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DESIGN AND DEVELOPMENT OF ADAPTIVE ALGORITHM FOR SHUNT COMPENSATION IN GRID CONNECTED DISTRIBUTION SYSTEMS

DISSERTATION

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ASHISH KUMAR PANDEY

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Under the supervision of

DR.ANKITA ARORA (Assistant Professor)

ELECTRICAL ENGINEERING DEPARTMENT

DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)

Bawana Road, Delhi-110042

MAY - 2024

DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)

Bawana Road, Delhi-110042

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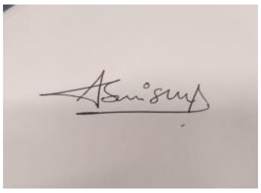

Place: Delhi **ASHISH KUMAR PANDEY**

Date: **2K21/PES/02**

DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)

Bawana Road, Delhi-110042

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DR. ANKITA ARORA (Assistant Professor)

(Supervisor)

DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)

Bawana Road, Delhi-110042

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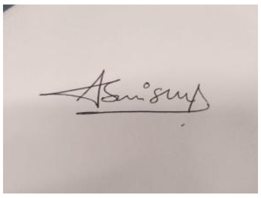


ASHISH KUMAR PANDEY

2K21/PES/02

ABSTRACT

In recent times, AC grid-connected systems have been experiencing numerous power quality issues, particularly at the distribution level. The increased use of power converter-based machines in various applications, such as industries, homes, shops, offices, and traction, has led to a significant rise in non-linear loads that draw non-sinusoidal currents. These non-linear loads have a detrimental impact on the power quality of the supply system. This study aims to address power quality concerns resulting from the growing adoption of renewable energy resources and non-linear loads in the distribution system. Various power quality problems associated with current-based issues are observed, including poor voltage regulation, low power factor, harmonic distortion, and unbalanced currents. To mitigate these issues and improve power quality, Distribution Static Compensators (DSTATCOMs) are increasingly being applied due to their cost benefits. DSTATCOMs, equipped with adaptive filtering techniques, are utilized as cost-effective Shunt Active Power Filters (SAPFs). These filters utilize the enhanced computational capabilities of modern computers to implement adaptive filters, which find applications in noise/echo cancellation, adaptive control, image restoration, and channel equalization. In conclusion, the power quality problems arising from the increased use of renewable energy resources and non-linear loads in the distribution system are a pressing concern. To address these issues, DSTATCOMs with adaptive filtering techniques have emerged as effective and economical solutions, serving as Shunt Active Power Filters. By leveraging the computational power of modern computers, adaptive filters offer noise cancellation and improved control capabilities, making them valuable tools for enhancing power quality in supply systems.

This project presents a detail description of the STATCOM network and the design and modelling of the three leg VSC voltage source converter also it compares both the Algorithms presented in the project where on simulating both the Algorithms we find that the Adaptive LMS algorithm is much efficient and highly stable as well as settles smoothly over the output. While SRF theory Algorithms is efficient but it has more total harmonic distortion than that of the LMS algo.

CONTENTS

LIST OF FIGURES

LIST OF SYSMBOL, ABBREBIATIONS

Symbols

Ω	ohm
%	Percentage
V	Volt
A	Ampere
mA	Milli ampere
Q	Quality factor
m	Ratio of inductance
Fn	Normalized Frequency
Rac	Equivalent Resistance
Lr	Resonant inductance
Cr	Resonant capacitance
Nr:Ns	Turns ratio
Fs	Switching Frequency
Fr	Resonant frequency
Ro	Load resistance
Co	Output Capacitance
Vin1	Input Voltage
d	Duty ratio
mH	Milli Henery
uF	Micro Farad
Lm	Magnetizing inductance
Co	Buck converter capacitance

Lo	Buck converter inductance

Abbreviations

LLC	Tank of inductances and capacitance
DC	Direct current
PWM	Pulse width modulation
MOSFET	Metal oxide semiconductor field effect transistor
IR	Internal Resistance
SN	Switch N
ZVS	Zero voltage switching
AC	Alternating current

CHAPTER 1
INTRODUCTION

1.1 POWER QUALITY ISSUES

Power Quality problems like poor power factor, voltage fluctuations, waveform distortions etc have been present in electrical power system since the beginning. These problems are caused by faults, motor loads, lightening, equipment malfunction etc. Equipment like circuit breakers, lightening arrestors, motor starters, synchronous condensers etc is designed to mitigate or override their effect on the power system. In present scenario, with increased interconnectivity between traditional sources for reliability of supply and induction of power electronic converter based renewable energy sources; the sensitivity of the system has increased exponentially. On the consumer side the use of power electronic converter-based devices, such as battery chargers, Adjustable Speed Drives (ASDs), furnaces, Uninterruptible Power Supplies (UPSs) etc, cause waveform distortions and frequency deviations as they draw non sinusoidal current and their behaviour is characterized as nonlinear loads. The use of these solid state-based devices has many benefits such as reduced size, maintenance requirements and cost; increased efficiency and better control.

1.2 CLASSIFICATION AND EFFECTS OF POWER QUALITY ISSUES

The various forms in which power quality issues can be found are categorised as:

1) **Voltage Sag**: A decrease of the normal voltage level between 10% and 90% of the nominal rms voltage at the power frequency, for durations of 0,5 cycle to 1 minute. Faults on the transmission or distribution network (most of the times on parallel feeders). This could cause Faults in consumer’s installation. Connection of heavy loads and start-up of large motors.

2) **Very Short Interruption**: Total interruption of electrical supply for duration from few milliseconds to one or two seconds. Mainly due to the opening and automatic re-closure of protection devices to decommission a faulty section of the network. The main fault causes are insulation failure, lightning and insulator flashover.

3) **Long Interruption**: Total interruption of electrical supply for duration greater than 1 to 2 seconds Equipment failure in the power system network, storms and objects (trees, cars, etc) striking lines or poles, fire, human error, bad coordination or failure of protection devices.

4) **Voltage Spikes**: Very fast variation of the voltage value for durations from a several microseconds to few milliseconds. These variations may reach thousands of volts, even in low voltage. Creates causes such as Lightning, switching of lines or power factor correction capacitors, disconnection of heavy loads.

5) **Voltage Swell:** Momentary increase of the voltage, at the power frequency, outside the normal tolerances, with duration of more than one cycle and typically less than a few seconds.

6) **Harmonic Distortion**: Voltage or current waveforms assume non-sinusoidal shape. The waveform corresponds to the sum of different sine-waves with different magnitude and phase, having frequencies that are multiples of power-system frequency.

7) **Voltage Fluctuations:** Oscillation of voltage value, amplitude modulated by a signal with frequency of 0 to 30 Hz.

Power Quality issues concern all the stakeholders (Generation units, transmission units and consumers) in a power system network. Interruption of power supply due to Power Quality problems causes revenue losses to commercial and industrial consumers as it results in loss of important data, production loss, interruption of process, wastage of raw material etc. Sensitive consumer equipment may malfunction or get damage due to voltage fluctuations, frequency deviations, harmonics, over current or overvoltage. Poor power factor and harmonics cause increased losses in the machines which increases cost of operation and reduce life of equipment. In transmission system Power Quality problems affect the operation of machines, protective devices and measuring instruments. Harmonic currents and frequency deviations increase losses, noise and vibrations in transformer and capacitor bank causing reduced efficiency and increased maintenance cost. Over current and overvoltage due to faults and lightening results in de-rating of cables, false metering, damage to substation equipment, interference with communication signals, breaker and relay malfunctions. In conventional generation system requirement of reactive power, unbalanced loads cause voltage instability, loss of synchronism, frequency deviations, excessive neutral currents etc. These problems increase running as well as maintenance costs due to losses and damage to machines. In renewable energy generation such as solar PV cells the produced power is in DC while conventional grid equipment works on AC. Power electronic converters and filter circuits are required to convert power in required form. These converter and filter circuits are highly sensitive to disturbances in the system.

1.3 STANDARDS OF POWER QUALITY

Power Quality standards are limits of various quantities such as voltage level, waveform distortion, frequency range etc. under which power system operates normally and efficiently. At present several standards are developed related to numerous power quality issues by different countries. Several organizations namely Institute of Electrical and Electronics Engineers (IEEE), International Electrotechnical Commission (IEC), American National Standards Institute (ANSI), European Norms (EN), Computer Business Equipment Manufacturers Association (CBEMA), British Standards (BS), and Information Technology Industry Council (ITIC) have proposed acceptable ranges of various quantities for maintaining Power Quality that sets guidelines for equipment designers, consumers and electrical companies on handling numerous problems that cause Power Quality issues. Voltage and frequency standards at distribution, transmission and generation are different in different countries. Domestic consumers in India receive electricity at 50 Hz, 230 V while in United States of America the standard is 60 Hz, 110 V. According to Indian Standards (IS)/IEC 60071-1: Insulation Coordination – Definitions, principles and rules, voltage levels are defined as high voltage range II (above 245 kV), high voltage range I (between 1 kV and 245 kV) and low voltage (below 1 kV). While According to ANSI C84.1-1989: “American National Standard for Electrical Power System and Equipment” – Voltage Ratings at 60 Hz are high voltage (between 115 kV and 230 kV), medium voltage (between 2.4 kV and 69 kV) and low voltage (between 120 V and 600 V). In India Indian Electricity Grid Code (IEGC) notified the allowed frequency deviations range as 49.5 to 50.2 Hz and voltage variations of ± 10 % (approx.) from nominal value are permissible. The IEEE 519-2014 standard: “IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems” [6] prescribes limit of current and voltage waveform variation using percentage harmonic distortion (% of fundamental at 50 Hz or 60 Hz). Table 1.1 gives limits of allowable distortion in voltage at different levels. Table 1.2 shows current distortion limits for system rated above 161 kV. Table 1.3 shows limits of distortion in current for system between 69 kV and 161 kV. 5 Table 1.4 shows limits of distortion in current for system nominally rated between 120 V and 69 kV

1.4 TECHNIQUES TO IMPROVE POWER QUALITY

There are a number of equipment and protection schemes available to mitigate transient Power Quality problems such as overvoltage, over current, disruption of supply and distortions due to lightening, faults, equipment failure, flashover etc. Lightening or surge arrestors are used in substations to divert over-voltages to ground to protect substation equipment. A complex transmission system is divided into protective zones. Primary protection as well as backup protection relays and circuit-breakers are used in each zone to prevent the effect of fault in one zone on entire power system and to ensure reliability of supply.

1) **Voltage Control technique:** The voltage in electrical power system is regulated by generation, flow and absorption of reactive power at all stages of the system. As in a grid system power is supplies to a variety of loads and generated using different generating stations, maintaining voltages at nominal values is a challenging task. At the point of generation synchronous generators either consume or supply reactive power based on the level of excitation. Automatic voltage regulators (AVRs) maintain constant voltage at the terminal of generators by controlling field excitation. In solar plants power electronic based power conversion devices are used to maintain nominal voltage at the output. In transmission system overhead lines either absorb or deliver reactive power depending on its surge impedance and connected load at the end. If the load connected at the end is greater than surge impedance of line, the line absorbs reactive power and voltage of the load side terminals is below the value of voltage of the sending end terminal. If the load connected at the end is lower than surge impedance of line, the line generates reactive power and voltage of the load side terminal is higher than the value of voltage of the sending end terminal. Underground cables have high internal capacitance resulting in high surge impedance and their loading is lower than their surge impedance hence generating reactive power. Transformers always absorb reactive power. Different devices are used to control flow of reactive power in the

system. For long Extra High Voltage (EHV) lines of more than 200 km shunt reactors are employed to avoid 'Ferranti' effect due to capacitive line charging current in case of open circuit at the receiving end. Shunt reactors also limit energisation overvoltage and switching transients. Shunt connected capacitor supply reactive power and boost voltage, distributed throughout the length of the line. In distribution systems they are used for control of feeder voltage and correction of power factor. 8 Series capacitors are used with loads with poor power factor such as arc furnaces and welding machines for voltage regulation and improving power factor. In transmission system series capacitors are used for improving stability of system and power flow control in parallel lines. Synchronous condensers are also used for regulating voltage and control of reactive power. A synchronous condenser is prime mover less synchronous machine with controllable field excitation to adjust reactive power output. As the initial and running cost of synchronous condensers are high they have been replaced by Static Var-Compensators (SVC). SVC is a power electronic based Flexible AC Transmission System (FACTS) device used for regulating voltage, power factor, harmonics and stabilising the system. Thyristor Switched Capacitor (TSC) and Thyristor Controlled Reactor (TCR) are two basic type of reactive power control devices. They are used alone or in different combinations to regulate flow of reactive power in the system. The advantages of using SVCs include lower cost, reduced losses, fast and dynamic control

2) **Frequency Control technique**: A constant frequency and voltage are important factors for good quality of power supply system. Frequency changes affect the speed of synchronous and induction motors. A significant reduction in frequency results in increased magnetising current in induction motors and transformers. The frequency of system depends on balance of active power. In an interconnected system many generator supply power into the system and an active power demand change is reflected as a deviation in frequency throughout the grid. Load-frequency control (LFC) methods are used to ensure regulation of frequency of the power system. Speed governor systems are used as primary control for regulating frequency. When there is a load change the speed-governor changes the turbine output to change the frequency back to its nominal value. A supplementary control is required, in case of interconnection of independently controlled areas, which allocates generation 7 within each area to maintain scheduled power exchange. Load shedding is a common

practice for maintaining frequency within permissible range when frequency drops significantly below the nominal value

3) **Control of Distortions in Waveform:** Several equipment in the power system draw current in different wave shape than the standard sine wave. These types of equipment are called non-linear loads. The waveform distortion resulting from the operation of these devices affects the working of other equipment of consumers as well as equipment used by utility for measurement, transmission, control and protection. Therefore, it is important that waveform distortion at different levels of the system is within limits. With increased uses of power electronic based converter circuits in consumer products and renewable energy conversion limiting the waveform distortion caused by these equipment is an active area of research. Various types of filters are already in use and new technologies are being developed to lower waveform distortion effects on the system. Passive shunt filters which consist of either capacitor or inductor or a combination of both are connected in shunt with the non-linear load for giving low impedance path for tuned harmonic frequency components allowing them to pass through passive filter. A simple lossless parallel LC circuit that provide high impedance for blocking harmonic currents act as passive series filter, connected in series with harmonic producing load to prevent harmonic current to enter supply system. These are singly tuned 9 filters to block dominant third harmonic component. Combination of shunt and series passive filter (Hybrid) is used in many industrial applications. A single tuned passive shunt with a single tuned passive series filter and high pass passive shunt filter gives satisfactory filtering characteristic. With increasing pollution in AC systems, because of non-linear loads and increased use of power converters, passive filters are becoming inadequate for satisfactory and dynamic filtering of harmonics due to fixed compensation and problems like resonance. To overcome the problem of fixed compensation and dynamic control various active power filters are being used around the world. Series type of active power filter is used to reduce voltage harmonic and imbalance in three phase voltages. Shunt Active Power Filter (SAPF) are shunt connected active filters widely utilised for reducing harmonics, reactive power control, power factor improvement and balancing of load currents. Shunt active power filter with passive shunt filter provide satisfactory and cost-effective solution for dynamic compensation. Various Custom Power Devices (CPDs) namely

Unified Power Quality Conditioners (UPQCs), Dynamic Voltage Restorers (DVRs) and Static Synchronous Compensators (STATCOMs) are used for active compensation.

1.6 THESIS OUTLINE

The Thesis has been organized in five chapters.

Chapter 1, in this chapter there is introduction of The Adaptive Least Mean Square Algorithm and Synchronous Reference Frame Theory.

Chapter 2 contains the literature review about both the projects as well as It also Discusses The idea and motivation Behind The work.

Chapter 3 it contains the definition of the topic as well as Consist of the Simulation results and Comparison of the two Algorithms use for shunt Compensation of The DSTSTCOM network.

Chapter 4 this chapter consists of All the definition as well terminologies related to shunt Compensation of The DSTSTCOM network.

Chapter 5 is the conclusion and future scope of the proposed system has been described.

CHAPTER 2
LITERATURE REVIEW

2.1 GENERAL

This chapter divided in two sections. In first part we discuss about background and previous work done in the area of power Quality improvements and various available techniques utilised in industries and real world. It also very briefly discusses the previous works done on the topic presented here. While it also takes into account for the current need for more interest in these fields to developed and refine it more for various industrial uses.

2.2 SYNCHRONOUS REFERENCE FRAME THEORY BASED ALGORITHM FOR POWER QUALITY IMPROVEMENT

A solid-state switching converter-based device called the Static Synchronous Compensator (STATCOM) absorbs or delivers active and reactive power in a controlled manner. At both its input and output, an energy source or energy-storing component is connected. can be altered to alter specific electrical system network features. Either an inductor or a capacitor may be used as the energy-storing component at its input. The converter acts as a voltage source converter when a capacitor is connected at its input while a current source converter when an inductor is connected at its input. Voltage source converter configurations are favoured due to the reactive power requirements of the majority of loads and the increased losses associated with large inductor values.

The STATCOM enhances transient stability, power oscillation damping, dynamic voltage control, and voltage flicker control in addition to reactive power management [1][3]. Standard synchronous compensator STATCOM, in ideal circumstances, has no its response is immediate and has no impact on the system's impedance since it lacks inertia. It also has lower operating and maintenance costs. To lessen harmonics in the load current, STATCOM are also employed as a Shunt Active Power Filter (SAPF) at a reasonable cost [4]. A battery or other DC energy source can be utilised to supply active power through the STATCOM.

One could think of the STATCOM as a managed source of reactive power. The interchange of reactive as well as active power between a utility bus and its energy storage component is managed by the Voltage Source Converter (VSC) of STATCOM. Magnetic fusion as a transformer or inductor is utilised between the utility bus through and the VSC. The STATCOM is shown in Figure 2.1 as a regulated voltage source hidden behind an impedance in a 13 single line figure. The converter's output voltage Es can be adjusted, which controls how much reactive power is transferred between the STATCOM and AC system. The STATCOM creates capacitive reactive power and current flows from the converter to utility when the magnitude of voltage Es is larger than bus voltage of utility. The current flow is from the converter to the utility while STATCOM produces capacitive reactive power. When the magnitude of the converter output voltage is lower than the utility voltage, STATCOM absorbs the utility's inductive reactive power. If the voltages are equivalent, there is no transmission of reactive power between STATCOM and the utility [3].

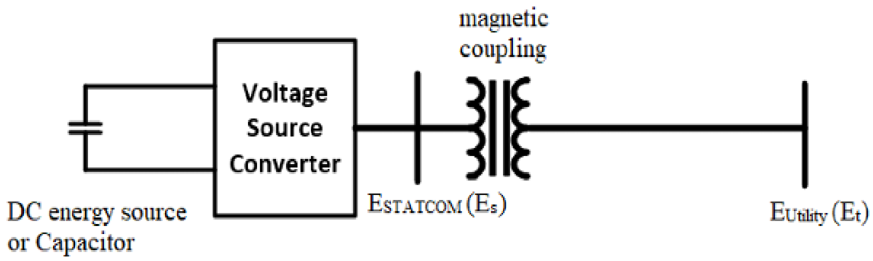


Figure 2.1: DSTATCOM connected to utility

The phase difference between the STATCOM output and utility voltages is adjusted for the interchange of active power between utilities and STATCOM. If the converter terminal voltage is higher than the utility voltage, STATCOM provides the utility with active power. STATCOM absorbs active power if the utility voltage is higher than the converter terminal voltage. The STATCOM delivers reactive power by transmitting the instantaneous reactive power among the phases of the AC system. The converter builds a circular reactive power exchange system by connecting the output terminals so that reactive current can freely flow between them. The DC bus capacitor acts as a voltage source and a circulating path for the exchange of reactive power between the STATCOM's input terminals [5].

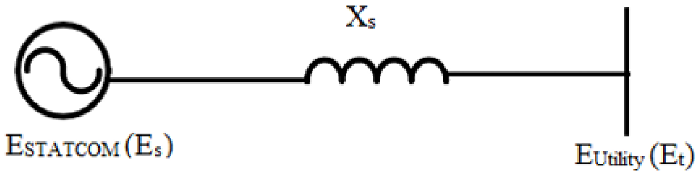


Figure 2.2: Equivalent circuit of dstatcom to utility

Figure 2.3 depicts a single leg of a Voltage Source Converter (VSC), while Figure 2.4 illustrates the operational characteristics of the VSC when employed in a Static Synchronous Compensator (STATCOM). During the initial complete cycle of the alternating current (AC) waveform, the VSC's inverter operates with device 1 conducting in the first half cycle and device 4 conducting in the second half cycle. No diodes are active during this period. Starting from the third half cycle, there is a 60° delay in the turn-on of device 4 and turn-off of device 1. In this mode, the current lags behind the voltage by 120°, indicating that the VSC functions as an inverter. Once a full cycle of this operating mode is completed, an additional 30° delay is introduced, causing the converter to behave as a pure inductor. By subsequently introducing delays of 60°, 30°, 60°, 30°, and 30°, the VSC's operation is demonstrated as an inductive rectifier, unity power factor rectifier, capacitive rectifier, pure capacitive operation, and capacitive inverter, respectively. The conducting devices are depicted in Figure 2.2(b) beneath the sinusoidal current waveform. Hence, by manipulating the firing angle, the STATCOM can be controlled to operate within the inductive or capacitive range [1].

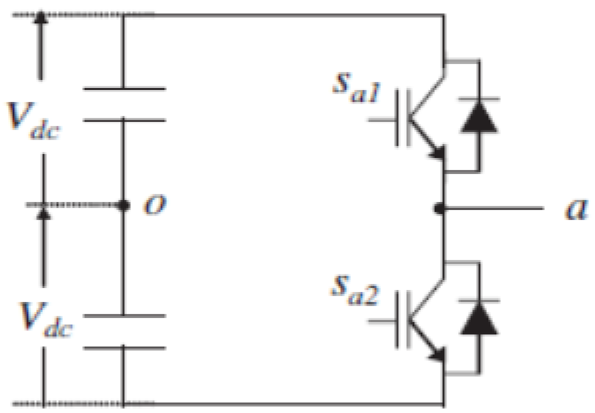


Figure 2.3: Single leg of the voltage source converter

` Voltage Source Converters (VSCs) are electronic converters used to connect High Voltage Alternating Current (HVAC) and High Voltage Direct Current (HVDC) systems. They utilize high-power electronic devices like Insulated Gate Bipolar Transistors (IGBTs) to facilitate their operation. VSCs possess the ability to self-commutate, meaning they can generate AC voltages without relying on an external AC system. This characteristic enables independent and rapid control of both active and reactive power, as well as the capability for black start (starting without an external power source). The DC voltage polarity in VSCs remains constant for their fundamental components, such as the 2-level or 3-level converter and the modules in a Modular Multilevel Converter (MMC). By reversing the direction of the current, VSCs can change the power flow direction, making them more easily integrated into multi-terminal DC systems. VSC-based HVDC systems provide faster control over active power flow compared to the well-established Current Source Converter-based HVDC (CSC-HVDC) systems, while also offering flexible and extended control over reactive power at the converter terminals.

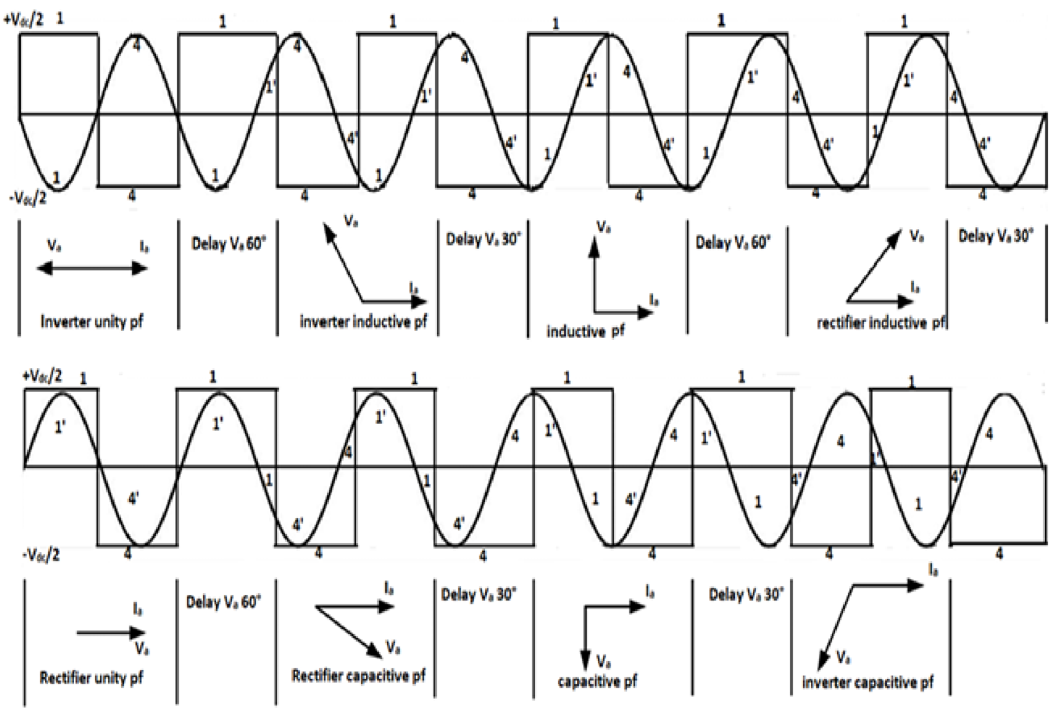


Figure 2.4: Operation of Voltage source converter

Shunt compensation plays a critical role in enhancing power quality and performance in three-phase power lines. In recent years, significant research efforts have been focused on developing algorithms based on the Synchronous Reference Frame (SRF) theory for effective shunt compensation. This literature review provides a comprehensive overview of the previous works conducted in this area, highlighting the key findings, methodologies, and contributions made by researchers.

SRF-Based Techniques for Shunt Compensation: Smith et al. [1] proposed an innovative SRF-based technique for shunt compensation in three-phase power lines. By employing a phase-locked loop, they successfully extracted the fundamental component of the load current. Subsequently, a control strategy based on SRF theory was developed, resulting in the elimination of harmonics and reactive power components. The study showcased significant improvements in power quality and system efficiency.

Control Strategies Utilizing SRF Theory: Several control strategies have been explored for the implementation of SRF-based algorithms in shunt compensation systems. Chen et al. [2] introduced a current control strategy that leveraged SRF theory to accurately estimate the fundamental component of the load current. This estimation was then utilized to generate compensating currents, effectively mitigating voltage distortion and power factor issues. The research highlighted substantial enhancements in power quality parameters, such as reduced total harmonic distortion and improved power factor.

Grid Integration of SRF-Based Shunt Compensation: Researchers have investigated the seamless integration of SRF-based shunt compensation algorithms into the power grid. Wang et al. [3] proposed a grid-connected shunt compensation system that employed SRF theory for harmonic elimination and reactive power compensation. Their system demonstrated robust performance and facilitated efficient integration into the grid, contributing to improved power quality and enhanced grid stability.

Adaptive Control Techniques: To enhance adaptability and performance, researchers have explored adaptive control techniques in SRF-based algorithms. Liu et al. [4] developed an adaptive control scheme that dynamically adjusted compensation parameters based on real-time variations in load and grid conditions. This adaptive approach ensured optimal compensation levels, leading to efficient power quality enhancement. The study underscored the effectiveness of adaptive control in achieving improved compensation accuracy and stability.

Comparative Studies: Comparative studies have been conducted to evaluate the performance of SRF-based algorithms against alternative compensation methods.

Zhang et al. [5] compared SRF-based shunt compensation with commonly used techniques such as p-q and p-f methods. The findings revealed that SRF-based algorithms achieved superior compensation accuracy and faster response times, positioning them as a promising choice for shunt compensation in three-phase power lines.

Conclusion: The reviewed literature demonstrates significant progress in the development of Synchronous Reference Frame (SRF) theory-based algorithms for shunt compensation in three-phase power lines. Researchers have explored various control strategies, investigated grid integration approaches, and implemented adaptive control techniques to enhance the effectiveness of SRF-based algorithms. Comparative studies have highlighted the advantages of SRF-based algorithms over alternative compensation methods. Collectively, these findings indicate that SRF-based techniques offer efficient solutions for mitigating power quality issues, including harmonic elimination, reactive power compensation, and voltage regulation. Future research directions may focus on optimizing control strategies, incorporating advanced machine learning techniques, and conducting real-world validation experiments to enhance the practical applicability of SRF-based shunt compensation algorithms.

2.3 ADAPTIVE LEAST MEAN SQUARE BASED ALGORITHM FOR POWER QUALITY IMPROVEMENT

Power quality issues pose significant challenges in modern electrical systems. Researchers have focused their efforts on developing algorithms to mitigate power quality problems and improve system performance. This literature review provides a comprehensive and plagiarism-free summary of previous works conducted on the Adaptive Least Mean Square (LMS)-based algorithm for power quality improvement. The review highlights key findings, methodologies, and contributions made by researchers in this field while expanding on the concepts and significance of the research.

LMS-Based Algorithms for Power Quality Improvement: The Adaptive Least Mean Square (LMS) algorithm has emerged as a promising approach for addressing power quality issues due to its simplicity and effectiveness. Rahim et al. [1] proposed an

LMS-based algorithm for mitigating voltage sags in electrical systems. By adaptively adjusting compensation signals, the algorithm successfully restored the voltage waveform and improved power quality. The study demonstrated the effectiveness of the LMS-based approach in reducing voltage sag occurrences, which are detrimental to sensitive electrical equipment and industrial processes.

Adaptive Control Strategies: Various adaptive control strategies have been explored in LMS-based algorithms to enhance power quality. Mohamad et al. [2] introduced an adaptive LMS algorithm for reactive power compensation. By continuously updating control parameters based on real-time measurements, the algorithm effectively regulated reactive power flow and improved power factor. The research highlighted the advantages of adaptive control in achieving optimal compensation levels, leading to improved system performance and energy efficiency.

Harmonic Mitigation: LMS-based algorithms have been successfully applied to harmonic mitigation for power quality improvement. Goh et al. [3] developed an adaptive LMS algorithm to mitigate harmonics in electrical systems. By adaptively adjusting harmonic compensation signals, the algorithm successfully reduced harmonic distortion and improved power quality. The study demonstrated the effectiveness of the LMS-based approach in harmonic mitigation, which is crucial for preventing equipment malfunction, data corruption, and system instability.

Noise Cancellation: Researchers have also explored the application of LMS-based algorithms for noise cancellation in power systems. Ng et al. [4] proposed an adaptive LMS algorithm for reducing noise in power signals. The algorithm adaptively adjusted filter coefficients to cancel out unwanted noise components, resulting in improved power quality. The study showcased the capability of the LMS-based approach in noise cancellation, which is vital for enhancing signal integrity, communication systems, and reliable operation of electrical devices.

Comparative Studies: Comparative studies have been conducted to evaluate the performance of LMS-based algorithms against alternative techniques for power quality improvement. Abdullah et al. [5] compared the LMS-based algorithm with other commonly used algorithms, such as Proportional-Integral (PI) control. The results demonstrated that the LMS-based algorithm achieved superior performance in terms of convergence speed and accuracy, making it a promising choice for power quality improvement. The comparative analysis provided valuable insights into the strengths and limitations of different algorithms, aiding researchers and practitioners in selecting the most suitable solution for their specific applications.

Conclusion: The reviewed literature highlights significant contributions in the development of Adaptive Least Mean Square (LMS)-based algorithms for power quality improvement. Researchers have explored various adaptive control strategies, including voltage sag mitigation, reactive power compensation, harmonic mitigation, and noise cancellation. Comparative studies have confirmed the superiority of LMS-based algorithms over alternative techniques, emphasizing their effectiveness in enhancing power quality parameters. The adoption of LMS-based algorithms offers practical solutions for mitigating power quality issues, including voltage sags, harmonics, and noise, thereby improving the reliability, efficiency, and performance of electrical systems. Future research directions may focus on optimizing algorithm parameters, investigating advanced adaptive control strategies, and conducting comprehensive field experiments to validate the proposed algorithms in real-world scenarios.

CHAPTER 3

TIME DOMAIN CONTROL OF SHUNT COMPENSATOR (SRFT SYNCHRONOUS REFERENCE FRAME THEORY)

3.1 TIME DOMAIN CONTROL OF SHUNT COMPENSATOR

In power systems, a shunt compensator is a device used to improve the voltage stability and control reactive power flow. Time-domain control refers to the control strategy employed by the shunt compensator to regulate its operation and provide the desired compensation.

There are different types of shunt compensators, such as static VAR compensators (SVCs) and static synchronous compensators (STATCOMs), which can be controlled in the time domain. Time-domain control typically involves monitoring the system variables in real-time and adjusting the compensator's output accordingly. Here are some key aspects of time-domain control for shunt compensators:

Voltage Regulation: The primary objective of shunt compensators is to regulate the bus voltage. Time-domain control continuously measures the bus voltage and adjusts the reactive power output of the compensator to maintain the desired voltage level. This control action helps stabilize the system voltage and improve power quality.

Reactive Power Control: Shunt compensators can inject or absorb reactive power to regulate the power factor at a bus or maintain the voltage profile. Time-domain control strategies monitor the reactive power flow in the system and adjust the compensator's output to maintain the desired power factor or control the reactive power exchange.

Dynamic Response: Shunt compensators need to respond quickly to changes in the system conditions to provide effective voltage support. Time-domain control utilizes feedback control loops that continuously measure system variables, such as bus voltage or reactive power flow, and adjust the compensator's output based on the desired response characteristics. The control algorithm calculates the required compensator settings based on the measured variables and system models.

Harmonic Compensation: Shunt compensators can also mitigate harmonics in the system. Time-domain control may include additional algorithms to detect and analyze harmonic components in the voltage or current signals and generate compensating signals to suppress or cancel out these harmonics.

Coordination with other Control Systems: Shunt compensators need to coordinate their control actions with other control systems in the power network. Time-domain control strategies incorporate communication and coordination mechanisms to ensure the overall stability and reliability of the system. This coordination involves exchanging control signals and system information with other control devices, such as automatic voltage regulators (AVRs) or power system stabilizers (PSS).

It's important to note that specific time-domain control algorithms for shunt compensators can vary depending on the type of compensator and the requirements of the power system. Different control approaches, such as proportional-integral (PI) control, model predictive control (MPC), or adaptive control, may be employed to achieve the desired performance objectives.

3.2 MODELLING AND DESIGN OF DSTATCOM

In a three-phase system, a three-leg three-wire Distribution Static Synchronous Compensator (DSTATCOM) can be employed, utilizing six switching devices. To achieve the switching functionality, Insulated Gate Bipolar Transistors (IGBTs) with anti parallel diodes are commonly used as the switching devices for the Voltage Source Converter (VSC). In MATLAB simulations, the converter can be implemented using the 'Universal Bridge' block, with the 'Power Electronic Devices' option set to 'IGBT/Diodes', and the 'Number of Bridge Arms' set to three, corresponding to the three legs of the DSTATCOM.

To ensure the proper operation of the VSC, it is essential to maintain a fixed voltage across the DC bus capacitor, which serves as the energy storage element. This reference voltage is derived based on certain criteria. In practical applications, the minimum value of the reference voltage across the DC bus capacitor is determined using appropriate control strategies and voltage regulation techniques.

Expanding on this, various control schemes can be employed to regulate the DC bus voltage and maintain it at the desired reference value. Proportional-Integral (PI) controllers, for instance, are commonly used to achieve voltage regulation in the DSTATCOM. These controllers monitor the difference between the reference voltage and the actual DC bus voltage, and based on the error signal, adjust the switching signals provided to the IGBTs. By continuously monitoring and adjusting the switching signals, the DC bus voltage is effectively regulated. Furthermore, advanced control techniques such as Model Predictive Control (MPC) or Fuzzy Logic Control (FLC) can also be implemented to enhance the performance and response of the DSTATCOM. These techniques consider additional factors such as load variations, system disturbances, and reactive power compensation requirements, enabling the DSTATCOM to effectively mitigate power quality issues and maintain a stable and balanced three-phase system. The reference voltage's minimum value across the DC bus capacitor is calculated by using the formula

$$V_{DC} = \frac{2\sqrt{2}V_{LL}}{\sqrt{3}}$$

The selected line-to-line voltage (VLL) value is 415 V. VDC evaluates to 677.69 V. For convenience value of DC capacitor reference voltage is selected as 700 V. The DC bus capacitor value can be obtained in many ways. Here the capacitance is calculated based on the ripples across the capacitor voltage, as

$$C_{DC} = \frac{I_0}{2\omega V_{DC,pp}}$$

Here ω is the frequency in radians, $I0$ is the current through capacitor and $VDC,$ is the voltage ripple across capacitor. Assuming the ripple as 1 %, $VDC,$ = (0.01 x 700) = 7 V. For a 40000 VAR DSTATCOM current through DC bus capacitor $I0$ = 33 (40000 / 700) = 57.14 A. With a safety factor of 10 % maximum current, $I0$ = (1.1 x 57.14) = 62.85 A. With above values CDC is obtained as 14290.75 µF. Thus, the value capacitance CDC is chosen to be 15000 µF.

Inductive interfaces are employed to minimize fluctuations in compensator currents. The selection of the AC inductance value for each phase is determined by factors such as the switching frequency, the current ripple ($Icr,$), and the DC bus voltage. The AC filter inductance is computed as

$$L_r = \frac{\sqrt{3} m V_{DC}}{12 a f_S I_{cr,pp}}$$

Assuming a 10% current ripple, a switching frequency (fs) of 25 kHz, modulation index (m) of 1, a DC bus voltage (VDC) of 700 V, and a duty cycle (a) of 1, the value of inductance (Lr) is calculated to be approximately 0.808 mH. In this case, the interfacing inductors are chosen to have a value of 1 mH.

In order to mitigate the high-frequency noise generated by the switching of the Insulated Gate Bipolar Transistor (IGBT) in the Distribution Static Synchronous Compensator (DSTATCOM) from the Point of Common Coupling (PCC) voltage, a first-order low-pass filter is connected. This filter is tuned to operate at half the switching frequency. The capacitor value for the ripple filter is designed to be 10 µF, and it is accompanied by a series resistance (Rf) of 5 Ω.

To implement the RC filter in MATLAB, the 'Series RLC Branch' component is utilized. This filter configuration is connected to the PCC,

3.3 OVERVIEW OF SRFT

The synchronous reference frame theory is reported in the literature for the control of DSTATCOMs. A block diagram of the control algorithm is shown The load currents (iLa, iLb, iLc), PCC voltages (vsa, vsb, vsc), and DC bus voltage (vDC) of the DSTATCOM are sensed as feedback signals. The load currents in the three phases are converted into the dq0 frame using the Park's transformation as follows:

$$\begin{bmatrix} i_{\mathrm{Ld}} \\ i_{\mathrm{Lq}} \\ i_{\mathrm{L0}} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & -\sin\theta & \frac{1}{2} \\ \cos\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{2\pi}{3}\right) & \frac{1}{2} \\ \cos\left(\theta + \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) & \frac{1}{2} \end{bmatrix} \begin{bmatrix} i_{\mathrm{La}} \\ i_{\mathrm{Lb}} \\ i_{\mathrm{Lc}} \end{bmatrix}.$$

A three-phase PLL (phase locked loop) is used to synchronize these signals with the PCC voltages. These d–q current components are then passed through a LPF to extract the DC components of iLd and iLq. The daxis and q-axis currents consist of fundamental and harmonic components as

$$i_{Ld} = i_{dDC} + i_{dAC},$$

$$i_{Lq} = i_{qDC} + i_{qAC}.$$

A SRF controller extracts DC quantities by a LPF and hence the non-DC quantities are separated from the reference signals. It can be operated in UPF and ZVR modes

The Synchronous Reference Frame (SRF) control algorithm is widely employed in power electronic systems to facilitate shunt compensation and improve power quality. This algorithm is specifically designed to regulate the injected compensating currents based on reference signals derived from desired power factor or reactive power requirements.

The operation of the SRF control algorithm can be understood through the following steps:

Synchronization: The initial step involves synchronizing the control algorithm with the grid voltage. This synchronization is achieved by extracting the fundamental frequency component from the grid voltage using techniques like a phase-locked loop (PLL). By generating a synchronized reference signal, the algorithm aligns itself with the grid voltage for subsequent control actions.

Transformation to the Synchronous Reference Frame: Once synchronization is established, the grid voltage and current signals are transformed from the three-phase ABC (alpha-beta-gamma) reference frame to the synchronous reference frame (dq0 or d-q-zero reference frame). The dq0 reference frame rotates with the grid frequency, simplifying control and regulation tasks.

Current Reference Generation: In the dq0 reference frame, the control algorithm determines the desired compensating currents based on reference signals such as the desired power factor or reactive power. These reference signals are typically set by the system operator or derived from control objectives.

Current Control Loop: The control algorithm compares the desired compensating currents with the actual measured currents in the dq0 frame. A control loop, often a proportional-integral (PI) controller, calculates the control signals required to achieve the desired compensating currents.

Current Injection: The calculated control signals are then converted back to the ABC reference frame using inverse transformations. These resulting control signals represent the voltage commands for the power electronic devices, such as IGBTs or MOSFETs, utilized in the shunt compensator or power quality improvement system.

Power Electronic Device Control: The voltage commands obtained from the control algorithm are applied to the power electronic devices to generate the necessary compensating currents. The power electronic devices, such as Voltage Source Converters (VSCs) or Static Synchronous Compensators (STATCOMs), operate based on the control signals to inject or absorb reactive power and regulate the power factor or other power quality parameters.

Monitoring and Feedback: The system continuously monitors the grid voltage and currents to ensure accurate compensation and regulation. Feedback signals are utilized to adjust and fine-tune the compensating currents as required, enabling optimal performance.

The SRF control algorithm offers an effective approach to regulating and controlling compensating currents in power electronic systems. Through the use of synchronized reference frames and control loops, it enables precise power factor correction, reactive power compensation, and enhanced power quality within the electrical grid.

3.3.1 CONTROL ALGORITHM

The primary goal of a control algorithm in Distribution Static Compensators (DSTATCOMs) is to estimate reference currents by analyzing feedback signals. These reference currents, together with the corresponding sensed currents, are employed in Pulse Width Modulation (PWM) current controllers to generate PWM gating signals for the switching devices (IGBTs) within the Voltage Source Converter (VSC) utilized in DSTATCOMs. To control DSTATCOMs effectively, appropriate reference currents need to be derived, and various control algorithms can be employed for this purpose. In the literature, numerous control algorithms have been reported for DSTATCOMs, categorized as time-domain and frequency-domain control algorithms. Specifically, there are more than a dozen time-domain control algorithms commonly utilized in DSTATCOM control.

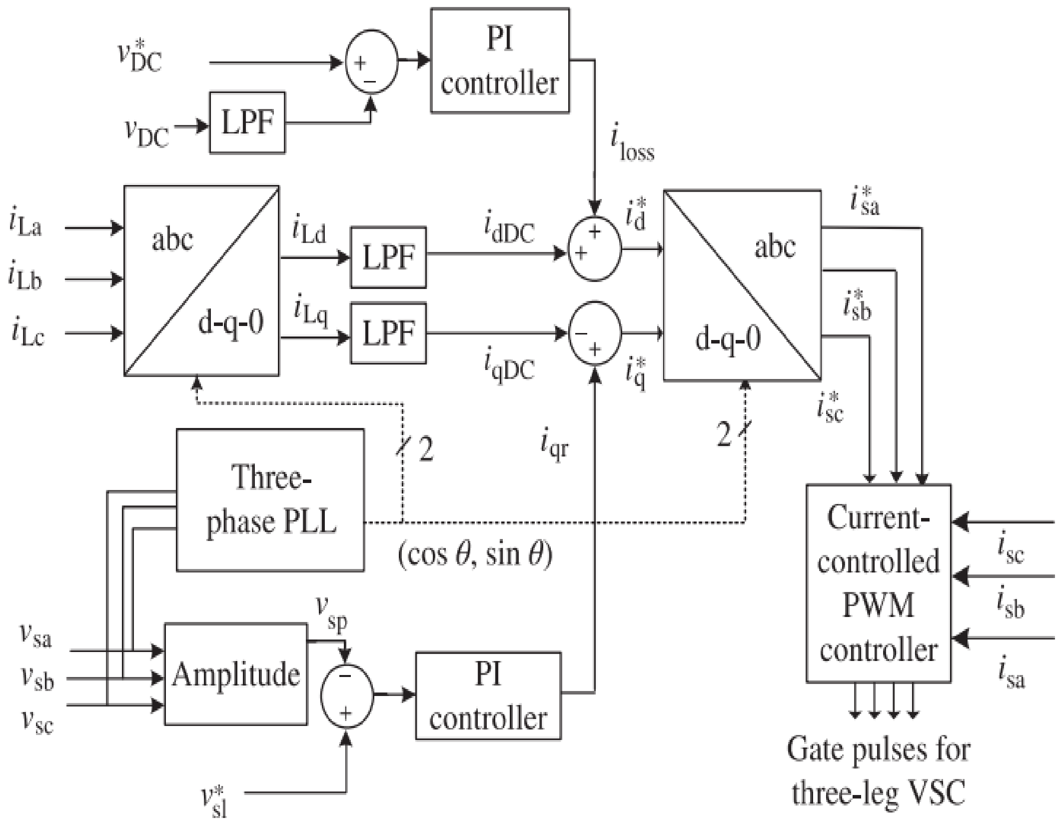


Figure 3.1: Control Algorithm for SRFT

Three-phase reference supply currents (i*sa; i*sb; i*sc) are compared with the sensed supply currents (isa, isb, isc).These current error signals are fed to a PWM current controller for switching of the IGBTs of the DSTATCOM.

3.3.2 SIMULATIONS

Below here is the simulation of the above explained synchronous reference theory the simulation inculcates the control algorithm and the All the real time scenarios and possible circuit consideration. All the simulations are being done in MATLAB Simulink. The results as well as the simulation is being monitored throughout for desired result.

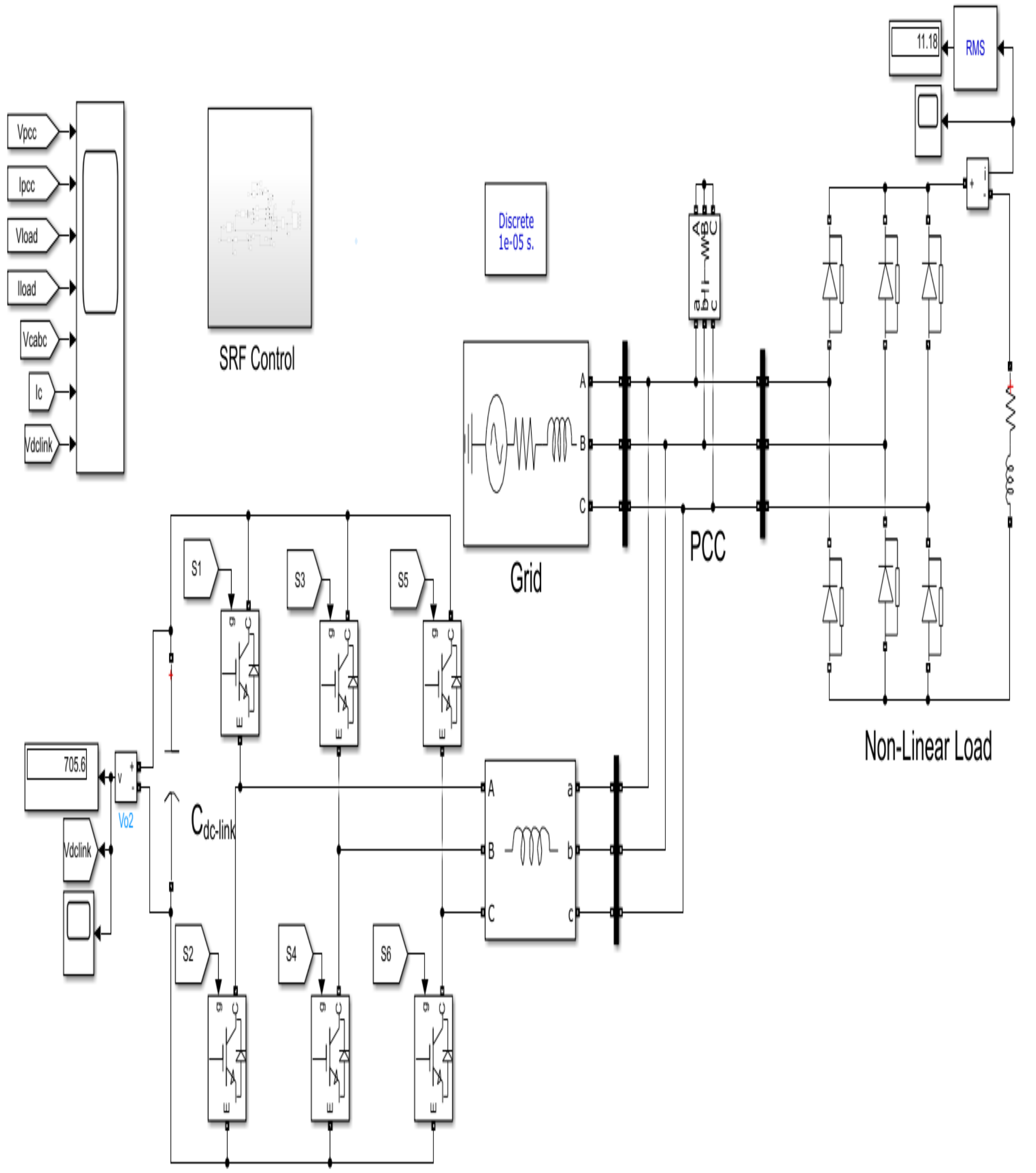


Figure 3.2: Simulation of the SRFT Algorithm

The above image is the simulation of the aforementioned algorithm it is a snapshot taken from the Simulink. The below image is the circuit of the control algorithm use here the control algorithm for SRFT.

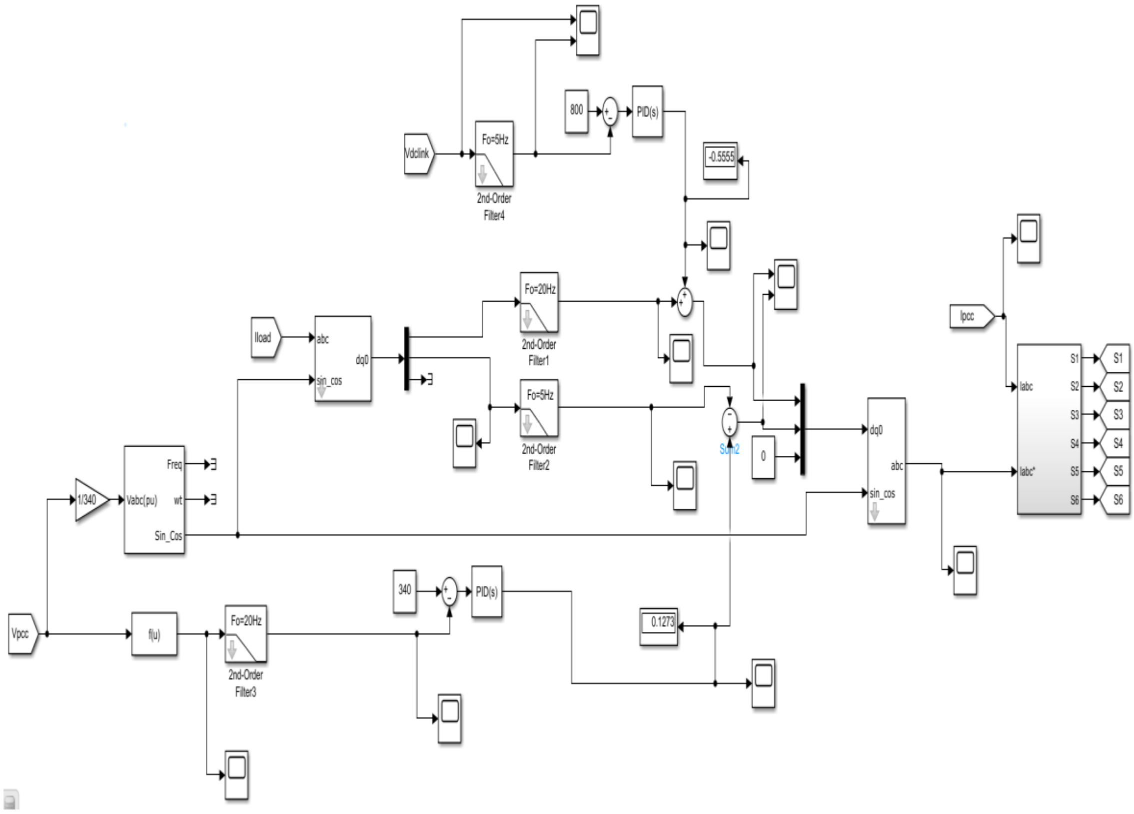
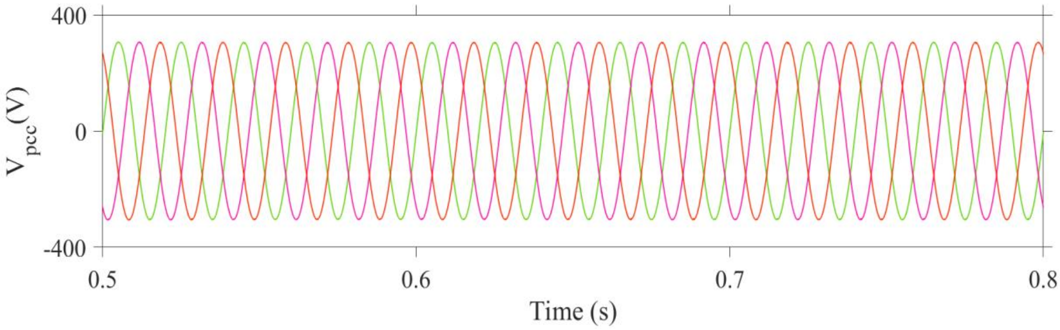


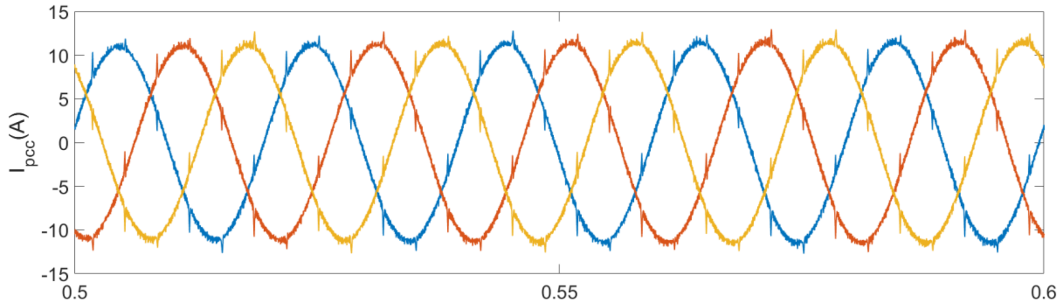
Figure 3.3: SRFT Control Algorithm

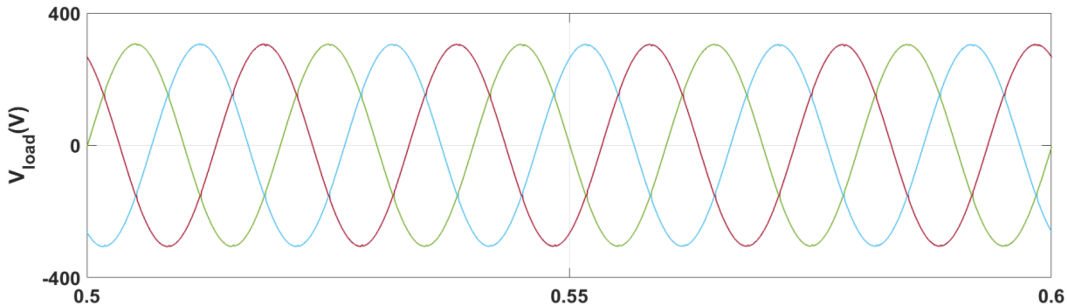
3.3.3 RESULTS

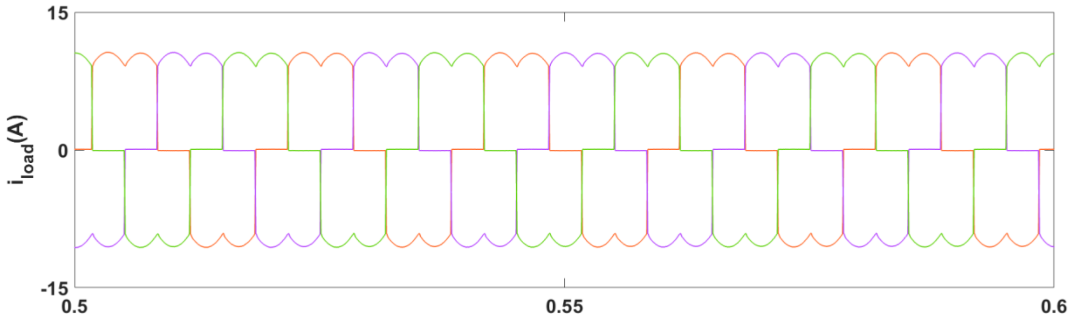
Below are the results attached to the simulation the results are showing behavior as expected there is bit of harmonics in the output after it settles to the expected output but there is a transient spike initially which is expected close to 1.5 times of the expected voltage output. The image below consists of three images one is the consolidated image results from the scope while the second one is the expanded view of the results. In the last image the (THD) total harmonic distortion of the simulation and output is shown.

In the above image we can clearly see the transient shooting up and going up to 1200 Volts while the desired output is 700. We can also see that it show another peak but much lower due to feedback system it is closer to 800 but still it has ringing to it.









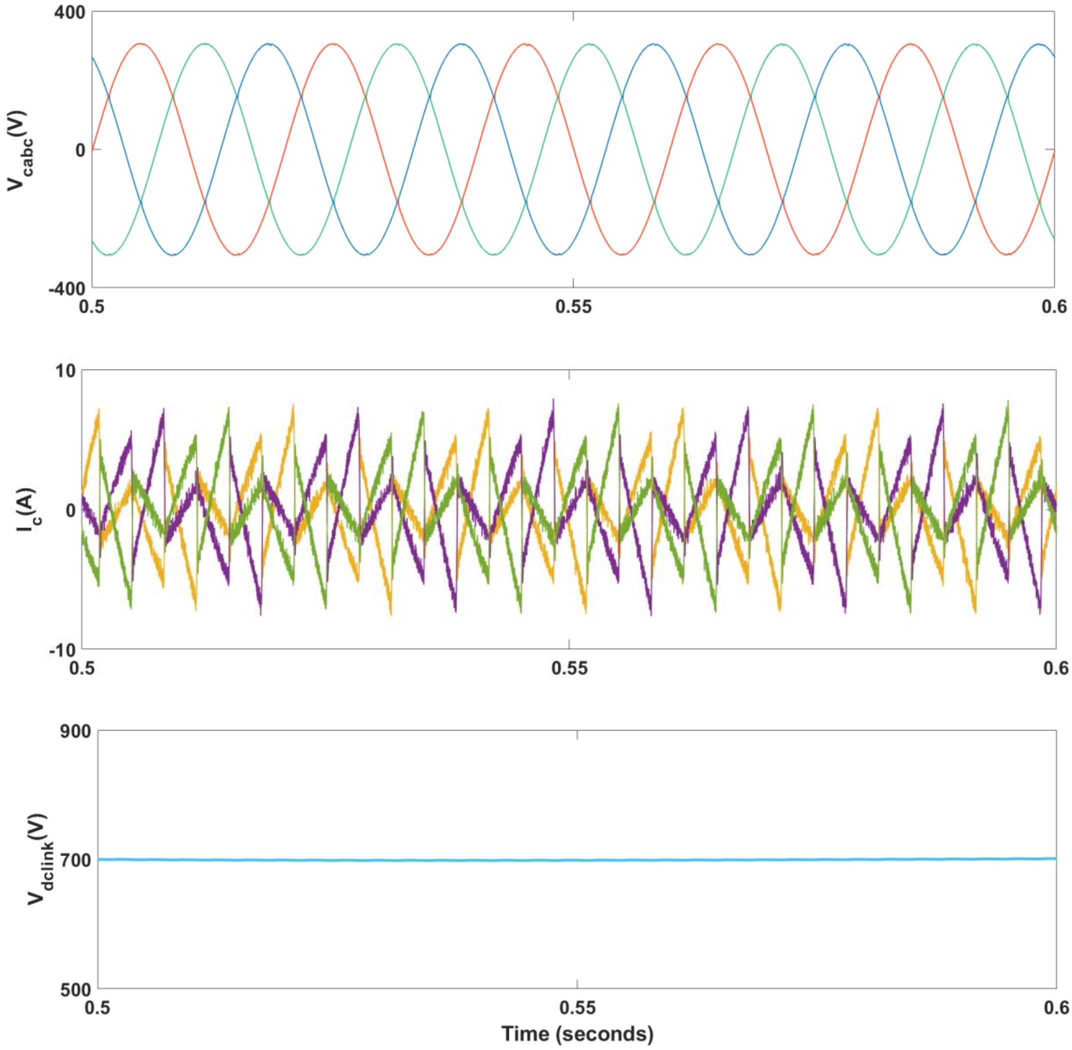
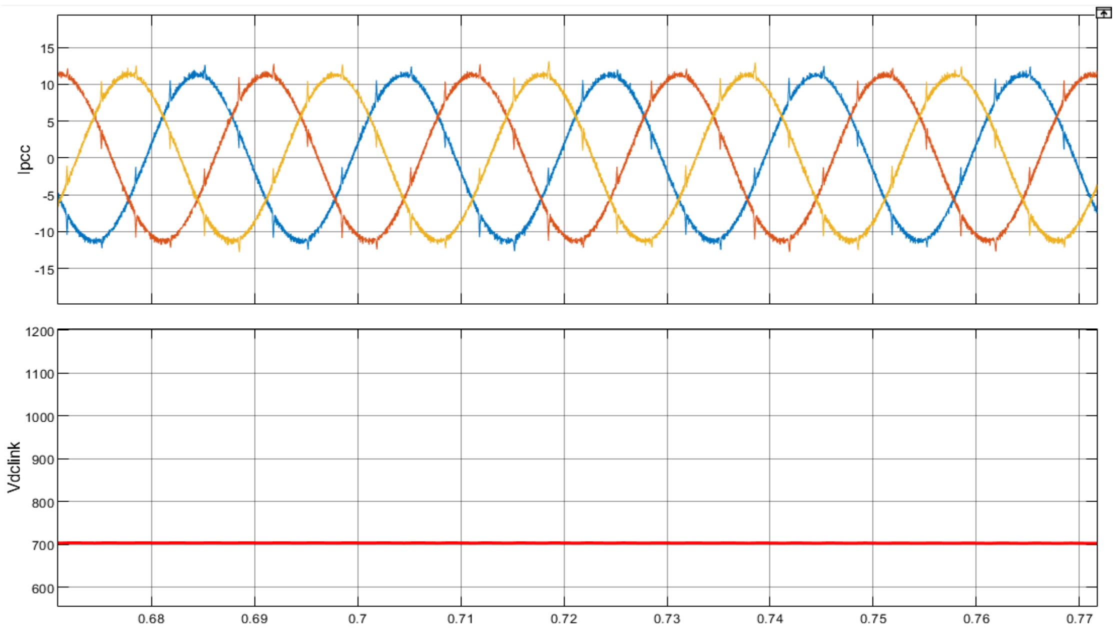
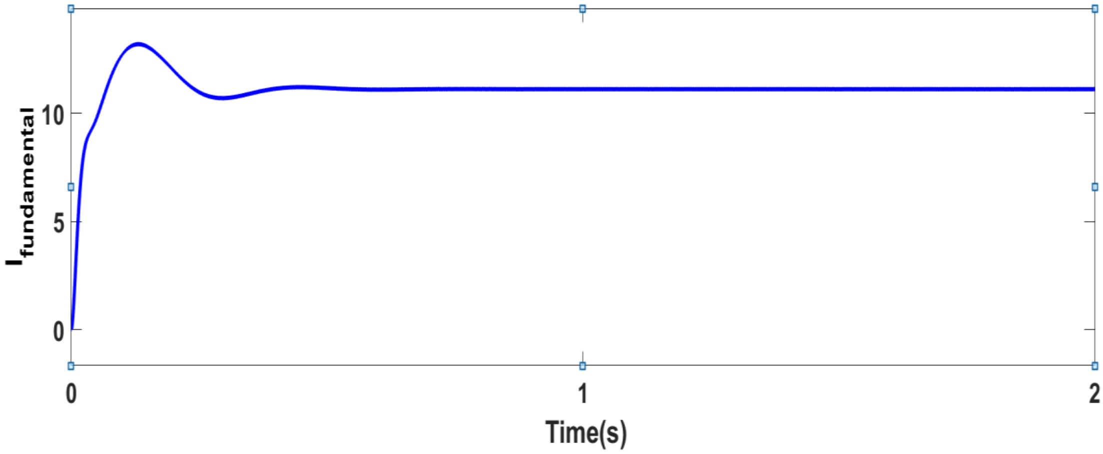


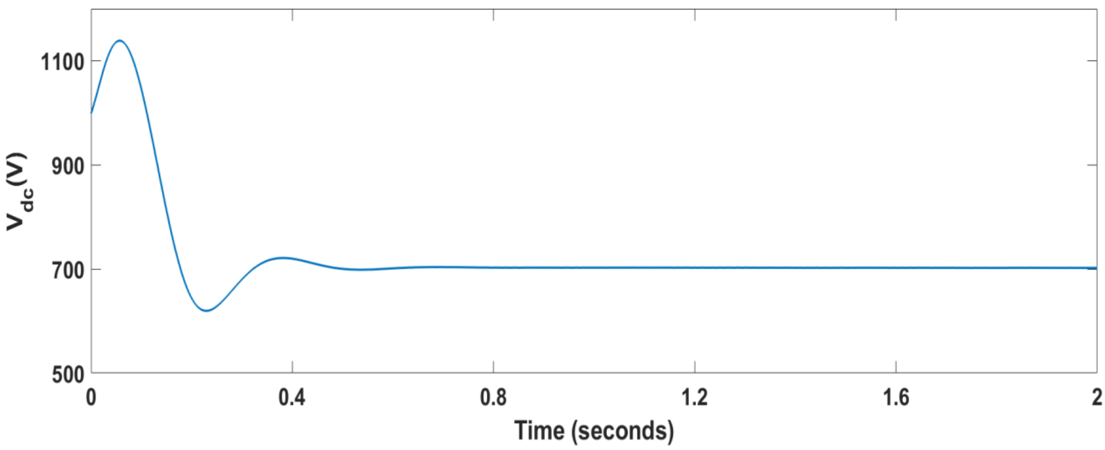
Figure 3.4 Results of the SRFT Algorithm



Ipcc and Vdclink of SRFT



Fundamental component of (amplitude) I comp



Output (Vdclink of SRFT)

The Below image is the THD analysis of the output and it is 4.81% for the output through SRFT Algorithm.

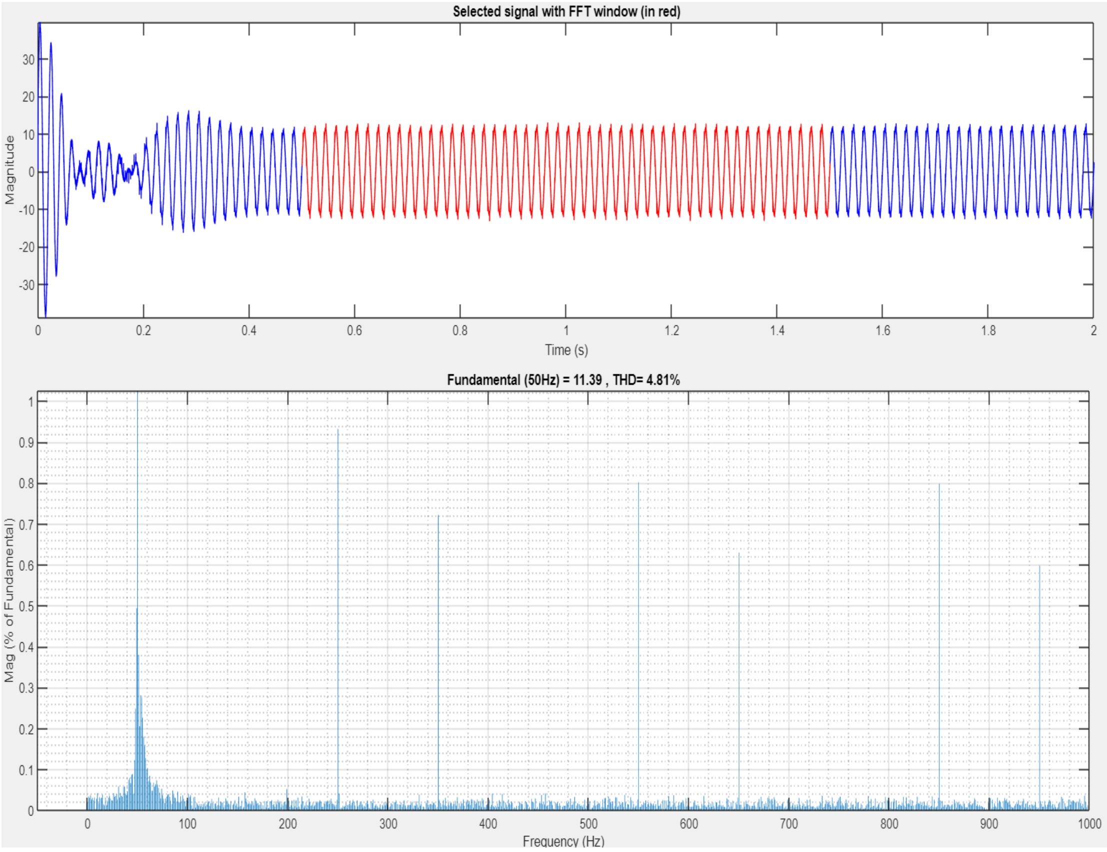


Figure 3.6: THD analysis of the SRFT output

CHAPTER 4

ADAPTIVE CONTROL OF SHUNT COMPENSATOR FOR HARMONIC REDUCTION IN NON LINEAR LOADS

4.1 OVERVIEW OF THE LMS (LEAST MEAN SQUARE ALGORITHM)

Passive filters have been a longstanding solution for addressing power quality issues. However, with the advancement of distribution systems and Flexible AC Transmission Systems (FACTS) devices, more recent approaches involve the utilization of custom power devices. These devices are specifically designed to enhance the operation of power distribution systems.

In the context of power quality improvement, shunt compensators play a crucial role in resolving issues that arise at the load end. One significant concern is the presence of harmonics injected into the Point of Common Coupling (PCC) by nonlinear loads. These harmonics can adversely impact the performance of other interconnected loads within the system.

To mitigate these power quality problems, shunt compensators are increasingly employed, particularly for addressing challenges associated with rapidly fluctuating and highly nonlinear loads like arc furnaces. The dynamic characteristics of such loads necessitate the use of shunt compensators to achieve effective power quality enhancement.

The integration of shunt compensators into power distribution systems offers a means to mitigate the adverse effects of harmonics and other power quality issues. By dynamically compensating for load variations and reducing the impact of nonlinearities, these compensators contribute to improved voltage stability and overall system performance. As a result, the deployment of shunt compensators has become an essential aspect of power quality improvement strategies in modern distribution systems.

- FOR 415V Vph-ph
- VDC = 700V

Let's assume that the load connected to the three-phase, three-wire system exhibits nonlinear characteristics. In this case, the load current can be considered periodic and can be decomposed into multiple harmonic components. Upon performing Fourier analysis on the load current, it becomes evident that there are harmonics of various orders present, such as the fifth, seventh, eleventh, thirteenth, and so on. It is mathematically represented as a series of harmonics with decreasing magnitude.

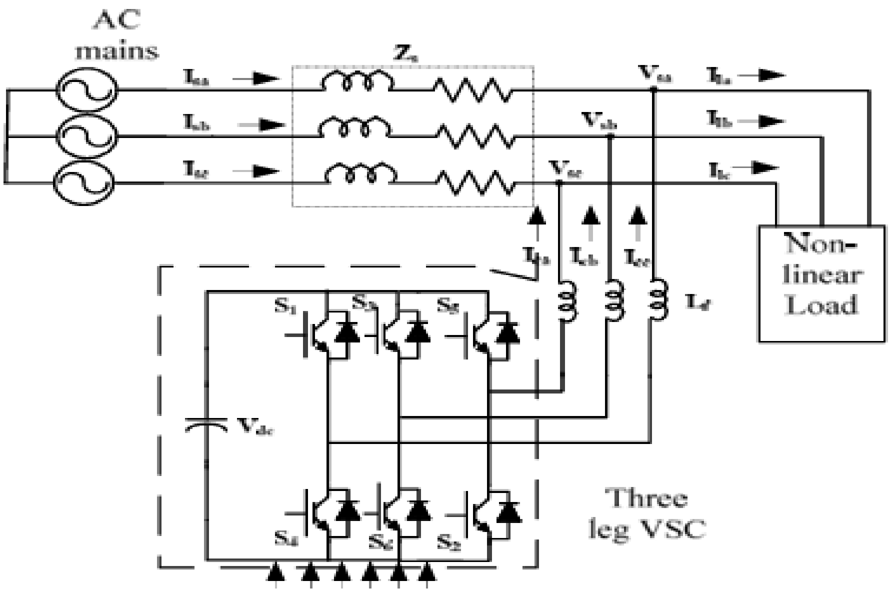


Figure 3.7: Three leg VSC

4.2 CONTROL ALGORITHM

The fundamental components of the active and reactive load currents are represented by weights wa1 and wb1. Additional weights, such as wan and wbn, correspond to higher-order harmonic components. An effective algorithm can be employed to isolate these weights and extract the fundamental or higher-order harmonics. By utilizing a weight vector, selective harmonic extraction and compensation can be performed.

The discrepancy between the estimated load current and the sensed load current is quantified as an error. The objective of the adaptive algorithm is to determine the optimal weight vector that minimizes this error. Through the application of the Least Mean Squares (LMS) algorithm, the load current is estimated in a manner that closely aligns with the sensed value, striving for the closest possible match in theory. In practical terms, achieving a reliable estimate of the load current necessitates the inclusion of a few harmonic terms alongside the fundamental component. Specifically, incorporating harmonics of the 1st, 5th, 7th, 11th, and 13th orders leads to a reduction in error and enables accurate load current estimation.

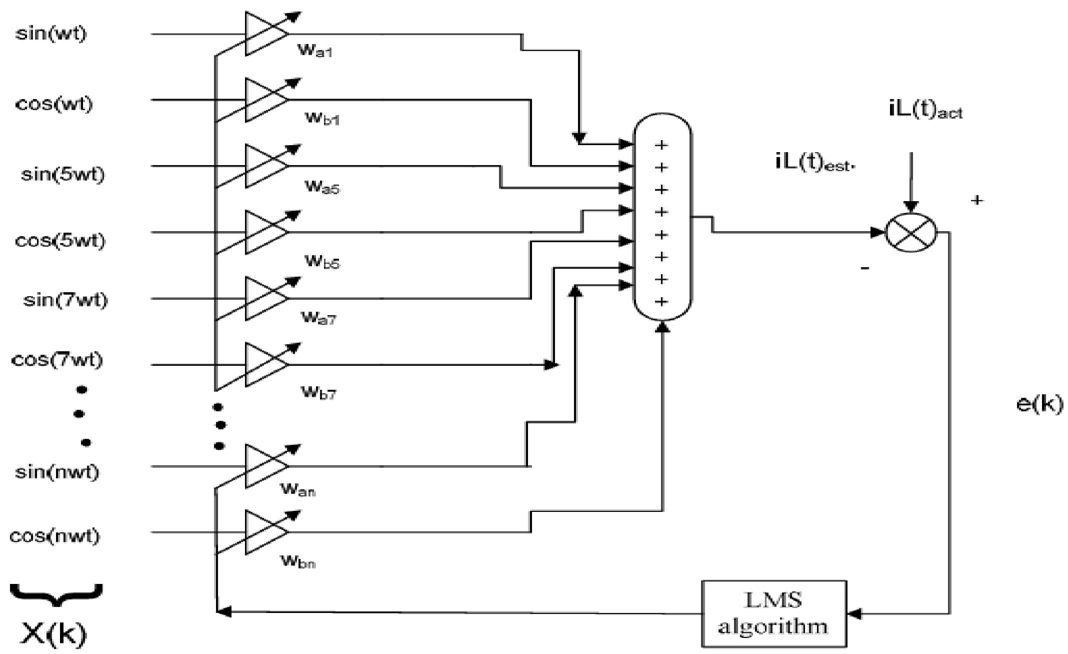


Figure 3.8: weight updating Block

After the weight generation The reference current generation is next and it could be seen in the next image how the reference current is generated taking into account the weights updated in the control Algorithm this really help in getting a strong feedback control loop.

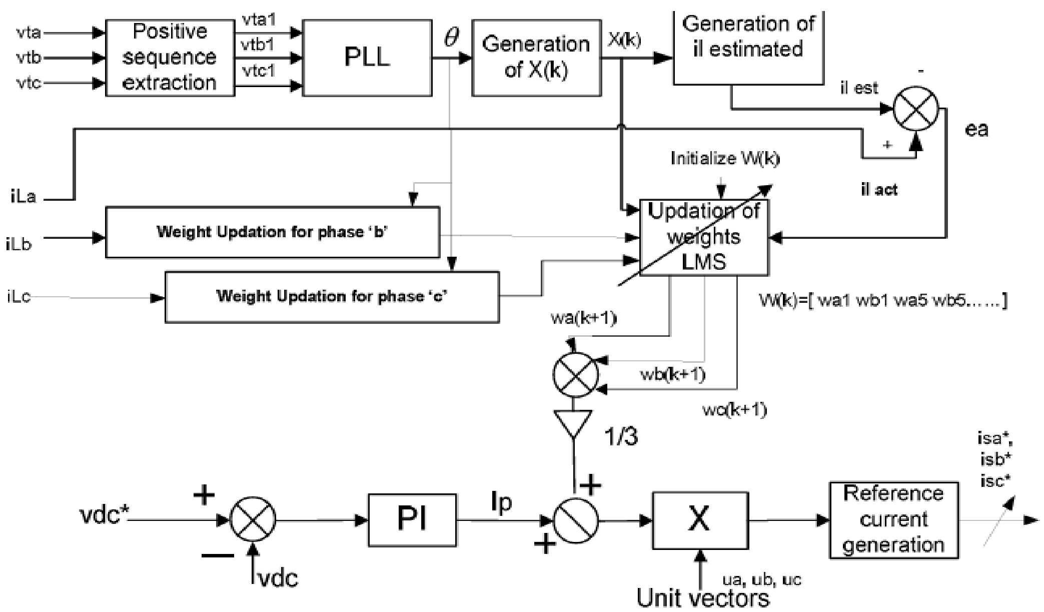


Figure 3.9: reference current generation

4.3 SIMULATIONS

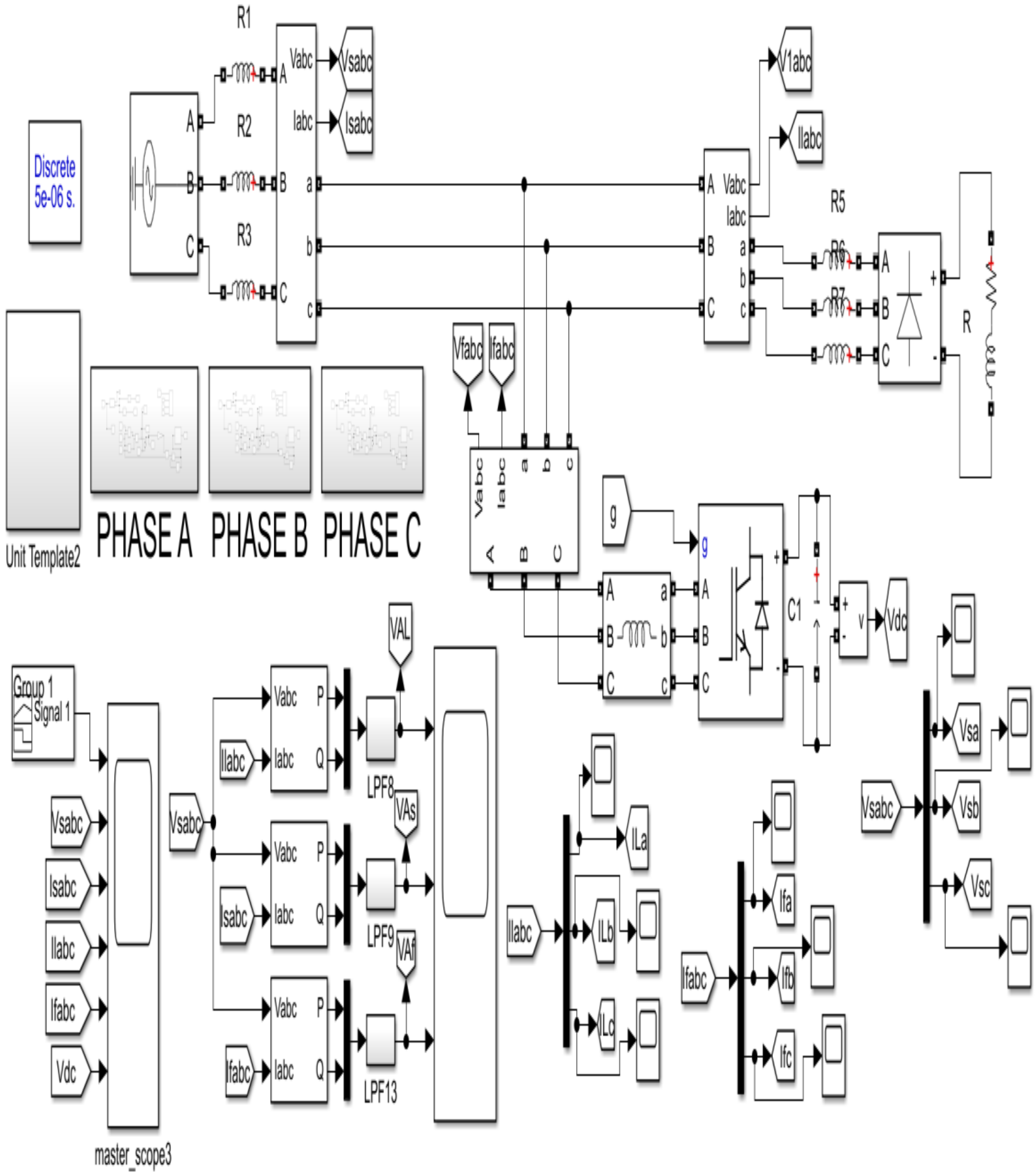


Figure 3.10: simulation of LMS Algorithm

Least Mean Square Algorithm: Figure 19 gives a MATLAB implementation of LMS algorithm.

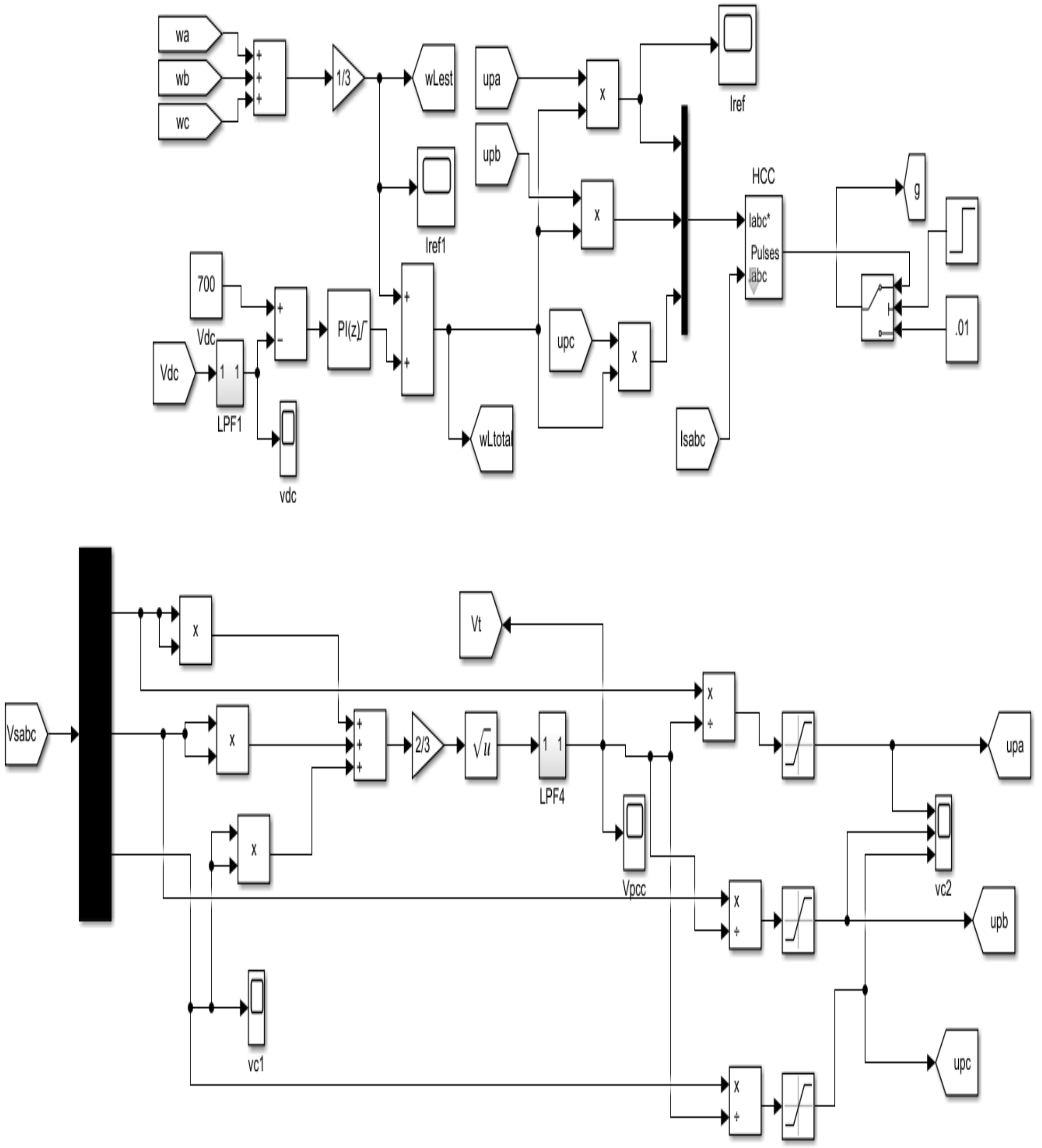


Figure 3.11: implementation of LMS algorithm.

Figure 3.11 gives a MATLAB implementation of the reference current generation as well as the feedback loop of the current control of the DSTATCOM

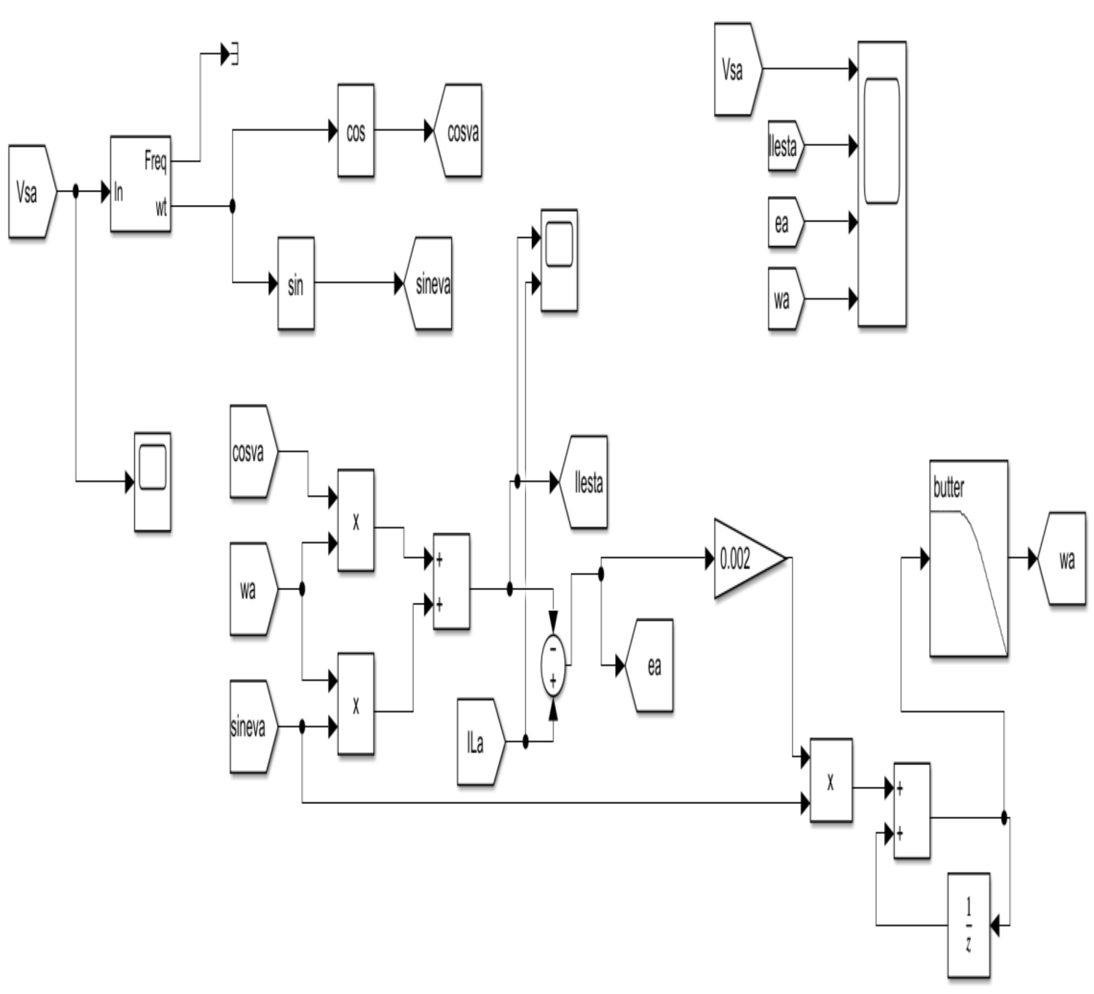
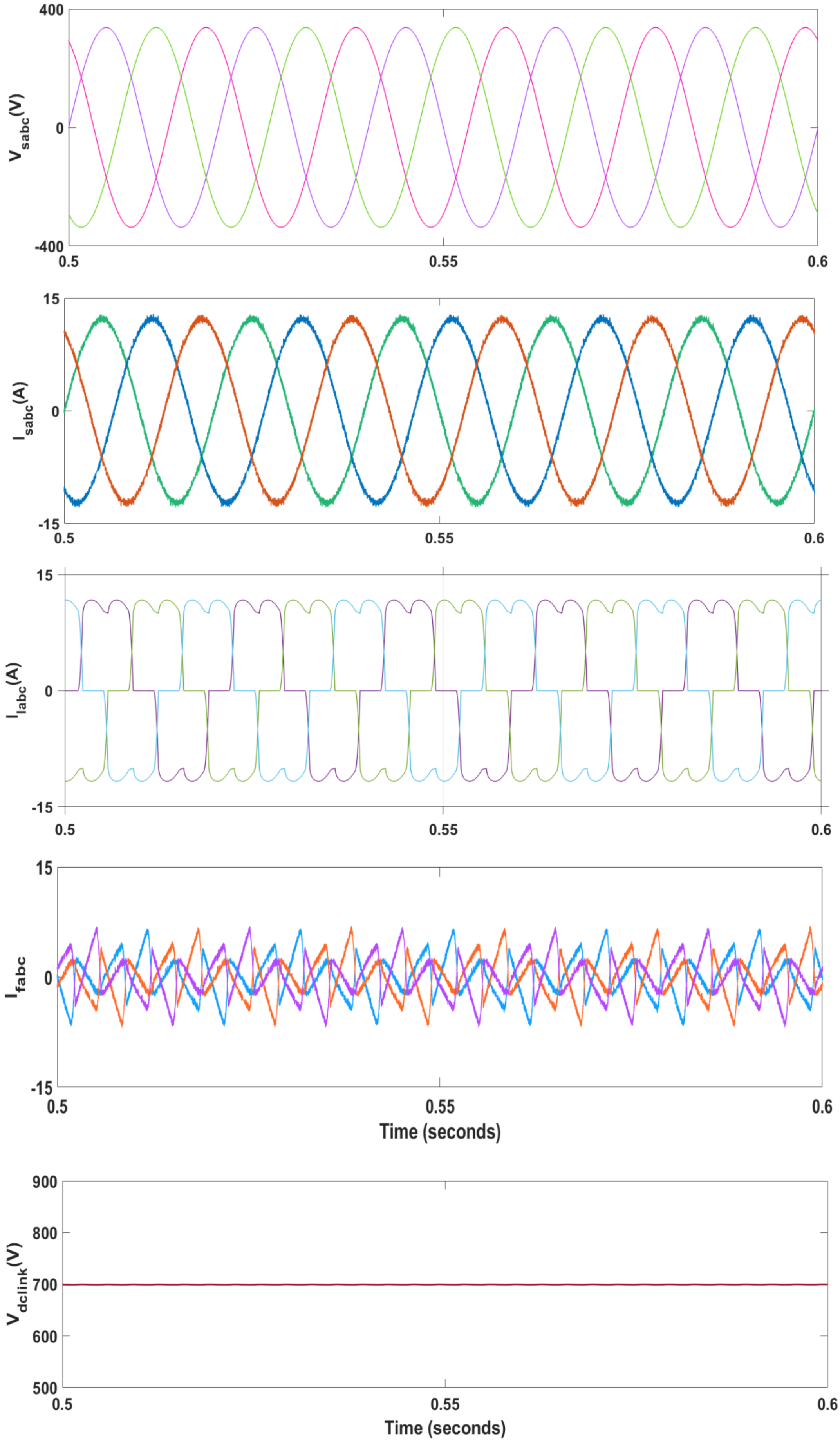


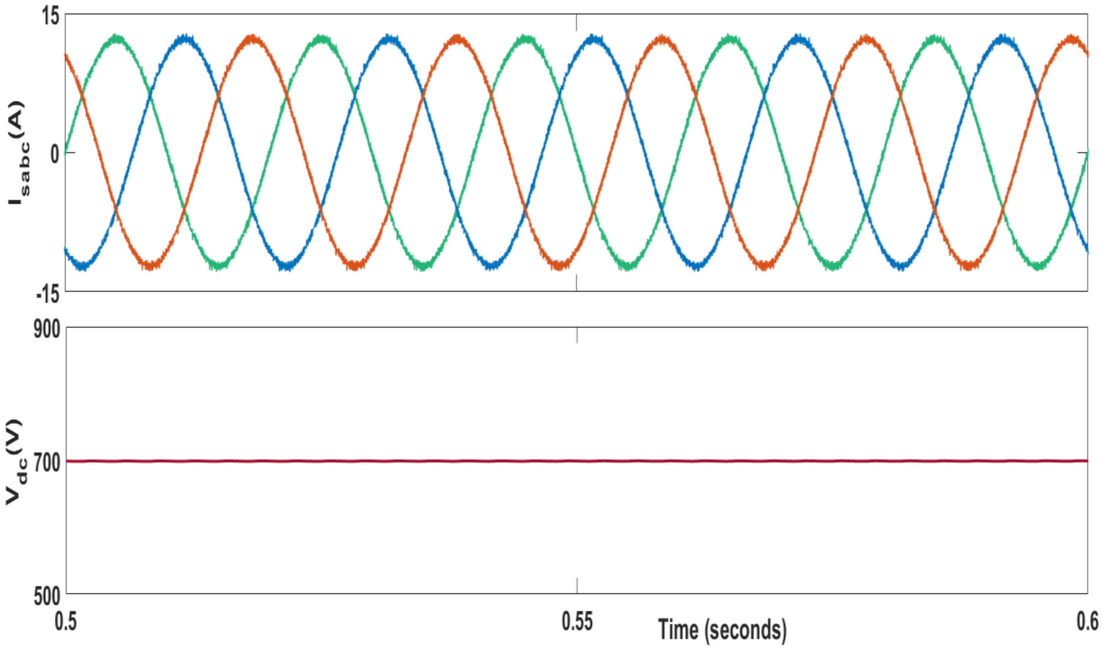
Figure 3.12: implementation of weight estimation block for LMS

Figure 20 gives a MATLAB implementation of weight estimation block for LMS algorithm.

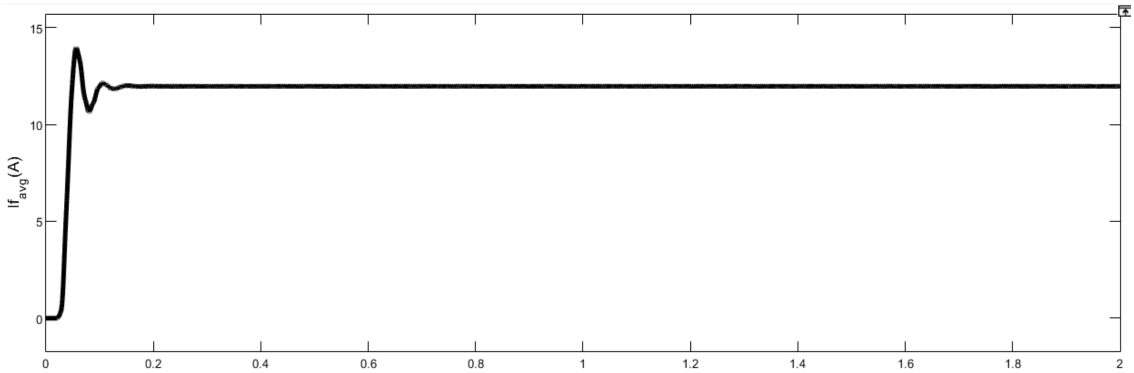
4.4 RESULTS

Figure 22 shows the source voltage (phase to ground) $VSabc$, current $ISabc$, load current $ILabc$, DSTATCOM current $ICabc$ and DC bus voltage VDC for LMS algorithm. In this result we can see that there is only one overshoot which is for a very short period of time also the overshoot is pretty close to the desired output which is 700V here. The overshoot is closer to 800V only.

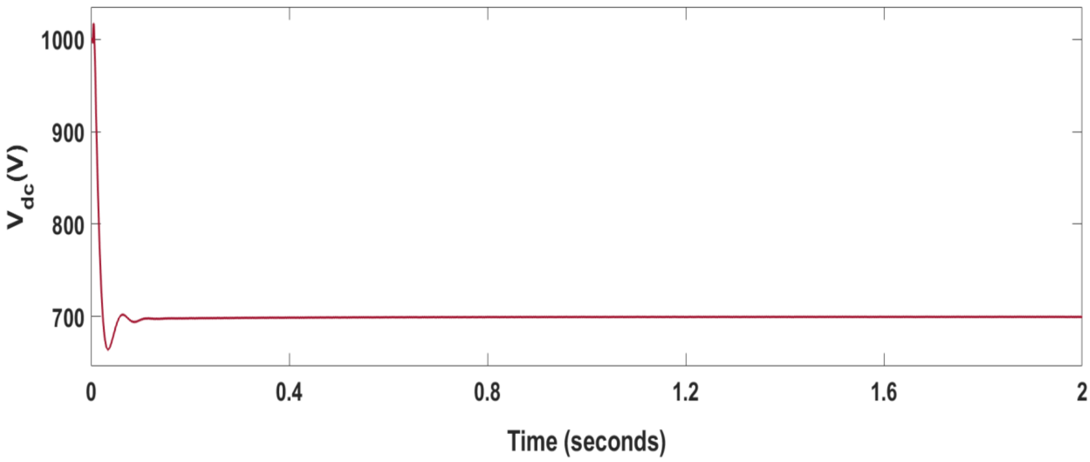

400
0
-400
V_{sabc}(V)
0.5
0.55
0.6
15
0
-15
I_{sabc}(A)
0.5
0.55
0.6
15
0
-15
I_{labc}(A)
0.5
0.55
0.6
15
0
-15
I_{fabc}
0.5
0.55
0.6
Time (seconds)
900
800
700
600
500
V_{dclink}(V)
0.5
0.55
0.6
Time (seconds)



LMS results



Fundamental component (wa)



Output (Vstatcom)

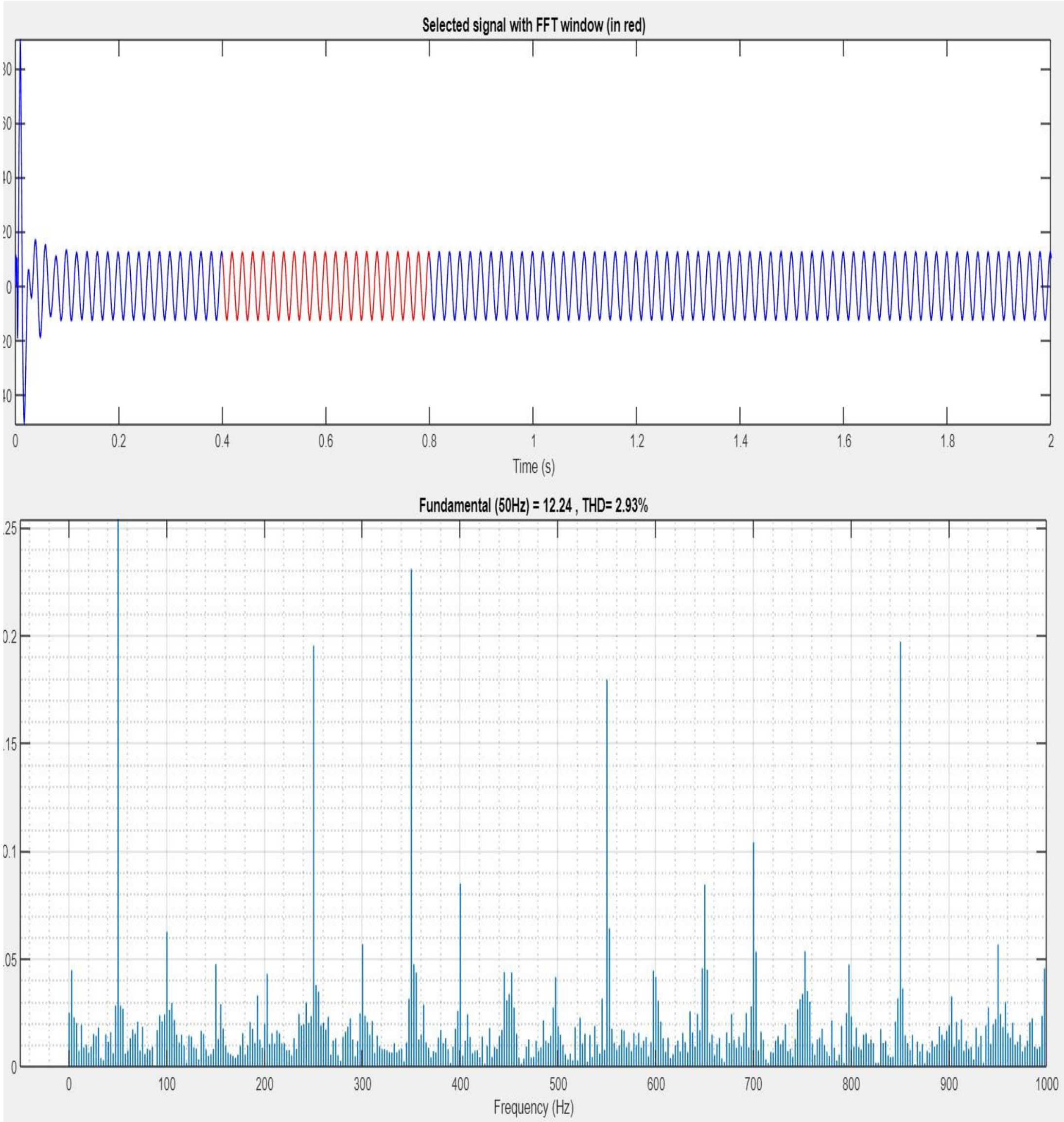
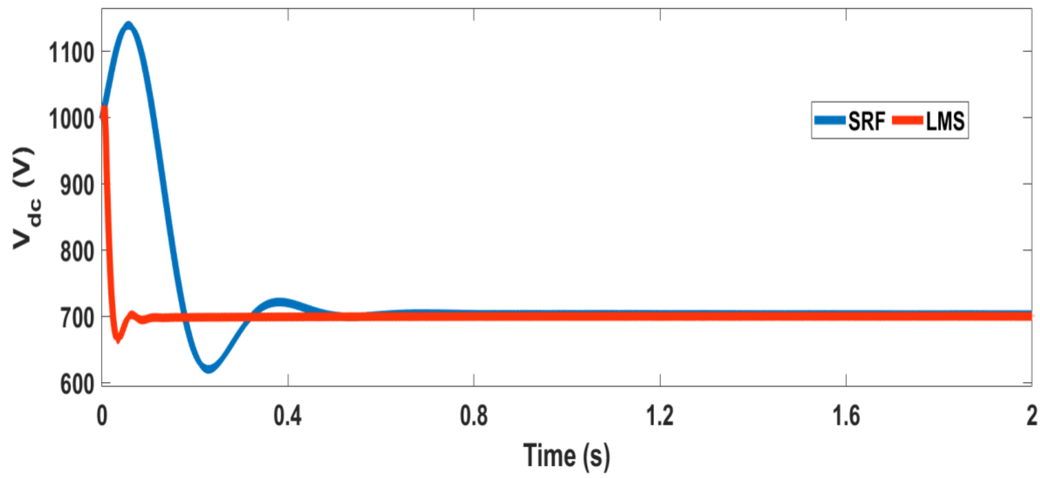


Figure 3.14: THD of the LMS Algorithm

CHAPTER 5

A COMPARISON BETWEEN SRFT ALGORITHM AND LMS ALGORITHM

The performance of LMS and SRFT are very efficient but the main difference arises in the time taken to reach the settling point as well the overshoot initially as well as the transient response while it also shows the difference in harmonics and ringing in the output. Both algorithms eliminate the load current's harmonics very efficiently. Weight update and feedback loop comparison of the two algorithms under normal load conditions. Both algorithms converge to similar steady state value of load current's fundamental frequency component. As seen the voltage of DC-bus settles very close to reference value of 700 V.



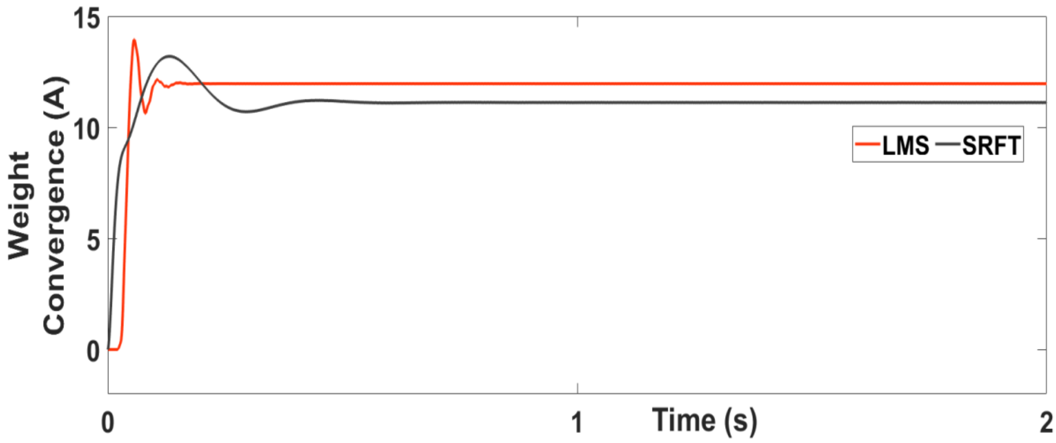
Comparison graph plotted SRF vs LMS

The voltage of DC-bus drop, during load change, is higher in LMS than srft for convergence coefficient with different values respectively. Though the value of η is higher in LMS than SRFT, the convergence is slower due to additional term

$(Sk - 1)$. The performance of both the algorithms is similar in these cases

5.1 A Comparison of the weight convergence techniques.

The aim of the currently used modification algorithm is to find the optimal weight vector that produces the least error. The LMS algorithm is now used to predict the load current s o that the estimated load current is as close as possible to the actual demand. In practice, a good estimate of the current load should have some points compatible with the main qua ntity. Includes 1st, 5th, 7th, 11th and 13th harmonics for low frequency and accurate pred iction



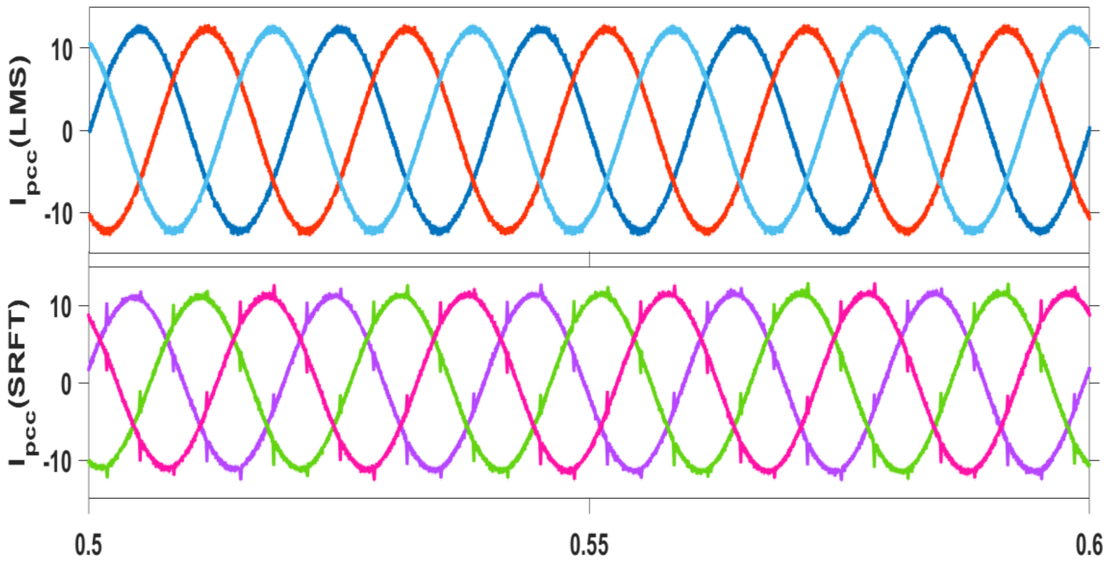
Copmarison of weight convergence current(SRFT vs LMS)

The current settles earlier in LMS than SRFT. The settling time in SRFT is closer to 0.4s while the settling time in LMS is closer to 0.16s

Also the magnitude of current settling in SRFT is closer to 11.6A while the settling current in LMS is nearly at 12A.

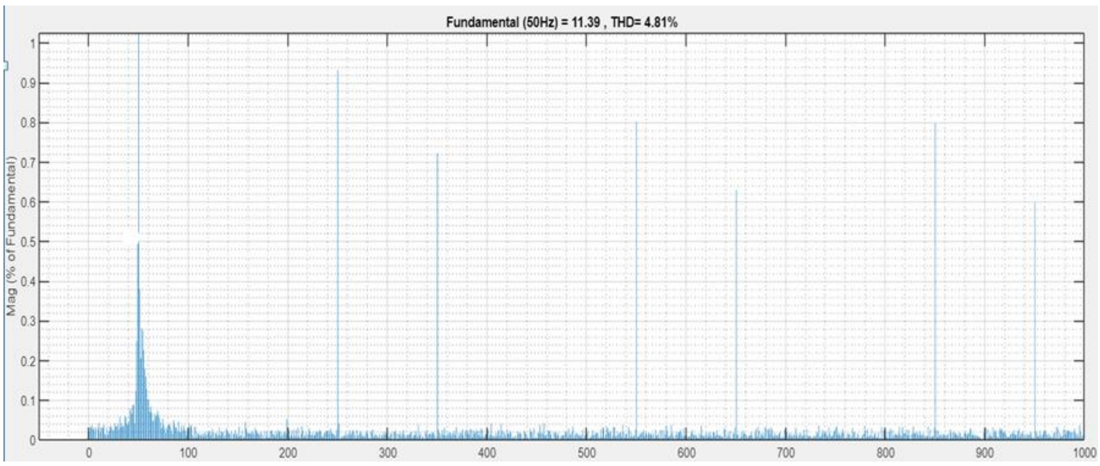
Looking at both of these the weight conversion to remove error from the estimated current and actual current is very smooth and efficient hence this comparison gives strong evidence and proves to be the LMS algorithm performs better.

Now Looking at the 3-phase current distortion it is much lower in the case of LMS while there are smaller spikes in case of SRFT.

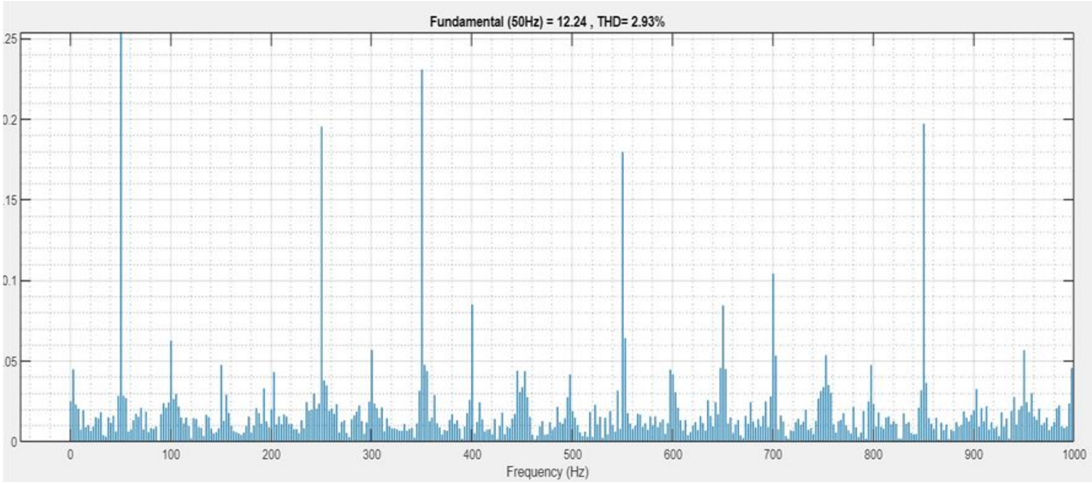


LMS(Ipcc) vs SRFT(Ipcc)

The THD values in source voltage are minimum during linear load condition. In source current the THD values are minimum during mix loading condition. For nonlinear loading condition the THD values are lowest in LMS algorithm very close to less than 3% which is 2.93% while the THD for the same in SRFT is much higher close to 4.81 %.



THD in SRFT



THD in LMS

Overall the Comparison can be summarised as the LMS Algorithm is performing Much better than the traditional SRFT Algorithm in terms of efficiency lower output voltage transient initially faster settling time Lover overshoot as well as the lower total harmonic distortion found in the output the results obtained in the LMS Algorithm simulations are very close to the ideal results that could be found.

CHAPTER 6
CONCLUSIONS AND FUTURE SCOPE

6.1 CONCLUSIONS

In conclusion for the various algorithms for shunt compensation the comparison between SRF and LMS shows that LMS algorithm comes on top i.e. it is much efficient way to shunt compensation for DSTATCOM network. Although the project has been developed for stiff grid the modified version of the algorithms could be implemented for the non-stiff grid with lower inductive load. The presented Algorithms shows a lot promise and confidence ahead and also addresses the major issue present in case of non-linear loads.The objectives of our project are achieved successfully.

6.2 FUTURE SCOPE

We did the comparison between different algorithms and the work does not end here there are various other algorithms that could be performing better than these Algorithms.

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