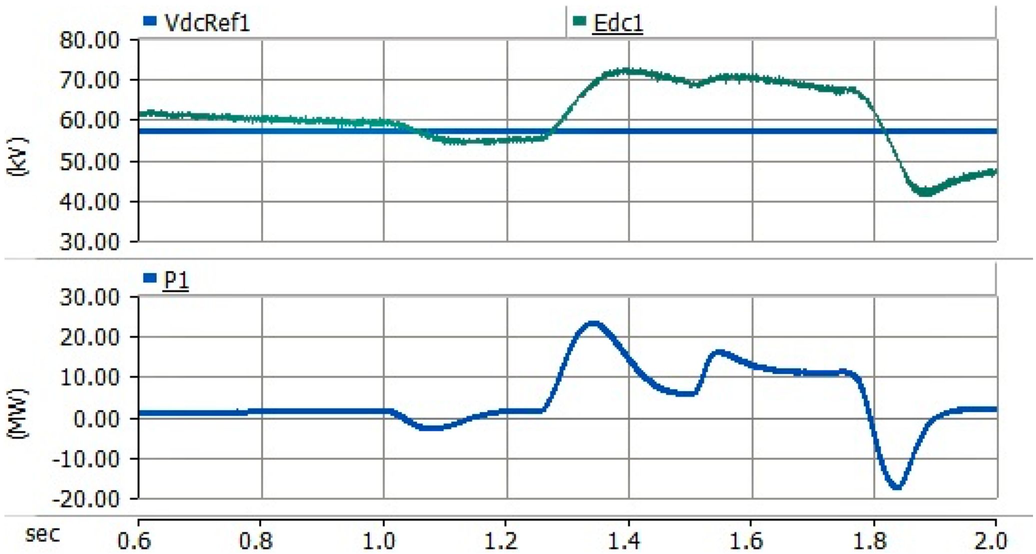


Figure 7.2: Case 1: STATCOM output 2

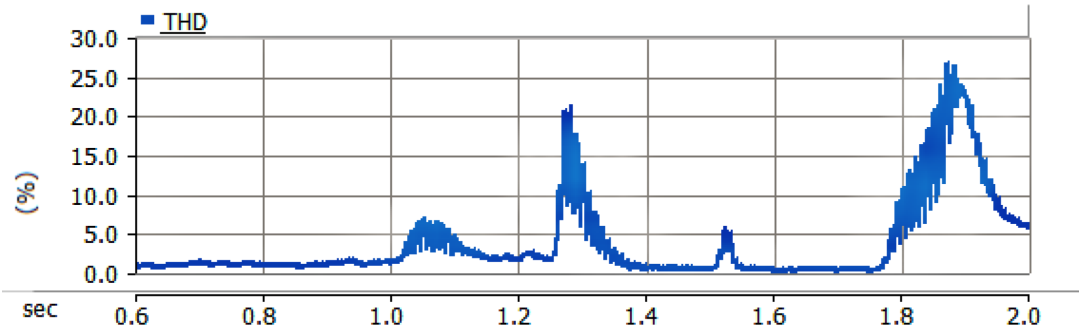


Figure 7.3: Case 1: THD

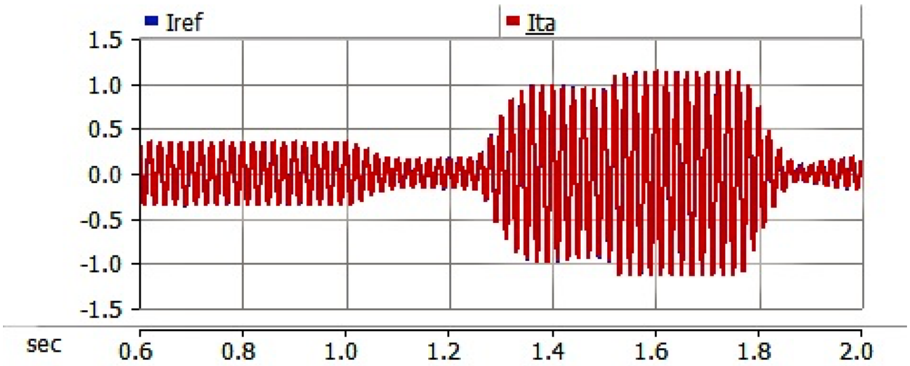


Figure 7.4: Case 1: Reference and transformer current

The effect of installing a STATCOM is most prominent in Figure 7.1. The first plot shows the reference voltage, the time-dependent system/source voltage and the STATCOM controlled transformer voltage. All voltages are plotted in per unit. It is clear that the STATCOM action opposes voltage changes and aims to preserve the desired reference transformer voltage, 1 pu. The system voltage is fixed and not affected by the STATCOM.

While the system voltage changes close to instantly, the AC voltage controller acts slower. The sudden voltage change is detected almost immediately, but retaining the new equilibrium takes about 0.1 seconds. The settling time is noticeable, especially for greater voltage steps. The controller tuning assures a stable response with sufficient damping. Enforcing a too fast controller response can lead to undesirable overshoots and oscillations.

The theory section states that the STATCOM supplies reactive power during low voltages. The system voltage is below the desired voltage reference throughout the entire simulation. The reactive power plot shows a zero or a negative reactive power flow toward the STATCOM. This indicates that the STATCOM operates in line with the presented theory as it operates in a capacitive manner.

The STATCOM rating is set to be 200 MVA. This limits the STATCOM regulating range. As a result, the STATCOM is not able to retain the reference voltage during too large system voltage deviations. The system voltage is 0.92 pu at 1.5 seconds. The STATCOM cannot supply sufficient reactive power while operating within its rating. The maximum possible power flow is reached. The transformer voltage settles at only 0.97 pu. However, this is more than within the given voltage limit.

The final plot in Figure 7.1 shows the current outline. The current amplitude corresponds with the supplied reactive power. The current outline is shown again in Figure 7.4. The transformer current and calculated reference current are almost identical. This suggests that the controller acts close to optimal and that the error is insignificant.

Figure 7.2 shows the DC link voltage and power. The DC link voltage is maintained by active power. In other words, the active power charges the DC link. The DC voltage PI controller tuning assures sufficient damping. Oscillation causes additional stress, losses and heating. The lifetime of capacitors can be reduced as the result of large oscillations. The reduction of oscillations is preferred at the expense of the rise and the settling time.

The steady state THD is close to zero. This confirms that the STATCOM produces few harmonic currents. Harmonics are considered steady state distortions. However, sudden or abrupt changes in the system configurations, such as a voltage change, inflict transients. The transients are short-lived, but visible in Figure 7.3. The transients cause the THD to rise. However, the THD converges towards a value close to zero shortly after the voltage change as the transients are damped out. How fast the transients are damped out is dependent on the magnitude of the voltage change. A higher steady state THD value would have suggested that the controller had failed. The MMC or other system components should not contribute with a significant amount of harmonic currents.

In general, the results of Case 1 support the presented theory. The figures show that the traditional STATCOM behavior is intact with the combined controller. The controller tries to maintain the desired voltage and disables the harmonic compensation loop, as no harmonic currents are detected. Hence, the combined controller acts in the same way as the traditional STATCOM controller should.

7.2 Case 2

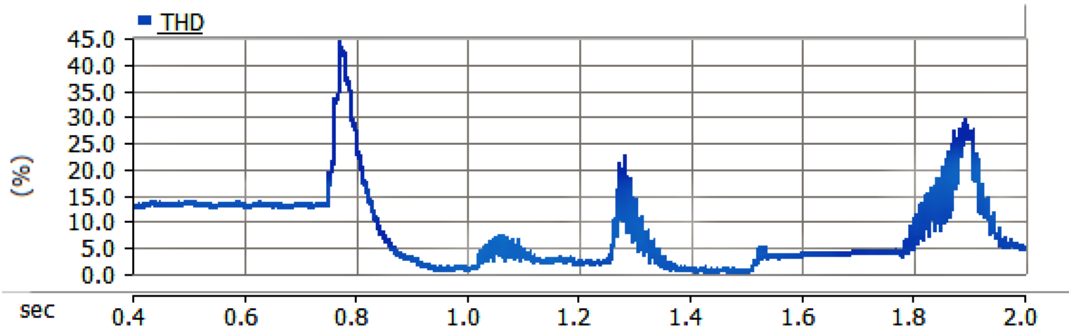
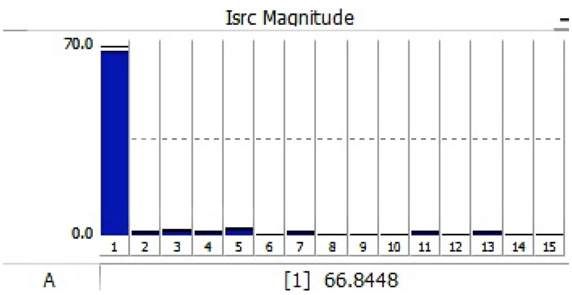
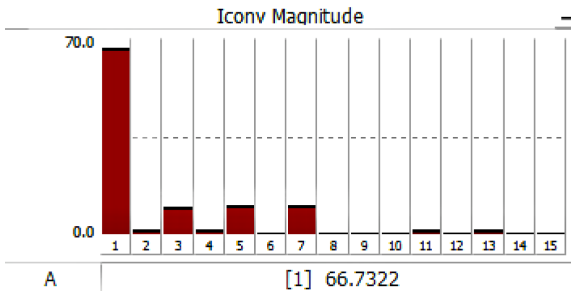


Figure 7.5: Case 2: THD



(a) Isrc magnitude



(b) Iconv magnitude

Figure 7.6: Case 2: Frequency scanner: current magnitude at after 1 second

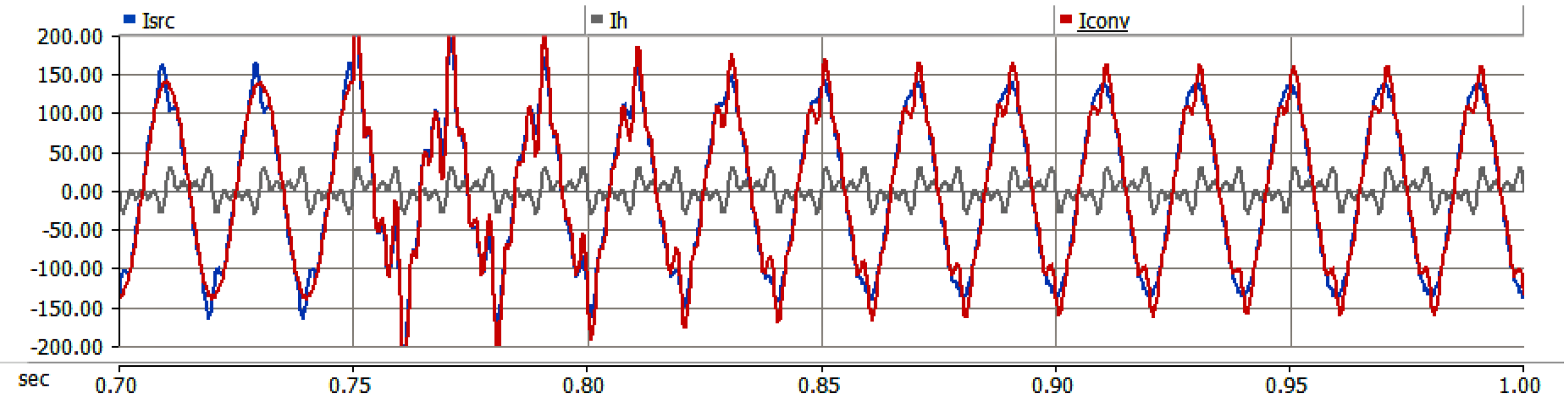


Figure 7.7: Case 2: Voltage source, harmonic current injection and STATCOM current

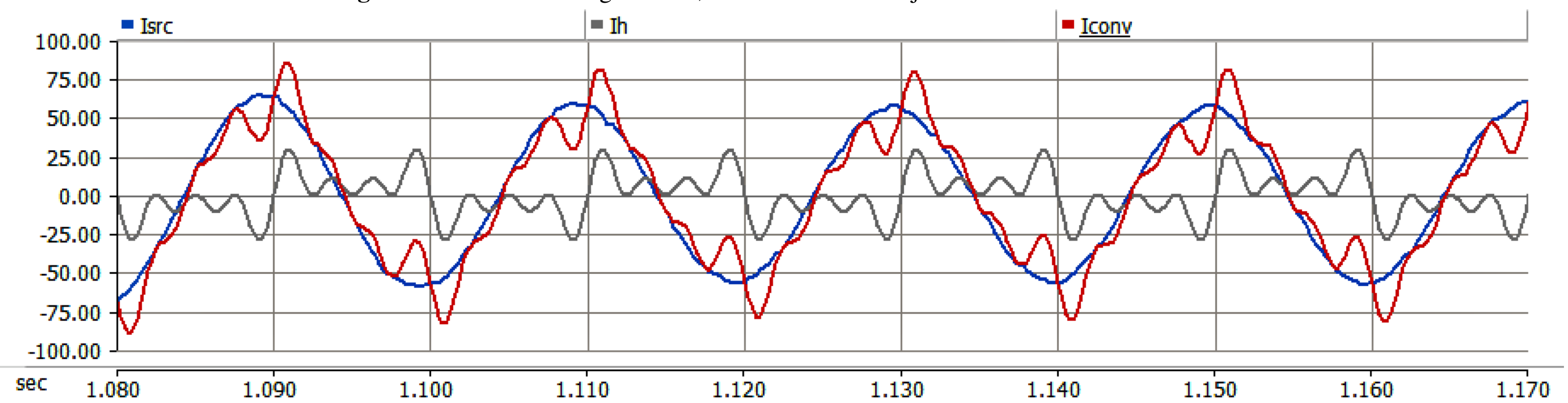


Figure 7.8: Case 2: Close up voltage source, harmonic current injection and STATCOM current waveform, constant system voltage

The Case 2 STATCOM output plots corresponding to Case 1 Figure 7.1, 7.2 and 7.4 are added to Appendix D.1. These Case 2 figures are equal the corresponding Case 1 plots in outline and order of magnitude. Thus, the Case 1 discussion of figures and control applies for the Case 2 plots as well. In addition to reactive compensation, the developed STATCOM of Case 2 performs active filtering. This cannot be confirmed by these figures.

The presence of harmonic currents current are obvious in Figure 7.5. While the steady state THD for Case 1 is close to zero, the steady state THD level is higher than 15% before the active filtering is activated. Active filtering is enabled at 0.75 seconds. The immediate reaction of enabling active filtering is a temporary spike in THD. The phase and magnitude of the harmonic compensation current are not in line with the desired values. However, PI controllers assure that the active filtering is adapted to the system configuration within 0.5 seconds. Thus, the THD converges towards a value close to zero. From this point on, the THD of the Case 1 and 2 systems are almost identical due to the active filtering. As for Case 1, the THD increases each time the system voltage changes. However, the transients are soon damped out.

At 1.5 seconds, the THD settles at a greater value than for Case 1. As for Case 1, the STATCOM has reached its rated value. Further reactive and harmonic compensation are not possible as the STATCOM must operate within its ratings. For this case, the THD is still relatively low.

Active filtering can again bed confirmed by Figure 7.6. The magnitude of the different current components that makes up the voltage source current (*Isrc*) and STATCOM current (*Iconv*) are shown. The figure shows the situation after 1 second. The STATCOM produces currents of the same amplitude as the measured injected harmonic currents. The harmonic currents are canceled out, instead of having the voltage source supply or absorb them. This only works if the STATCOM harmonic compensation current is phase shifted by 180 degrees compared with the injected harmonic currents. This is confirmed, as the only significant voltage source current component is the fundamental current. Additional plots confirming the correct phase is added to Appendix C.1.

Figure 7.7 shows the current waveform of the voltage source (*Isrc*), STATCOM (*Iconv*) and harmonic current injection component (*Ih*). The figure shows how the STATCOM alters both its own and the voltage source current waveform. The STATCOM current transforms from being sinusoidal to non-sinusoidal. At the same time, the voltage source current goes from a non-sinusoidal waveform into a more sinusoidal waveform. It is clear by these figures that the amplitude of the fundamental current component of both the STATCOM and voltage source stays more or less the same after active filtering is enabled. The temporary increased THD is visible for about 0.1 seconds. Figure 7.8 shows the sinusoidal voltage source current waveform up close. It is clear that the STATCOM harmonic compensation current is in phase with the harmonic injected current, Ih. However, the currents are actually of the opposite phase but measured in opposite directions.

The presented figures confirm that the harmonic compensation loop works. The harmonic currents are canceled out and further dissipation is prevented by active filtering. At the same time, the STATCOM performs reactive compensation as for Case 1.

7.3 Case 3

Regulating the voltage of the New England power system requires more power than for Case 1 and 2. Keeping the reactive power balance is more demanding for such a large system. The STATCOM will, therefore, hit its rating easier. The reference ac voltage is set to 0.98 pu, to reduce the demanded reactive power during low voltage. Thus, reducing the time the STATCOM operates at a full load. Ideally, the reference voltage should be implemented as a span corresponding to the given limits.

By default, the arc furnace current amplitude is set to vary in both a sinusoidal and Gaussian manner. To limit the possible variations and provide some consistency, the Gaussian variation is removed. The current amplitude varies with a frequency of 8.8 Hz.

Case 3 is the last case. However, multiple scenarios with different system configurations are simulated. This way, multiple aspects can be reviewed. First, the base case results are shown. Then the arc furnace is moved around and finally the transmission line T16_24 is opened.

7.3.1 Case 3a: Base Case

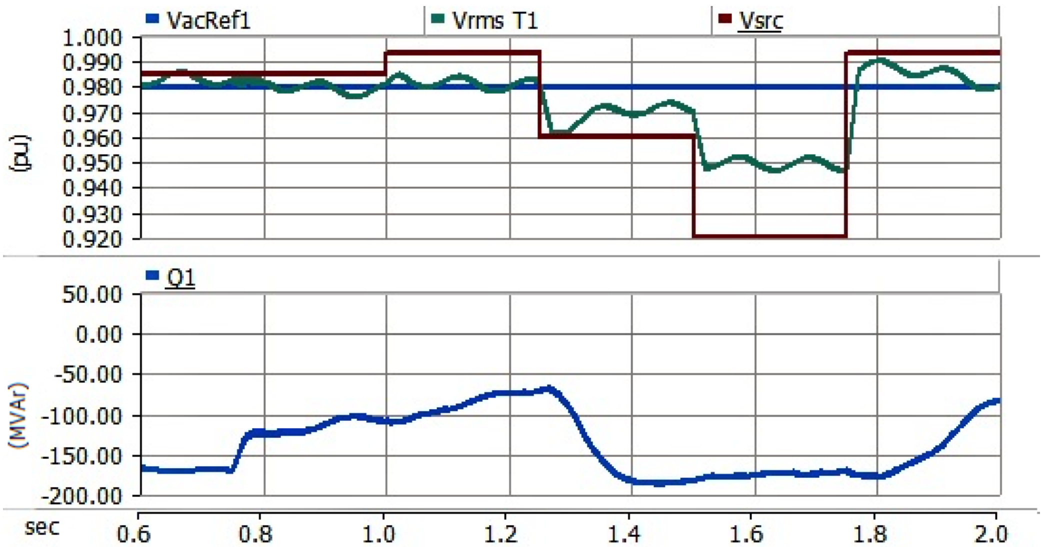


Figure 7.9: Case 3a: STATCOM output

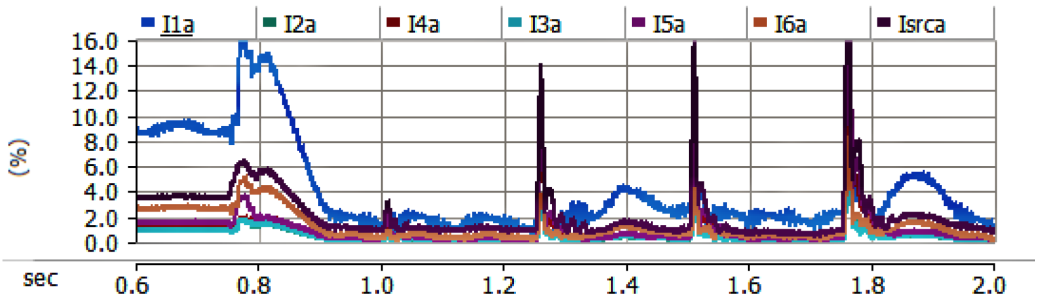


Figure 7.10: Case 3a: THD

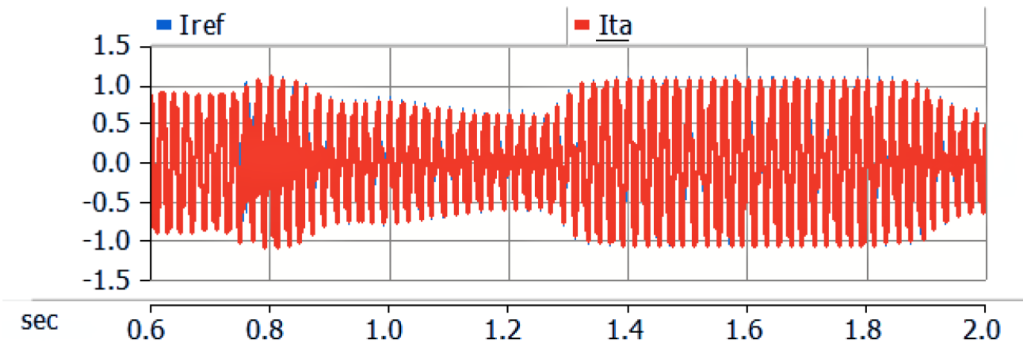


Figure 7.11: Case 3a: Reference and transformer current

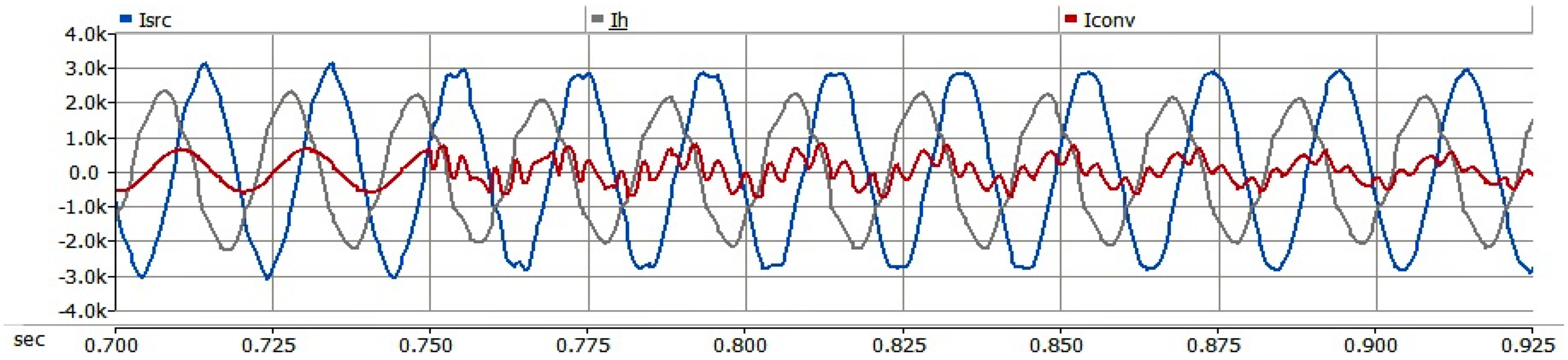


Figure 7.12: Case 3a: Voltage source, harmonic current injection and STATCOM current

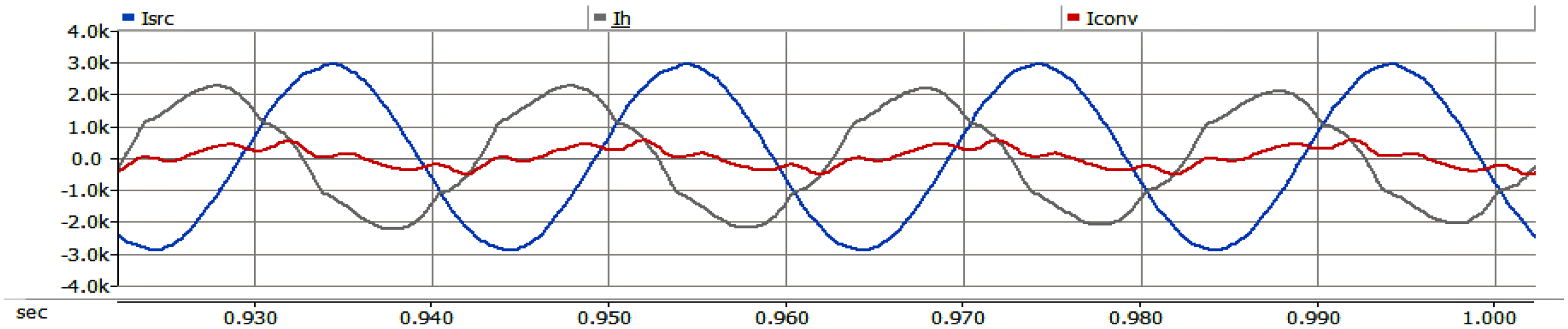


Figure 7.13: Case 3a: Voltage source, harmonic current injection and STATCOM current close up

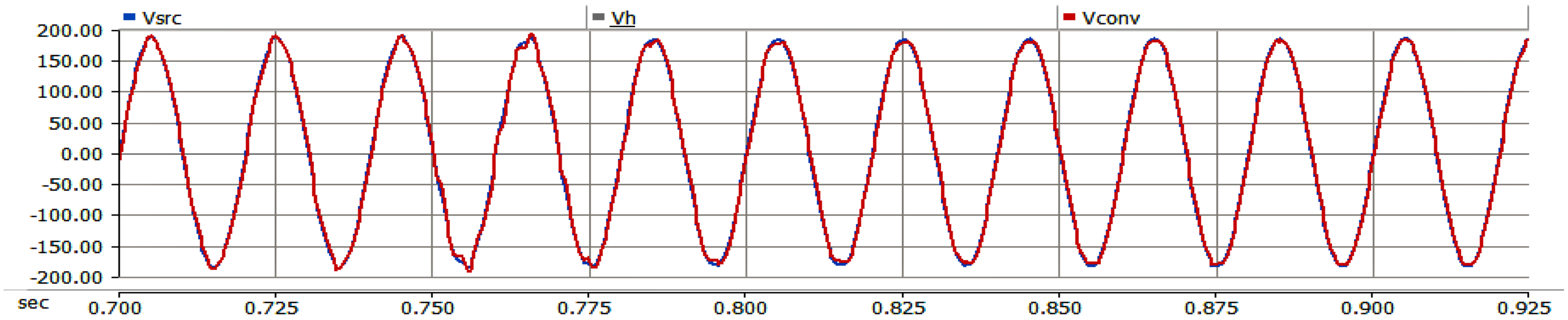


Figure 7.14: Case 3a: Voltage source, harmonic current injection and STATCOM voltage

The results presented in Figure 7.9 and 7.10 are similar to the ones for the previous cases. The reactive compensation increases and improves the STATCOM transformer voltage level. However, the reference voltage has been reduced to 0.98 pu. The primary effect of this is the reduction of reactive power demand. Regardless, the STATCOM still reaches its rating when voltage deviation becomes too great. The behavior of the AC and DC controllers are covered by the Case 1 discussion.

The main change compared with Case 1 and 2 is caused by the sinusoidal varying arc furnace amplitude. The active filter controller gain is dependent on the amplitude of the harmonic content. Thus, the RMS STATCOM transformer voltage continues to vary in a sinusoidal manner after active filtering is enabled. As for the previous cases, the voltage source is fixed and is, therefore, not affected by the STATCOM or the arc furnace. This does not mean that the STATCOM does not impact its surroundings. Voltage improvement can be seen further from bus 24.

Simulations without a varying arc furnace current amplitude show similar results as the base case only without the fluctuating behavior. The figures corresponding to Figure 7.9 and 7.10 are added to Appendix E.1.2.2. However, the sinusoidal varying amplitude is kept as it resembles the actual arc furnace behavior.

Figure 7.10 shows the THD of the measured lines. The THD is reduced almost immediately after active filtering is enabled. The THD of all the measured lines becomes less than 3%. However, the THD of all the measured lines continues to fluctuate in a sinusoidal manner. The controller acts too slowly to incorporate the varying amplitude. The controller action is not adequate as the varying harmonic amplitudes are visible in the THD plot. The optimal gain is calculated too slowly. So within implementing the new gain, the harmonic current amplitude has changed. Nevertheless, the objective of installing active filtering is not the cancellation of such transients.

Harmonic currents are defined as unwanted steady state currents. By definition, the controller eliminates the dissipation of all harmonic currents, without having to act faster. No additional measure is taken to reduce the THD further. Although the fluctuating behavior and mismatch are highly undesirable.

Temporary THD spikes are visible in Figure 7.10 whenever active filtering is enabled or the voltage changes. The reasons for this are explained by the Case 1 and Case 2 discussion.

The controller is not able to recreate the control signal as well as for the previous cases. The mismatch in reference current and transformer current can be seen in Figure 7.11 The transformer current amplitude is less than the reference. In spite of this, the error is considered insignificant.

Figure 7.12, 7.13 and 7.14 show the voltage source (*Isrc*), STATCOM (*Iconv*) and arc furnace currents (*Ih*) and voltage. These plots are somewhat different compared to the

Case 2 plots. The arc furnace fundamental current component is much larger compared with components of a higher order. Thus, the arc furnace current waveform is closer to the optimal fundamental sinusoidal waveform. The voltage source current waveform is also closer to the fundamental waveform before active filtering, as the harmonic content is less significant. However, the effect of active filtering is still visible. Before active filtering is enabled at 0.75 seconds, the current waveform is closer to a triangular signal, rather than a sinusoidal one. This is true for the voltage signal as well, only to a much less degree. The system configurations improves the system strength which reduces the arc furnace's impact on the system voltage. This suggest that the voltage THD is less than the current THD.

Likewise, as for the Case 2 plots, the amplitude of the fundamental current component of both the STATCOM and voltage source is more or less the same before and after active filtering is enabled.

The Case 3a figures confirm that the developed STATCOM can be placed in a more complex system. The voltage level is improved and the dissipation of steady state harmonics are contained. However, the varying amplitude of the arc furnace current has a negative impact on the RMS STATCOM transformer voltage.

7.3.2 Case 3b: Arc Furnace Connected to Bus 16

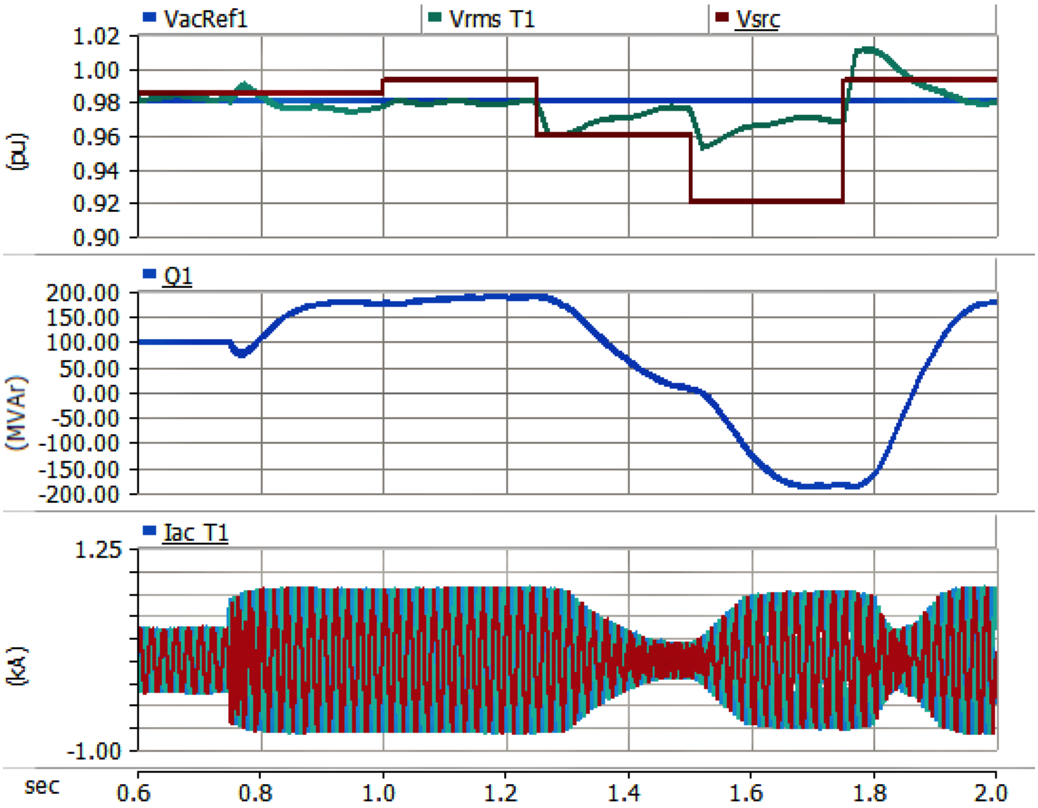


Figure 7.15: Case 3b: STATCOM ouput

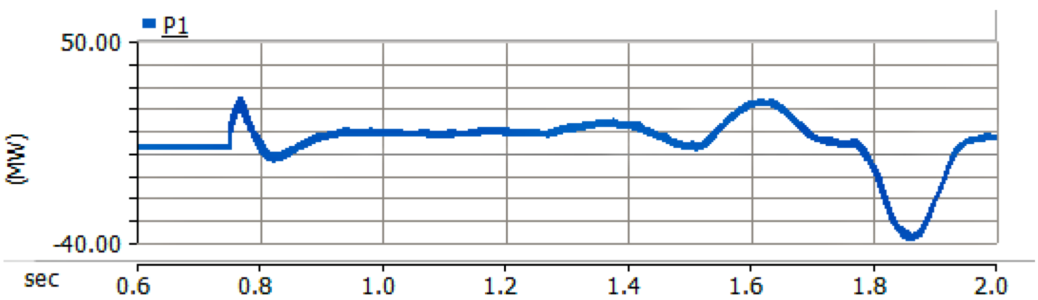


Figure 7.16: Case 3b: STATCOM output 2

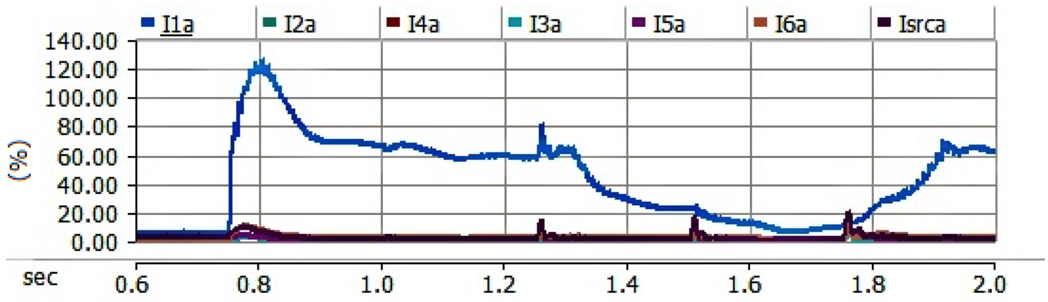


Figure 7.17: Case 3b: THD

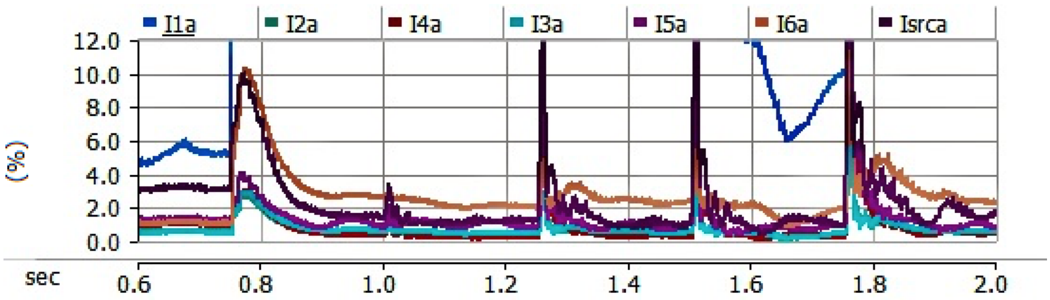


Figure 7.18: Case 3b: THD close up

Moving the arc furnace alters the system configuration. The change in system configuration affects the system power flow and other parameters. This is obvious when plotting the same parameters as for the previous cases.

As mentioned, the voltage at bus 16 is fixed. Connecting the arc furnace to bus 16 does therefore not reduce the bus voltage, even though the load increases. It is not guaranteed that this would be the case for a real system. In spite of this, the fixed voltage source is kept to simplify the analysis. The direct outcome is a stronger grid with less voltage fluctuations. The supply of reactive power is no longer as crucial. To the contrary, the STATCOM absorbs reactive power. This has to do with the reduced reference voltage. Absorbing reactive power is not really necessary. The voltage is well within the given voltage limits. However, as mentioned, the reference voltage is implemented as a constant, not a span. The supply of reactive power is not needed before the voltage source is set to 0.92 pu.

Figure 7.17 shows an increasing THD of T16_24($I1a$) when active filtering is enabled. The immediate theory may be that the active filtering does not work. However, the increased THD implies that the active filtering is in fact working. The source of harmonic content and STATCOM is no longer placed near the same bus. Thus, the harmonic compensation currents must be transmitted from bus 24 to bus 16. T16_24 offers the path of least impedance. The harmonic compensation current almost doubles up the line loading, resulting in a THD well over 50% even after the overshoot. The THD of T23_24(*I6a*) does also increase after active filtering is enabled. This reason for this is believed to be a small mismatch in phase and magnitude caused by the transmission line impedance. However, no measure is taken to account for the transmission impedance as the impact is minimal. A solution could be to measure the harmonic content closer to the STATCOM. The shift in phase and magnitude are then avoided. However, only parts of the harmonic content would be measures as the harmonic content dissipates throughout the entire system. Unlike the THD of T16_24(*I1a*) and T23_24(*I6a*), the THD of the remaining lines is reduced.

The THD of T16_24(*I1a*) is suddenly reduced at 1.25 seconds and continues to decrease until the voltage at bus 16 is increased at 1.75 seconds. The reduction of THD can be explained by the increased current flow at bus 16. The arc furnace current is dependent on the bus voltage. The voltage at bus 16 decreases from 0.993 pu to 0.96 pu and then 0.92 pu during this period. This gives a significant rise in the arc furnace current. Due to the active filtering, the increased arc furnace harmonic current components are still canceled out as long as the STATCOM operates within its rating. The decreasing THD is, therefore, a result of the increasing fundamental arc furnace current. As stated, the THD is inversely coupled with the fundamental current component. The harmonic content is close to constant due to active filtering throughout this period.

The THD of the remaining lines is more or less the same after active filtering is enabled until 1.75 seconds. This can be viewed in Figure 7.18 The minor increase of THD is caused by the STATCOM reaching its rating. The STATCOM is no longer able to increase its power output. Possible reactive compensation has stagnated and the harmonic compensation is reduced. Nevertheless, the THD of the measured line is still low. Note that the steady state THD of the lines further away from the harmonic source is never above 2%, even before active filtering is enabled. The reduction of the THD of these lines is not the primary objective. The minor reductions are just an added positive outcome.

7.3.3 Case 3c: Arc Furnace Connected to Bus 23

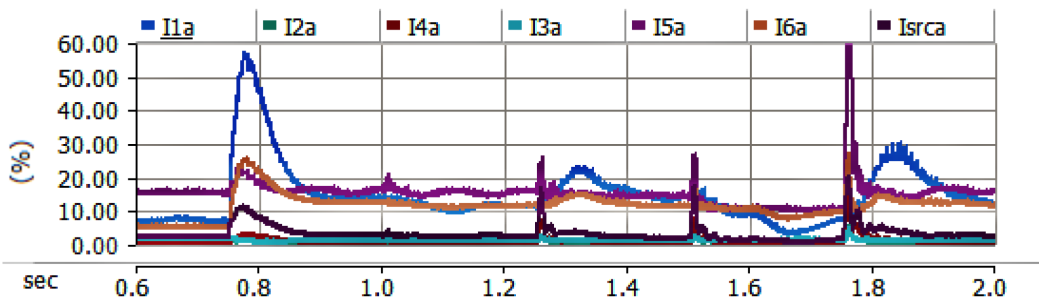


Figure 7.19: Case 3c: THD

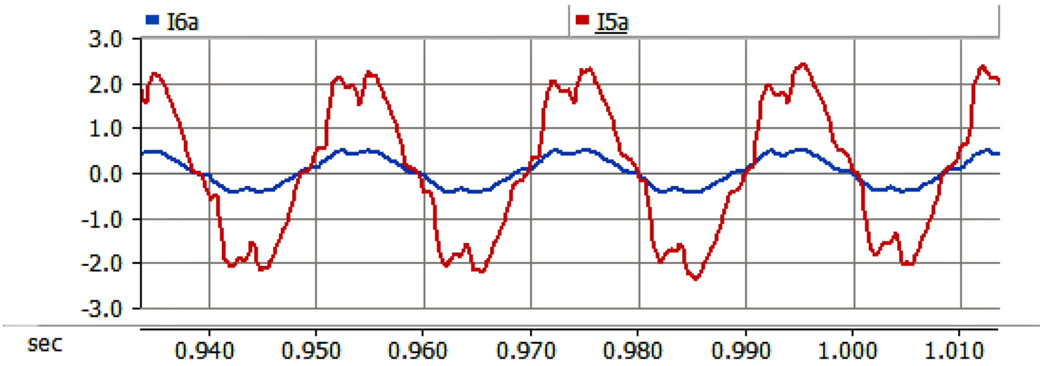


Figure 7.20: Case 3c: T23_24 Current

Moving the arc furnace to bus 23 does not alter the STATCOM output significantly compared to bus 16. The outline of the STATCOM output plots is similar to the Case 3b plots shown in Figure 7.15 and 7.16. The Case 3c STATCOM output plots are added to Appendix E.1.2.5.

The wide known saying; ”current flows through the path of least impedance” becomes evident in this scenario. The system impedance affects the dissipation of the harmonic currents. Before active filtering is activated, much of the harmonic content gets dissipated through T22_23. This suggests a low impedance of T22_23, which is true. The system impedance affects the path of the harmonic compensation current as well.

Figure 7.19 shows how the THD of the measured lines. The THD of T12_21(*I5a*), T16_24(*I1a*) and T23_24(*I6a*) increases after active filtering is enabled. This suggests that the harmonic compensation current is transmitted not only through T16_24 but T16_21, T21_22 and T22_23 as well. T23_24 offers the shortest and direct path between the STATCOM and the arc furnace. However, the impedance of this line is relatively high. The harmonic compensation current simply avoids the high impedance line. This can be confirmed as the THD of the alternative path is high.

The currents through T23_24 and T16_21 are shown in Figure 7.20. The figure confirms that T23_24(*I6a*) is less loaded than T16_21(*I5a*). The THD of T16_21(*I5a*) stays pretty much the same after active filtering is enabled. This would not be that case if T23_24 were to carry the harmonic compensation current. The alternative path with less impedance reduced the conduction losses. In spite of this, using the alternative path is highly unwanted as larger parts of the system are exposed to unwanted and possibly damaging currents.

7.3.4 Case 3d: Arc Furnace Connected to Bus 24 and T16_24 Opened

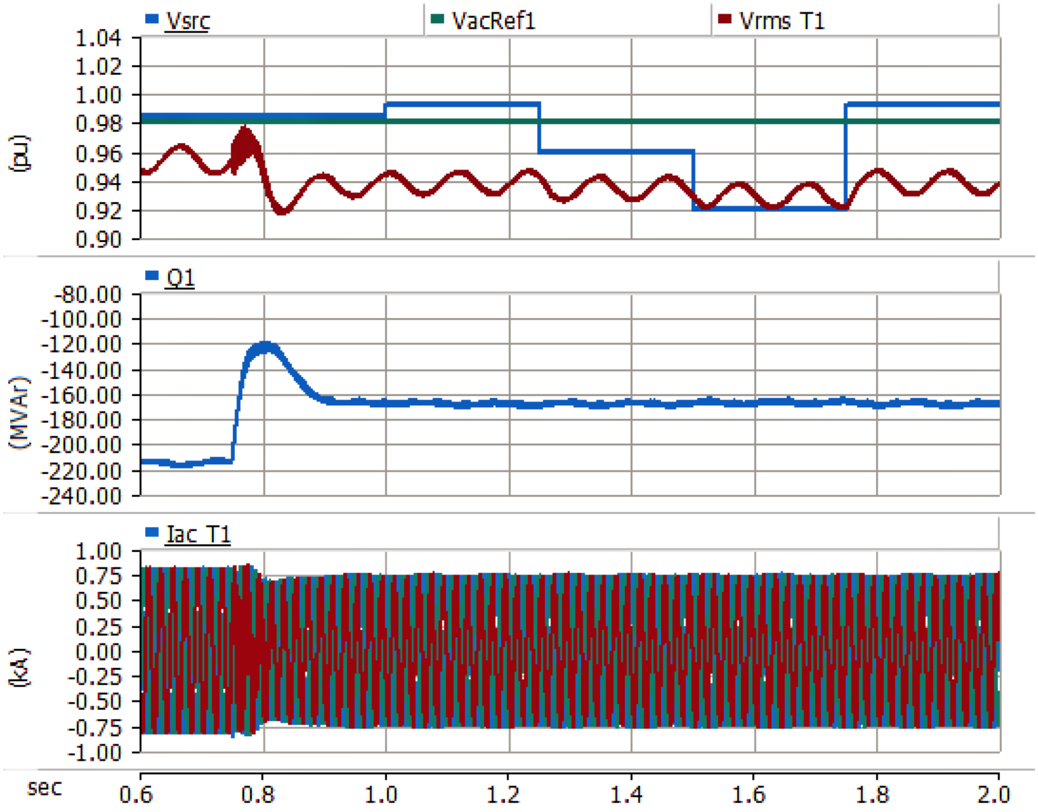


Figure 7.21: Case 3d: STATCOM output

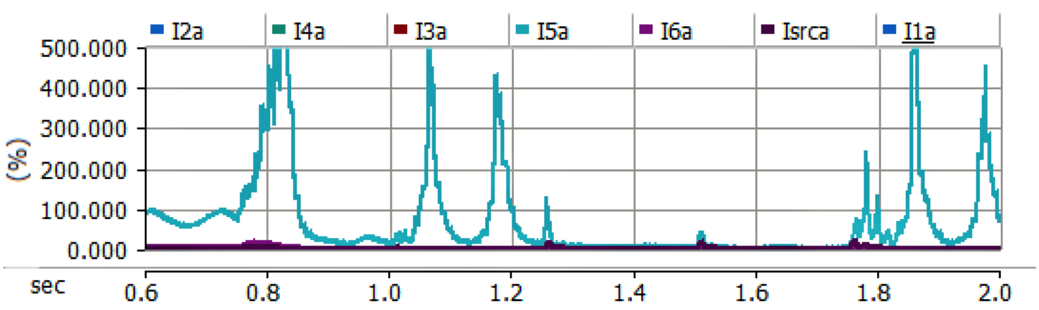


Figure 7.22: Case 3d: THD

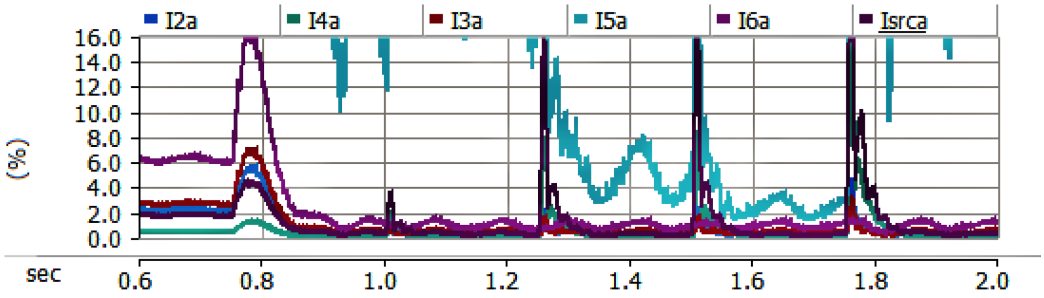


Figure 7.23: Case 3d: THD close up

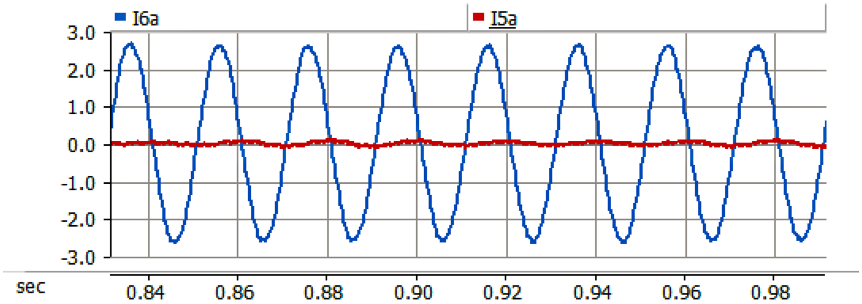


Figure 7.24: Case 3d: Currents through T16_21 and T23_24

Removing T16_24 alters the system configuration significantly. No alternative pathway for the STATCOM and arc furnace current is available. All current must flow through T23_24.

Removing the transmission line weakens the voltage in that area. The STATCOM is not able to maintain the reference voltage while operating within its rating. The STATCOM increases the voltage. However, the reactive power compensation is limited by the STATCOM rating. The reactive power rating is conditional on the nominal voltage and current. As a result, less reactive power is supplied during low voltages. The low STATCOM transformer voltage and the active filtering limit the possible reactive power to 165 MVAr. In spite of the limited reactive power, the THD of most lines is reduced. This can be seen in Figure 7.23.

Placing the STATCOM and arc furnace at the same bus reduces the harmonic content and THD of most lines. However, as discussed the STATCOM is not able to cancel the time-varying amplitude of the harmonic content. These currents are instead transmitted throughout the gird. Although these harmonic currents have small amplitudes, they could give rise to the THD if the fundamental loading of a line is low.

This is the case for T16_21. The system configuration has resulted in a heavy reduction in loading of T16_21 compared to the other system configurations. Although the THD is reduced by enabling the active filtering, the THD is still high. The low loading of the line can be confirmed by Figure 7.24. Compared to T23_24, the loading of T16_21 is more than 10 times less. As a result, the THD of line T16_21(*I5a)* is higher, even though the harmonic content of T23_24 is actually higher than for T16_21.

The STATCOM operates in line with the requirements, despite the high THD of T16_21. The STATCOM is not supposed to cancel transient currents. This, together with low loading of the line, causes the high THD.

Chapter 8

Discussion

This chapter discusses the model implementation and the general results of the simulation. Both the controller implementation and the performance are evaluated. Implementation decisions are discussed and considered in light of the final results. The results are best compared with the scenario without a STATCOM and the traditional STATCOM without the AF feature.

8.1 Limitations and Simplifications

The combined controller is proposed based on the findings of the previously conducted literature study. The presented control strategy is not claimed to be universal. Nevertheless, the choice was made after evaluating the literature findings and is believed to be the best and simplest alternative for this project. Alternative control strategies such as the PQ controller and the $\alpha\beta$ reference frame are not simulated, the time is rather spent on focusing and implementing the more promising controller.

In order to focus on the combined controller, the remaining model is considered less important. As a result, some parts of the original controller are kept without an extensive performance evaluation. This mainly applies to the H-Bridge M2C PWM block. ABB states that the majority of STATCOM VSCs utilize the PWM [5]. The evaluation of alternative modulation units is therefore considered a less important aspect of the model in regards to the project outline. Optimizing such parts of the model may reduce the time of calculation. However, possible improvements are believed to be limited and outside the project scope.

The controller and model are complex. A complex controller assures that the STATCOM operates in line with the requirements. The complex system model is necessary to reflect and incorporate the system behavior. For some cases, an even more complex and dynamic controller may be preferable and better suited. However, the complexity of the combined controller is limited. There are several clear reasons for this. Business wise, the cost is an important aspect. The cost of installing a simplified STATCOM and its control system is less than for a more complex one. However, the cost is only assessed to a limited extent in this paper. A more significant aspect for the engineer is how a simpler combined controller facilitates the implementation and post-analysis. This is not in conflict with the project outline. To the contrary, a less complicated controller is less error-prone and reduces the time of implementation and calculation.

Simplification may reduce the possible impact of the STATCOM or validity of the model. Hence, the simplifications must be sufficiently justified e. g. a faster response, reduction of cost and so forth. An example of this is the limited current compensation frequency spectrum. The controller used during simulation allows cancellation of the 3rd, 5th and 7th order. This reduces the number of PI controllers and tuning. Harmonics of a lower order are considered as they often have a larger amplitude. The possible damage caused by harmonic currents is coupled with the current amplitude. The amplitude of harmonic currents is generally less for higher orders as the amplitude and order are inversely coupled, due to frequency-dependent impedances. Still, the model can easily be expanded or adapted to cancel out the harmonic current of other orders.

By simplifying the controller, troublesome and time-consuming implementation can be avoided. Instead of varying time delays, static time delays are used. This simplifies the model but is not optimal. Time delays must be tuned for each system configuration. This is not necessary for the varying gains, as the PI controllers are used. Still, it is believed that implementing the varying gain could be implemented more efficiently with fewer PI controllers. Using the original PI controller with larger bandwidths to do this is one option. This may not be feasible. However, it could reduce the time of calculation, but implementing such a solution is believed to consume much time.

The final current control signal is obtained by the addends; the harmonic - and reactive compensation current control signal. The harmonic compensation current control signal does not include a fundamental current component. So adding these two addends works well. In traditional AFs, the fundamental component of the quadratic harmonic compensation current can supply reactive compensation. For the developed STATCOM, the fundamental quadratic harmonic compensation current component would double up the reactive compensation. The time before this is adjusted by feedback loops would be significant. To simplify and improve the controller, the fundamental harmonic compensation current is therefore completed disregarded.

The initial STATCOM voltage level is affected by the harmonic compensation current. The ICC initial input is no longer is optimal, considering only reactive power compensation. Feedback assures that this is corrected. Although obtaining the desired voltage level takes more time. Altering the controller may fix this or at least reduce the settling time. Nevertheless, the harmonic currents, and therefore, the corresponding control signals are assumed to have a less order of magnitude compared with the reactive compensation current. The contribution of the compensation current control signal and therefore the possible time delay is considered to be insignificant when it comes to obtaining the desired voltage output. By not accounting for this, the implementation is simplified. Either way, hard limiters are implemented to make sure that the STATCOM operates within its rating. The STATCOM rating was in the original model considered by the voltage controllers. For the combined controller, the rating is considered after the summation of the harmonic and reactive compensation current control signals.

8.2 Simulation

The TDD of the transmission lines is not measured as the line ratings are unknown. Instead, THD is measured. The THD and the fundamental component are inversely coupled. Much information is lost if the fundamental component is not known. Still, analyzing the THD plots provides much information when done with care. If the fundamental current components stay constant, one can assume that a decreasing THD is equivalent to a decrease of harmonic currents.

The THD is always higher or equal the TDD. Thus, the TDD limits can not automatically be used when analyzing the THD. However, if the THD is equal or less the given TDD limit, it is guaranteed that the TDD is equal or less than the limit too. Thus, the THD should be as low as possible. If the fundamental loading is low, higher THD is accepted.

8.2.1 General Observations

The simulation and discussion of the different cases shows and identifies multiple strengths and weaknesses of the developed STATCOM. Furthermore, different system configurations affect and alter the results.

For all the simulated cases, the developed STATCOM performs reactive compensation. The developed STATCOM aims to retain the reference voltage regardless of system configuration. This is believed to be the case whichever ever bus the developed STATCOM is connected to. How successful the developed STATCOM is depends on the system configuration and grid strength. For the simulated cases, Bus 1/24 voltage is kept equal to its reference voltage as long as the voltage source voltage deviation is limited and T16_24 is intact. Both the ability to supply and absorb power is limited during large voltage deviations. The STATCOM does also improve voltages at nearby buses. The STATCOM provides better reactive balancing of the entire system. As discussed, the voltage at bus 16 is fixed.

MMC technology enables continuous reactive compensation. The amount of reactive compensation is adapted to meet the system demand. If the STATCOM rating allows it, the action of the controllers makes sure the voltage reference is obtained almost instantly. The tuning of the controllers results in some voltage overshot. However, the overshot is never greater than the initial voltage source voltage deviation. Besides, the voltage converges towards the reference voltage fast without oscillations.

The overshoot and settling time of the DC voltage controller is significant. The Case 1 discussion cover this. However, this applied to all the cases as the same DC voltage controller is applied. Further tuning may enhance the performance. However, correct tuning of a control system is challenging. Also, the tuning of the PI controller is more limited than for the PID controller. A PI controller is cheaper at the expense of the controller performance. Nevertheless, unwanted behavior must still be avoided i. e. DC voltage oscillation. Thus, a robust system is considered more important than a short settling time. Hence, the controller tuning is kept as shown.

The developed STATCOM performs active filtering while regulating the voltage level. The harmonic content is significantly reduced for all the simulated cases when active filtering is enabled. This is best observed by analyzing the TDD. However, the reduction of the harmonic content is also confirmed by the THD plots. For illustration purposes, harmonic compensation is enabled 0.55 seconds after reactive compensation. The STATCOM rating limits the harmonic compensation during significant voltage deviation. However, some improvements are still visible during such times.

After the initial spike, the THD of all measured lines in Cases 1, 2 and 3a is reduced. As the fundamental current component stays close to constant for all these cases, the decreasing THD confirms the reduction of harmonics. This suggests that also the TDD is reduced. Still, the THD of some lines increases when active filtering is enabled. This is the case whenever the STATCOM and arc furnace are not placed at the same bus. After active filtering is enabled, lines with an initial low loading of harmonic currents may need to carry the harmonic compensation current. Thus, the THD and TDD of these lines increases. However, this is necessary in order to reduce the dissipation of harmonic currents in the remaining system. Moreover, the voltage variations do also affect the THD as the voltage and current are coupled. Unlike the THD, the TDD is believed to be constant in spite of a varying voltage. Active filtering keeps the harmonic content constant. This is only true if the STATCOM operates within its rating.

The sources of harmonic currents are known for all the simulated cases. The original system does not produce sufficient harmonic currents to justify active filtering. The harmonic injection component and arc furnace are added to impose the need for filters.

However, the STATCOM should be able to prevent further dissipation of harmonic caused by unknown sources as well. Instead of measuring the current at the harmonic source, one could measure the current through a line closer to the STATCOM. No such case is simulated as the original harmonic content of the original models is insignificant. However, as previously mentioned measuring the harmonic current far from the source is not optimal. The harmonic currents get dissipated throughout the entire system. The meter will only detect the harmonic current through this particular line.

The Case 3 simulations suggest that the STATCOM must be placed keeping the grid configuration in mind. If not, the harmonic content may impact more than the necessary amount of lines and components. Out of the simulated alternatives, the alternative with the STATCOM and arc furnace connected to the same bus shows the best results. This way, the harmonic dissipation is contained. No additional lines must carry the harmonic compensation current. Still, sudden failures or contingencies alter the power flow. This must be considered when operating the system. Placing the arc furnace and STATCOM at the same bus may not be feasible. Then, a more detailed power flow analysis of alternative system configurations must be conducted.

The presented findings suggest that the combined controller acts in line with the presented theory. The combined controller must fulfill the presented objectives since the developed STATCOM does. The simulations show that the voltage level is improved and the harmonic content is reduced. This supports the installment of the developed STATCOM. However, other alternative devices are not simulated. As a result, the analysis is subjective and only comparable to a scenario without active filtering and a scenario without the STATCOM. Also, the developed STATCOM model and simulation results do not reflect all of the STATCOM advantages and disadvantages. The model does not take into account the fact that the amount of renewable energy production will increase. The STATCOM will become even more beneficial in a system with a higher penetration of renewable energy. Nor does the model consider the high cost of installing a STATCOM compared with alternative measures. These and other aspects are previously discussed but not weighted against each other as this is not the primary objective of the project. Still, these factors must be considered before deciding to install a developed STATCOM.

8.2.1.1 Possible Improvements

The STATCOM and its controller operate in line with the objectives. Nevertheless, further improvements are possible. General improvements, e. g. faster control, less overshoot and a simpler or more complex model depending on the need are most likely possible. Such measures may provide significant improvements.

The calculation of the ideal time delay should be performed by PI controllers. Thus, the controller does not need to be altered when the system configuration changes. If this is implemented, the controller is believed to be universal.

The THD of a line should converge towards a constant value if the system operates in steady state. The varying arc furnace amplitude suggests that the system is not in steady state. As mentioned, the objective of active filtering is to filter out the steady state harmonic currents, not transient currents.

Still, that the amplitude varies in a sinusoidal manner suggests it can be predicted, quantified and that countermeasures can be implemented. However, in real life, the arc furnace current would never vary in a pure sinusoidal manner. The amplitude is by default set to vary in both a sinusoidal and Gaussian manner. The Gaussian variation cannot be predicted. Nevertheless, the gain is not altered fast enough to account for the time-varying amplitude. The PI controller is too slow to account for the transient behavior.

So rather than trying to compensate the time-varying amplitude, the PI controller should obtain an optimal constant gain. Filters can be used to remove the time varying component of the gain signal. Then, at least the STATCOM current, voltage and power output becomes steady state values. The THD would still fluctuate as transients are still present.

Implementing a voltage reference span would reduce the demand for both supply and absorption of reactive power. Then, the STATCOM would spend less time operating at its rated value. If necessary, the unused capacity can be used to supply additional harmonic compensation.

Chapter 9

Conclusion

A STATCOM can perform active filtering, also known as harmonic compensation. Such a device is referred to as a developed STATCOM. However, the traditional controller must be altered to enable this. A controller combining reactive and harmonic compensation is proposed. The controller is simple and combines the traditional controller of a STATCOM and an AF. Hence, the controller is referred to as a combined controller. To the author's knowledge, no identical controller is previously proposed.

The combined controller does not impose large changes to the traditional STATCOM MMC controller. The main changes are located in the outer control loop. Dq frame theory is used to calculate the reference harmonic compensation current. Then the reactive and harmonic compensation currents are added and fed into an inner current control loop. The inner current control loop output is later feed into a PWM generator and VSC. The reactive compensation current is calculated in the same way as for traditional STATCOMs. The voltage controllers, current controllers and VSC blocks are almost identical to the traditional STATCOM.

Simulations of the combined controller and developed STATCOM confirm that the controller operates in line with the presented objectives and the requirements of the traditional STATCOM. The voltage is improved and harmonic content reduced for all the simulated cases and system configurations. With minor alterations and adaptations, it is believed that the controller works for all other systems as well.

9.1 Further Work

Limitations and assumptions are made in order to limit the project scope. The thesis focuses on the MMC and MMC controller. It is the MMC controller that enables active filtering. Moreover, the MMC is considered the most significant component of the STATCOM. Limitations are made so that more time could be spent on implementing and analyzing the MMC controller. Future work should continue and exploit on the work presented in this thesis. It is desirable that further work addresses limitations, shortcomings and question the model assumptions.

If I had more time, I would have liked to implement the possible controller improvements, suggested in Chapter 8.2.1.1. The thesis does not focus on the controller tuning and a sensitivity analysis is not performed. With more time, I would have liked to investigate this further.

Based on my experience and observations, suggestions for further work are presented. These suggestions may form the objective of future projects.

1. Other alternative control methods should be modeled and simulated the same way as the combined controller . The combined controller should be compared against these alternatives. The combined controller is believed to be the most promising. Future work may or may not find this to be true. Further work should focus on and go forward with the optimal one.

2. The developed STATCOM and combined controller should be tested in the lab. Laboratory results should be used to assess the validity of the model and model results. However, further verification and testing of the model in PSCAD is needed in order to proceed with laboratory work. The model must be updated to match the lab equipment. I. e. the MMC model should be altered to match the MMC available in the lab.

The thesis does not state that the combined controller is the optimal controller for a STATCOM with active filtering. However, the results are promising. Further work that presents extensive simulations and laboratory work focusing on both the proposed controller and alternatives is necessary before one can conclude on an optimal controller.

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Appendix A

A.1 Power Flow Equation

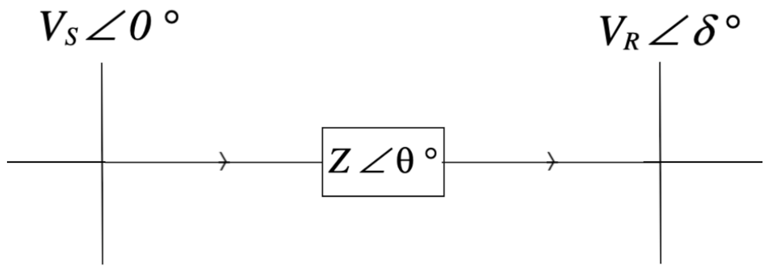


Figure A.1: Two bus system

The receiving power flow expressed by Equation 1.

$$\begin{aligned} \mathbf{S}_R &= \mathbf{V}_R \mathbf{I}_R^* \qquad (1) \\ &= \mathbf{V}_R \frac{(\mathbf{V}_S - \mathbf{V}_R)}{\mathbf{Z}}^* = V_R e^{j\delta} \frac{(V_S - V_R e^{-j\delta})}{Z e^{j\theta}} = \frac{V_R V_S e^{j\delta - j\theta}}{Z} - \frac{V_R^2 e^{j\delta - j\delta - j\theta}}{Z} \\ &= \frac{V_R V_S}{Z}(cos(\delta - \theta) + jsin(\delta - \theta) - \frac{V_R^2}{Z}(cos(\delta - \delta - \theta) + jsin(\delta - \delta - \theta) \end{aligned}$$

The active and reactive power are then given by Equation 2 2

$$P = Re[\mathbf{S}_R] = (\frac{V_R V_S}{Z}(cos(\delta - \theta) - \frac{V_R^2}{Z}(cos(\delta - \delta - \theta)) \qquad (2)$$

$$Q = Im[\mathbf{S}_R] = (\frac{V_R V_S}{Z}(sin(\delta - \theta) - \frac{V_R^2}{Z}(sin(\delta - \delta - \theta))$$

A.2 Reference Frame Transformation

Clark Transform

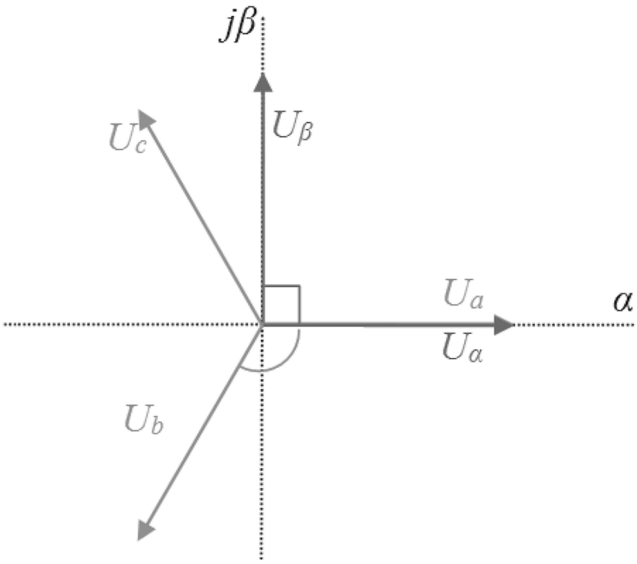


Figure A.2: Reference frame

$$\begin{bmatrix} \alpha \\ \beta \\ 0 \end{bmatrix} = K_{\alpha\beta} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} \alpha \\ \beta \\ 0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -sin(120-90) & -sin(120-90) \\ 0 & cos(120-90) & -cos(120-90) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \tag{4}$$

The amplitude is adjusted by the factor $\frac{2}{3}$ to obtain the equal amplitude in both reference frames.

Direct-Quadrature-Zero Transform

$$\begin{bmatrix} d \\ q \\ 0 \end{bmatrix} = K_{dq0} \begin{bmatrix} \alpha \\ \beta \\ 0 \end{bmatrix} = K_{dq0} K_{\alpha\beta} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \tag{5}$$

$$\begin{bmatrix} d \\ q \\ 0 \end{bmatrix} = \begin{bmatrix} cos\theta & sin\theta & 0 \\ sin\theta & cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \tag{6}$$

$$= \frac{2}{3} \begin{bmatrix} cos(\theta) & cos(\theta - \frac{2\pi}{3}) & cos(\theta + \frac{2\pi}{3}) \\ sin(\theta) & sin(\theta - \frac{2\pi}{3}) & sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix}$$

A.3 Mathematical Representation

The system is described by Equation A.3.

$$\frac{d}{dt} \begin{bmatrix} i_d \\ i_q \\ v_{dc} \end{bmatrix} = \begin{bmatrix} \frac{-R}{L} & \omega & \frac{-k_p}{L} S_d \\ -\omega & \frac{-R}{L} & \frac{-k_p}{L} S_q \\ \frac{3k_p S_d}{2C} & \frac{3k_p S_q}{2C} & \frac{-1}{CR} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ v_{dc} \end{bmatrix} + \frac{1}{L} \begin{bmatrix} v_{s,d} \\ v_{s,q} \\ 0 \end{bmatrix}$$

The voltage drop is given by the difference in v_s and v_c. The DC voltage drop is equal to the time derivative of the v_{dc} for all small steps. The voltage drops are functions of the switching functions, shown in Equation 7.

$$\begin{bmatrix} w_{c,d} \\ w_{c,q} \\ w_{dc} \end{bmatrix} = \begin{bmatrix} (v_{s,d} - v_{c,d}) \\ (v_{s,q} - v_{c,q}) \\ \frac{i_{dc}}{C} - \frac{1}{CR} v_{dc} \end{bmatrix} = \begin{bmatrix} v_{s,d} \\ v_{smq} \\ \frac{3}{2C}(k_p S_d i_d + k_p S_q i_q) \end{bmatrix} - \begin{bmatrix} k_p S_d & k_p S_q & \frac{-1}{CR} \end{bmatrix} v_{dc} \tag{7}$$

The switching functions in Equation 7 are expressed by Equations 8.

$$\begin{bmatrix} S_d \\ S_q \end{bmatrix} = \frac{1}{k_p v_{dc}} \left(\begin{bmatrix} v_{sd} \\ v_{sq} \end{bmatrix} - \begin{bmatrix} w_{c,d} \\ w_{c,q} \end{bmatrix} \right) \tag{8}$$

Combining the above equations gives a the mathematical model expressed by Equation 9.

$$\frac{d}{dt} \begin{bmatrix} i_d \\ i_q \\ v_{dc} \end{bmatrix} = \begin{bmatrix} \frac{-R}{L} & \omega & 0 \\ -\omega & \frac{-R}{L} & 0 \\ 0 & 0 & \frac{-1}{CR} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ v_{dc} \end{bmatrix} + \begin{bmatrix} \frac{1}{L} w_{c,d} \\ \frac{1}{L_p} w_{c,q} \\ w_{dc} \end{bmatrix} \tag{9}$$

Negative sequence

Equation 10 is equivalent to EquationA.3 for a unbalanced system.

$$\frac{d}{dt}\begin{bmatrix} i_{d-p} \\ i_{q-p} \\ i_{d-n} \\ i_{q-n} \\ v_{dc} \end{bmatrix} = \begin{bmatrix} \frac{-R}{L} & \omega & 0 & 0 & \frac{-k_p}{L}S_{d-p} \\ -\omega & \frac{-R}{L} & 0 & 0 & \frac{-k_p}{L}S_{q-p} \\ 0 & 0 & \frac{-R}{L} & \omega & \frac{-k_p}{L}S_{d-n} \\ 0 & 0 & -\omega & \frac{-R}{L} & \frac{-k_p}{L}S_{q-n} \\ \frac{3k_pS_{d-p}}{2C} & \frac{3k_pS_{q-p}}{2C} & \frac{3k_pS_{d-n}}{2C} & \frac{3k_pS_{q-n}}{2C} & \frac{-1}{CR} \end{bmatrix} \begin{bmatrix} i_{d-p} \\ i_{q-p} \\ i_{d-n} \\ i_{q-n} \\ v_{dc} \end{bmatrix} + \frac{1}{L}\begin{bmatrix} v_{s,d-p} \\ v_{s,q-p} \\ v_{s,d-n} \\ v_{s,q-n} \\ 0 \end{bmatrix} \tag{10}$$

Appendix B

B.1 Current Controller

The inner current controller is a PI controller with decoupling of the coupled components in Equation 9. The reference decoupled voltage drop is shown in Equation 11

$$\begin{bmatrix} w_{d,decoupled} \\ w_{q,decoupled} \end{bmatrix} = \begin{bmatrix} K_{pd} + \frac{K_{id}}{s} \\ K_{pq} + \frac{K_{iq}}{s} \end{bmatrix} \begin{bmatrix} (i^*_{c,d} - i_{c,d}) \\ (i^*_{c,q} - i_{c,q}) \end{bmatrix} + \omega L \begin{bmatrix} -i_{c,q} \\ i_{c,d} \end{bmatrix} \tag{11}$$

B.2 Phase-Locked Loop

The PLL paramter θ is expressed the Equation 12.

$$\theta = \frac{(K_{pd} + \frac{K_{id}}{s})(v_{s,d} - v_{s,q}) - \omega_{offset}}{s} \tag{12}$$

B.3 Voltage Controller

The active and reactive power are calculated by a PI controller. The constant 2/3 assures amplitude invariant quantities in the dq reference frame. Using the constant $\sqrt{2/3}$ obtains power invariant quantities. Alignment of the direct axis and the voltage vector gives a zero quadrature voltage component. The apparent power in the dq reference is shown by Equation 13.

$$\mathbf{S} = 3\mathbf{V}_{abc}\mathbf{I}^*_{abc} = 3\mathbf{V}_{dq}\mathbf{I}^*_{dq} = 3[\frac{(v_d + jv_q)}{\sqrt{2}}\frac{(i_d + ji_q)}{\sqrt{2}}^*] = \frac{3}{2}[v_d i_d - jv_d i_q] \tag{13}$$

The reference active and reactive power are calculated by a PI controller. The input of the PI controller is the voltage error. The reference currents become as shown by Equation 14

$$i^*_d = \frac{\frac{2}{3}(K_{pd} + \frac{K_{id}}{s})(v^*_{dc} - v_{dc})}{v_{s,d}} \tag{14}$$

$$i^*_q = \frac{\frac{2}{3}(K_{pd} + \frac{K_{id}}{s})(v^*_{c,dq} - v_{c,dq})}{v_{s,d}}$$

B.4 pq-Theory

The system voltage and line current dependent power flow expressed by Equation 15.

$$\begin{bmatrix} p_{l,\alpha\beta} \\ q_{l,\alpha\beta} \\ p_{l,0} \end{bmatrix} = \begin{bmatrix} v_{s,\alpha} & v_{s,\beta} & 0 \\ -v_{s,\beta} & v_{s,\alpha} & 0 \\ 0 & 0 & v_{s,0} \end{bmatrix} \begin{bmatrix} i_{l,\alpha} \\ i_{l,\beta} \\ i_{l,0} \end{bmatrix} \tag{15}$$

$$\begin{bmatrix} p_l \\ q_l \end{bmatrix} = \begin{bmatrix} p_{\alpha\beta} + p_{l,0} \\ q_{l,\alpha\beta} \end{bmatrix} \tag{16}$$

Using an alternating and a continuous component, the power flow in a line become as shown by Equation 17.

$$\begin{bmatrix} p_{\alpha\beta} \\ q_{\alpha\beta} \\ p_0 \end{bmatrix} = \begin{bmatrix} \overline{p}_{\alpha\beta} + \widetilde{p}_{\alpha\beta} \\ \overline{q}_{\alpha\beta} + \widetilde{q}_{\alpha\beta} \\ \overline{p}_0 + \widetilde{p}_0 \end{bmatrix} \tag{17}$$

Δp^*_c is given as Equation 18.

$$\Delta p^*_c = p_{l,\alpha\beta} + p_{l,0} - \overline{p}_{l,\alpha\beta} \tag{18}$$

The continuous component is the desirable component delivered by the grid, the alternating component need to be compensated by the APF. To obtain the AC power component feed-forward loops with low pass filters are used. The cutoff frequency must be above the fundamental frequency. Both components of the reactive power must be compensated. The power system must supply power to cover the capacitor power loss and VSC. The power covering this is equal to $p_{F,\alpha\beta}$. The reference values are shown by Equation 19.

$$\begin{bmatrix} p^*_{c,\alpha\beta} \\ q^*_{c,\alpha\beta} \\ p^*_{c,0} \end{bmatrix} = \begin{bmatrix} p_{l,\alpha\beta} - \overline{p}_{l,\alpha\beta} - p_{F,\alpha\beta} \\ q_{l,\alpha\beta} \\ p_{l,0} \end{bmatrix} \tag{19}$$

The above equation suggests that the reference current can be expressed by Equation 20.

$$\begin{bmatrix} i^*_{c,\alpha} \\ i^*_{c,\beta} \\ i^*_{c,0} \end{bmatrix} = \begin{bmatrix} v_{s,\alpha} & v_{s,\beta} & 0 \\ -v_{s,\beta} & v_{s,\alpha} & 0 \\ 0 & 0 & v_{s,0} \end{bmatrix}^{-1} \begin{bmatrix} p^*_{c,\alpha\beta} \\ q^*_{c,\alpha\beta} \\ p^*_{c,0} \end{bmatrix} \tag{20}$$

$$= \frac{1}{v^2_{s,\alpha} + v^2_{s,\beta}} \begin{bmatrix} v_{s,\alpha} & -v_{s,\beta} & 0 \\ v_{s,\beta} & v_{s,\alpha} & 0 \\ 0 & 0 & v_0(v^2_{s,\alpha} + v^2_{s,\beta}) \end{bmatrix} \begin{bmatrix} p^*_{c,\alpha\beta} \\ q^*_{c,\alpha\beta} \\ p^*_{c,0} \end{bmatrix}$$

Appendix C

C.1 Frequency Scanner Meter Output RL-Impedance

$$H(s) = r + Ls = 1.75 + 0.099s \tag{21}$$

Frequency [Hz]	Z [Ohm]	Phase [degrees]
1e-5	1.75	0.204e-4
50	31.152	86.78
100	62.22	88.39
150	93.32	88.93
200	124.42	89.19
250	155.52	89.35
300	186.62	89.46
350	217.72	89.54
400	248.82	89.60
450	279.92	89.64
500	311.02	89.68
550	342.12	89.71
600	373.22	89.73
650	404.33	89.75
00	435.43	89.77

Table C.1: Frequency scanner output

Appendix D

D.1 PSCAD Control Scheme

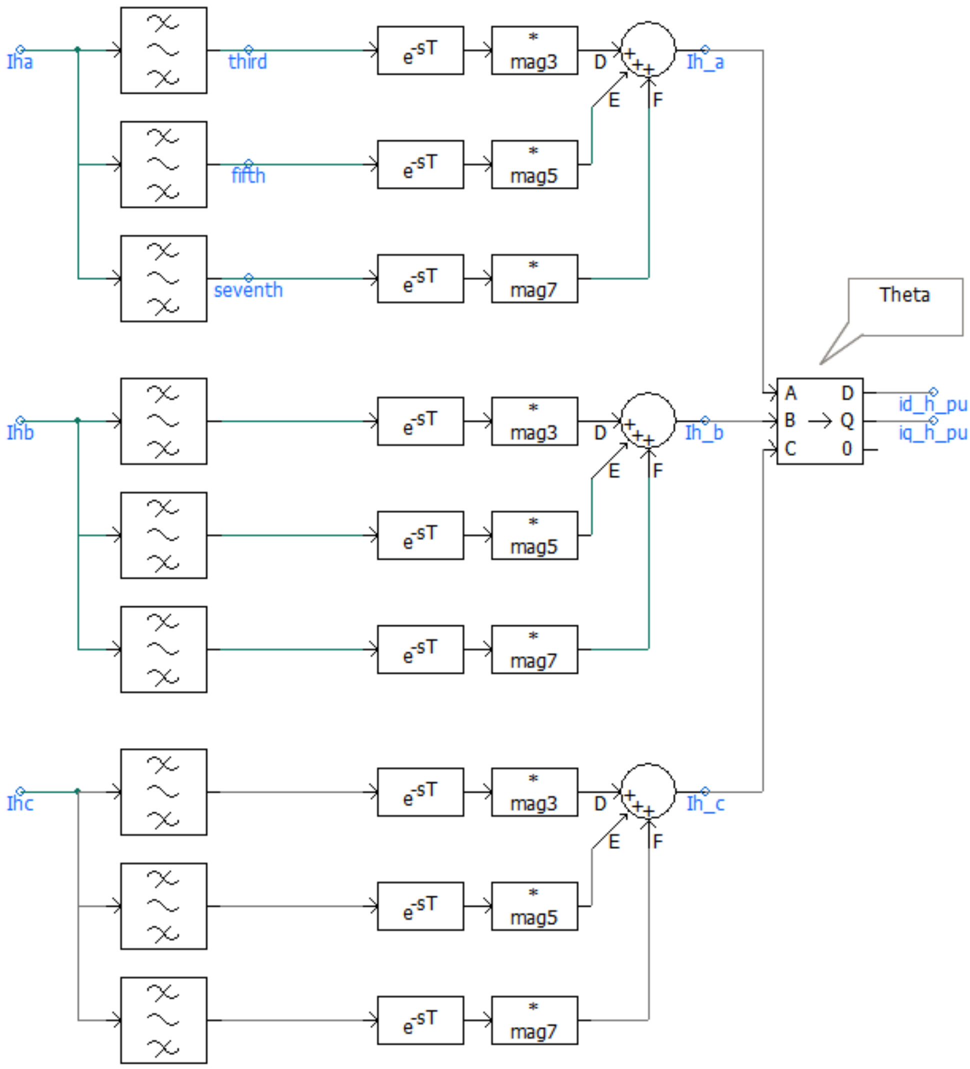


Figure D.1: Calculation of harmonic compensation current

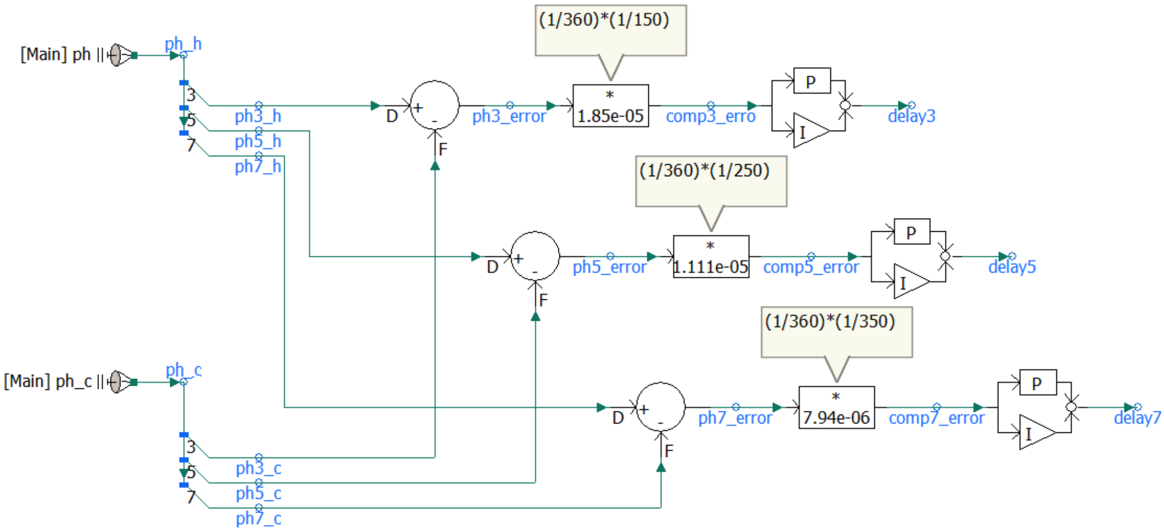


Figure D.2: Phase shift controllers

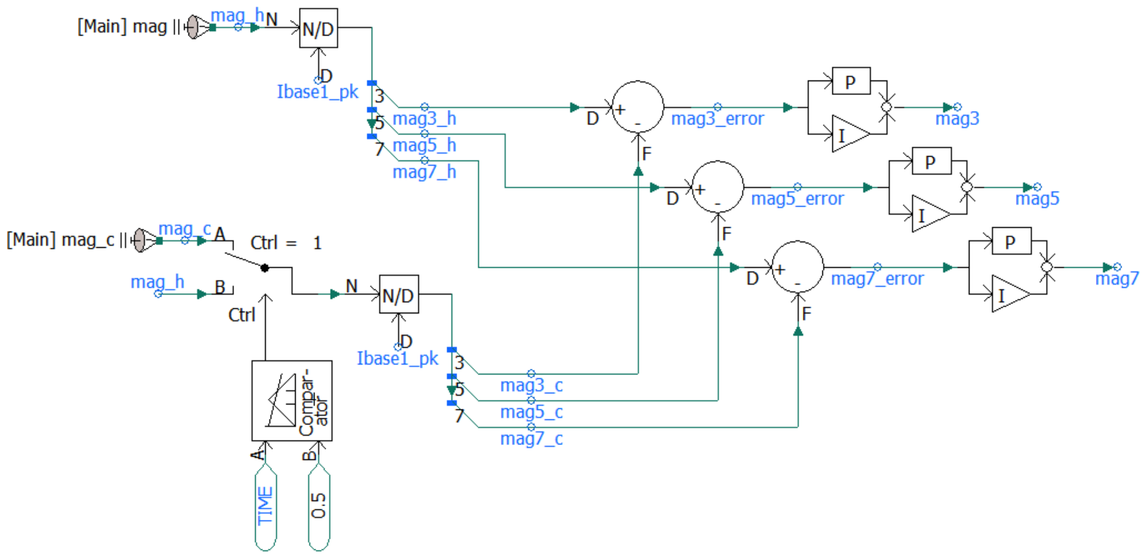


Figure D.3: Amplitude compensation controllers

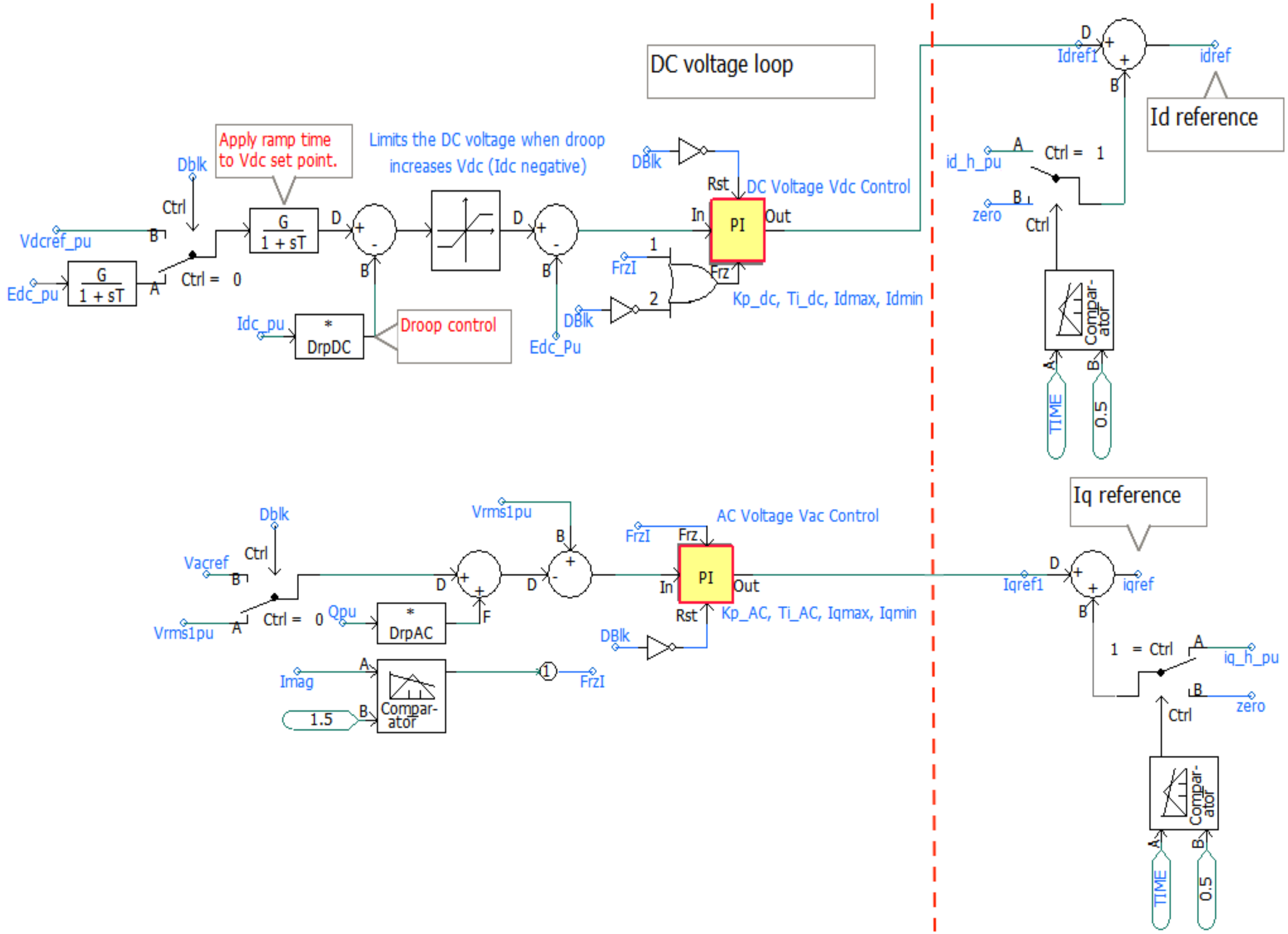


Figure D.4: DC and AC voltage control, original model left of dotted line

Appendix E

E.1 Simulation Results

E.1.1 Case 2: Varying System Voltage

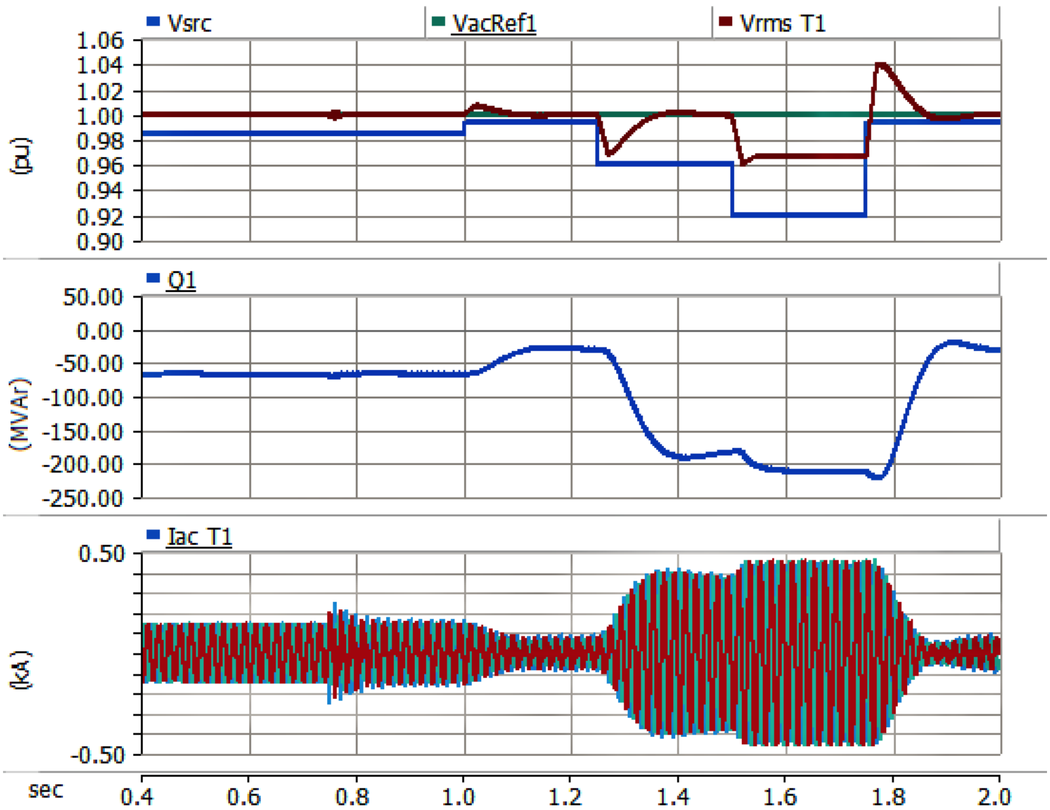


Figure E.1: Case 2: STATCOM output

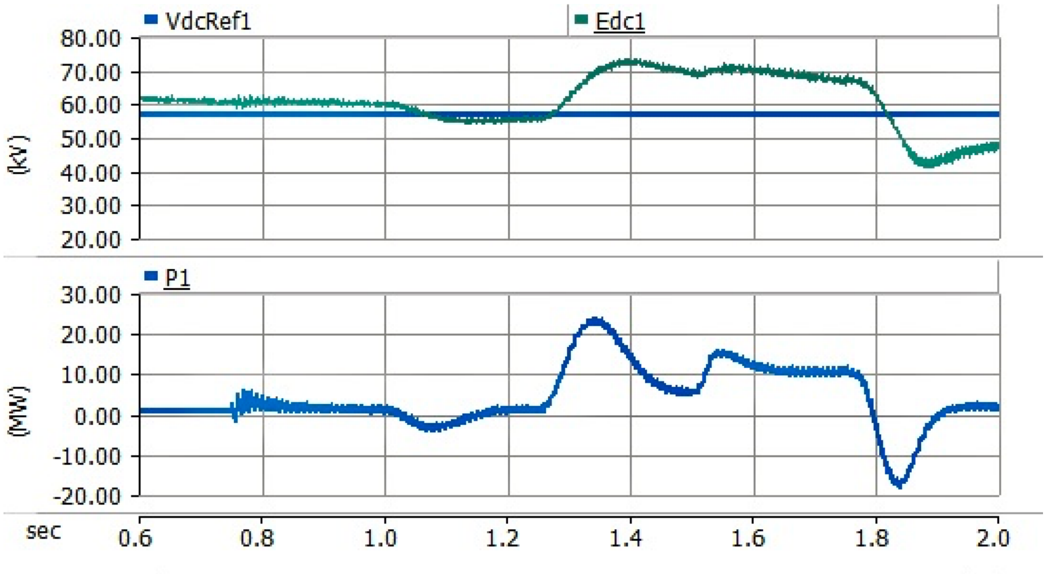


Figure E.2: Case 2: STATCOM output 2

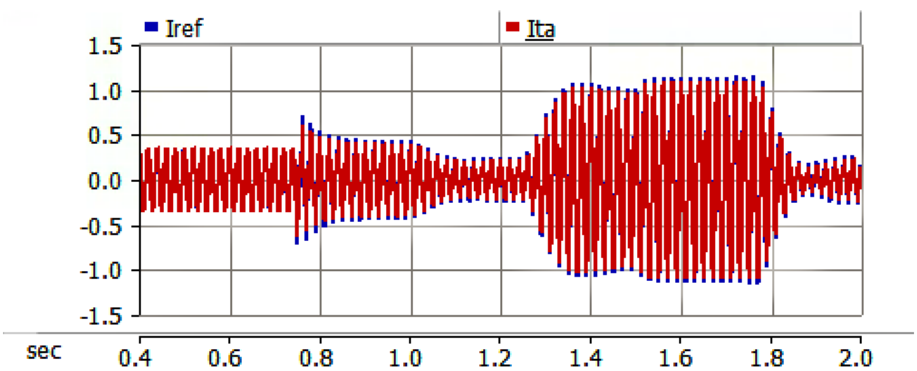
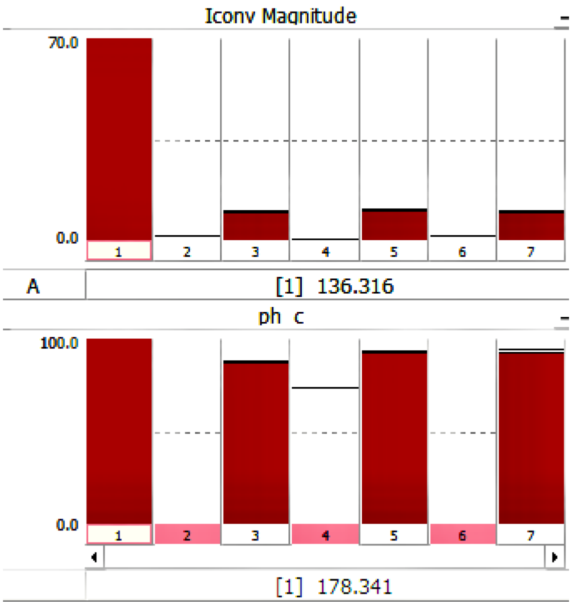
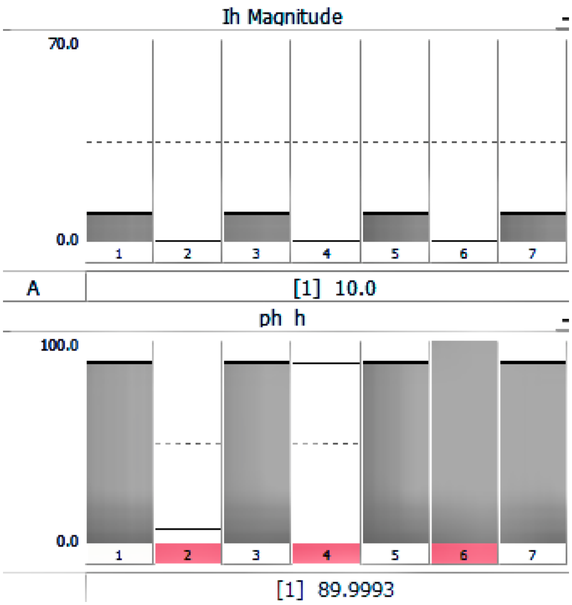


Figure E.3: Case 2: Reference and transformer current



(a) STATCOM current



(b) Harmonic current injection

Figure E.4: Case 2: Frequency scanner: current magnitude and phase at 1 second

E.1.2 Case 3

E.1.2.1 Case 3a

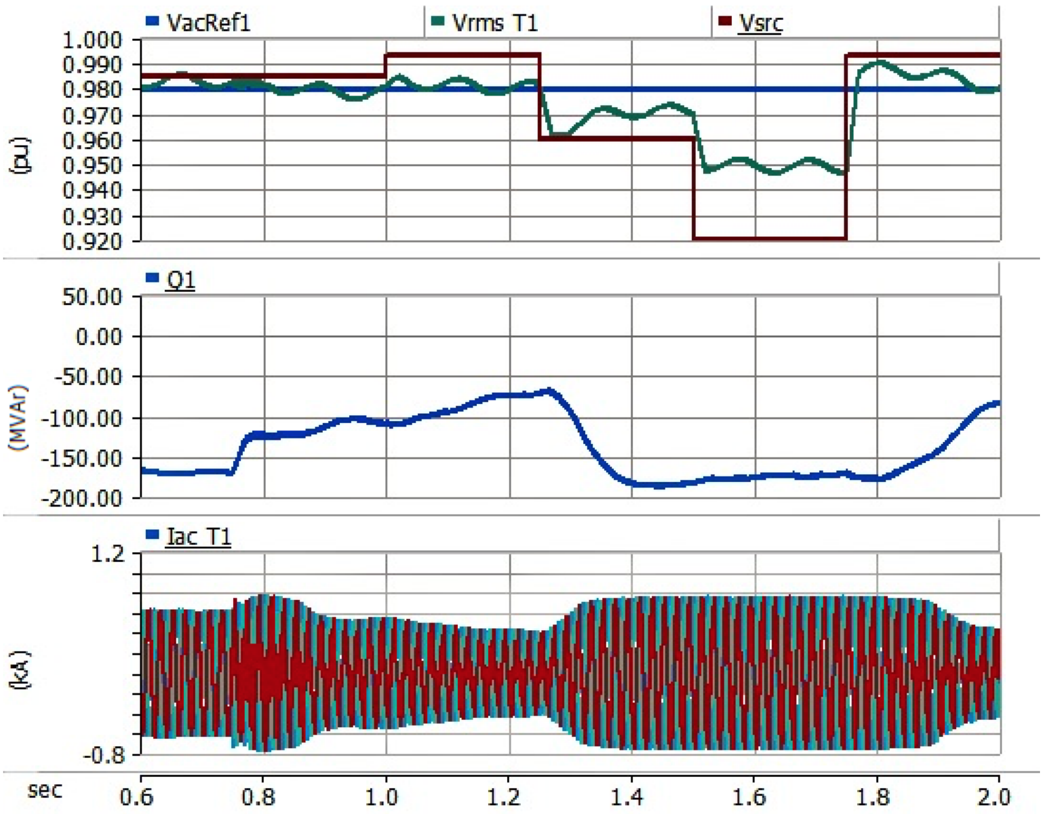


Figure E.5: Case 3a: STATCOM output

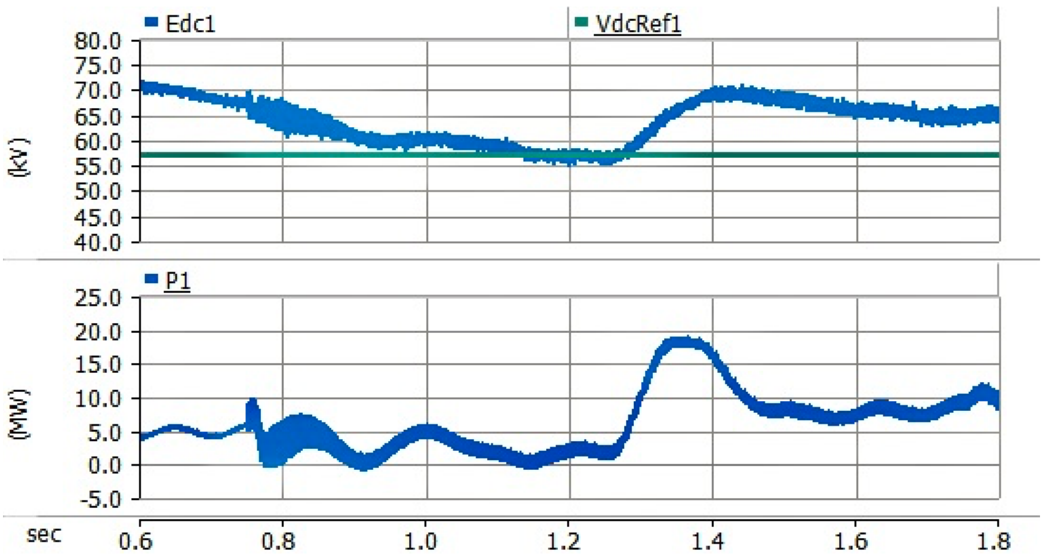


Figure E.6: Case 3a: STATCOM output 2

E.1.2.2 Case 3a Constant Arc Furnace Current Amplitude

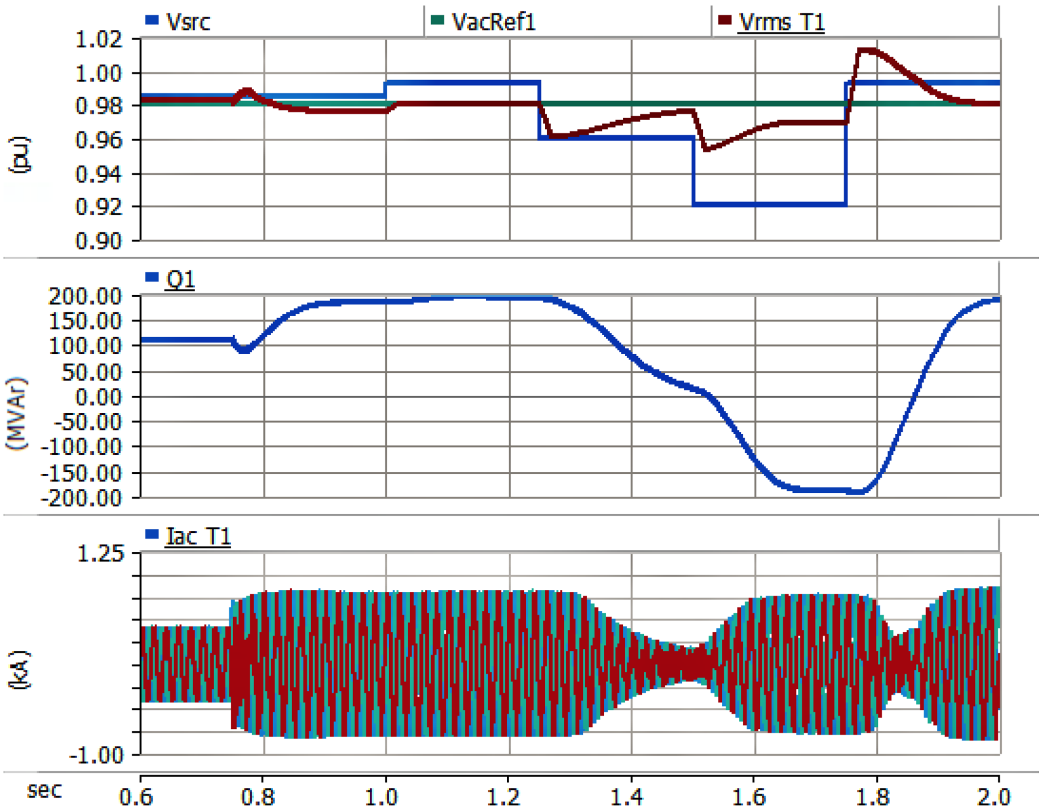


Figure E.7: Case 3a: STATCOM output

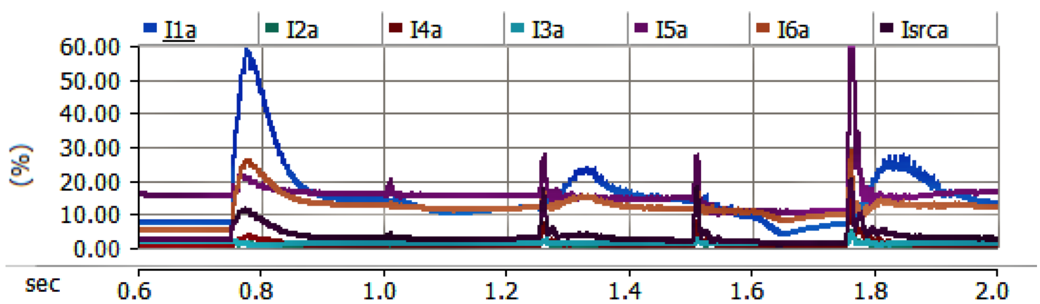


Figure E.8: Case 3a: STATCOM output

E.1.2.3 Case 3b

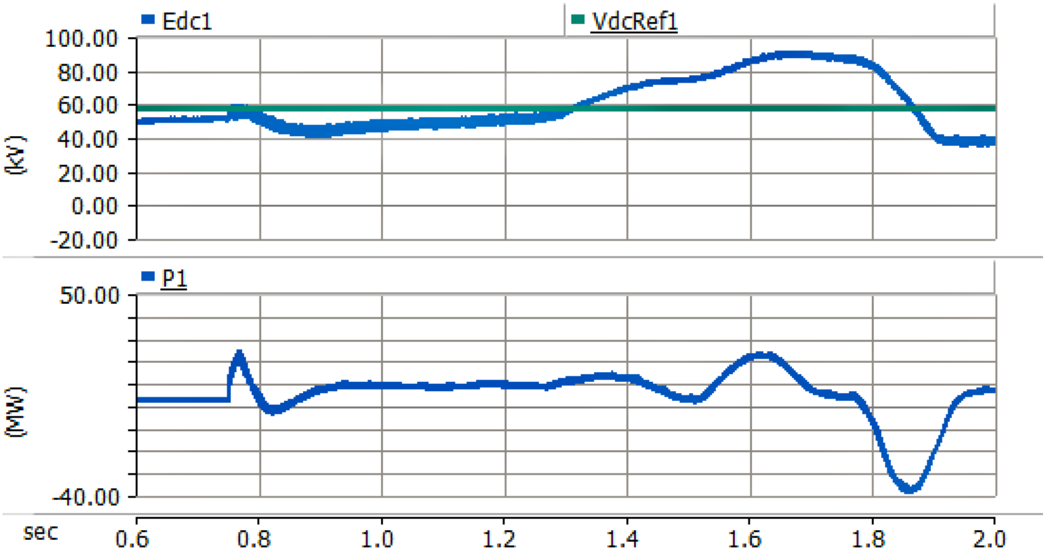


Figure E.9: Case 3b: STATCOM output 2

E.1.2.4 Case 3b

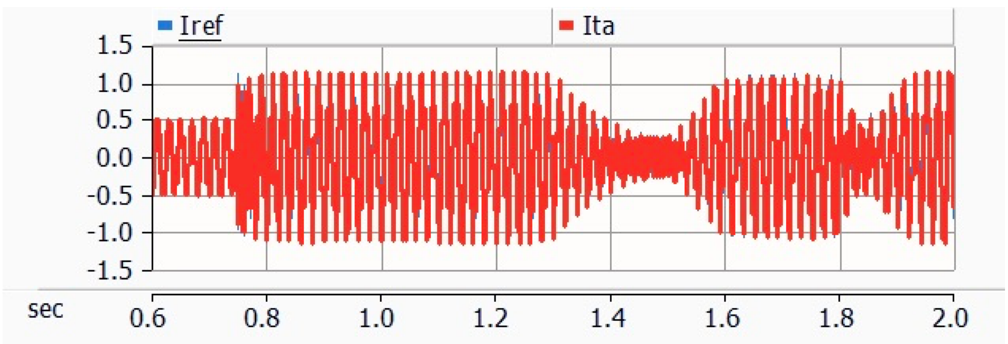


Figure E.10: Case 3b: Reference and transformer current

E.1.2.5 Case 3c

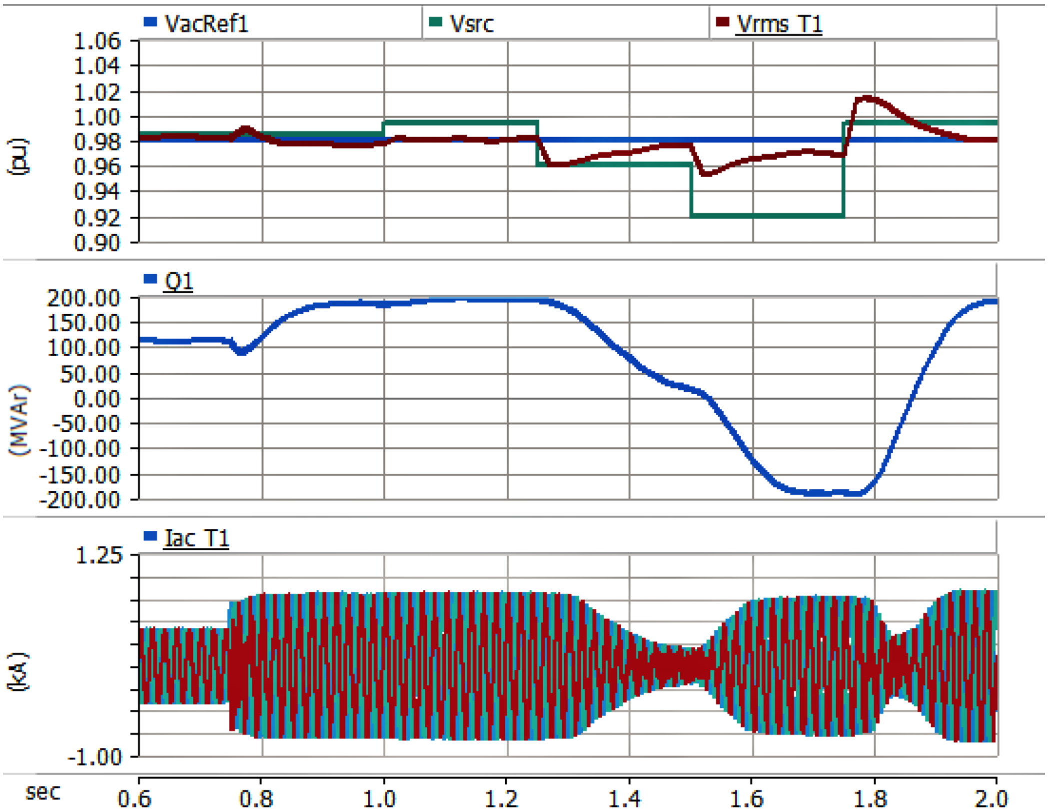


Figure E.11: Case 3c: STATCOM output

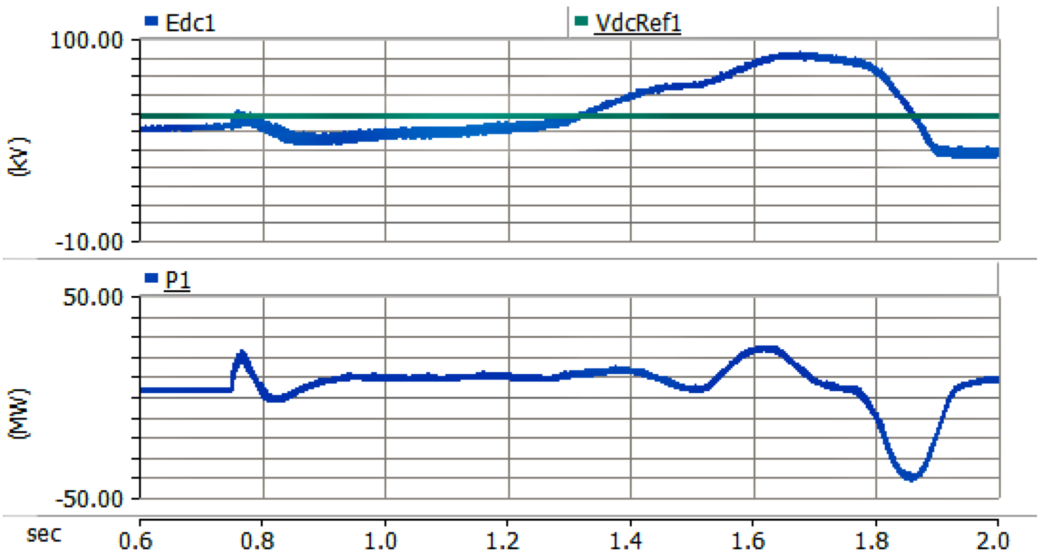


Figure E.12: Case 3c: STATCOM output 2

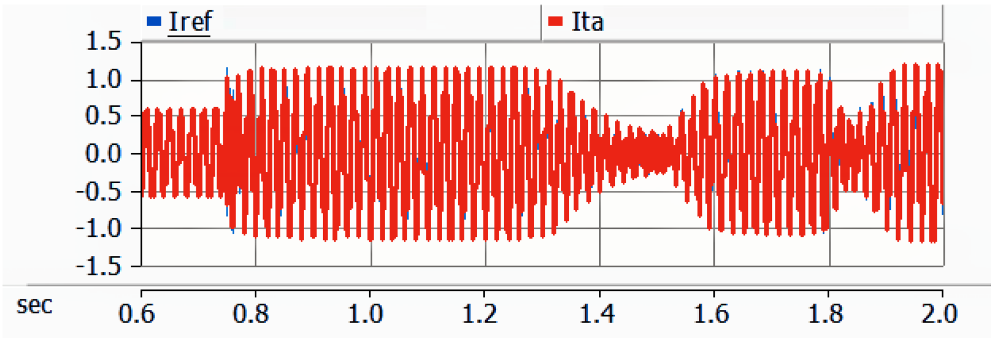


Figure E.13: Case 3c: Reference and transformer current

E.1.2.6 Case 3d

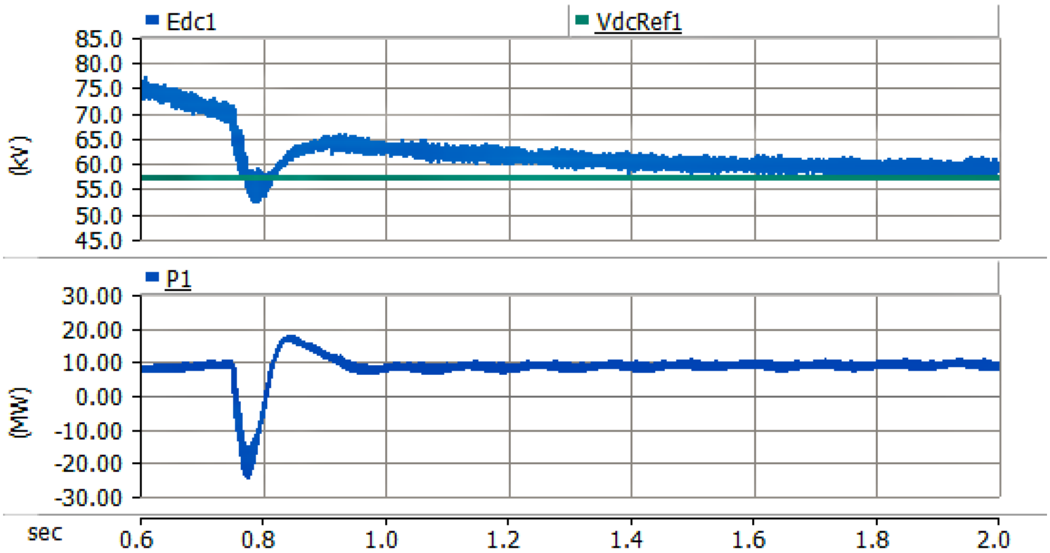


Figure E.14: Case 3d: STATCOM output 2

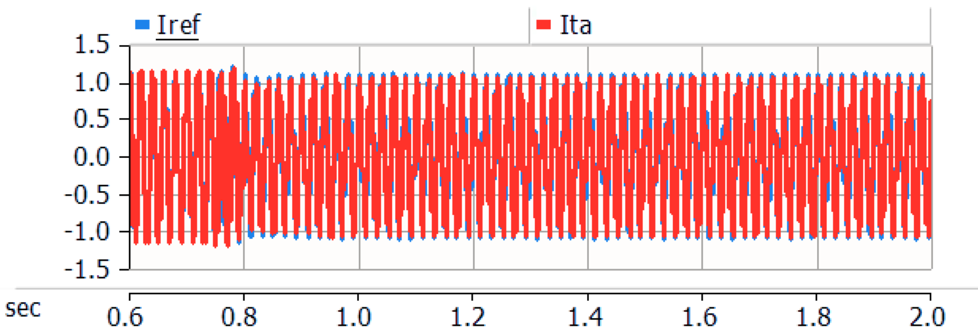


Figure E.15: Case 3d: Reference and transformer current

Appendix F

F.1 ”STATCOM - Voltage Stability” - Excerpt

The following pages show the modelling and simulation of a STATCOM in PSS/E. The paper is written and simulations conducted by the author, Hanna Authen. The full paper is submitted as the final assessment in the course ELK-16 at NTNU. The paper is not published.

III. Modelling

By the means of PSS/E, simulation is used to show the effect of a STATCOM in a grid. PSS/E is a simulation tool offered by Siemens. The article ”Performance Analysis of Smart Device - STATCOM For Grid Application” [1] provides nose curves, PV curves, to show the effect of increased power transfer in the Indian grid at 400kV . This report includes similar simulations for an example grid offered by Siemens. Siemens offer a simple grid, called Sample. Figure 7 shows a snapshot of the system Sample. A STATCOM is connected to the bus 154 DOWN TN. The mentioned article includes some contingency cases, the same will be shown for the Sample grid.

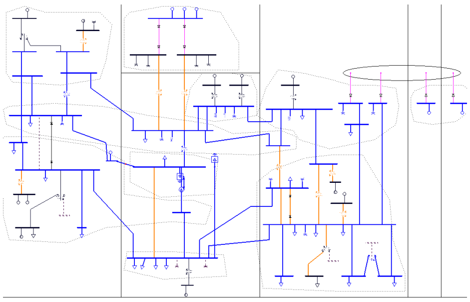


Fig. 7: The example grid, Sample

Some alternations are done to the original model. The STATCOM in the updated model is connected to the added bus 1 STATCOM. The voltage level at the remote bus 154 controls the STATCOM. The initial settings of the STATCOM provides an ideal device with no limits. In, addition a more realistic STATCOM with 140 Mvar max shunt is considered. The static Var compensators connected to bus 154 is disconnected, to enhance the effect of the STATCOM. An ideal generator is added to bus 3006 and the load at bus 154 is increased.

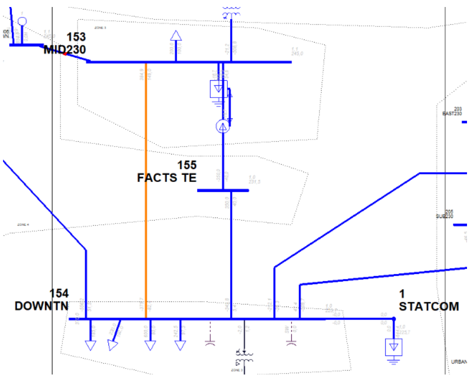


Fig. 8: Close up of example grid with alternations, Sample

In addition, a series of connected FACTS device is connected between bus 154 and 154 in the original model. This component is not considered in this report.

To calculate the PV curves Python is used. The appendix include scripts: the subsystem description file, a monitored element file and contingency description data file. The subsystem description file defines the system, the monitored element file defines the scope of the simulation and contingency description data file defines the contingency cases.

IV. Results

A. PV curves

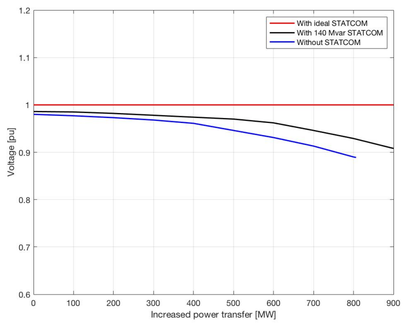


Fig. 9: Base case

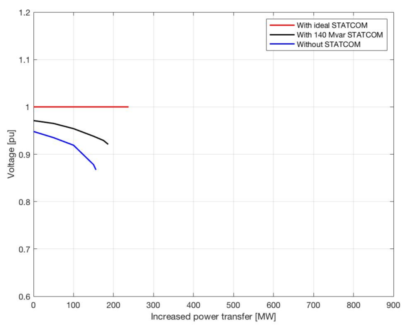


Fig. 10: Disconnected bus 153 MID230

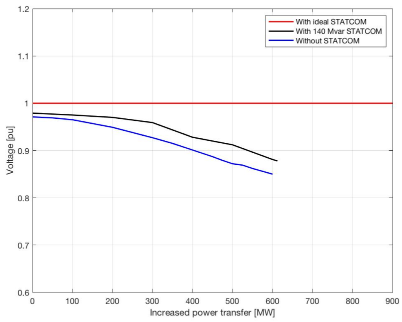


Fig. 11: Disconnected line between bus 153 MID230 and 154 DOWNTN

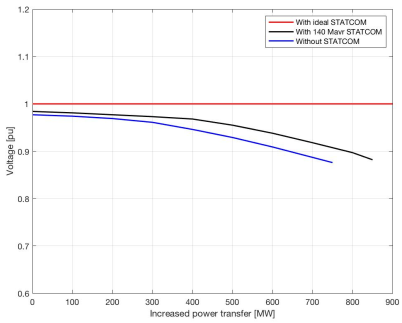


Fig. 12: Disconnected bus 155 FACTS TE

V. Discussion

The results from the simulation clearly show a correlation between increased power transfer and voltage level. The STATCOM counteract the drop in voltage due to increased power transfer. For all the simulated cases the STATCOM keeps the voltage level above the case without. The ideal STATCOM can produce unlimited amount of reactive power. The STATCOM has the ability to keep the voltage at the desired value, 1 pu, regardless the amount of change of reactive power. The same effect is visible for the STATCOM with a rating of 140 Mvar. Due to the limited capacity the compensation will also be limited. Still, the 140 Mvar STATCOM improve the power quality. In line with the theory, the voltage drops during increased power transfer, due to increased reactive power loss. Without compensation, the voltage will level drop faster than the case without STATCOM.

The voltage security limits are not considered when plotting the results. Operating within these limits limit the power transfer further. Disregarding voltage level, the decisive factor limiting the increased power transfer is system mismatch. Typically, a mismatch is caused by exceeding rating of swing bus. Considering the contingency cases, the outage of lines or buses increase the current through the remaining components. Increased current increase both active and reactive power losses. As a consequence, the production of power must be increased to cover the power losses. Increased power production, but reduced power transfer, cause a mismatch at less transfered power. The ratings of the generators are the same regardless operation, ceiling the maximum possible production of power. Even though the the possible increased power transfer is reduced, operating the system with zero increased power transfer is within security limits for all the cases.

Line capacity is another limiting factor. This factor is not considered during the PV analysis. As shown in Figure 7, multiple lines are close to their rated values, marking by the color orange. Including the line capacity would limit the analysis. The line capacity limits the possible power transfer between the source and sink area, limiting the solution area. The effect of compensation would not have been clear as wanted if one were to consider the line capacity.

Direction of the power flow is another aspect of the analysis. In this case, only a unidirectional current flow is considered. As stated, the subsystem file define the source, bus 3006, and sink, bus 154, when plotting the PV curves. The source increase the production, while the sink increase the demand. The result of a decreasing demand, meaning a decreasing power transfer would have the opposite effect. Decreasing production would cause an increasing voltage. To counteract this change would the STATCOM would consume reactive power, operating as an inductor.

VI. Conclution

The motivation for installing the STATCOM is to keep the voltage at a desired level. Reactive power production is increased to compensate reactive power loss during increased power transfer. If the power transfer was decreasing would the STATCOM would consume reactive power. Voltage stability is crucial when operating the grid. There are security constraints, exceeding these can cause a voltage collapse. Installing a compensating device such as a STATCOM increases the possible operating range. As well as improve the voltage level, operators can increase possible power transfer range by installing a STATCOM. In that way, installing a STATCOM is an alternative to upgrade the whole system.

The simulation presented in this paper verify the conclusion " A. Higher active power transfer capability" presented in the paper "Performance Analysis of Smart Device - STATCOM For Grid Application" [1]

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NTNU
Norwegian University of
Science and Technology