Voltage Source Converter based Hybrid STATCOM for Reactive Power Compensation in Utility Grid

Aditya Kumar Bhatt

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By: **Aditya Kumar Bhatt**

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Signed by the final examining committee:

______________________________ Chair
Dr. Yousef R. Shayan

______________________________ Examiner, External To the Program
Dr. Anjali Awasthi

______________________________ Examiner
Dr. Luiz A.C. Lopes

______________________________ Supervisor
Dr. Pragasen Pillay

Approved by: ______________________________
Dr. Yousef R. Shayan, Chair
Department of Electrical and Computer Engineering

20th February 2020

____
Dr. Amir Asif, Dean
Faculty of Engineering and Computer Science

ABSTRACT

Voltage Source Converter based Hybrid STATCOM for Reactive Power Compensation in Utility Grid

Aditya Kumar Bhatt

The availability of high voltage, high current and high-speed power electronic devices has led to increase in popularity of several power electronic applications such as FACTS. A STATCOM is one such power electronic converter, from the FACTS family, which can be used to improve the power factor of a transmission line, maintain the connected bus at the required voltage level, etc. In distribution power level, D-STATCOMs are used to achieve the same objectives. Several power converter topologies have been proposed for STATCOMs and D-STATCOMs, ranging from a standard two-level VSC based topology to a cascaded full-bridge based topology. The cascaded full-bridge based topology might be suitable for high power STATCOM applications but might not be the best option at the lower power level of a D-STATCOM. D-STATCOMs therefore often use a standard two-level converter-based topology owing to cost constraints.

The research work presented in this thesis proposes a new power electronic topology which can be used for D-STATCOM applications. This topology is essentially composed of multiple cascaded h-bridge cells in each phase of a standard two-level converter. The two-level converter provides bulk of the power output and operates at a low switching frequency, whereas the h-bridge cell operates at a higher switching frequency and achieve power quality objectives. This research work initially presents simulations to validate the proposed topology. Outer control is proposed to operate the proposed topology as a D-STATCOM. Inner control loops are proposed to maintain the DC-link voltage of the h-bridge cells. An experimental prototype of the proposed topology is also developed. The results obtained from the proposed topology are compared with that obtained from a standard two-level converter-based topology. It is shown that due to the h-bridge cell action in the proposed topology, the obtained current THD is low in comparison to a standard two-level VSC based topology being used as a D-STATCOM.

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Table of Contents

List of Figures

List of Tables

1. Introduction

The advances in the power system network have brought great innovation to power management technologies. Nowadays, the power system is no longer works locally and is interconnected through one common centralized grid system. Across the country, the power is generated from various resources and is shared in various forms over the grid. It is distributed among remote areas and utilized by the remote consumers. The modern power system is a very complex power system and every time it experiences threats regarding voltage instability leading to voltage collapse. The voltage collapse is the process by which voltage instability leads to loss of voltage in a significant part of a system. This occurs when the system is heavily loaded or not able to maintain generation and transmission plants [1]. The main cause of voltage collapse is the inability of the system to regulate the voltage with proper compensation of reactive power flows. Hence, it became equally important to make the system sufficiently secure to withstand the various contingencies occurring in the power system and adequate reactive power support to the system so as to fulfill the requirement of Finest Quality Power (FQP). Thus, reactive power compensation plays a crucial role in a Centralized Grid System (CGS) for maintaining FQP. Power electronics are like medicine for every issue associated with the modern power system.

A Static Synchronous Compensator (STATCOM) is widely used for the reactive power compensation in power system. It is a shunt device that is used in the transmission systems for voltage regulation and reactive power compensation [2]. STATCOM allows for dynamic and quick control of its AC voltage magnitude and phase, by a fast variation in the injected reactive power to the grid ([2]-[4]). In practice, a STATCOM in a transmission grid-primarily is used to maintain the voltage of the bus to which it is connected, at a constant value. Voltage regulation is normally achieved with the help of automatic controllers and a voltage source converter (VSC) based STATCOM can achieve a quick response time (within a few milliseconds) [2]-[4]. The majority of the earlier installations of STATCOMs were either based on a two-level or three-level VSC [5]-[6]. These VSC have a considerable amount of switching losses associated with them and also introduce harmonics in the system and hence affect the power quality of the system [7]. To overcome the issue of power quality standards the conventional two-level VSC based STATCOM would either need to switch at higher frequencies or will need additional filters. Increasing the switching frequency will increase the switching losses and adding a filter will affect the cost of the STATCOM which is one of the major considerations for an optimal design. In this work, it is proposed to include active wave shaping units along this the conventional two-level switching frequency. The voltage harmonics generated by the two-level VSC are cancelled by the wave shaping units which are connected in series with the 2-Level VSC based STATCOM. Since the wave-shapers have a low power rating, hence the resulting losses will be very less than a conventional two-level VSC based STATCOM working independently. All simulation and work will be done in MATLAB and PSIM. This section presents an overview of reactive power compensation and a brief explanation of the operation of a two-level STATCOM.

1.1 Reactive Power Compensation Overview:

Static power compensators (STATCOMs) are representative of fast-acting static synchronous compensators in the Flexible AC Transmission Systems (FACTS) family [8-16]. They are used in power systems especially in transmission and distribution systems for reactive power control. The main objectives of reactive power compensation are as follow:

- Voltage regulation
- System stability
- Loss reduction (losses associated with the system)
- Better utilization of machines connected to the system

The stability limits of the power system are affected by the transmission lines impedance and the consumption of the reactive power by AC machines [17-22]. The voltage drop across the transmission lines has to be compensated by supplying higher voltage from the source. This causes more stress on the overall system and is unpredictable because the voltage drop is not constant. To solve this problem, capacitors were used to overcome the inductive effect of transmission lines and large motors used in industries. But this method is not dynamic and therefore is not a reasonable solution.

New methods have been developed in recent years, in particular, dynamic methods using better devices. The compensation is dynamic and therefore more effective. One of the means of achieving this is with the help of a STATCOM [23-34].

The majority of the loads in the power systems are inductive. They consume the reactive power for their operation. By regulating the reactive power supplied near the load, the line current can be minimized. This reduction in line current reduces, as a result, the losses through the power lines and improves the voltage regulation across the load terminals. The reactive power regulation can be done in three ways: through a voltage source, a current source or a capacitor. STATCOMs acts as a controllable current source.

The compensation techniques, in general, can be grouped into two main categories, namely; shunt compensation and series compensation. The series and shunt compensation techniques can be explained with the help of the phasor diagrams shown in fig. 1.1 to fig 1.3. In a series compensator, the compensation system is in series with the load. There are quite a few advantages of series compensation such as reduced voltage rating of the compensator.

Shunt compensation is another means of achieving reactive power compensation. In shunt compensation, the compensator is connected in shunt with the transmission system. Therefore, the voltage rating of the compensator is quite high, however the current rating is lower, depending on the reactive power that needs to be compensated.

Some of the features/ advantages of shunt compensation are listed as follows:

- A shunt compensator is connected in parallel with the circuit. Therefore, even its failure would not cause the entire system to fail, and the rest of the circuit would still be working.
- The compensation provided by the STATCOM can be controlled without any dependency on the system voltage. This is an important advantage and is not true in the case of other compensation techniques such as a fixed capacitor.
- The shunt compensator can not only provide the desired reactive power but at the same time can also cancel harmonics in the system by acting as an active filter.

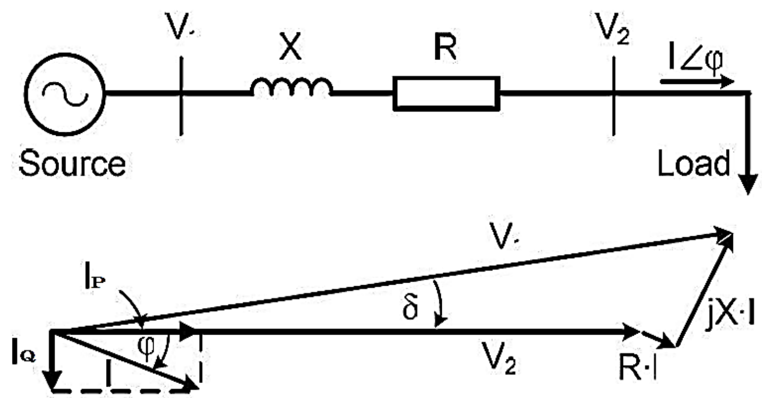


Fig. 1.1: An uncompensated transmission line operation and its phasor diagram

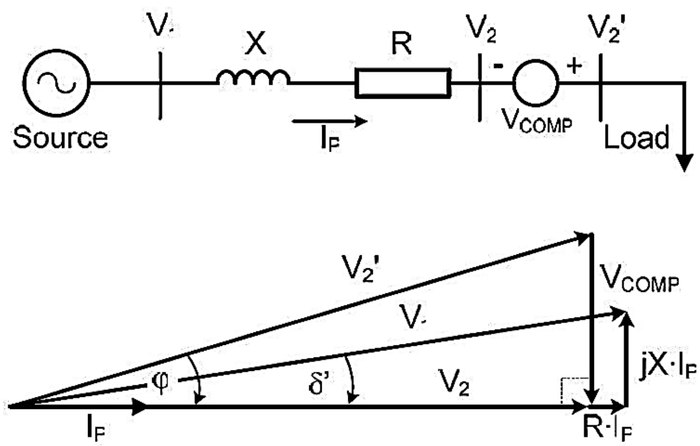


Fig. 1.2: Operation of a series compensated transmission line and its phasor diagram

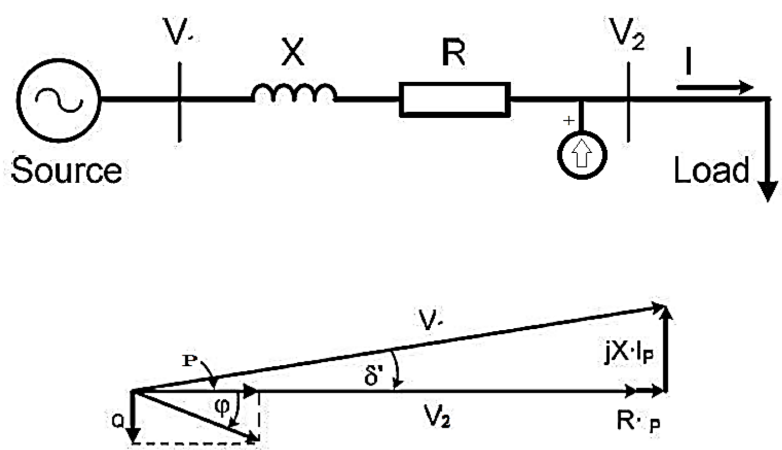


Fig. 1.3: Operation of a shunt compensated transmission line and its phasor diagram

1.2 Overview of the two-level STATCOM

A two-level converter is typically used in a conventional STATCOM. It is usually switched at a higher frequency around 1 kHz to 5 kHz and might require additional filters to limit the current THD within bounds. The $\frac{dv}{dt}$ of a two-level STATCOM is very high and therefore, reflects higher stress on the AC filters used if any. The main drawback of this type of STATCOM is its higher switching losses associated due to its high switching frequency requirement and will be discussed later in the thesis. Also, for high-power applications, the switching frequency of the two-level inverter is very much restricted due to the limitation of the available power semiconductor devices. This introduces an additional problem relating to the current waveform quality.

1.3 Motivation and Aim of the Project

For high power converter applications such as FACTS, the power losses in converter have a large cost implication associated with it. It is important to have converter losses as low as possible. As reported earlier, two-level STATCOMs impose a major challenge to achieve this. Therefore, it is important to develop new converter topologies, which have lower losses. This will reduce the operating cost and improve the efficiency of a STATCOM based reactive power compensation solution.

In this thesis, this objective is achieved by the introduction and development of a Hybrid STATCOM. The objective is realized in the following steps;

- Identification of causes of higher losses in the conventional STATCOM
- Development of a control strategy and design methodology of a Hybrid STATCOM topology, which will offer reduced losses as compared to the conventional solution.
- Perform simulations to validate the proposed design and control philosophy for the Hybrid STATCOM.
- Calculation of losses for the proposed topology and comparison with the existing conventional topology.

1.4 Objectives

The objectives of this thesis are as follows:

1) Identification for causes of higher losses in conventional STATCOM

2) Development of a control philosophy and design methodology of a hybrid STATCOM topology which will have lower losses as compared to the conventional STATCOM.

3) Perform simulations to validate the proposed design and control philosophy for the hybrid STATCOM.

1.5 Proposed Work and Model

In this thesis, a hybrid STATCOM is introduced and proposed for reactive power compensation.

A hybrid switching STATCOM consists of a two-level Voltage Source Converter [35-38] and series H-bridges acting as series wave-shaper. A schematic diagram of basic hybrid switching STATCOM is shown in Fig.1.4.

The two-level VSC based STATCOM and series-connected wave-shaper units together eliminate harmonics, which are injected by the conventional two-level VSC based STATCOM for switching at low frequency. When the STATCOM generates harmonics, after 2-4 cycles of current waveform the wave-shaper units start generating the harmonics voltage, which is injected in series and 180 degrees phase-shifted with the harmonic's voltage by STATCOM such that the low order harmonics will be cancelled out. The phase-angle control will assist the STATCOM to cover the reactive power demand and voltage regulation.

In order to get the hybrid system performance, individual components need to be modelled first and then combination will be evaluated to meet the expectation.

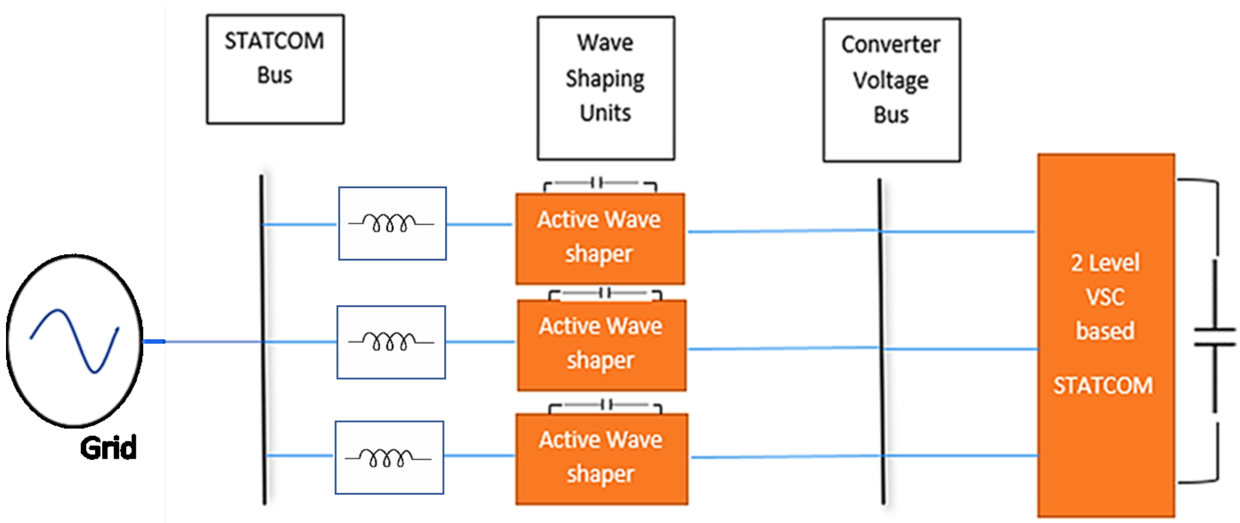


Fig. 1.4: Proposed research schematic diagram

As a first step, the simulation of STATCOM (i.e. as Front-End Converter) is conducted in the MATLAB environment for the reactive power compensation including various disturbances in the power system. Then, further in the next stage the H Bridges wave-shaper units are included to reduce the total harmonic distortion (THD).

The prime advantage of incorporating the wave-shaper is the reduction of the THD which is created by the two-level VSC based STATCOM. There is a rich selection of the approaches and several advances have been made and will be reviewed in the upcoming Chapters.

The modelling, simulations and related programming are carried out in MATLAB, due to the computational competency and inbuilt function database, for validation and analysis. Testing is done using the OPAL-RT controller module and various other parts, which are fabricated in Power Electronics and Energy Research laboratory at Concordia University.

1.6 Thesis Outline

The thesis is organized into 6 chapters, to understand the operation of STATCOM, proposed hybrid STATCOM, its operation and results along with detailed analysis and calculations. There are two main parts of the proposed hybrid STATCOM i.e. Conventional Two Level STATCOM and H-Bridge wave-shapers and both the parts are discussed in detail. The thesis outline are as follows:

Chapter 1: **Introduction** contains the brief introduction of the conventional two-level STATCOM used in the power system for reactive power compensation as well as series and shunt compensation. This chapter also briefly introduces H-Bridges, which are used as wave-shaping units later in the thesis.

Chapter 2: **Literature Review** reports the survey of the conventional methodologies reported in the field related to the proposed model.

Chapter 3: **Conventional Two-Level STATCOM and Proposed Hybrid STATCOM** discuss the requirements of two-level STATCOM, its design, and component selection of STATCOM along with its basic mathematical model. This chapter also contains the introduction to harmonic cancellation technique, active power filters its classification and the PWM switching scheme of the devices. Single-phase H-Bridge converter has also been discussed in detail along with the discussion on the sinusoidal pulse with modulation (SPWM).

Chapter 4: **MATLAB/Simulation and Results** contains the complete Simulink model of the proposed model. Parameters used for the simulation of various parts are also shown in this chapter. The simulation results of the model are included and discussed.

Chapter 5: **Hardware Development and Experimental Results** contains the experimental results of the proposed hybrid STATCOM using OPAL-RT. Hardware development is discussed in detail. The comparison of results with respect to switching loss for the topology of Hybrid two-level Voltage Source Converter as explained.

Chapter 6: **Conclusion and Future Scope** gives the conclusion of the contribution of the thesis and research done through the proposal of Hybrid STATCOM for reactive power compensation along with possibilities of future scope of its extension.

2. Literature Survey

Several researchers working in the area of STATCOM control have contributed to conventional vector control strategies. It is observed that the STATCOM using the conventional control strategies produces a lot of harmonics that affect stability, reliability and efficiency of the power system. Hence, it becomes mandatory to investigate reactive power control using STATCOM. There are various control strategies for control of STATCOM are still under investigation. A few relevant recent control strategies are discussed as follows:

2.1 Literature Review

In [1] authors have implemented a vector control technique for a Front-End Converter (FEC) of a 250-kVA rating. It was observed that for a high-power front-end converter (FEC) starting current transient is considerably high as the designed value of the filter inductor was very low. In order to limit the transient, an algorithm has been proposed as shown in Fig. 2.1.

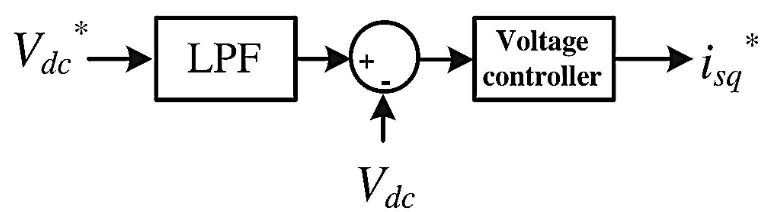


Fig. 2.1: Low-pass filter for the DC bus voltage reference to reduce transient in starting current.

The reference value of a DC bus voltage (V_{dc}) is ramped up from initial value to its final value for a particular time period. The time duration is large enough then its voltage loop time constant. First, the reference signal of a DC bus voltage is sent to a low-pass filter and later to a controller. Due to filter in the path, the rate of change of a reference signal of a voltage controller becomes slow and the voltage controller is able to track reference voltage more accurately. Therefore, the error gets reduced during starting, which leads to low starting current. But due to the addition of a low-pass filter in a path, the response time of a front-end converter starts lagging with respect to its DC bus reference voltage. During starting, the reactive power reference value is set at zero therefore the transient in starting current gets reduced. The DC bus voltage is pre-charged and when the unit vector generation reaches its steady-state value, the control procedure is executed, and the low-pass filter is added in the DC bus voltage reference path. The proposed work by author improve the results and mitigated the starting transient current inline side converter.

STATCOM four quadrant operations and its control have been discussed in various research publications. The Electric Power Research Institute (EPRI), USA has conducted numerous researches on high power STATCOM using GTO based Voltage Source Converters (VSCs) and prototyped STATCOM projects in collaboration with a number of institutes and organizations. In research publications, controllers are termed as Advanced Static VAR Compensator (ASVC), Advanced Static VAR Generator (ASVG), and Static VAR generator (SVG), Static Condenser (STATCON), Synchronous Solid-state VAR Compensator (SSVC) and Static synchronous compensator (SSC). Power industries such as ABB, GE, Toshiba, Mitsubishi etc. has done R&D and developed STATCOM based high-voltage transmission system along with Unified Power Flow Controller (UPFC). In the past decades, numerous topologies and configurations of the converter, its control strategy and algorithm, different switching techniques have been proposed and reported in the literature for grid distribution and transmission network. In [2] STATCOM controllers have been reviewed in detail for new research potential in the area. The idea of voltage re-injection in the DC link of the STATCOM topology working at a fundamental switching frequency will reduce the harmonics and improves the functionality and performance with minimal usage of solid-state devices. It was also concluded that among various multi-level converter circuits, the three-level topology is the most practical one. Beyond three-level converter topology, the controller for voltage balance across the DC capacitors, which are used as an energy storage device, is not easy. Therefore, higher level topologies are not practically used. Another scope of research is to improve controller to handle system dynamics when faults occur either asymmetrical or symmetrical in the high-voltage transmission systems. In order to improve this, algorithms such as fuzzy logic can be employed.

In [3] an open-loop control strategy has been proposed for a Voltage Source Inverter (VSI) for high-power applications. The inverter is prototyped for laboratory testing using high-power and low switching solid-state devices i.e. Integrated Gate Commutated Thyristors (IGCTs). It is observed that series compensators are IGBT based converters and operate at high-switching frequencies at low DC bus voltage. These compensators will generate the desired harmonic voltage to realize a sinusoidal output voltage. Numerous compensators are connected in series for medium-voltage applications as shown in Fig. 2.2

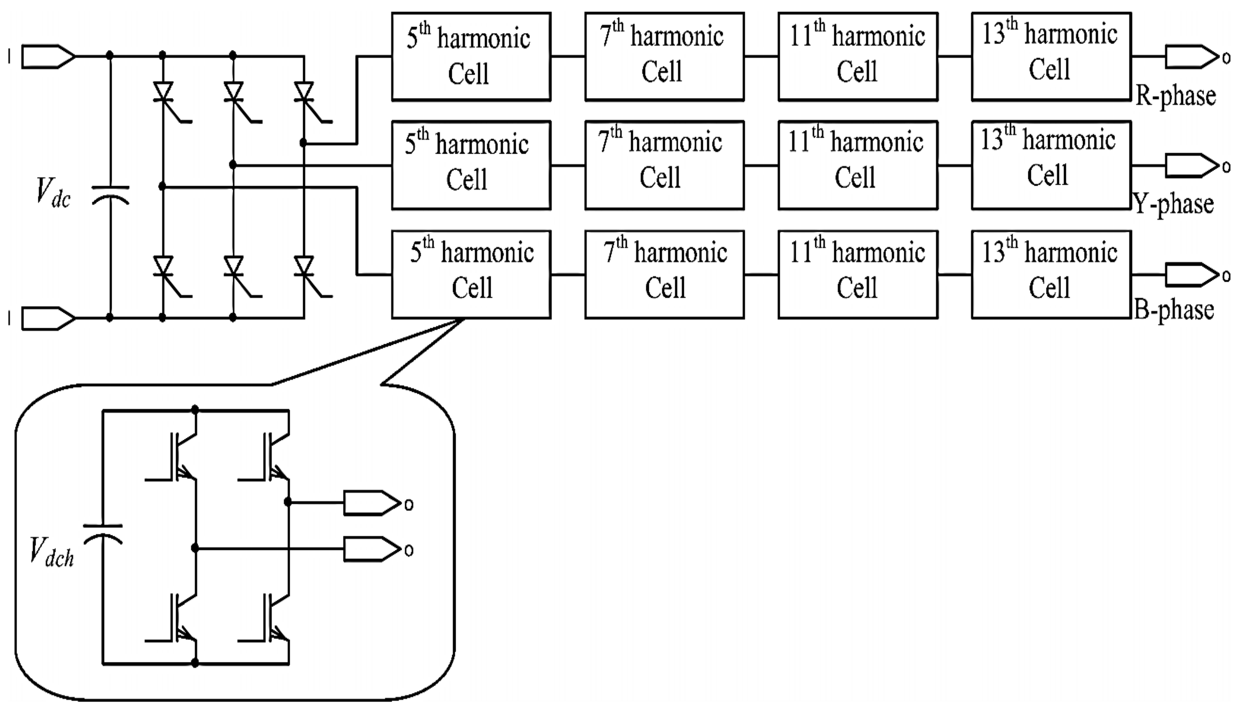


Fig. 2.2: Topology of a medium voltage level-based application [3]

Here, each compensator will compensate or eliminate the level of a particular harmonic. When the order of harmonics in the system increases, the level of the required DC bus voltage is reduced. It helps to use a higher switching frequency for the higher order of harmonics compensators. In the proposed technique, it is observed that there is no need for any external DC source or closed-loop controller. Therefore, the DC bus voltage remains charged by the active power available at the harmonic's frequencies. For other applications such as variable speed drives, the output voltage amplitude is controlled by maintaining the DC bus voltage of the inverter. For Static Synchronous Compensator (SSC) applications, DC bus voltage can be maintained by receiving a low magnitude of active power at the fundamental frequency from the grid.

In [4] a sinusoidal hybrid converter configuration has been proposed for the medium-voltage reactive power compensator as shown in Fig. 2.3

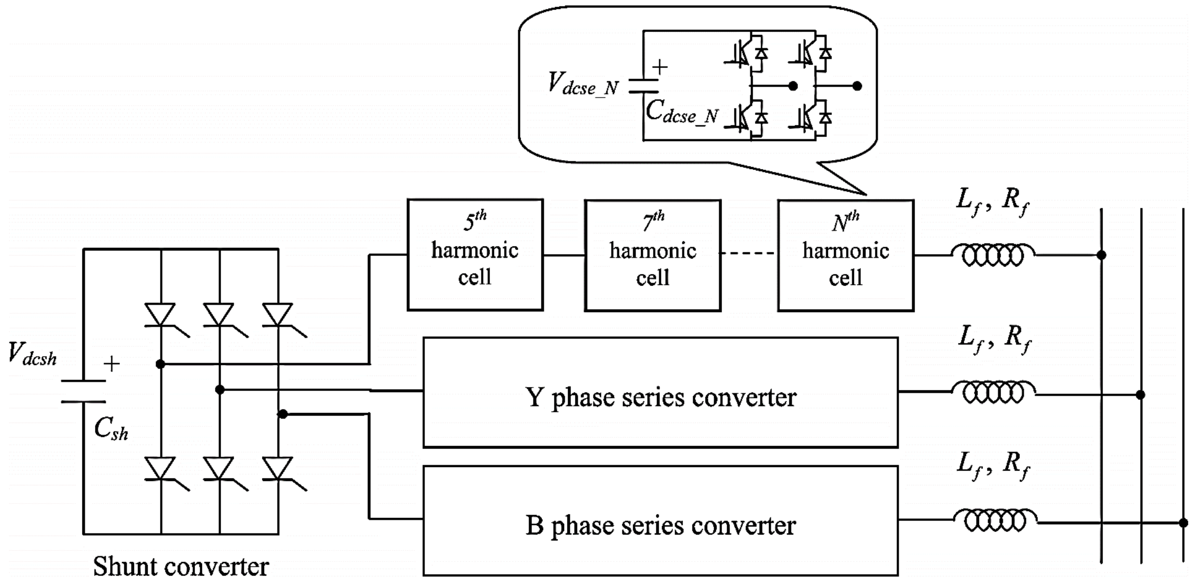


Fig. 2.3: Configuration for medium voltage reactive power compensator [4].

The main inverter that supplies the reactive power is named as shunt converter. It is a square-wave inverter and is responsible for generating fundamental reactive current. As the switching losses for this shunt inverter is low; hence, high voltage switching devices such a GTO and IGCT can be used. In order to eliminate harmonics voltage from the output voltage of the hybrid converter, various single-phase converters are connected in series. Two different methods have been proposed for open loop switching techniques. In the first method, the SPWM technique is used with a modulation index of unity and the reference voltage is in phase with the inverter harmonic voltage. In the second method, square waves are in phase with the harmonic's voltages, respectively of the series cells. It has been observed that the DC bus voltage of the series cells reaches the desired voltage level in both the proposed methodologies. Therefore, the harmonics are eliminated by the series cells and the resultant output voltages of the converter are sinusoidal. There is no need for sensing the DC bus voltages for its controller. The second method allows low switching frequency for its cells connected in series and hence increases in the voltage rating of these cells. Thus, it helps to achieve the medium voltage operation of the converter for reactive power compensator. By varying the DC bus voltage of the shunt converter, fundamental reactive power is controlled and to vary the DC voltage, the phase angle between the shunt converter and the grid voltage level have to be controlled. However, the rate of variation of the reactive current cannot be achieved quickly. An alternate technique to mitigate the harmonics generated by a square-wave inverter can be achieved by implementing active power filters in a shunt connection. This active power filter connected in shunt fashion can mitigate current harmonics whereas the proposed H-bridge which is connected in series reduces voltage harmonics. The proposed configuration is for medium-voltage applications and the device voltage and current ratings will be a concern in their selection.

In [5] PWM based voltage source inverter has been simulated with two different IGBT devices modulated with different modulation schemes and power losses have been compared. The Punch Through (PT) technology is introduced by Toshiba, whereas the Non-Punch Through (NPT) technology is introduced by Siemens. Both technologies have been investigated. Later, the modulation techniques are compared with sinusoidal modulation having third harmonics and a 60 ° non-active phase bridge modulation. The loss model discussed in the literature is based on the experimental results and then the devices are characterized using Advanced Measurement Power Electronics Components and Circuits (AMPEC) as shown in Fig. 2.4.

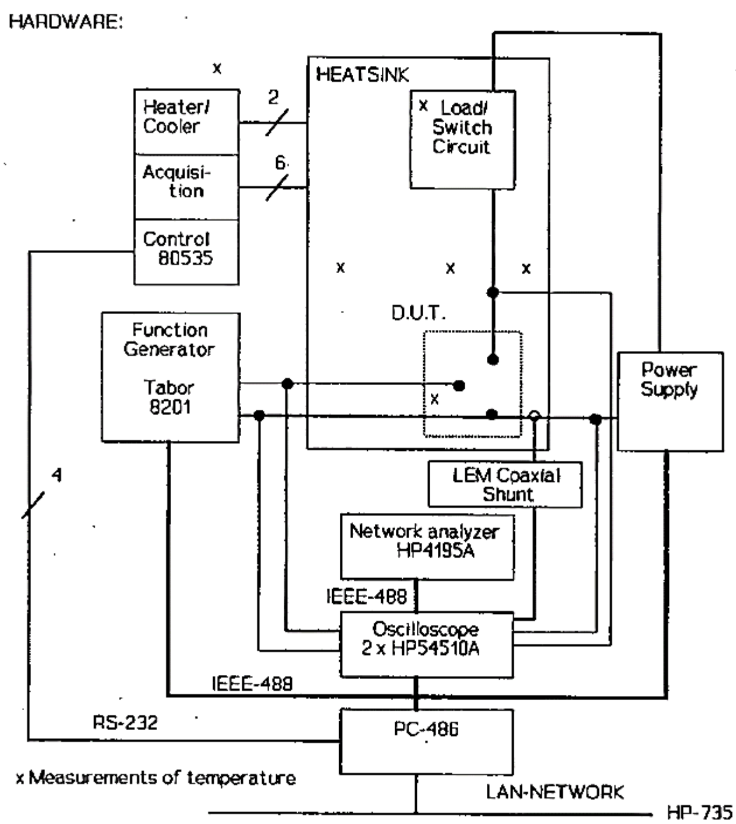


Fig. 2.4: Hardware schematic of AMPEC [5].

It was observed that 60° PWM based technique has reduced switching and hence, the general losses are less compared to the sinusoidal modulation added with a third harmonics. The NPT devices are suitable for higher switching frequencies whereas PT devices are more suitable for lower switching frequencies if the gate resistance used is of lower value. The PT devices are better when the load current is high. It was also observed through simulation that the losses in the inverter are proportional to the load current, switching frequency and modulation index.

In [6] a mathematical approach is introduced to analyze the losses for the two-level and three-level voltage source converter based HVDC transmission systems as shown in Fig. 2.5 and later the results are validated through software simulation. The obtained results show that due to the usage of a neutral point clamped three-level converter, the conversion losses are reduced since the switching frequency of the devices is reduced to half compared to that of a two-level converter configuration. The conversion losses in the two-level converter are around 63.74 % of the total losses whereas for the three-level converter the conversion losses are around 55.5 %. These losses can further be reduced if high voltage levels are used.

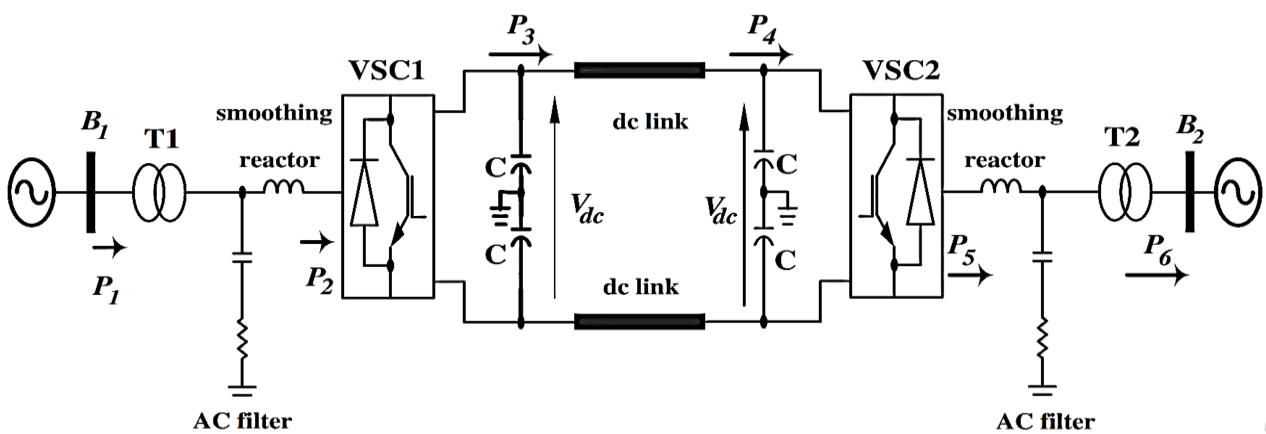


Fig. 2.5: VSC-HVDC transmission structure [6].

2.2 Motivation of thesis

In this thesis, in order to reduce switching losses in 2-level VSC, the low switching frequency around 540 Hz is used; however, the low switching frequency will introduce certain low order harmonics in the system which requires a bulky filter. In order to avoid the bulky inductor, it is desired to cancel the dominating harmonics, which are close to the fundamental frequency.

Among the various research strategies discussed so far, the wave-shaper units are found to be the most prominent technique, which can be used to cancel out the low order harmonics which are generated during the low-frequency operation of a 2 level VSC. Since these wave-shaper units have low DC bus value; therefore, the switching losses will also be less in the system. It developed the further motivation to start the investigation and analyze a Hybrid STATCOM, which is a combination of a two-level VSC with wave-shaper units targeting specific harmonics in order to reduce the semiconductor device losses and the filter size. Therefore, the novelty of the proposed technique is on-line voltage harmonic cancellation by the wave-shaper units (unlike the proposal in [3] and [4]).

2.3 Concluding Remarks

A literature survey is presented in the area of STATCOM controls which have contributed to conventional vector control strategies. It is observed that the STATCOM using the conventional control strategies produces a lot of harmonics that affect stability, reliability and efficiency of the power system. Hence, it becomes mandatory to investigate reactive power control using STATCOM. There are various control strategies for control of STATCOM are still under investigation.

3. Conventional Two-level STATCOM and Proposed Hybrid STATCOM

A Static synchronous Compensator (STATCOM) is widely used for reactive power compensation in the power system. It is a shunt connected system, which is used in the transmission system for voltage regulation and reactive power compensation. STATCOM allows for dynamic and quick control of its AC voltage magnitude and phase by a fast variation in the injected reactive power to the grid. In practice, a STATCOM in a transmission grid is primarily used to maintain the voltage at the bus to which it is connected, at constant. Voltage regulation is normally achieved with the help of automatic controllers and a voltage source converter (VSC) based STATCOM can achieve a quick response time typically a few milliseconds.

A STATCOM comprises of a 3-phase inverter (usually SPWM modulated) using SCRs, MOSFETs or IGBTs, a DC capacitor that maintains the DC bus voltage for the inverter, a link reactor which is used for linking the inverter output to the AC supply, filter to absorb the high-frequency components due to the PWM inverter. The generated voltage is further synchronized with the AC supply and depending on the phase of the current, either active or reactive power is supplied or absorbed.

3.1 Conventional Two-Level STATCOM

A STATCOM comprises of a voltage source inverter (VSI) that produces AC voltage from DC voltage and has the capability to transfer power in either direction. VSCs are the building blocks of HVDC and FACTS in the present age. There are two types of VSCs, the first one is square wave inverter with GTO as the switching device and the second one is PWM inverter with IGBT. The two-level converter topology, as shown in Fig. 3.1, is conventionally used in reactive power compensation in the modern power system as STATCOM. The control strategies used by these inverters to convert DC voltage into 3-phase AC voltage are based on PWM. In PWM techniques, an inverter is controlled through ON/OFF time control the inverter's switching devices. This topology has six IGBTs with anti-parallel diodes and has the highest switch utilization and low conduction loss among all 3-phase inverters [39]

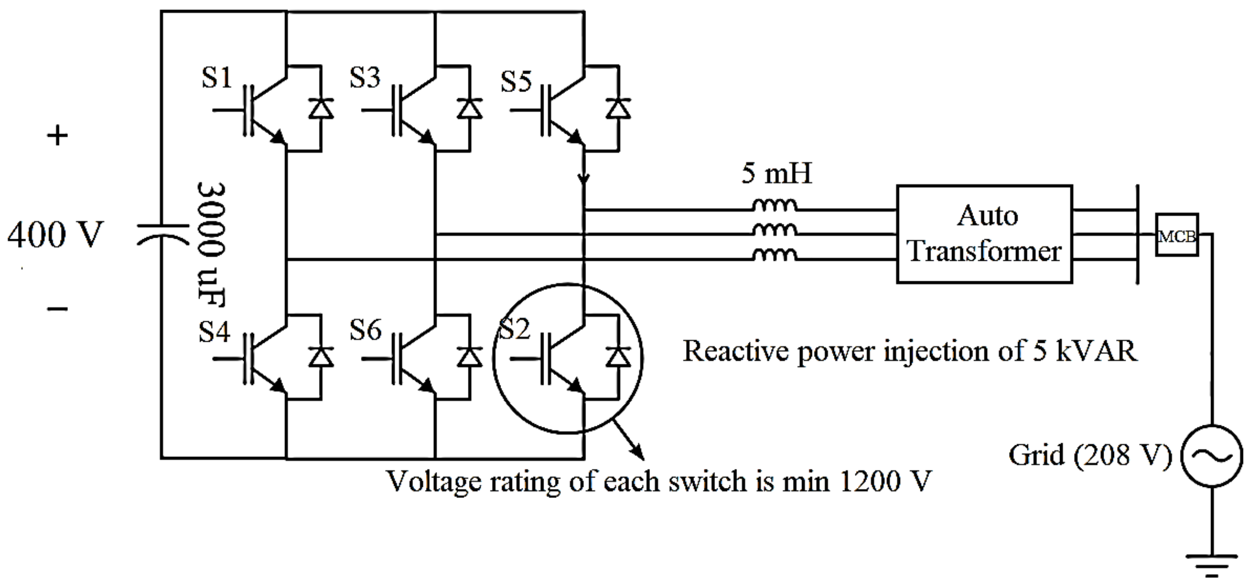


Fig. 3.1: Conventional Two-Level STATCOM for lab test

Inductive reactance is connected between the grid and the inverter. The sources are bound together by using this inductor in series that also acts as a filter. The flow of active and reactive power takes place through this inductance. It also helps to neutralize the harmonics at the point of common coupling (PCC). The harmonic filter may be active or passive. The function of the filter is to further reduce harmonics generated by two-level VSCs.

Hence, before implementing grid-connected STATCOM operation, the initial step is to test the two-level VSC as an inverter feeding different 3-phase loads such as R-L Load, pure inductive (L) load and at no load. Therefore, real-time simulation results of a two-level inverter have been done. The real-time simulation and hardware-in-loop testing (HIL) is done by using real-time OPAL-RT simulator (OP45610). Modelling and simulation are done in MATLAB.

Simulation is done by selecting the IGBT/diode module in the family of the available block in MATLAB. For calculating the power losses, the waveforms obtained from MATLAB-Simulink and the datasheet parameters of the devices will be used. The MATLAB model integrates the components required for different voltage levels of the inverter (multilevel inverter) and shows the power losses. An ambient for temperature is assumed as room temperature and for calculation of losses, a worst-case temperature of 125 degrees Celsius is chosen.

3.2 Proposed Hybrid STATCOM

The motivation and objective behind proposing a Hybrid STATCOM are to find means of reducing the switching frequency of the two-level converter while maintaining the same quality of the current waveform. A simple representation of how the Hybrid STATCOM works is shown in Fig. 3.2. As can be seen, the wave shaping units are H-Bridge cells connected in series with the main conventional two-level converter. These H-bridge wave-shaper cells basically have the objective of cancelling the harmonics generated by the two-level converter that is modulated at a lower-switching frequency. An exaggerated case of the two-level converter of the Hybrid STATCOM switching at a fundamental frequency and the wave-shaper cells switching cancelling the generated harmonics is shown in Fig. 3.3.

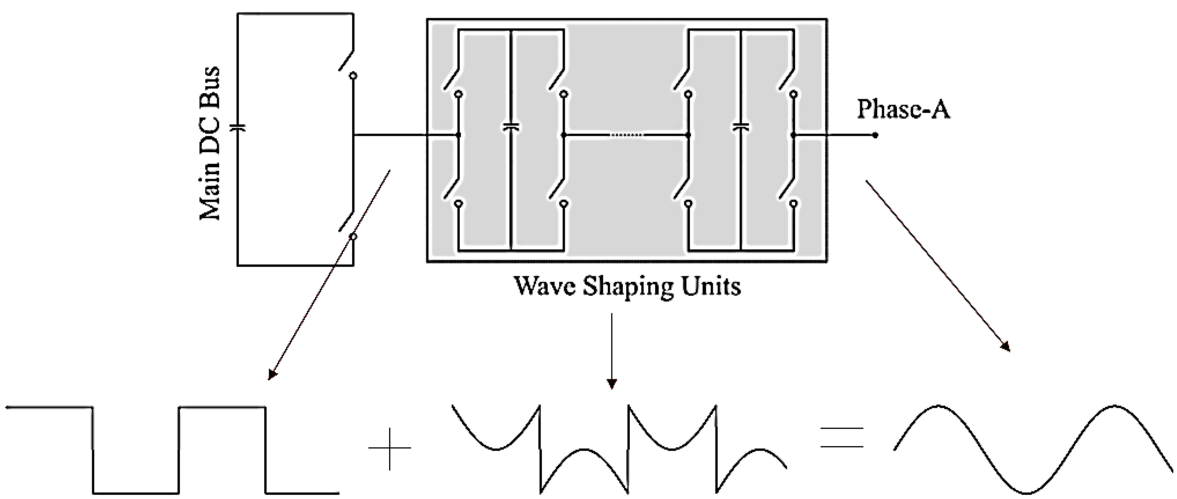


Fig. 3.2: Hybrid STATCOM: concept development

The schematic of the proposed converter design and analysis is shown in Fig. 3.3. As can be seen from Fig. 3.2, two H-bridge cells are considered per phase in the circuit. Optimization of the number of switches for H-bridges is not done. It is chosen in order to validate the concept of Hybrid STATCOM.

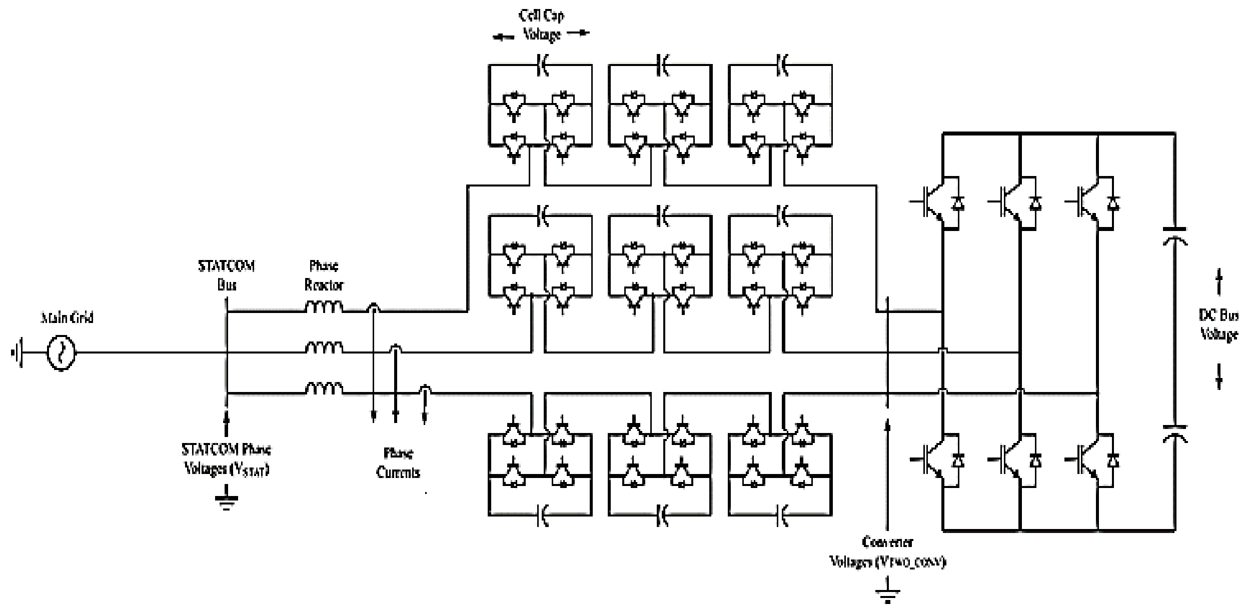


Fig. 3.3: Hybrid STATCOM: designed converter [40]

The switching frequency of the two-level converter in Hybrid STATCOM is reduced to 540 Hz. This is done to ensure that the switching losses reduce significantly. The wave-shaper cells, on the other hand, have the following objective;

a) Cell 1: Designed to cancel the 5^{th} and the 7^{th} harmonic, switching at 5000 Hz
b) Cell 2: Designed to cancel the 11^{th} and the 13^{th} harmonic, switching at 5000 Hz
c) Cell 3: Designed to cancel the 17^{th} and the 19^{th} harmonic switching at 5000 Hz

The voltage rating of the wave-shaper cells depends on the amplitude of the corresponding harmonics generated by the two-level converter. Based on the simulation and FFT analysis of the resultant voltage waveform of the two-level converter with dc bus voltage of 400 V switching at 540 Hz, it is observed that a cell voltage rating of around 50 Volts, for all the cells will be sufficient to cancel the corresponding harmonics.

Therefore, even though the switching frequency of the wave-shaper cells is quite high, since the voltage across the devices is much lesser, i.e., at 50 Volts instead of 400 Volts as for main STATCOM, the switching losses will not be very high. This will be validated in the upcoming sections to follow on the loss calculation.

3.3 Controller Design of Conventional Two-Level STATCOM

The conventional STATCOM control is well established and reported [1]. The idea is to control the inverter output voltage magnitude to inject the required reactive power. For this purpose, all quantities are converted to the rotating reference frame the signal to DC quantities. Once converted to DC, these voltages and currents are compared with their corresponding reference values with a PI controller, thus simplifying the controller implementation and design.

The steps to design a controller for the STATCOM are as follows,

- STEP 1: Identifying the rotating reference frame and designing PLL (Phase lock loop) for PCC voltage (fixed).
- STEP 2: Measured 3-phase currents are converted to fix DC- Quantities by using abc to dq0 transformation.
- STEP 3: For a STATCOM, assuming that the PLL locks the grid voltage vector on the d-axis, the d-axis current will correspond to the converter losses and the q-axis current will correspond to the reactive power that needs to be injected.

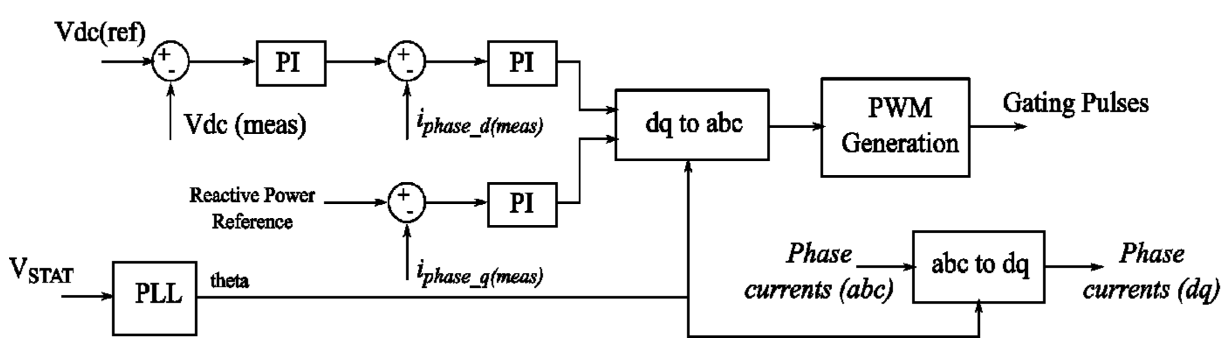


Fig. 3.4: Control diagram for the conventional STATCOM

So, in this topology, three PI controllers are used to control the various inputs as shown in Fig. 3.4. Firstly, the inner current control loop for the STATCOM. Secondly, the outer voltage loop for the STATCOM. The bandwidths of these controllers are chosen based on the speed of the dynamic response of every single controller.

- **Transfer Function of Inner Current Control Loop**

The transfer function of the plant as shown in Fig. 3.5 is given by,

$$G(s) = \frac{I_{d,q}(s)}{E_{dq}(s)} = \frac{1/R}{1 + s\tau} \tag{3.1}$$

The design of the inner current loop depends on the phase reactor and the associated resistance values.

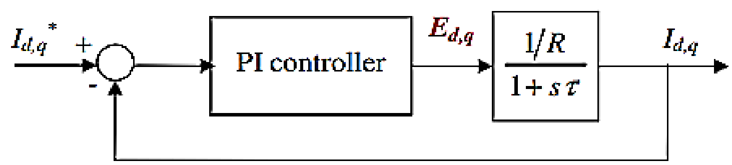


Fig. 3.5: Inner current control loop of a STATCOM

The current loop has a faster response than the voltage control loop. The inner current loop bandwidth of STATCOM is chosen as f_X = 30Hz (around 10 % of switching frequency) and the switching frequency f_{SW} considered in this work is 540 Hz. The nominal parameters are chosen as:

R = 1 mΩ

L = 5 mH

τ = L/R = 0.005/0.001 = 5

The crossover frequency is chosen as 30Hz and PM =60 degree

$$G_p(S) = \frac{1/0.001}{1 + s(0.005/0.001)} \tag{3.2}$$

$$G_p(jw_x) = \frac{1000}{1 + 5s} \quad 3.3)$$

$|G_p(jw_x)| = 1.429\ dB \qquad \varphi_p = 89.93^0$

The bode-plot of current loop transfer function is as shown in Fig. 3.6

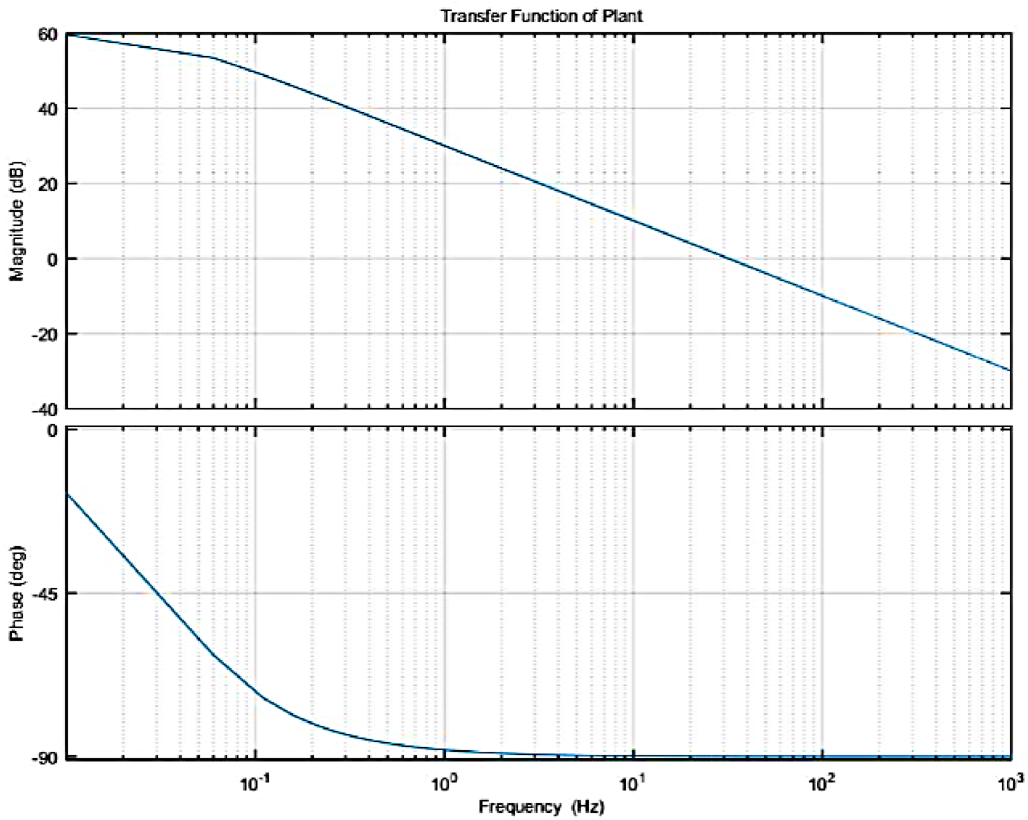


Fig. 3.6: Plant transfer function for the inner current loop

The phase margin of 59.8 deg is obtained at f=30 Hz.

$K_P = 0.84$

$K_I = 83.31$

$$Controller\ Transfer\ Function = K_P + \frac{K_I}{s} \qquad (3.4)$$

$$\tau = \frac{k_p}{k_i} \qquad k_i = \frac{k_p}{\tau}, \qquad k_p = 0.84 \qquad k_i = 83.31$$

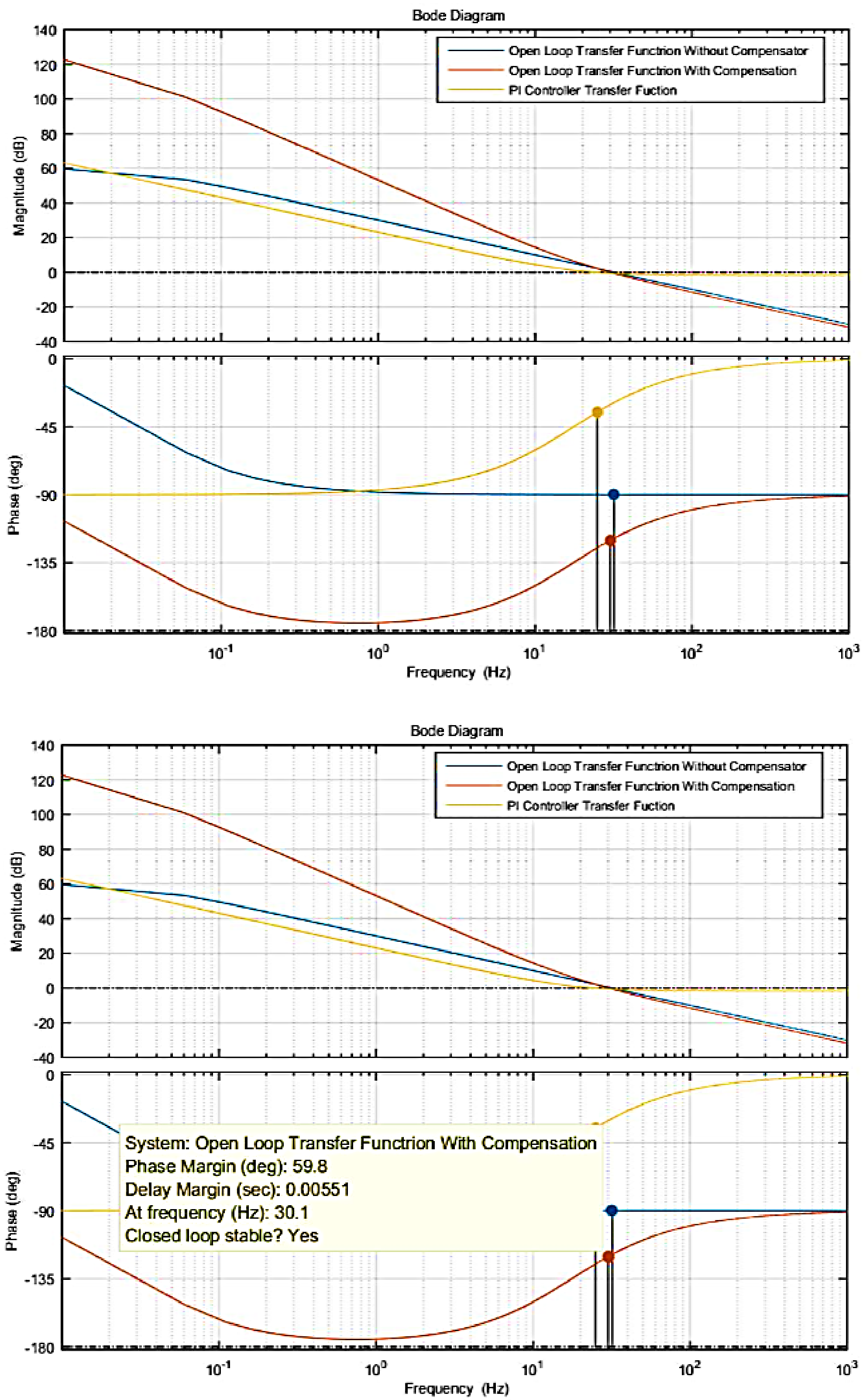


Fig. 3.7: Bode plot of inner current control loop with compensator and without compensator

As shown in the Fig. 3.7 the phase margin of 60 degree is obtained at the crossover frequency of 30 Hz approximately.

- **Transfer Function of Outer Voltage Control Loop**

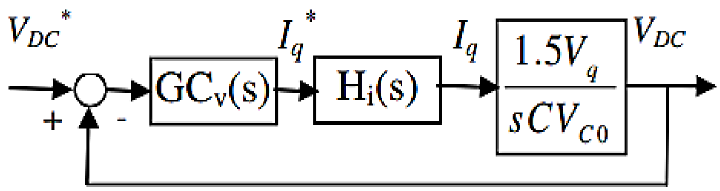


Fig. 3.8: Outer voltage control loop of a STATCOM

The voltage control loop as shown in Fig. 3.8 is slower than the current control loop; therefore, the bandwidth of the voltage control loop must be lesser than current control loop. The voltage control loop has been designed based on the current control loop of the STATCOM. The plant transfer function is given as

$$G(s) = \frac{V_c(s)}{I_q(s)} = \frac{\tilde{v}_c}{\tilde{\iota}_q} = \frac{1.5V_q}{sCV_{co}} \tag{3.5}$$

The bandwidth is chosen as f_X = 5 Hz and the phase margin PM = 60 degree.

$$G(s) = \frac{1.5(169.83)}{s(3000\mu F)(400)} \tag{3.6}$$

$$G(s) = \frac{254.745}{1.2s} \tag{3.7}$$

$$|G_p(jw_x)| = -16.58\ dB$$

$$\varphi_p = -90^0$$

The bode-plot of voltage control loop transfer function is shown in Fig. 3.9

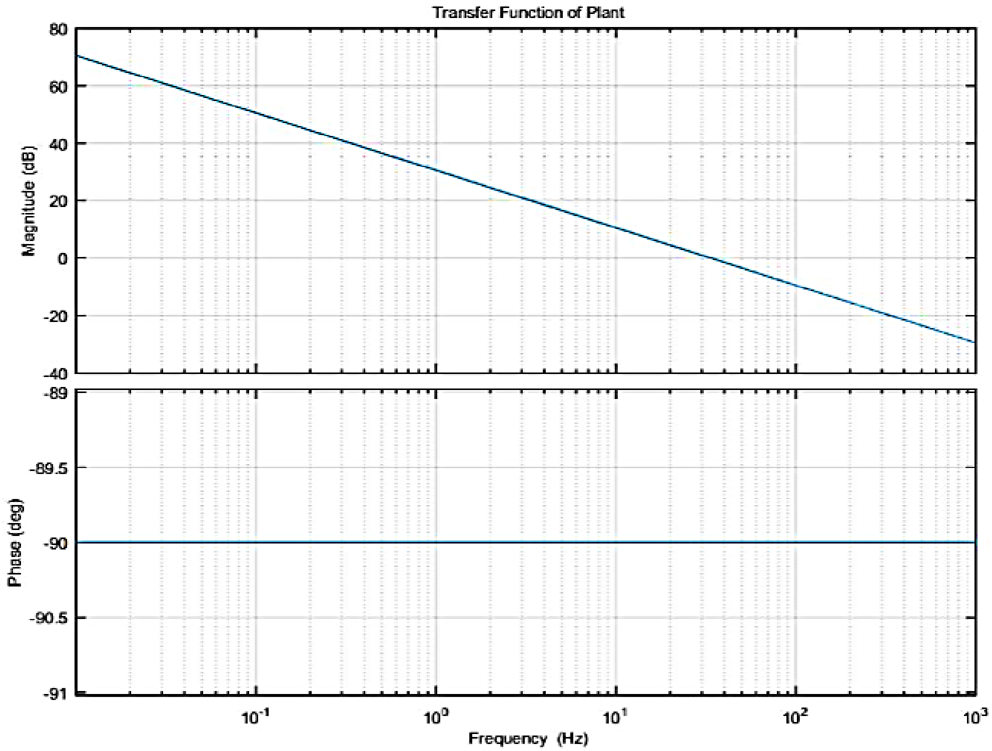


Fig. 3.9: Bode plot of plant for outer voltage loop

The controller type PI is chosen, and its parameters are following:

$$G_{pi} = K_P + \frac{K_I}{s} \tag{3.8}$$

The voltage control loop has been designed based on the current loop of STATCOM with the following values given as:

$$V_q = \frac{208}{\sqrt{3}} * \sqrt{2} = 169.83$$

$$V_{co} = 400\ volts$$

The transfer function can be given by:

$$G(s) = \frac{V_c(s)}{I_q(s)} = \frac{\widetilde{v_c}}{\widetilde{\iota_q}} = \frac{1.5V_q}{sCV_{co}} \tag{3.9}$$

$$G(s) = \frac{1.5(169.83)}{s(3000\mu F)(400)} = \frac{254.745}{1.2s} \tag{3.10}$$

The phase margin of 61.8 deg is obtained at f = 5 Hz.

$K_P = 0.148$

$K_I = 2.68$

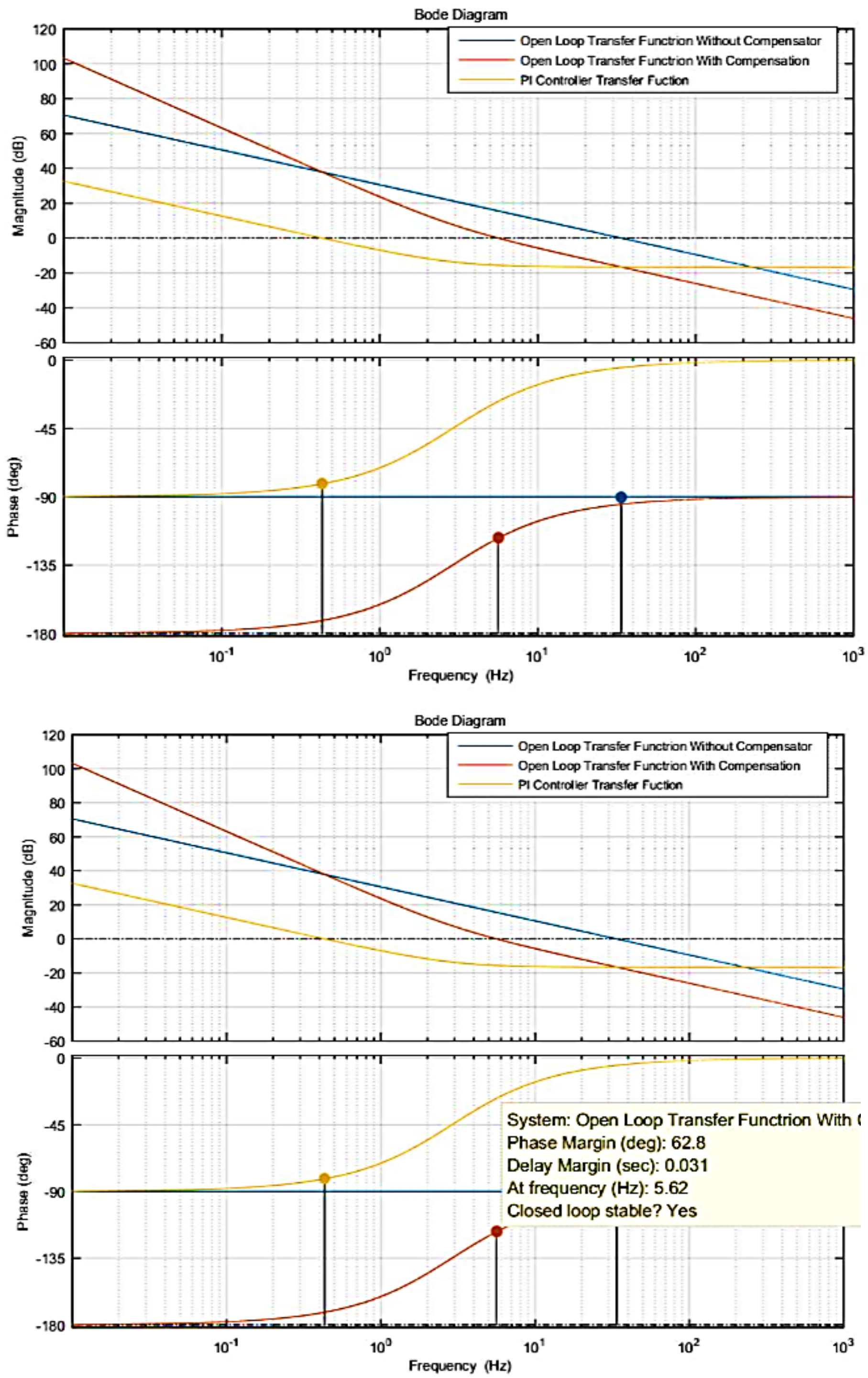


Fig. 3.10: Bode plot of outer voltage control loop with compensator and without compensator

As shown in Fig. 3.10, the phase margin of 60 degrees is obtained at the crossover frequency of 5 Hz. However, the switching frequency is 540 Hz.

- **Assumptions and Component Selection**

1. The direction of the power flow is assumed from the converter towards the grid for the entire analysis.
2. The inductance value of 5 mH is chosen based on the availability in the lab.
3. The capacitance value calculated from the energy balance equation from AC to DC side is 3000 uF and the value of ripple current is 21 A for the safer operation.
4. The IGBT is rated at 1200V/5A. However, the safer voltage is around nearly 600 V.
5. The DC link voltage used in the simulation is 400 V, so for the safer operation a 50 % voltage overshoot is considered.
6. Optimization of the number of switches for H-bridges is not done, it is chosen to validate the concept.
7. The working temperature is assumed as room temperature.

3.5 Controller Design of Hybrid STATCOM and Harmonic Extraction

Converter structures with series wave-shaper circuits, such as the Hybrid STATCOM have been reported in the literature. The novelty of the proposed control scheme is the online harmonic cancellation with the help of wave-shaper circuits. This is achieved by multiple PLLs at the pole voltage output of the two-level converter. First, the PLLs are locked at the corresponding harmonics to be extracted such that the corresponding d and q axis voltages are DC quantities. Then, with the help of low pass filters harmonics extracted. These harmonic voltages are applied as the desired output voltages (modulation references) for the three wave-shaper cells. The control philosophy of the Hybrid STATCOM and the wave-shaper circuits is shown in Fig. 3.11. A brief explanation of the same is presented below.

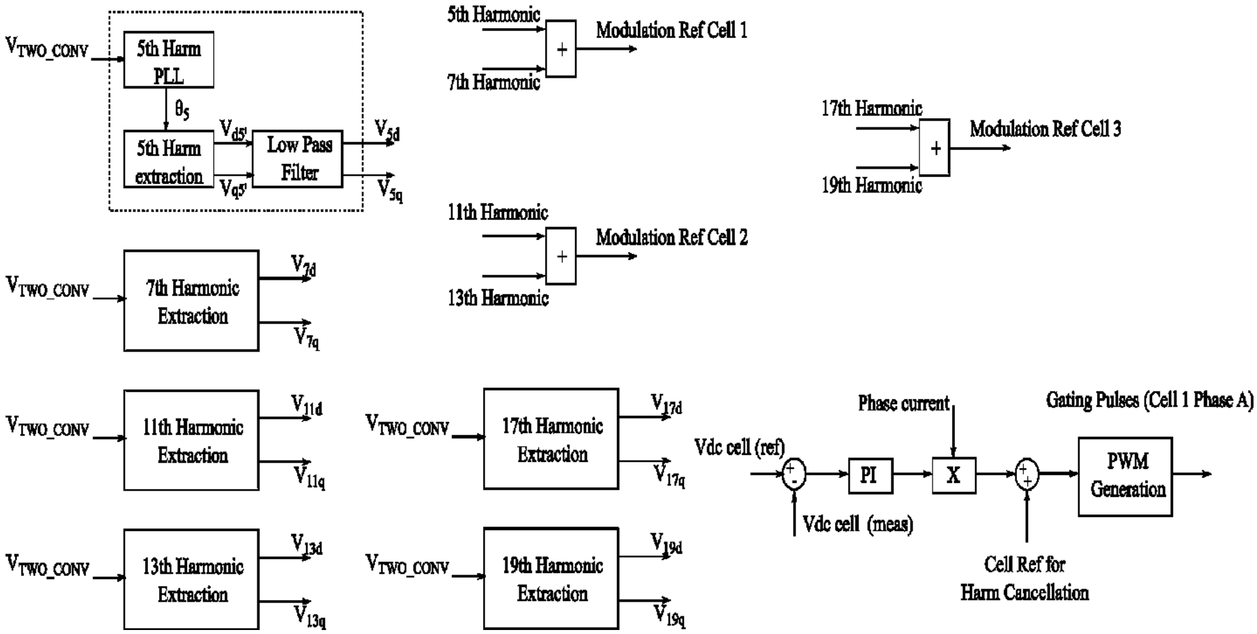


Fig. 3.11: Control Philosophy of the Hybrid STATCOM: Wave-shaper cells

The function of extracting the 5th, 7th, 11th, 13th, 17th and 19th harmonics is done with the help of multiple PLLs at the pole voltage output of the two-level converter. These PLLs are locked at the corresponding harmonics to be extracted such that the corresponding d and q axis voltages are DC quantities. Then with the help of low pass filters, these harmonics can be extracted easily. These harmonic voltages are applied as the desired output voltages (modulation references) for the three wave-shaper cells.

It is important to note here that there is no DC voltage source at the DC link of the wave-shapers, just as in the case of the two-level converter. The two-level converter of the Hybrid STATCOM has the same control as shown for the conventional STATCOM to maintain the DC link voltage at a fixed value and inject the required amount of reactive power. The wave-shaper cells in similar lines need to maintain their DC links at a constant value so that they can apply the required harmonic voltages and cancel relevant harmonics introduced by the two-level converter. The control structure for the DC link voltage control of the wave-shaper cells is shown in Fig. 3.12.

The controller ensures that independent of the current direction, the capacitance can be charged or discharged as required. The plant transfer function is quite simple; it is an integrator at the origin. The controller gains can be calculated based on this plant to achieve high bandwidth. The values of kp and ki for the controllers are calculated as 1 and 10, respectively. The harmonics to be added are extracted and directly added to the modulating reference of the wave-shaper cells. As the wave-shaper is a voltage source converter, when its DC link voltage is a fixed value, the desired harmonic voltages can be easily applied.

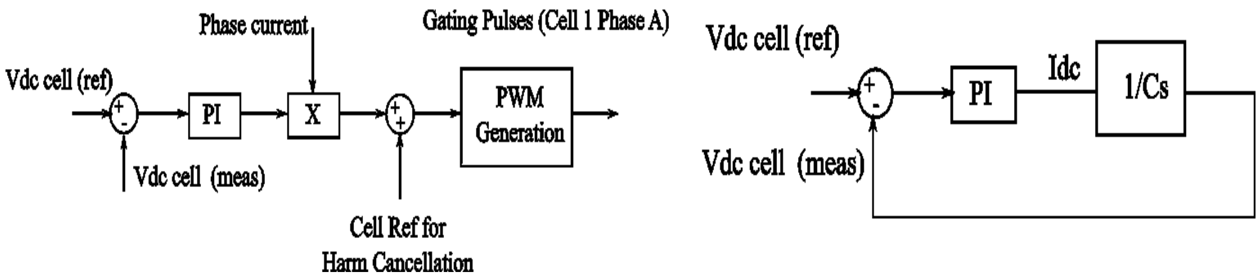


Fig. 3.12: Control structure of DC link voltage control for the wave-shaper cells

The voltage control loop has been designed based on the current control loop of the STATCOM.

3.6 Concluding Remarks

In this chapter, conventional two-level STATCOM and proposed Hybrid STATCOM has been discussed. The controller has been designed for both the STATCOM topology and MATLAB software is used for bode plots analysis. Also, the harmonic extraction technique has been explained. The next chapter presents the simulation results. The simulations have been performed in MATLAB® / SIMULINK®.

4. MATLAB Simulations and Results

The prime advantage of incorporating active wave-shaper is in the reduction of the current THD introduced by two-level VSC based STATCOM. The two-level VSC based STATCOM together with series active wave-shaper, cancels the harmonics injected in the system. When STATCOM introduces harmonics during its operation after 2-4 cycles the wave-shaper units are activated and start cancelling them by injecting voltage equal in magnitude and the 180-degree phase shifted. Voltage sensors in each phase are used to sense pole voltage and the signals are further sent to harmonic extractor units. The phase angle control will assist the STATCOM to cover the reactive power demand and voltage regulation until the shortage is depleted. In order to get the hybrid STATCOM system performance, individual components need to be modelled first and then combination will be evaluated to meet the expectation. Hence in this chapter the simulation of hybrid STATCOM is presented.

4.1 Simulation Results and Discussion

Most of the simulation/programming is carried out in MATLAB due to its computational competence and inbuilt data function database. Further testing is carried out using the OPAL-RT controller module (OP4510) and various other parts, which are fabricated in PEER Lab at Concordia University. Fig. 4.1 shows the reactive power injection control of Hybrid STATCOM.

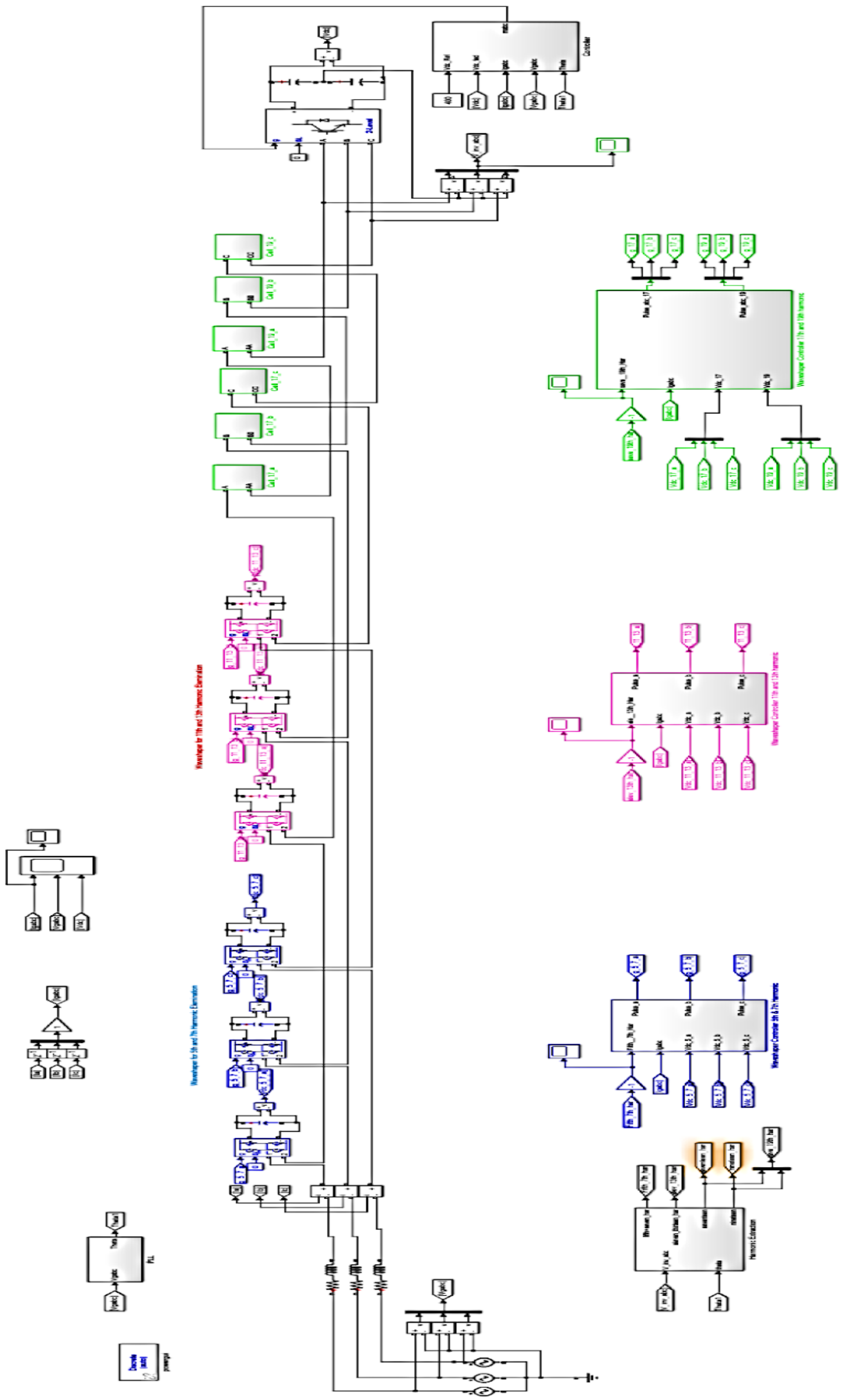


Fig. 4.1: Reactive power injection for control of Hybrid STATCOM

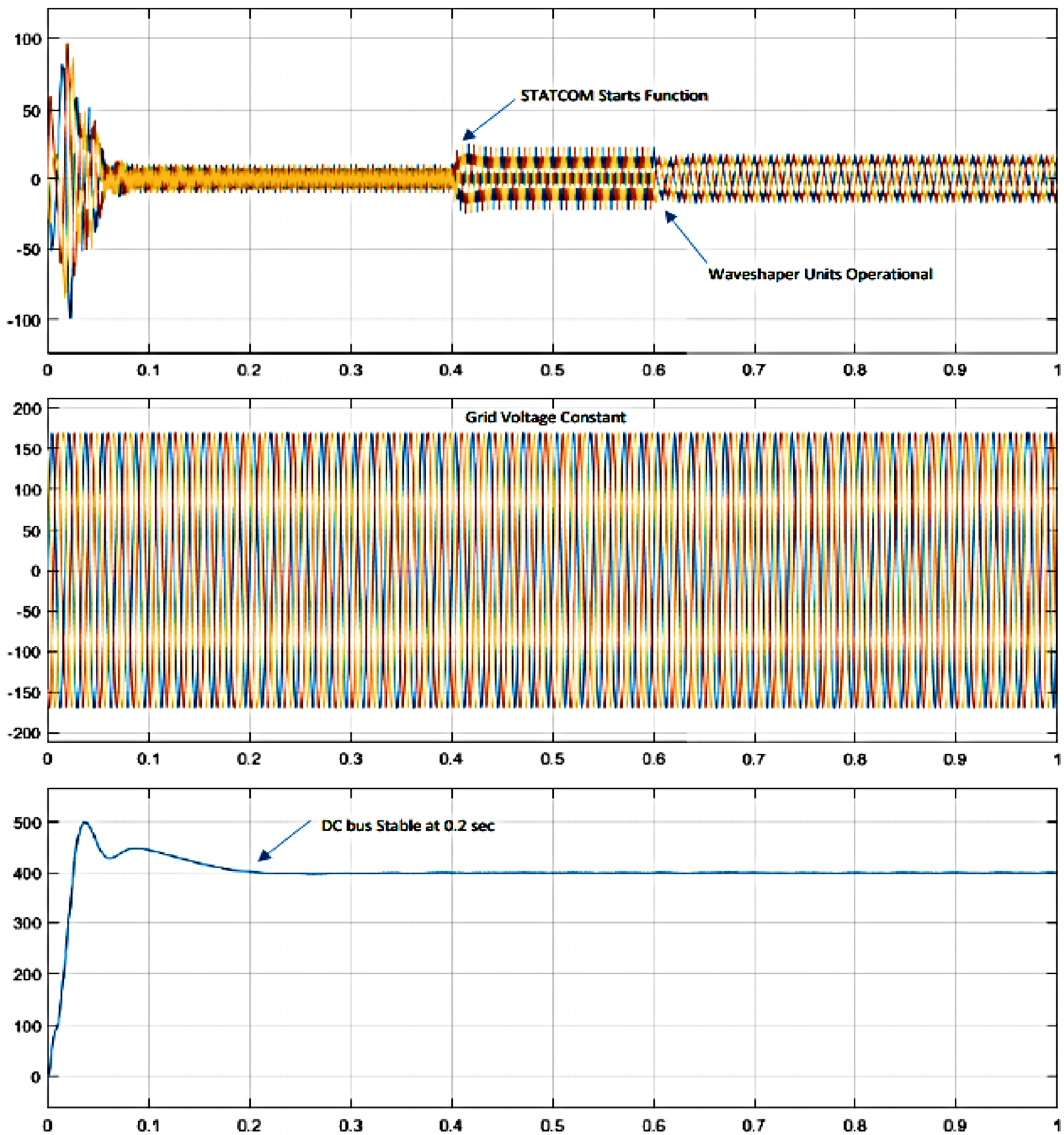


Fig. 4.2: Phase current, grid voltage and DC link voltage for the Hybrid STATCOM

Fig. 4.2 shows the DC link voltage and the phase current of the conventional STATCOM. As explained earlier for the STATCOM, the voltage reference is 400 V. The control for the STATCOM begins at around 0 seconds. There can be a transient change noticed at this time in both the current and the voltage waveforms. The DC link voltage stabilized at around 0.2 seconds. As mentioned earlier, the reactive power reference starts ramping at around 0. Until then the phase current is at a very small value but reaches the rated current of around 13.87 A after 0.4 seconds. It should be noted here that during the entire simulation, the DC link voltage of the capacitor is maintained at 400 V.

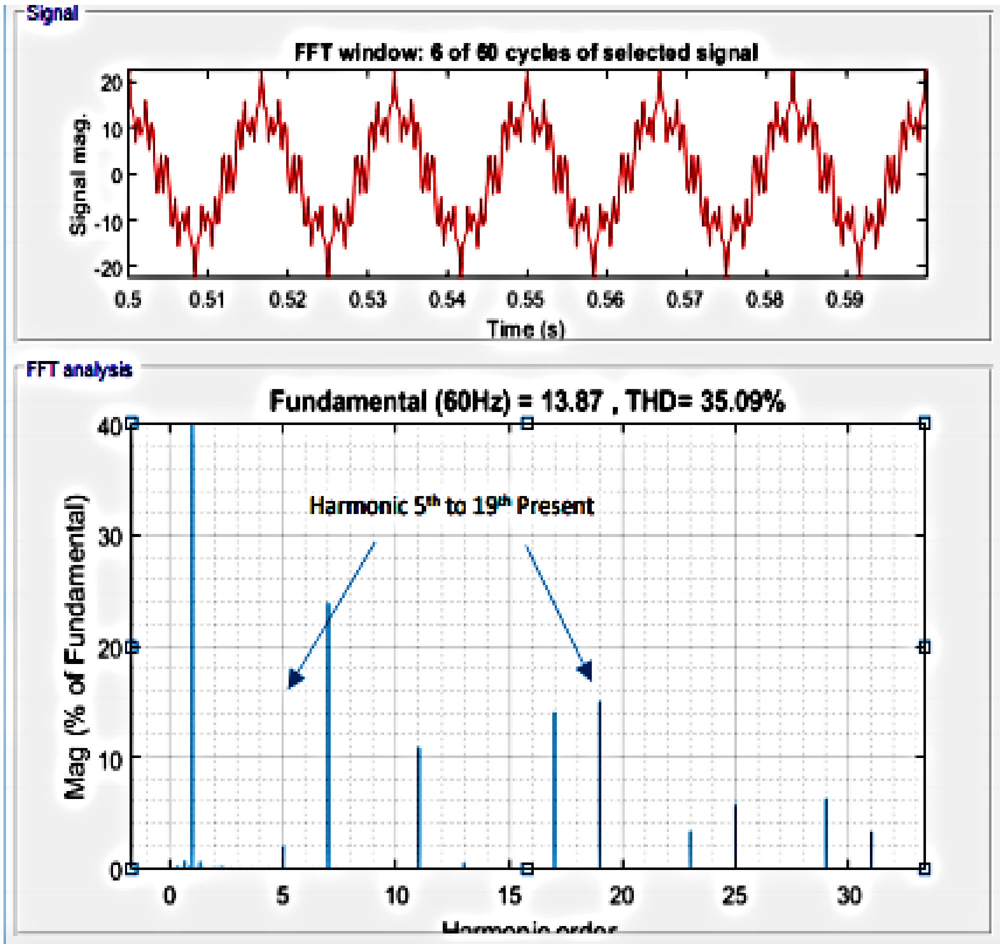


Fig. 4.3: Harmonic spectrum of phase current for conventional STATCOM

Fig. 4.3 shows the harmonic current of the phase current for the conventional STATCOM. As can be seen, the current THD is 35.09 % due to the choice of 540 Hz as the switching frequency. From the spectrum of the phase current in Fig. 4.3, the harmonic sidebands occur at and around 540 Hz. It should be noted that there are a few lower-order harmonics. These can be attributed to the large dead-time (around 5 μs) used when the simulation results were captured. It is also clear that the peak phase current is at its rated value around 20 A. It is shown in Fig. 4.2 that during 0.2 to 0.4 seconds, Hybrid STATCOM works as a conventional STATCOM and the wave-shaper cells are bypassed. At 0.6 seconds, the wave-shaper cells are activated and the reactive power compensation continues. It should be noted that the wave-shaper cells are not injecting any reactive power but the harmonic cancellation.

Fig. 4.2 clearly shows the impact of the wave-shaper circuits in terms of current waveform improvement. As mentioned earlier, the wave-shaper is bypassed until 0.4 seconds into the simulation. At around 0.6 seconds, the wave-shaper circuit starts filtering the harmonics injected by the two-level converter of the Hybrid STATCOM. It should be pointed out here that the two-level converter is switching at a much lower frequency of 540 Hz, as can be noticed from the poor current waveform as shown in Fig. 4.3. At 0.6 seconds when the wave-shaper circuit starts filtering, the current waveform improves significantly as shown in Fig. 4.4

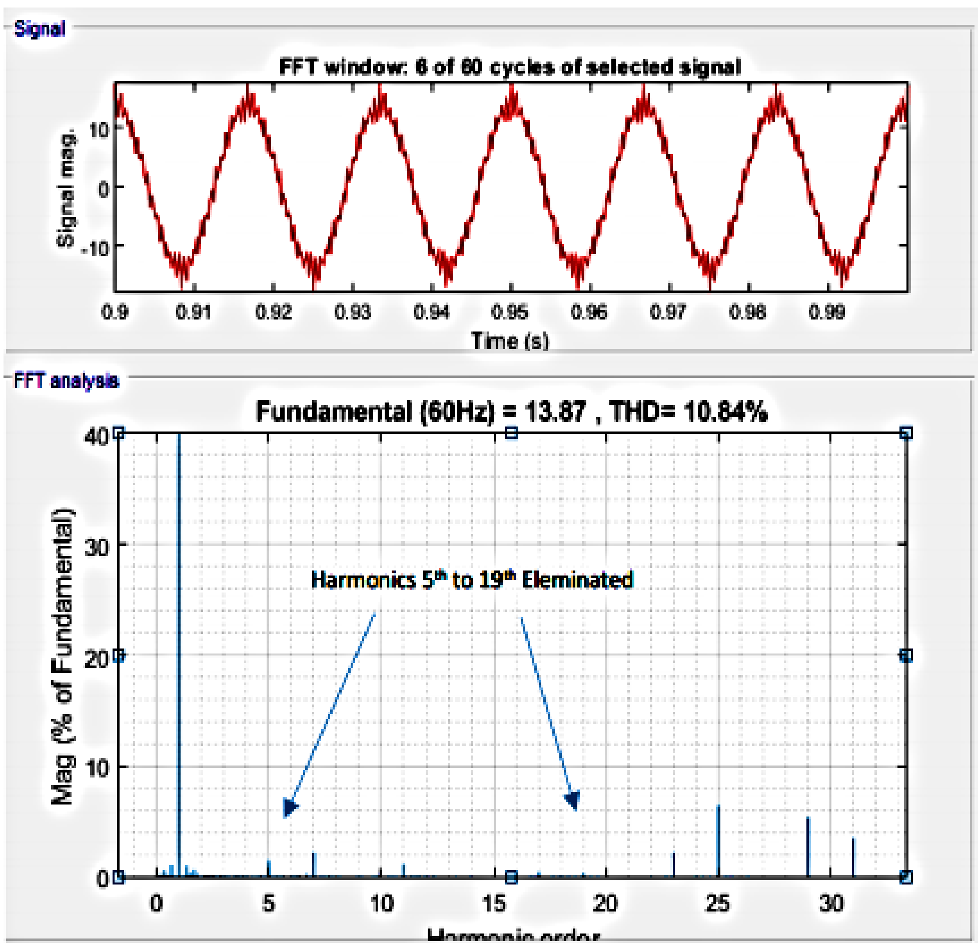


Fig. 4.4: Harmonic spectrum of phase current for Hybrid STATCOM

Fig. 4.4 presents clearly the functioning of the wave-shaper circuit in terms of the measured harmonic spectrum. As can be seen, in the first harmonic plot in Fig. 4.3, the THD is quite poor

(35.09 %). This is the period of the simulation where the wave-shaper is bypassed and it is just the two-level converter switching at a low switching frequency of 540 Hz feeding reactive power to the grid. It is clear from the harmonic spectrum that there are 5th, 7th, 11th, 13th, 17th and 19th harmonics in the spectrum. Fig. 4.4 is obtained when the wave-shaper starts functioning and cancels the above-mentioned harmonics. As can be seen from the new spectrum, the first dominant harmonics occur now at around 23rd harmonic. Thus, the THD is also much better at around 10.84 %. It should be stressed here that the two-level converter of the Hybrid STATCOM continues switching at the same frequency of 540 Hz. It is because of the wave-shaper circuit operation and cancellation of 5th through 19th harmonic, that the waveform improves significantly.

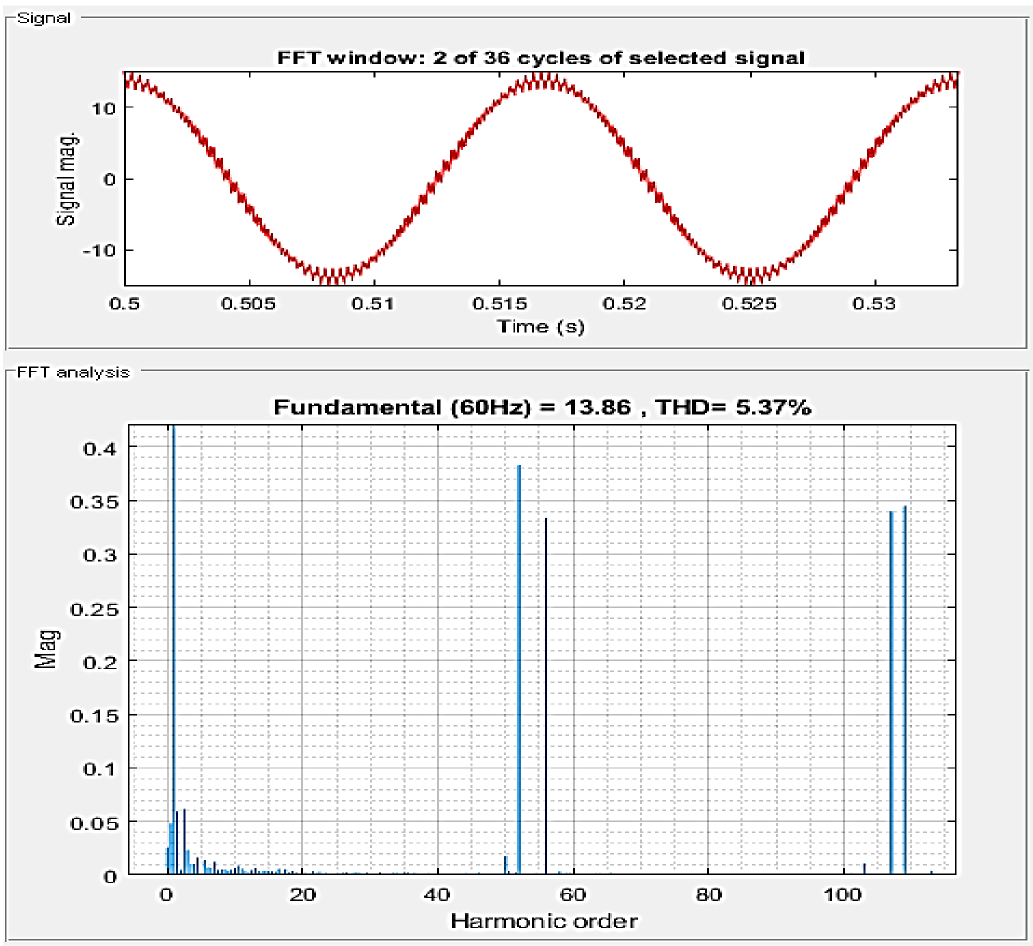


Fig. 4.5: Line Current of the conventional STATCOM operated at 3240 Hz switching frequency

Fig. 4.5 shows the harmonic current of the conventional STATCOM operated at 3240 Hz switching frequency. The current THD, as can be seen, is nearly 5 % due to the choice of 3240 Hz as the switching frequency from the harmonic spectrum of the current waveform, it is clear that the harmonics side-band occurs around 3240 Hz and at twice the switching frequency (3240 Hz) i.e. $m_f \pm 2$. There are few lower order harmonics because of dead-time during simulation results were taken.

4.2 Theoretical Analysis and Calculations

In this section, theoretical analysis and calculations based on the switching frequency and the ripple requirement is presented. For the conventional STATCOM, the switching frequency chosen is 540 Hz for a rated phase current of around 20 A peak. The IGBT used for hardware implementation is from Little fuse (MG1275S-BA1MM) rated at 1200 V/80 A. However, the safe operating voltage will be around 600 V. Now for the two-level converter, each arm is stressed with the DC link voltage and hence, the device should be able to withstand this voltage. A DC link voltage is 400 V, a 15 % voltage overshoot can be considered for a safer operation limit.

The 3-Phase system with VSC based STATCOM is shown in Fig. 4.6

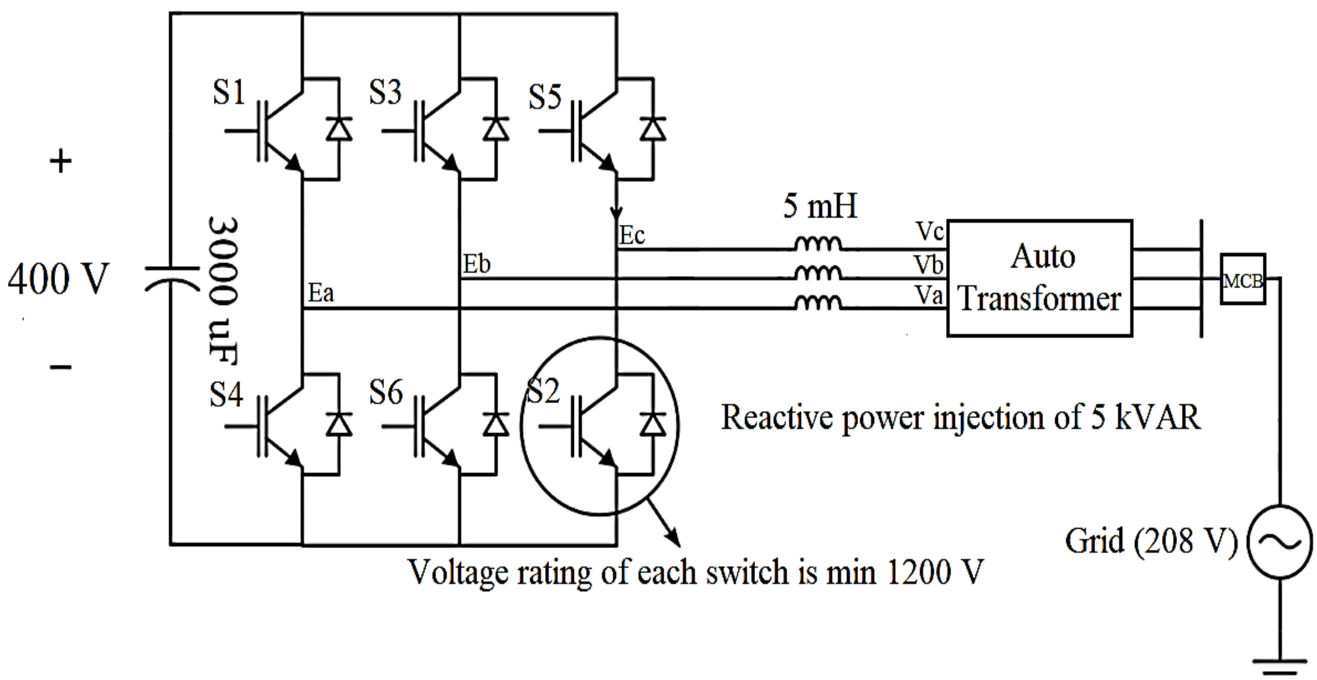


Fig. 4.6: Conventional Two-Level STATCOM

where E_a, E_b and E_c are the inverter voltages and V_a, V_b and V_c are the grid voltages. SPWM technique is used for the control of the converter voltage. All the calculations are done on the line to line voltages.

In SPWM, the carrier signal is a triangular wave at 540 Hz and is compared with the 3-phase sine modulating signals. Thus, the pulses obtained are given to the converter and converter produces voltages as desired.

Here, the fundamental frequency of 60 Hz is selected which is similar to the modulating signal frequency. It is also assumed that the system is providing 5 kVAR to the grid.

Amplitude modulation index m_a,

$$m_a = \frac{V_{control}}{V_{triangular}} \tag{4.1}$$

where, $V_{control}$ is the peak value of the control voltage.

$V_{triangular}$ is the peak value of the carrier which is fixed.

$$0 \leq m_a \leq 1$$

Frequency modulation index m_f

$$m_f = \frac{f_{sw}}{f_1} \tag{4.2}$$

m_f is the ratio of switching frequency and fundamental frequency.

Harmonic frequency of the converter can be given by:

$$f_h = \left(jm_f \pm k\right) * f_1 \tag{4.3}$$

A fundamental component of the line to line voltage:

$$V_{A0} = m_a * \frac{V_d}{2}; m_a \leq 1 \tag{4.4}$$

A fundamental component of the line to line voltage can be expressed as:

$$(V_{LL})_{1rms} = \frac{\sqrt{3}}{2\sqrt{2}} m_a V_d; m_a \leq 1 \tag{4.5}$$

The system is designed and developed for 208 volts (line to line) or 120 Volts (phase voltage).

So, for the three-phase VSC Based STATCOM,

$$X_L = \omega L = 2 * 3.14 * 60 * 1 * 10^{-3}$$

$$Q_{3\emptyset} = \sqrt{3} * V_L * I_L Sin\, \theta \tag{4.6}$$

Let’s assume that we have to supply 5kVA to the grid,

So, the current can be calculated as,

$$I_{s1} = \frac{Q_{3\emptyset}}{\sqrt{3} * V_L} = \frac{5000}{\sqrt{3} * V_L} = 13.8786\, A$$

To supply this reactive power, I lead V_s

$$V_{inv\_1} = V_s + jI_{s1}X_L \tag{4.7}$$

$$= 208 + (13.87 * 0.377)$$

$$= 213.2289\, V$$

So, we have to generate this line to line voltage from STATCOM in order to supply 5 kVAR to the Grid,

Now, for the DC bus calculation

Consider $m_a = 1$, for max utilization of inverter.

$$(V_{LL})_{1rms} = \frac{\sqrt{3}}{2\sqrt{2}}\, m_a V_d \tag{4.8}$$

$$213.2289 = \frac{\sqrt{3}}{2\sqrt{2}} * 1 * V_d \tag{4.9}$$

$$V_D = 348.201\, VDC$$

For absorbing 5 kVAR,

$$V_{inv_1} = V_s + jI_{s1}X_L \tag{4.10}$$

$$= 208 - (13.87 * 0.377) = 202.77\, V\, (rms)$$

For this, we will calculate the minimum value of m_a

$$(V_{LL})_{1rms} = \frac{\sqrt{3}}{2\sqrt{2}}\, m_a V_d \tag{4.11}$$

$$202.77 = \frac{\sqrt{3}}{2\sqrt{2}}\, m_a * 348.201$$

$$m_a = 0.9509$$

This is the minimum value to m_a to absorb reactive power from the grid.

For triggering IGBTs, the Sinusoidal Pulse width modulation Technique (SPWM) is used with a triangular carrier, which is discussed earlier.

$$f_{sw} = 540\ Hz$$

$$V_{cntrl} = 10\ V(peak)$$

In case of unipolar 3-phase full-bridge inverter dominant harmonic will appear in the second sideband around

$$f_h = \left(jm_f \pm k\right) * f_1 \quad (4.12)$$

For, $m_a = 1$

It is assumed to supply and absorb 5 kVAR at the utility side.

$$m_f = \frac{540}{60} = 9$$

Harmonic analysis is presented in the next section.

4.3 Harmonics Calculation

The simulation has been performed in MATLAB for a two-level VSC based STATCOM operating at 540 Hz switching frequency and providing 5 kVAR reactive power to the grid. Furthermore, the harmonics and frequencies are also determined along with their magnitude.

The fundamental component of the line to line voltage is given by,

$$(V_{LL})_{1rms} = \frac{\sqrt{3}}{2\sqrt{2}}\ m_a V_d; m_a \leq 1 \quad (4.13)$$

Dominant harmonic voltage magnitude for $f_{sw} = 540\ Hz$ is given by,

$$m_f = \frac{540}{60} = 9$$

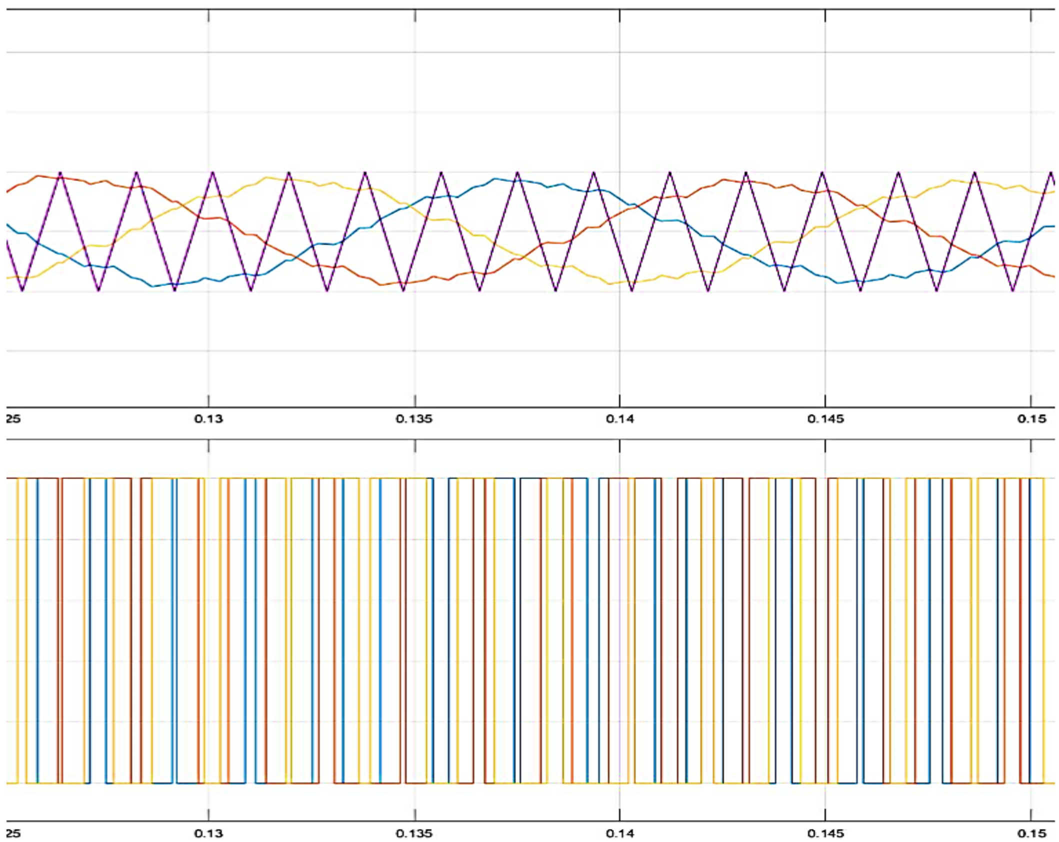


Fig. 4.7: Modulating voltage with a triangular voltage

Fig. 4.7 presents modulating voltage and triangular carrier wave along with PWM generation.

For the 3-phase VSC, the harmonics occur at the following frequencies,

Table 4.1: Harmonics of 3-phase Voltage Source Converter for $m_f = 9$

Order of Harmonics	For $m_f = 9$
$m_f \pm 2$	7th and 11th Harmonic
$m_f \pm 4$	5th and 13th Harmonic
$2m_f \pm 1$	17th and 19th Harmonic
$2m_f \pm 3$	15th and 21st Harmonic
$3m_f \pm 2$	24th and 29th Harmonic
$3m_f \pm 4$	23th and 31th Harmonic
$3m_f \pm 6$	21th and 33st Harmonic

For harmonics calculations, harmonic occurs at $m_f \pm 2$, i.e. sideband of m_f.

$$f_h = (m_f \pm 2) f_1 \tag{4.14}$$

$$f_h = 420\ Hz\ and\ 660\ Hz$$

Now, the approximated magnitude of the line to line voltage harmonic occurring at 420 Hz and 660 Hz can be calculated using Table 4.2.

Table 4.2: Generalized harmonics of v_{Ao} for a large m_f [39]

h \ m_a	0.2	0.4	0.6	0.8	1.0
1 Fundamental	0.2	0.4	0.6	0.8	1.0
m_f	1.242	1.15	1.006	0.818	0.601
$m_f \pm 2$	0.016	0.061	0.131	0.220	0.318
$m_f \pm 4$					0.018
$2m_f \pm 1$	0.190	0.326	0.370	0.314	0.181
$2m_f \pm 3$		0.024	0.071	0.139	0.212
$2m_f \pm 5$				0.013	0.033
$3m_f$	0.335	0.123	0.083	0.171	0.113
$3m_f \pm 2$	0.044	0.139	0.203	0.176	0.062
$3m_f \pm 4$		0.012	0.047	0.104	0.157
$3m_f \pm 6$				0.016	0.044
$4m_f \pm 1$	0.163	0.157	0.008	0.105	0.068
$4m_f \pm 3$	0.012	0.070	0.132	0.115	0.009
$4m_f \pm 5$			0.034	0.084	0.119
$4m_f \pm 7$				0.017	0.050

Note: $(\hat{V}_{Ao})_h / \frac{1}{2}V_d$ [$= (\hat{V}_{AN})_h / \frac{1}{2}V_d$] is tabulated as a function of m_a.

For $m_a = 0.8$,

$$\hat{V}_{m_f \pm 2} = 0.220 * 348.201\ volts = 76.60\ V\ (peak\ value)$$

Thus, the value of voltage harmonics at $(m_f \pm 2)$ will occur in pairs around m_f as shown in fig. 4.8.

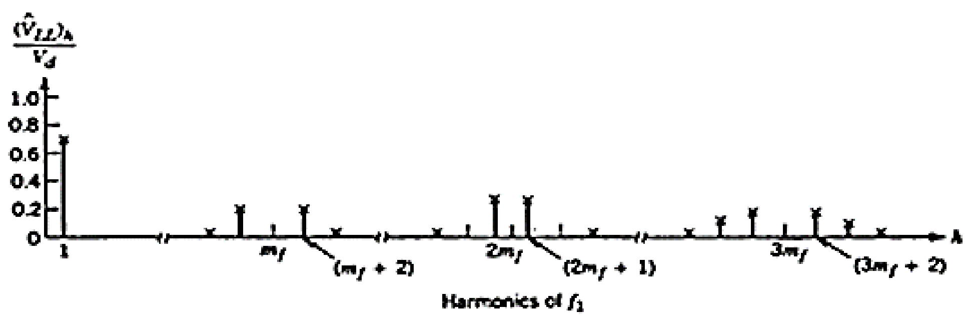


Fig. 4.8: Harmonics of three-phase Voltage Source Converter [39]

Harmonic occurs at $2m_f \pm 1$, i.e. sideband of $2m_f$.

$$m_f = \frac{540}{60} = 9$$

$$f_h = (2m_f \pm 1)f_1 \qquad (4.15)$$

$$f_h = 1020\ Hz\ and\ 1140\ Hz$$

Now, the magnitude of the line to line voltage harmonic occurring at 1020 Hz and 1140 Hz can be calculated as

$$\hat{V}_{2m_f \pm 1} = 0.314 * 348.201\ volts = \ 93.808\ \ V\ (peak\ value)$$

Thus, the value of voltage harmonics at $(2m_f \pm 1)$ will occur in a pair around m_f as shown in Fig. 4.7. Similarly, all the other harmonics values can also be calculated by using the same method as shown in Table 4.3.

Table 4.3: Simulated and calculated values of fundamental and harmonics components

Order of Harmonic	**Simulated Values (Volts) for** $m_a = 0.71$	**Calculated Values (Volts) for** $m_a = 0.8$
Fundamental Component (60Hz)	248.78	241.24
At 420 Hz	75.8	76.60
At 660 Hz	54.18	76.60
At 1020 Hz	107.92	93.8
At 1140 Hz	129.18	93.8

Real-time simulation results for 3-phase two-level inverter are taken using OPAL-RT (OP510) and analyzed as shown in Fig. 4.9 for the line to line voltage and Fig. 4.10 for phase current.

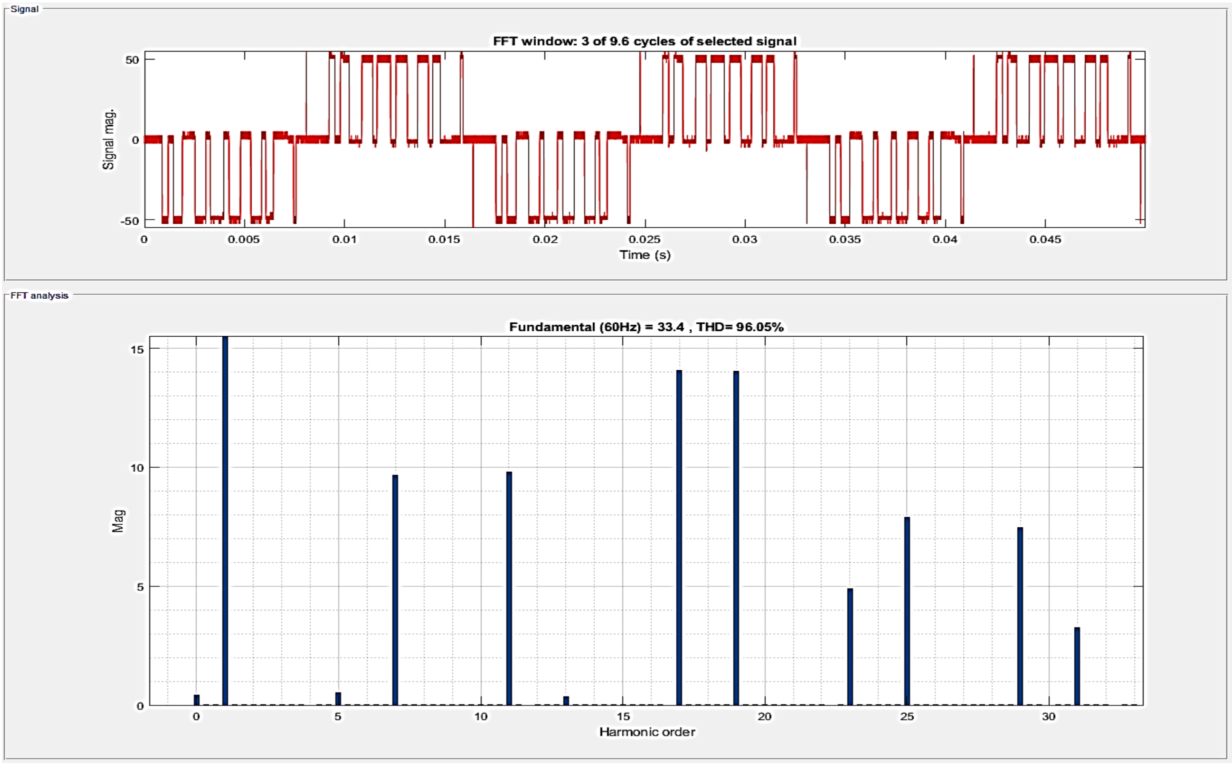


Fig. 4.9: Inverter line to line voltage waveform FFT analysis

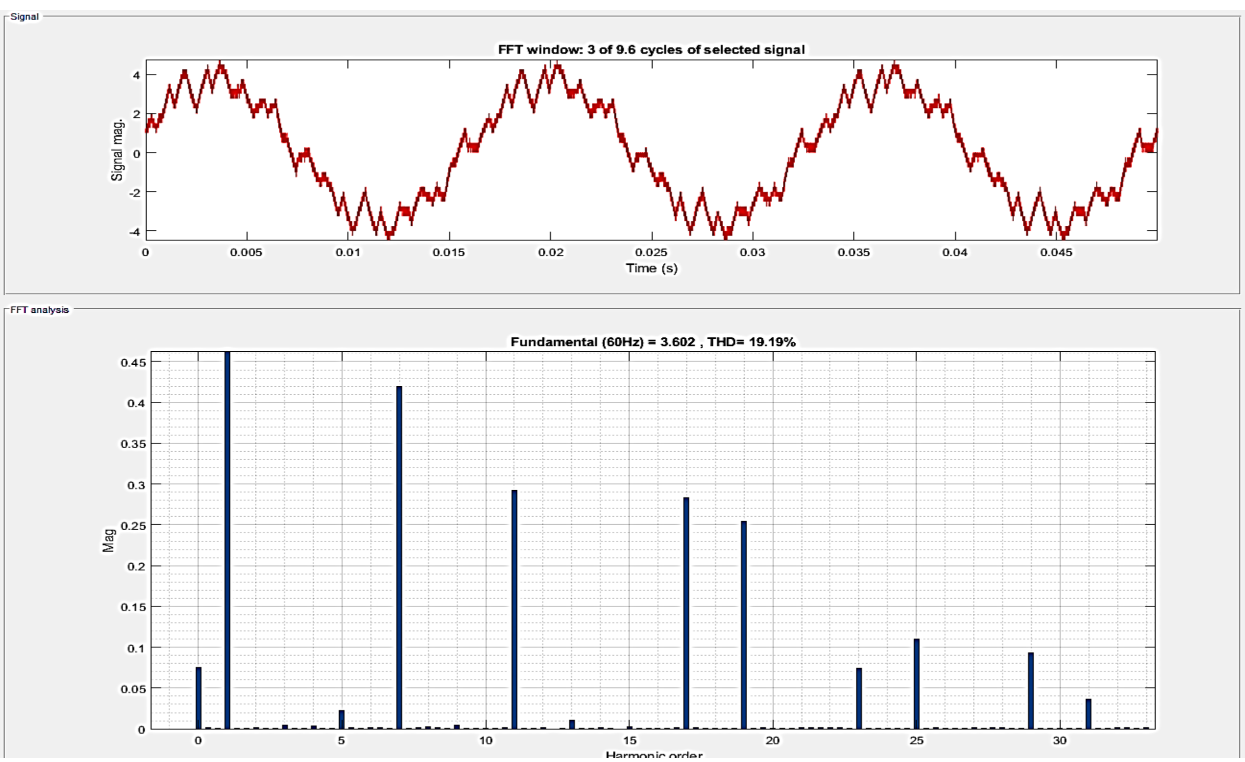


Fig. 4.10: Phase current (I_a) FFT analysis

Here V_{DC} for the inverter is chosen as 50 V and the switching frequency of the two-level inverter is 540 Hz. As it can be seen in FFT analysis that the voltage harmonics occur at side-bands $m_f \pm 1$ *and* $2m_f \pm 1$. This validates that inverter is working satisfactorily at 50 V DC

4.4 Concluding Remarks

This chapter presented simulation results for conventional STATCOM and hybrid STATCOM. It has been demonstrated through simulation results that hybrid STATCOM performs satisfactorily and reduces the THD and improves the harmonic spectrum. The next chapter presents the details of the hardware platform and its development along with experimental results.

5. Hardware Development and Experimental Results

As discussed in the previous chapter, the proposed hybrid STATCOM structure makes use of wave-shaping units along with the conventional two-level VSC to ensure high quality waveform at relatively low switching frequencies. An experimental prototype of hybrid STATCOM rated at 250 VAR was designed and developed in the laboratory to verify the proposed control. The two-level VSC is developed to operate at a low voltage level of 50 V. The voltage rating of the wave-shaper cells depends upon the amplitude of the corresponding harmonics generated by the two-level converter. Therefore, for the wave-shaper units 5 V is selected. OPAL-RT® based real-time simulator (OP4510) is used for testing the proposed control on the developed hardware prototype.

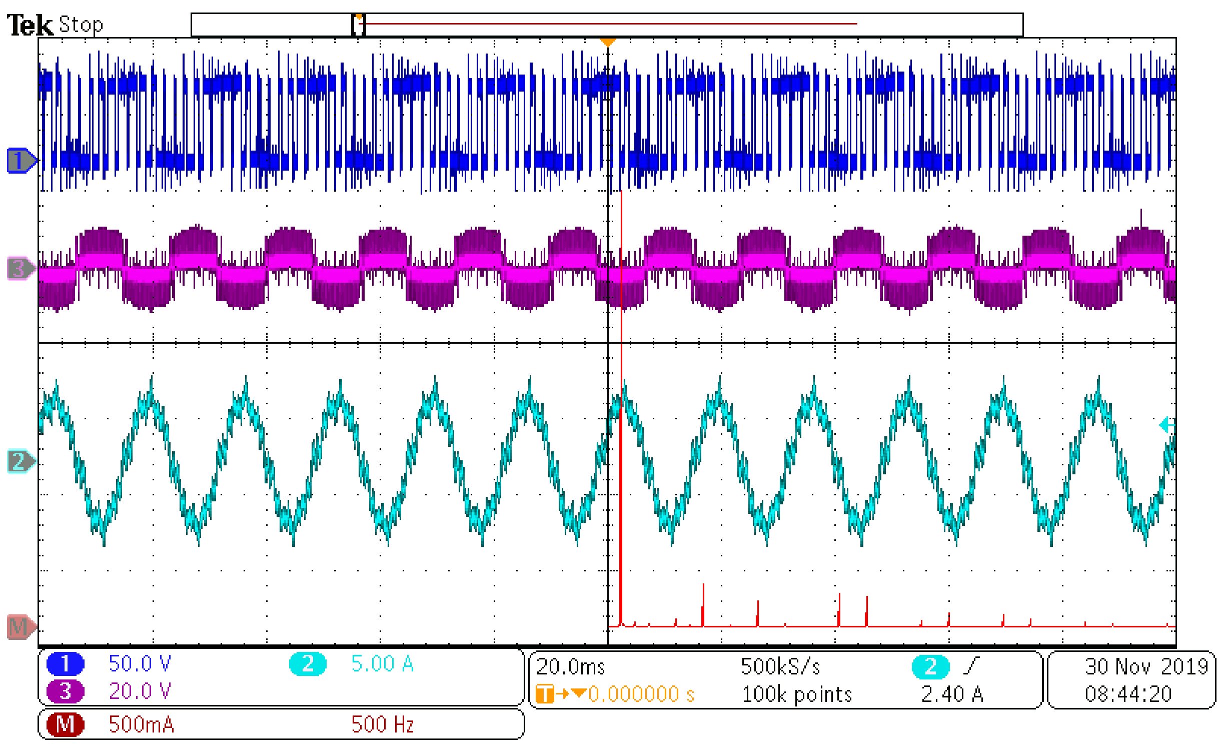


Fig. 5.1: Without Harmonic Cancellation; CH1: Inverter terminal voltage, CH2: Injected voltage by series H-bridge, CH3: line current, CH4: Real-time FFT of current waveform CH3

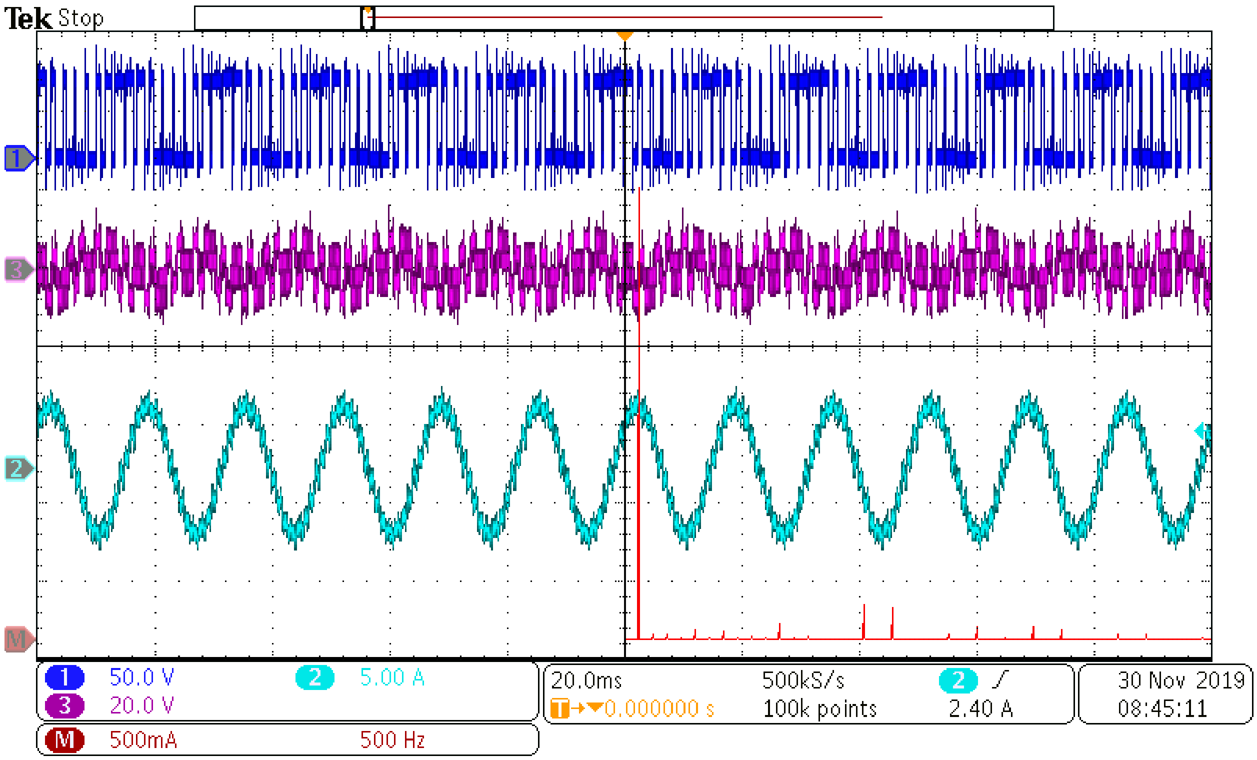


Fig. 5.2: With Harmonic Cancellation; CH1: Inverter terminal voltage, CH2: Injected voltage by series H-bridge, CH3: line current, CH4: Real-time FFT of current waveform CH3

The IGBT module MG1275S-BA1MM (from Little Fuse) is used for the two-level converter and MG1250S-BA1MM (from Little Fuse) is used for H-bridges. The maximum blocking voltage V_{ce} of the IGBT is 1200V to have a safe operating mode and considering the marginal safety. The current capacity of switch is 80 A peak. Semikron SKHI61R gate driver module is used for giving gate pulses to the IGBTs.

The gating pulses are generated by the OPAL-RT digital output port. The hall-effect sensors LV-20P and LA-55P are used to sense grid voltage and output current, respectively. Furthermore, the OPAL-RT sensor box is used for measuring the pole voltage of the converter to extract the real time-harmonic components. The switching frequency for the main inverter of the STATCOM is chosen as 540 Hz and the dead time of 5 µs has been chosen. The waveforms of inverter terminal voltage, injected voltage by wave-shaper unit, line current, and real-time FFT are presented without and with harmonic cancellation in Fig. 5.1 and Fig. 5.2 respectively. It should be from Real-time FFT waveform of Fig. 5.1 and Fig. 5.2 (Channel 4) that the harmonics close to the fundamental frequency are reduced significantly. Also, the quality of current waveform shown on channel 2 has been improved with harmonic cancellation in Fig. 5.2 compared to shown in Fig. 5.1.

5.1 Results of Harmonic Cancellation for a Two-Level VSC Connected to Grid

In this section, the experimental results are shown and discussed for the complete system of the hybrid STATCOM as shown in Fig. 4.1 of last chapter with both STATCOM and wave-shaper units. The experimental results with both cases, with and without wave-shaper unit, are shown in this section and tabulated in Table 5.1. To test the validity of the proposed idea, simulations are performed on an OPAL-RT® based real-time simulator (OP4510) [41-42].

The proposed hybrid STATCOM structure makes use of the wave-shaping units along with the conventional two-level VSC to ensure good waveform quality at relatively low switching frequencies. The wave-shaping units are basically H-bridge cells, which are connected in series with the conventional two-level VSC. In the proposed structure, the two-level VSC switches at a low frequency. The resulting voltage harmonics generated by the two-level VSC are cancelled by the wave-shaping units (H-bridge cells). Therefore, the H-bridge converters must switch at a relatively higher switching frequency to allow the harmonic voltage generation.

Table 5.1: Details of hybrid STATCOM Lab Prototype

Parameters	**Value**
DC reference voltage	50 V
Switching frequency (f_{sw})	540 Hz
Quadrature axis reference current (I_q ref)	4 A peak
Modulation frequency index (m_f)	540/9= 9
Harmonics occur at a frequency	(m_f +2), (m_f -2), (2m_f+1), (2m_f-1)
DC reference voltage for the H-bridge wave-shaper unit	5 V
Switching frequency for H-bridge wave-shaper units	5000 Hz

Therefore, the proposed hybrid STATCOM has several power converters switching at different frequencies. In terms of bandwidth, the current loop and the voltage loop of the two-level converter have a bandwidth of 30 Hz and 5 Hz, respectively, which is quite adequate for a large power rating. The wave-shaper units have a bandwidth of 5000 Hz for the voltage control loop. As discussed in the previous chapter, the wave-shaper units only require one control loop to maintain its cell voltage at a fixed value.

A. DC Bus Voltage Build Up during Start-up

The DC bus voltage for main STATCOM is chosen as 50 V as shown in Fig. 5.3. The operation of converter is tested by connecting it to an autotransformer (grid). In the beginning the DC bus is charged by the back to back diode up to 40 V and when the control starts, it gets pulled to 50 V. A high current peak is observed in the transient, which is due to the in-rush current from the grid to the capacitor. But it is well within the limit as shown in Fig. 5.3.

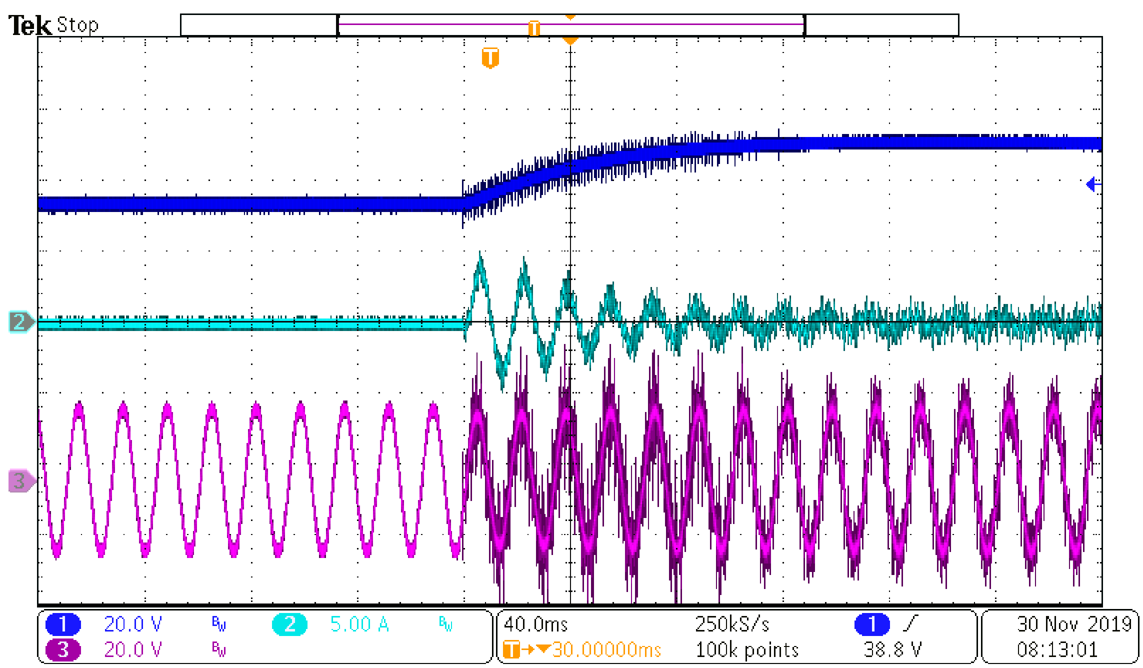


Fig. 5.3: DC voltage build-up, CH1: DC bus Voltage of STATCOM, CH2: Current waveform, CH3: Voltage injected to the grid

B. STATCOM Startup (Injecting Reactive Power i_q = 4 A)

As mentioned earlier, by varying i_q current, the reactive power can be injected or absorbed from the grid. As shown in Fig. 5.4 during startup, the phase current is at a very small value but reaches the rated current of around 4 A peak after 2 seconds. It should be noted here that during the entire simulation, the DC link voltage of the capacitor of the STATCOM is maintained at 50 V.

The operation of STATCOM starts by injecting i_q = 4 A peak. Considering the phase voltage of AC supply from the autotransformer as 20 V and i_q taken as 4 A, the reactive power injected for a 3-phase system can be calculated as:

$$Q\ in\ Var\ = 3 * Phase\ voltage\ of\ grid\ (auto\ transformer) * \frac{i_q\ (peak\ value)}{\sqrt{2}}$$

$$Q = 3 * 20 * \frac{4}{\sqrt{2}}$$

$$Q = 169.73\ Var$$

As shown in Fig. 5.4 the DC bus is stable when the current i_q = 4 A is injected in to the grid. This validates the proper functioning of current control.

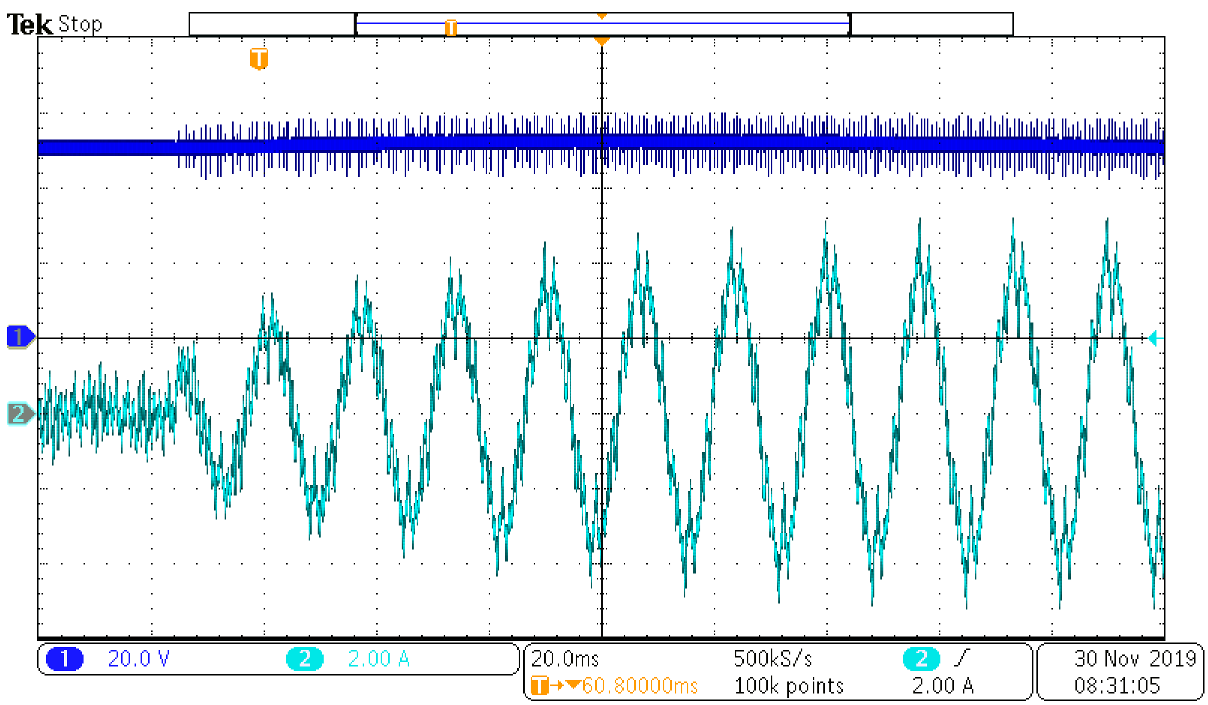


Fig. 5.4: STATCOM startup (Injecting Reactive Power i_q = 4 A peak) CH1: DC bus of STATCOM, CH2: phase current

Fig. 5.5 presents the harmonic spectrum of the phase current of STATCOM while feeding reactive power in to the grid. The i_q value chosen is 4 A; therefore, the line current of 4 A peak is injected into the gird. From the harmonic spectrum, it can be seen that 7^{th}, 11^{th}, 17^{th} and 19^{th} are the dominant harmonics that have significant value. However, there are certain lower order harmonics like 5th etc., which are due to the dead time of the main inverter.

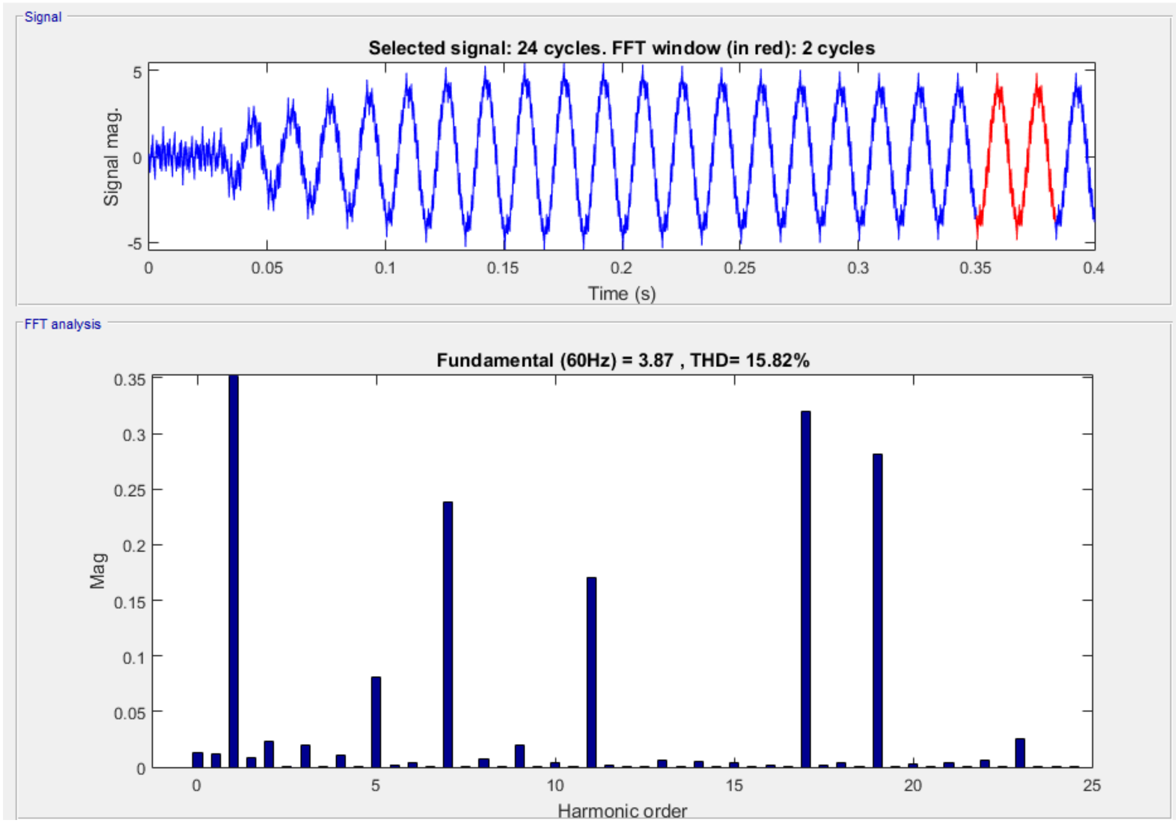


Fig. 5.5: Harmonics analysis of the line current waveform (when $i_q = 4$ A)

C. Control Testing by i_q Reversal

The control performance of the STATCOM is also checked by reversing the direction of the current i_q from + 4 to – 4 and vice versa as depicted in Fig. 5.6. It is observed that in spite of changing the direction of i_q, the control of the STATCOM is stable, which validates the robustness of the designed controller and the inverter. The operation of the converter and the power supply operating together within the current limit (normal) condition is shown in Fig 5.6.

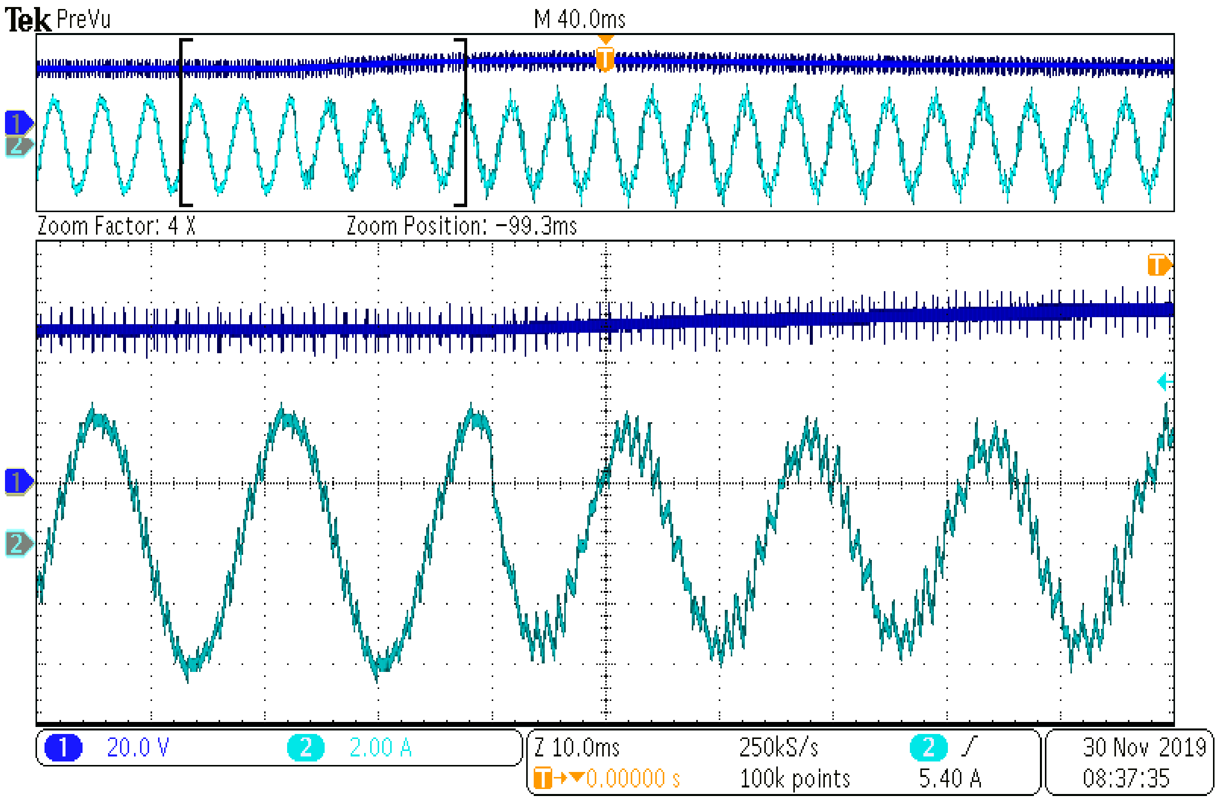


Fig. 5.6: For i_q Reversal (Reactive power flow control); mention the details of the waveforms

Hence forth, the controller response is instantaneous as the change in load current is responded by the STATCOM.

D. STATCOM Output Waveform

Fig. 5.7 and Fig. 5.8 represent the STATCOM phase current prior to the wave-shaper function and its harmonic spectrum, respectively. It should be noted from the harmonic spectrum that the presence of the 5th ,7th and 11th harmonics are the one which are closest to the fundamental, resulting in poor current waveform quality.

Fig. 5.9 and Fig. 5.10 presents the STATCOM phase-current after the wave-shaper units start functioning followed by its harmonic spectrum respectively. It should be observed from the harmonic spectrum that the 5th ,7th and 11th harmonics which are closest to the fundamental are mitigated after the wave-shaper units become functional, improving the current waveform quality.

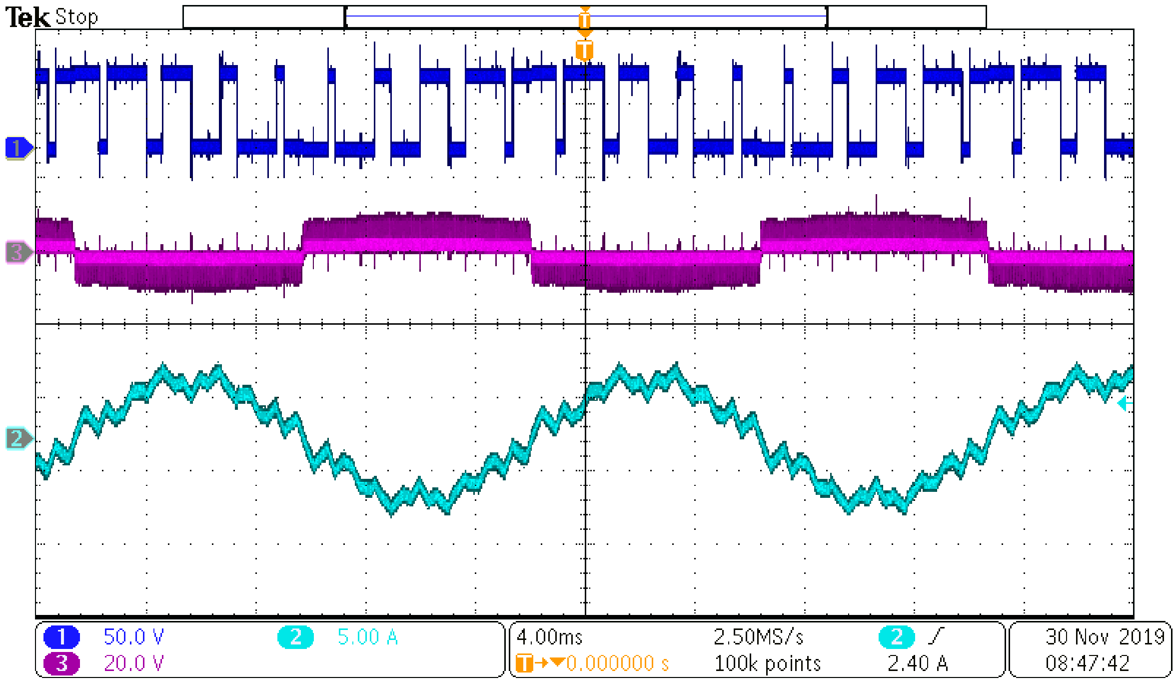


Fig. 5.7: Current wave-shape before wave-shaper starts functioning, CH1: Pole voltage wrt DC bus negative terminal, CH2: Line current, CH3: H-bridge injected voltage

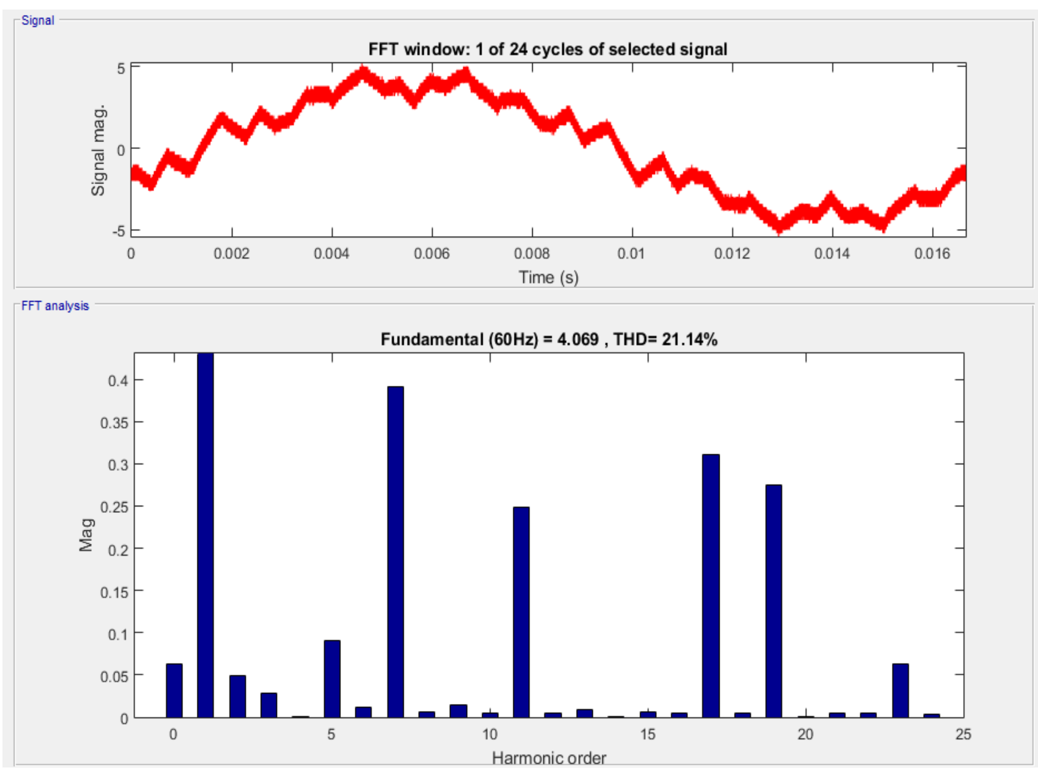


Fig. 5.8: Harmonic spectrum of the hybrid STATCOM phase current before the wave-shaper functioning

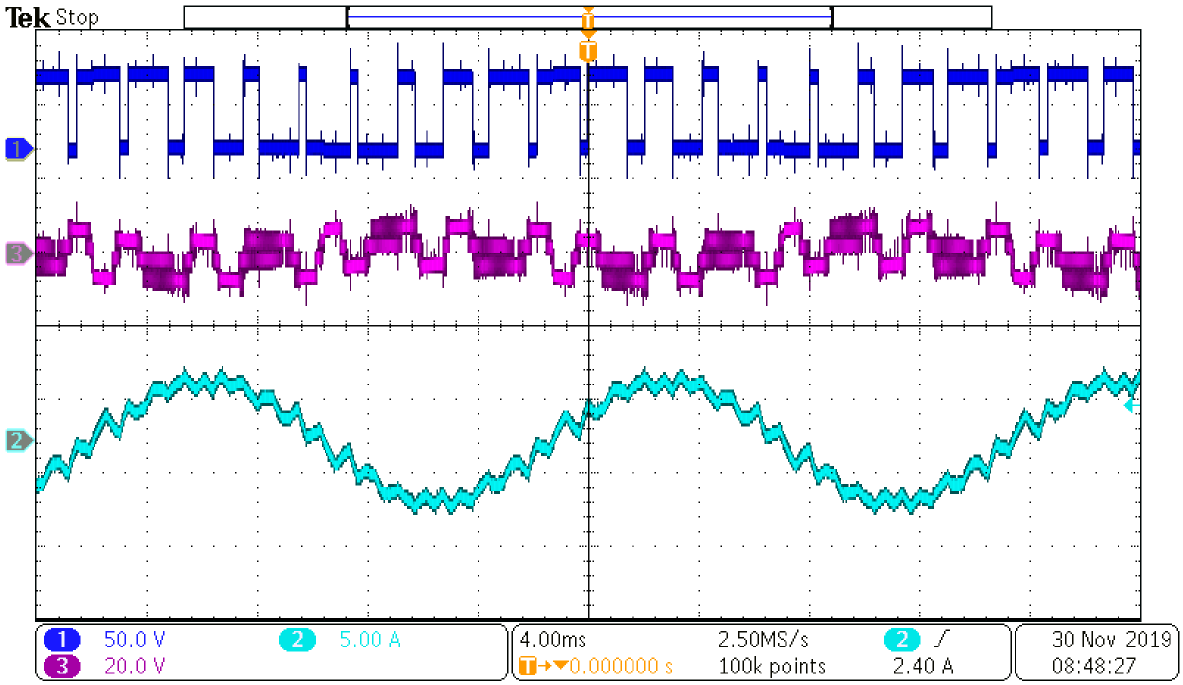


Fig. 5.9: Current wave-shape after the wave-shaper functioning, CH1: Pole voltage wrt DC bus negative terminal, CH2: Line current, CH3: H-bridge injected voltage

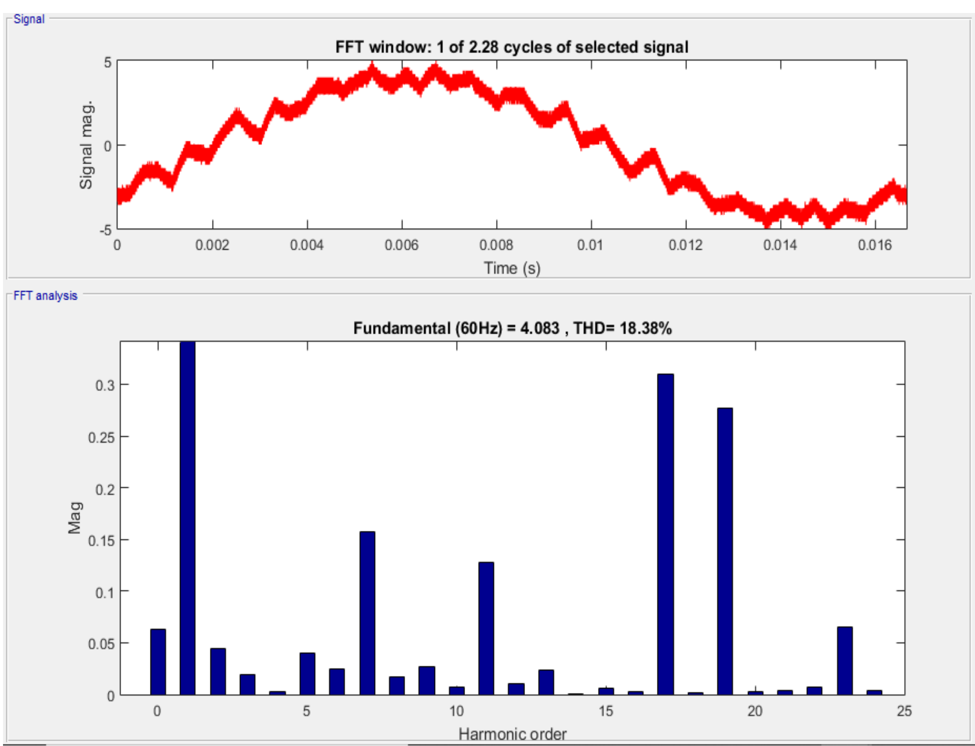
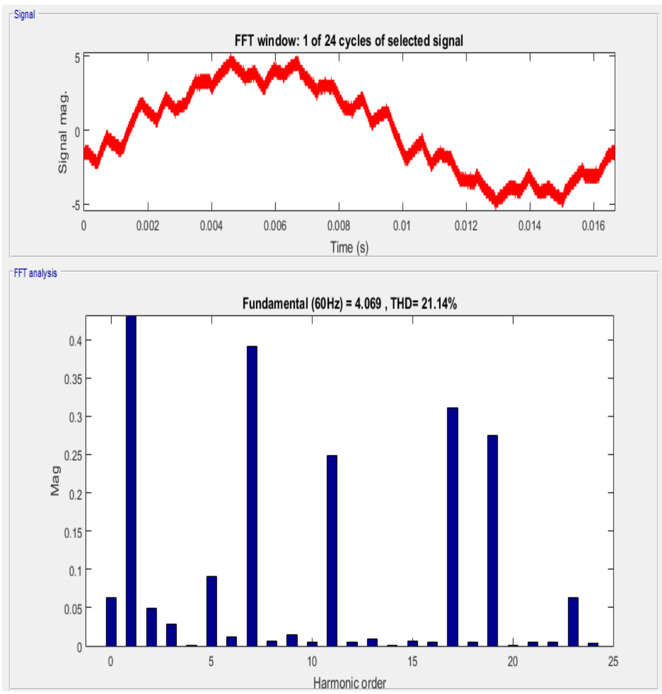
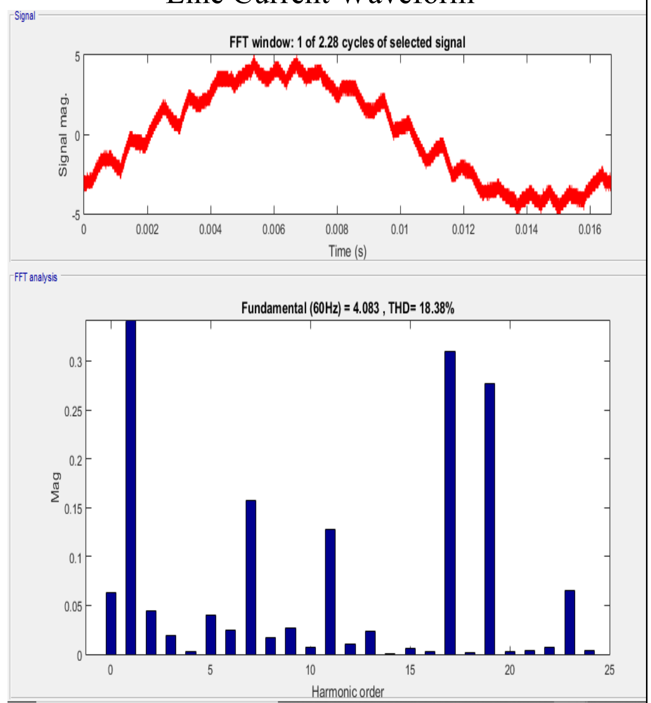


Fig. 5.10: Harmonic spectrum of the hybrid STATCOM phase current after the wave-shaper functioning

Table 5.2: Comparison of line current with and without harmonic cancellation

Without Harmonic Cancellation (Base Case)	**With Harmonic Cancellation**
Line Current Waveform  Harmonic spectrum of the hybrid STATCOM phase current before the wave-shaper functioning	Line Current Waveform  Harmonic spectrum of the hybrid STATCOM phase current after the wave-shaper functioning
Reduction in Targeted Harmonics: Harmonic components: 5th = 0.1 A (Due to dead time) 7th = 0.4 A (for m_f = 9; (m_f – 2)) 11th = 0.25 A (for m_f = 9; (m_f + 2))	Harmonic components: 5th = 0.05 A (50 % reduction) 7th = 0.16 A (60 % reduction) 11th = 0.14 A (44 % reduction)
Total Harmonic Distortion: THD = 21.14%	THD = 18.38%

The phase-current waveform has the 5th, 7th and 11th harmonic before the wave-shaper units starts functioning. Once the wave-shaper units start, it takes a few cycles for the wave-shaper units to stabilize after which these harmonics 5th, 7th and 11th are reduced, thus improving the overall current waveform quality.

It should be observed from Table 5.2 that the lower order harmonics (5th, 7th and 11th) are reduced. Also, there is a significant reduction in the targeted harmonics 5th, 7th and 11th and total harmonic distortion is improved by 13.05 % with respect to the base case. The presence of DC component in the harmonic spectrum of the both cases i.e. with or without wave-shaper unit functional should be noted. This DC component is due to error in sensors and OPAL-RT. Since, the proposed wave-shaper units can cancel out harmonics. The proof-of-concept is verified, and similarly, other harmonics can be targeted and programmed for reduction in their values or complete elimination. Furthermore, the results can be improved when testing the hybrid STATCOM at higher voltages levels.

5.2 Concluding Remarks

The proposed hybrid STATCOM for the grid connection is implemented to evaluate and demonstrate its performance on the scale-down prototype and is reported in this chapter. The pole voltage is used to extract harmonics, which is then injected by the two-level STATCOM. Based on the proposed harmonic cancellation method, the specific harmonics are extracted and only the targeted harmonics are reduced to improve the power quality for the entire system. The results can be further improved by testing at higher voltage and scale-up prototype. Therefore, the performance of the hybrid STATCOM is verified through the simulations and experimental results. The next chapter, concludes the thesis and presents the guidelines for future work.

6. Conclusions and Future Scope

6.1 Contribution and Conclusions

This thesis proposes and validates an idea of harmonic reduction in conventional STATCOM using additional wave-shaper circuits. The proposed hybrid STATCOM (Conventional STATCOM with wave-shaper units) is developed and demonstrated to have lower THD compared to the conventional STATCOM. The following are the foremost conclusions of this thesis;

- The two-level converter in the conventional STATCOM is switched at a higher frequency as compared to the Hybrid STATCOM. Further, the conventional STATCOM might require additional filters to limit the current THD within bounds.
- The Hybrid STATCOM has lower losses as compared to the conventional STATCOM. Though it has a higher number of switches, the savings in losses might offset the additional cost of the switches within a few years.
- The control for the Hybrid STATCOM was developed, which could inject the required amount of reactive power from its two-level converter and cancel the required harmonics from the wave-shaper cells.
- The Hybrid STATCOM could pose some challenges, especially since the wave-shapers are connected in series. For example, an open circuit fault of the wave-shapers can disrupt the complete reactive power flow. But this can be addressed by bypassing the faulty wave-shaper cells.

6.2 Future Scope

This thesis presented a preliminary analysis of a Hybrid STATCOM for reactive power compensation. This Hybrid STATCOM had lower THD as compared to the conventional STATCOM. More work is required in this area to strengthen the concept and is listed below;

- Currently an SPWM is used at a constant switching frequency for the two-level converter of the Hybrid STATCOM. Other PWM schemes, such as selective-harmonic-elimination, optimum PWM, etc., can be explored.

- Further, based on this, the number of wave-shapers and their switching frequencies can be optimized ensuring the lowest losses for the complete system.
- The wave-shapers can do series Var injection apart from the harmonic cancellation. This will require a system-level control and can be investigated in the future.

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