Implementation of Power Factor Controller using STATCOM

Major Project report

Submitted in Partial Fulfillment of the Requirements for the Degree of

MASTER OF TECHNOLOGY

IN

ELECTRICAL ENGINEERING

(Power Electronics, Machines and Drives)

By

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Certificate

This is to certify that the Major Project Report entitled ”Implementation of Power Factor Controller Using STATCOM”, submitted by Ms. Twinkle Solanki (12MEEP36) towards the partial fulfilment of the requirements for the award of degree in Master of Technology (Electrical Engineering) in the field of Power Electronics, Machines and Drives of Nirma University is the record of work carried out by her under our supervision and guidance. The work submitted has in our opinion reached a level required for being accepted for examination. The results embodied in this major project work to the best of our knowledge have not been submitted to any other University or Institution for award of any degree.

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Undertaking for Originality of the Work

I, Solanki Twinkle Prakash, Roll No. 12MEEP36, give undertaking that the Major Project entitled ”Implementation of Power Factor Controller Using STATCOM technique” submitted by me, towards the partial fulfilment of the requirements for the degree of Master of Technology in Power Electronics, Machines and Drives, Electrical Engineering, under Institute of Technology of Nirma University, Ahmedabad, Gujarat is the original work carried out by me and I give assurance that no attempt of plagiarism has been made. I understand that in the event of any similarity found subsequently with any published work or any dissertation work elsewhere, it will result in severe disciplinary action.

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- Twinkle Solanki

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Abstract

With the advancement of technology, the demand for electrical energy has also increased. The demand of electricity has become the parameter of development of a nation. An electrical utility company has to use its existing transmission capacity to feed it ever increasing demand for electricity, due to that the transmission lines has to be operated near its thermal stability limits. Operating the transmission lines near or above thermal stability limits makes system vulnerable to faults, moreover, it also increases the losses in the system. One way to increase the transmission capacity of the system without operating it to its thermal stability level is to provide reactive power compensation at various locations so that its power factor is maintained. Reactive power compensation improves the voltage profile of the system, increases the power transfer in the lines and reduces losses.

A Flexible AC Transmission System (FACTS)is an AC transmission system incorporating power electronic based or other static controller which provides better power flow control and enhanced dynamic stability by control of one or more ac transmission system parameters (voltage, phase angle and impedance).

STATCOM (Static compensator) can be a series, a shunt, or a combination of both devices which is generally used to solve power quality problems in distribution systems and also used in correcting power factor, maintaining constant distribution voltage and mitigating harmonics in a distribution network. However, majority applications are done with a Shunt Compensation because of the simplicity of implementation. STATCOM is mostly a Voltage Source Converter (VSC) based shunt device generally used in distribution system to improve power quality. The main advantage of STATCOM is that, it has a very sophisticated power electronics based control which can efficiently regulate the current injection into the distribution feeder or bus. The other advantages are: Canceling the effect of poor load power factor, Suppressing the effect of harmonic content in load currents, Regulate the voltage of distribution bus against sag/swell etc. compensation the reactive power requirement of the load.

Abbreviations

FACTS..Flexible AC Transmission System
STATCOM..Static Synchronous Compensator
CP..Custom Power
VSC..Voltage Source Converters
CSC..Current Source Converters
PWM...Pulse Width Modulation
C_{dc}..DC link Capacitor
IGBT...Insulated Gate Bipolar Transistors
GTO..Gate Turn-off
IGCT..Integrated Gate Commutated Thyristors
MCT..Mosfet Controlled Thyristor
VAR..Voltage Ampere Reactive
SVC..Static VAR compensator
SSSC...Static Synchronous Series Compensator
TCSC...Thyristor Controlled Series Capacitor
IPFC..Interline Power Flow Controller
UPFC..Unified Power Flow Controller
TCPST...Thyristor Controlled Phase Shifting Transformer
HVDC...High Voltage DC Transmission
PLL...Phase look loop
PD..Phase Detector
LF..Loop Filter
VCO...Voltage Control Oscillator
VCM..Voltage Control Mode
PFCM.. Power Factor Control Mode
APCM..Active Power Control Mode

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Chapter 1

Introduction

1.1 General Overview

Power Generation and Transmission is a complex process, requiring the working of many components of the power system in tandem to maximize the output. One of the main components to form a major part is the reactive power in the system. It is required to maintain the voltage to deliver the active power through the lines. Loads like motor loads and other loads require reactive power for their operation. Due to these Power Factor at Load side deteriorates. To improve the performance of ac power systems, we need to manage this reactive power in an efficient way and thus improves the Power Factor. There are two aspects to the problem of reactive power compensation:

- Load compensation and
- Voltage support.

Load compensation consists of improvement in power factor, balancing of real power drawn from the supply, better voltage regulation, etc. of large fluctuating loads.

Voltage support consists of reduction of voltage fluctuation at a given terminal of the transmission line. There are two types of compensation that can be used:

- Series compensation and
- Shunt compensation.

These modify the parameters of the system to give enhanced VAR compensation. In recent years, static VAR compensators like the STATCOM have been developed. These quite satisfactorily do the job of absorbing or generating reactive power with a faster time response and come under FACTS. This allows an increase in transfer of apparent power through a transmission line, and much better stability by the adjustment of parameters that govern the power system i.e. current, voltage, phase angle, frequency and impedance.

The development of technology and consequent up gradation of the loads of power system has brought about a paradigm change in the customer's outlook for the electrical power he is willing to receive. Adding to the problem of reactive power compensation, the proliferation of nonlinear loads is causing a higher level of harmonics in the received voltage. An alert customer now asks for a power supply that is voltage regulated, balanced, flickers free, without harmonics and without any outages. The concept of custom power was introduced by Hingorani. Similar to FACTS devices which are used to solve issues related to the transmission lines, the CP devices relates to the use of power electronic controllers to solve issues related to the distribution systems. Of the many CP devices available, STATCOM can solve most of the customer's load related power quality problems. The concept of compensation has its genesis to reactive power compensation, which initially was conceived with fixed or passive capacitors. Later, Static VAR Compensator came into use for VAR compensation and voltage regulation at the load end. These systems suffered from the following drawbacks:

- Suffered from granularity or the minimum amount of var compensation possible,
- They exhibited poor dynamic performances,

- They had to be supplemented with filters as they injected harmonics into the network,
- They failed under low voltage conditions and,
- They did not provide for load balancing and load leveling.

The answer to the above was found in the STATCOM, which was conceived from the concept of STATCOM used for transmission line compensation.

1.2 Reactive Power

Reactive power has never done any work but without reactive power very little work will be done. Attempts to describe what reactive power is can make the reader more confused than enlightened. This is not because Reactive Power is a badly defined quantity; it is rather because it is a quantity that does not exist in our real world.

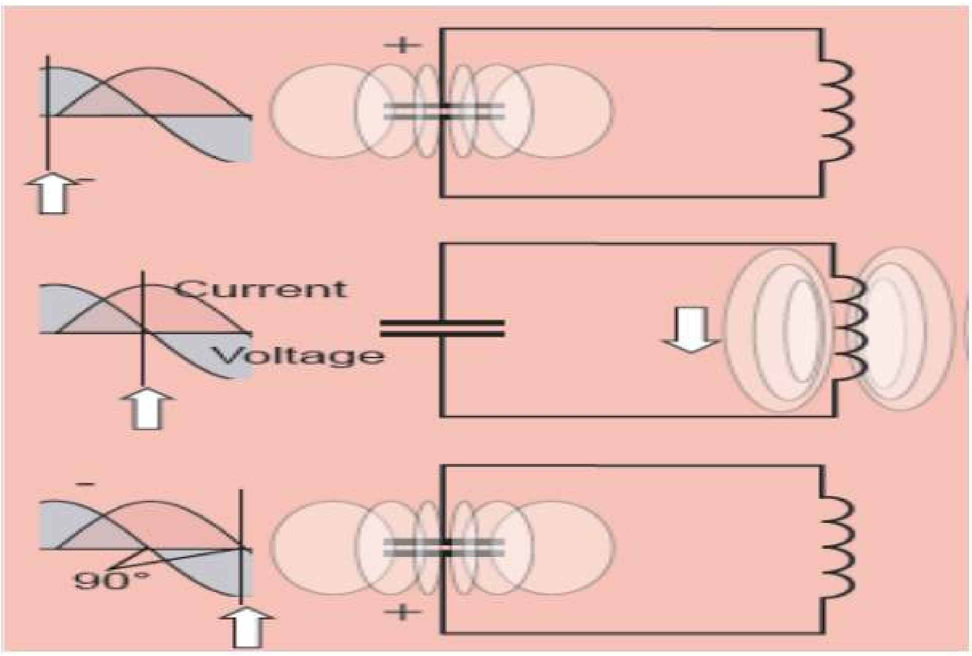


Figure 1.1: LC Circuit

An electrical system with a capacitance and a reactance can be brought into oscillation. The system alternates between Energy stored as an electrical field in the capacitor and a magnetic field in the reactor.

The electric field is built up by a voltage over the capacitor. This voltage will drive a current through the reactor. When the electric field over the capacitor is neutralized all the energy is converted to a magnetic field in the reactor.

The current is maintained by this magnetic field until all the energy has been transferred to the capacitor as an electric field, but now with reversed polarity.

The system does not do any work; it just oscillates and will continue doing so infinitely if there is no resistance in the system. This is pure reactive power. A very intuitive reflection on the above is that a capacitor can build-up a field supported voltage and an inductor can drain this voltage in order to build up a magnetic field.

In the LC-circuit above, the alternating between electric and magnetic energy makes the angler shift between voltage and current 90°.

$$ActivePower : V \times I \times \cos 90^\circ = 0 \tag{1.1}$$

$$ReactivePower : V \times I \times \sin 90^\circ = V \times I \tag{1.2}$$

1.3 Scope of the Work

The main aim of this project work is of developing a hardware model of Power Factor Controller Using STATCOM technique which can improve power factor at load side, maintaining constant distribution voltage, compensation the reactive power requirement of the load and mitigating harmonics in a distribution network.

Various literatures are available and various techniques has to be studied for Power factor improvement.

1.4 Objective of the Project

To design and implement a Power Factor Controller Using STATCOM technique. Main objectives are to design a controller with the following requirements:

- 3MVAR STATCOM bridge (3-ph IGBT bridge)
- LC damped filters connected at the inverter output where, L = 800μH and C = 100μF.
- C_{dc} = 10000μF capacitor acting as a DC voltage source for the inverter.
- DC link of V_{dc} = 2.4kV
- A PWM pulse generator using a modulation frequency of 1.68 kHz

1.5 Literature Survey

Literature survey plays a very important role in project. Literature survey consists of power topology, control schemes and related papers that includes mathematical modeling, simulation and experimental results. Some important information related to power factor improvement, PWM technique, control schemes are obtain. Papers are taken from IEEE conference proceedings, journal proceedings, and other standard publications.

1.5.1 Referred Books

- Ned Mohan, Tore M. Undeland, William P. Robbins In this book, "Power Electronics, Converters, Applications and Design" describes a basic inverter scheme is given. Also different semiconductor switches with its gate and base drive circuits.
- Dr. Xiao-Ping Zhang, Dr. Christian Rehtanz, Bikash Pal In this book, "Flexible AC Transmission Systems: Modeling and Control" describes a FACTS family

is emphasize and its advanced modeling, analysis and control techniques of FACTS is elaborated, power calculations of STATCOM and its modeling is also describe.

- R. Mohan Mathur, Rajiv K. Varma In this book, "Thyristor-based Facts Controllers for Electrical Transmission System", he explains the principle of operation of STATCOM, its characteristics and steady state model.

- Hirofumi Akagi, Edson Hirokazu Watanabe and Mauricio Aredes In this book, "Instantaneous Power Theory and Applications to Power Conditioning" describes a instantaneous power theory which converts three phase system to two phase system (pq(clarke's) transformation).

1.5.2 Referred Papers

- Ravilla Madhusudan and G. Ramamohan Rao In this paper titled "Modeling and Simulation of a Distribution STATCOM (D-STATCOM) for Power Quality Problems Voltage Sag and Swell Based on Sinusoidal Pulse Width Modulation (SPWM)", describes a power quality is an occurrence manifested as a nonstandard voltage, current or frequency that results in a failure of end use equipments. The major problems dealt here is the voltage sag and swell. To solve this problem, the device D-STATCOM, which is the most efficient and effective modern custom power device is used in power distribution networks. D-STATCOM injects a current in to the system to correct the voltage sag and swell. The control of the Voltage Source Converter (VSC) is done with the help of SPWM.

- Mitsubishi Electric Power Products, USA and Electric Corporation, Japan and Vermont Electric Power Co., Inc., USA In this paper titled "The VELCO STATCOM-Based Transmission System Project", describes a STATCOM system installed at the Vermont Electric Power Company's Essex 115 kV substation has an effective rated capacity of +133/-41 MVA. It rapidly responds to system disturbances, provides smooth voltage control over a wide range of operating conditions, for reactive power compensation and improves power factor.

- Hendri Masdi, Norman Mariun, S.M.Bashi A. Mohamed, Sallehhudin Yusuf In this paper titled "Design of a Prototype D-Statcom using DSP Controller for Voltage Sag Mitigation", describes a simulation model of the 12-pulse D-STATCOM has been designed. The control strategy for the D-STATCOM was the AC side voltage or reactive power control. PI controller is used to control the flow of reactive power to and from the DC capacitor. Phase Lock Loop components were used in the control to generate the switching signal, i.e. triangular waves, and reference signals, i.e. sinusoidal wave. PWM switching control was used to switch on and off the IGBTs. In the traditional power transmission system, controllable devices are restricted to the slow mechanisms such as transformer tap changer and switched capacitor. Due to developments in the semiconductor technology this restrictions are removed.

- Jianye Chen, Shan Song, Zanji Wang In this paper titled "Analysis and Implement of Thyristor-based STATCOM", describes that a conventional STATCOM is based on self-commutated devices. Based on its detailed analysis of commuting process, the authors find that as STATCOM operated in the state of absorb reactive power, only turn-on signals is available, and turn-off signals have no effects. And when STATCOM generates reactive power, only turn-off signals are available. Hence, this paper proposed a new kind of STATCOM, where thyristors-based VSC (Voltage source converter) instead of self-commutated devices are used as switching devices. By its results, it shows that STATCOM can absorb inductive reactive power by adjusting its fire angle and has the same characteristics as ordinary STATCOM within its inductive operating range.

- Mehrdad Ahmadi Kamarposhti and Mostafa Alinezhad In this paper titled "Comparison of SVC and STATCOM in Static Voltage Stability Margin Enhancement", he explains that one of the major causes of voltage instability is the reactive power limit of the system. Improving the system's reactive power handling capacity via Flexible AC transmission System (FACTS) devices is a remedy for prevention of voltage instability and hence voltage collapse. SVC and STATCOM increase static voltage stability margin and power transfer capability and which one is more efficient.

- Anil Antony P, R. Punitharaji In this paper titled "Transient Stability Enhancement of Grid by Using Fuzzy Logic Based STATCOM", describes that it regulates the voltage at the point of common coupling (PCC) by injecting reactive power. This also plays a vital role in enhancing stability for small and large transient disturbances in power system. Fuzzy logic controller forces the system to return back the steady state value faster than the PI controller. The fuzzy logic controller is robust and has a fast response during disturbance and parameters variation.

- P. S. Sensarma, K. R. Padiyar and V. Ramanarayanan In this paper titled "Analysis and Performance Evaluation of a Distribution STATCOM for Compensating Voltage Fluctuations", describes that a small-signal model of the system, with a distribution line, is derived. Predictions based on frequency-domain analysis are made. This model can be used for controller design where sub-cycle voltage transients are to be compensated. It is shown that the voltage controller, so designed, can accomplish voltage sag mitigation.

Chapter 2

Flexible AC Transmission System (FACTS) Family

2.1 Introduction to FACTS Family

The large interconnected transmission networks (made up of predominantly overhead transmission lines) are susceptible to faults caused by lightning discharges and decrease in insulation clearances by undergrowth. The power flow in a transmission line is determined by Kirchhoff's laws for a specified power injections (both active and reactive) at various nodes. While the loads in a power system vary by the time of the day in general, they are also subject to variations caused by the weather (ambient temperature) and other unpredictable factors. The generation pattern in a deregulated environment also tends to be variable (and hence less predictable). Thus, the power flow in a transmission line can vary even under normal, steady state conditions.

The occurrence of a contingency (due to the tripping of a line, generator) can result in a sudden increase/decrease in the power flow. This can result in overloading of some lines and consequent threat to system security.

A major disturbance can also result in the swinging of generator rotors which contribute to power swings in transmission lines. It is possible that the system is subjected to transient instability and cascading outages as individual components (lines and generators) trip due to the action of protective relays. If the system is operating close to the boundary of the small signal stability region, even a small disturbance can lead to large power swings and blackouts.

The increase in the loading of the transmission lines sometimes can lead to voltage collapse due to the shortage of reactive power delivered at the load centers. This is due to the increased consumption of the reactive power in the transmission network and the characteristics of the load (such as induction motors supplying constant torque).

The factors mentioned above leads to the problems faced in maintaining economic and secure operation of large interconnected systems. The problems are eased if sufficient margins (in power transfer) can be maintained. This is not feasible due to the difficulties in the expansion of the transmission network caused by economic and environmental reasons. The required safe operating margin can be substantially reduced by the introduction of fast dynamic control over reactive and active power by high power electronic controllers. This can make the AC transmission network 'flexible' to adapt to the changing conditions caused by contingencies and load variations. FACTS is defined as 'Alternating current transmission systems incorporating power electronic-based and other static controllers to enhance controllability and increase power transfer capability'. The FACTS controller is defined as 'a power electronic based system and other static equipment that provide control of one or more AC transmission system parameters'.

As these controllers operate very fast, they enlarge the safe operating limits of a transmission system without risking stability. Needless to say, the era of the FACTS was triggered by the development of new solid-state electrical switching devices. Gradually, the use of the FACTS has given rise to new controllable systems.

Today, it is expected that within the operating constraints of the current-carrying thermal limits of conductors, the voltage limits of electrical insulating devices, and the structural limits of the supporting infrastructure, an operator should be able to control power flows on lines to secure the highest safety margin as well as transmit electrical power at a minimum of operating cost. Doing so constitutes the increased value of transmission assets.

The study of shunt connected FACTS devices is a connected field with the problem of reactive power compensation, power factor control and better mitigation of transmission related problems in today's world.

SVC and TCSC are some of the commonly used FACTS controllers, The developments in the field of power electronics, particularly GTO based devices, have introduced a new family of versatile FACTS controllers, namely Static Synchronous Compensator (STATCOM), the STATCOM is one of the custom power devices that received much attention for improving system stability, with the development of power electronics technology, custom power devices play important role in bringing unprecedented efficiency improvement and cost effectiveness in modern electrical power system. The custom power is relatively new concept aimed at achieving high power quality, operational flexibility and controllability of electrical power systems. The possibility of generating or absorbing controllable reactive power with various power electronic switching converters has long been recognized.

In general, FACTS controllers can be classified into two different generations:

- The first generation is based on the line-commutated thyristor devices with only gate turn-on but no gate turn-off capability. These are SVC and TCSC.
- The second generation of FACTS controllers is based on self-commutated VSC, which utilize thyristors/transistors with gate turn-off capability.

FACTS controllers can be realized by either a VSC or a CSC, however, most of the papers published worked on STATCOM has been on using VSC topology. The reasons behind the choice of VSC over CSC are as follows:

- A CSC is more complex than a VSC in both power and control circuits. Filter capacitors are used at the ac terminals of a CSC to improve the quality of the output ac current waveforms. This adds to the overall cost of the converter.

Furthermore, filter capacitors resonate with the ac-side inductances. As a result, some of the harmonic components present in the output current might be amplified, causing high harmonic distortion in the ac-side current. Besides, conventional bi-level switching scheme cannot be used in CSC.

- Unless a switch of sufficient reverse voltage withstanding capability such as Gate-Turn-Off Thyristor used, a diode has to be placed in series with each of the switches in CSC. This almost doubles the conduction losses compared with the case of VSC.
- The dc-side energy-storage element in CSC topology is an inductor, whereas that in VSC topology is a capacitor. The power loss of an inductor is expected to be larger than that of a capacitor. Thus, the efficiency of a CSC is expected to be lower than that of a VSC.

As a result of the recent developments in the control of CSC and the technology of semiconductor switches, the above situation is likely to change for the following reasons:

- Due to the presence of the ac-side capacitors, both voltage and current waveforms at the output terminals of a CSC are good sinusoids. The capacitors are the inherent filter for the CSC. Although a 48-pulse VSC STATCOM does not require a filter, the cost of the filter is transferred to the cost of multi-converters and multi-winding transformer. Additional filter has to be used in a VSC STATCOM if operating at a lower frequency. It is possible to operate a CSC STATCOM under 900 Hz of switching frequency with a single converter. This reduces the filtering requirements compared with the case of a VSC. The problem of the resonance between the capacitances and inductances on the ac-side can be overcome by careful design of the filter capacitors and introduction of sufficient damping using proper control methods. Furthermore, all the switching problems faced in the early stages of CSC development can be overcome by employing tri-level switching scheme, which has become a standard technique in the control of CSC.

- Featuring high ratings, high reverse voltage blocking capability, low snubber requirements, lower gate-drive power requirements than GTO, and higher switching speed than GTO, IGCT is the optimum combination of the characteristics demanded in high-power applications. Using the state-of the- art technology of the semiconductor switches, there will be no need for the series diode in the CSC topology anymore.

- The dc-side losses are expected to be minimized using superconductive materials in the construction of the dc side reactor. The research on the CSC topology and its applications in power systems has been an on-going process. When applied to STATCOM, CSC topology offers a distinct advantage over VSC topology. The direct output of a CSC is a controllable ac current, whereas that of a VSC is a controllable ac voltage.

VSC based STATCOM is used for voltage regulation in transmission and distribution systems. Over-currents and trips of the STATCOM during and after system faults or bus voltage harmonic distortions may occur in STATCOM without PWM control. Selecting proper C_{dc} may keep negative sequence and harmonic currents low, and as a result, prevent over-currents within the STATCOM. However, the capacitor value depends on the type of voltage distortion.

2.2 Classification of FACTS Controllers

The FACTS controllers can be classified as:

- Shunt connected controllers
- Series connected controllers
- Combined series-series controllers

- Combined shunt-series controllers

2.2.1 Shunt Controllers

As in the case of series controllers, the shunt controllers may be variable impedance, variable source, or a combination of these. In principle, all shunt controllers inject current into the system at the point of connection. Even a variable shunt impedance connected to the line voltage causes a variable current flow and hence represents injection of current into the line.

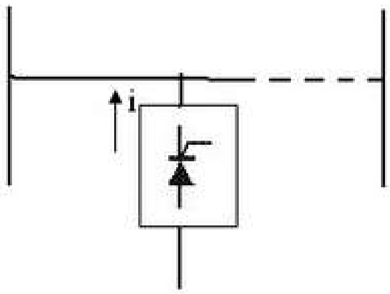


Figure 2.1: Shunt controller

As long as the injected current is in phase quadrature with the line voltage, the shunt controller only supplies or consumes variable reactive power. Any other phase relationship will involve handling of real power as well.

2.2.2 Series Controllers

The Series Controller could be variable impedance, such as capacitor, reactor, etc., or power electronics based variable source of main frequency, sub synchronous and harmonic frequencies (or a combination) to series the desired need. In principal, all series Controllers inject voltage in series with the line.

Even variable impedance multiplied by the current flow through it, represent an injected series voltage in the line. As long as the voltage is in phase quadrature

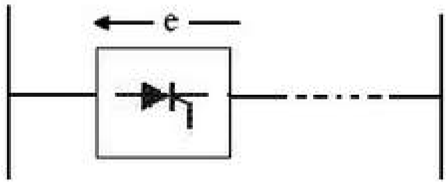


Figure 2.2: Series controller

with the line current, the series controller only supplies or consumes variable reactive power. Another phases will also handle both active or reactive power.

2.2.3 Combined Series-Series Controller

This could be a combination of separate series controllers, which are controlled in a coordinated manner, in a multiline transmission system. Or it could be a unified Controller, Figure 2.2, in which series controllers provide independent series reactive compensation for each line but also transfer real power among the lines via the power link.

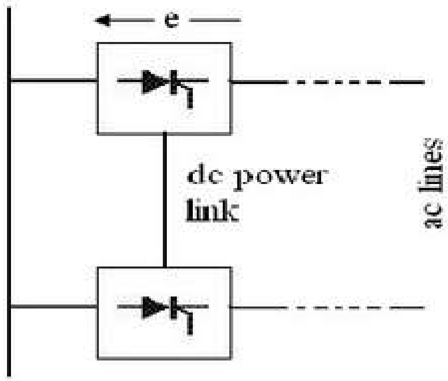


Figure 2.3: Combined series-series controller

The real power transfer capability of the unified series-series controller, referred to a Interline Power Flow controller, makes it possible to balance both the real and relative power flow in the lines and thereby maximize the utilization of the transmission system. Note that the term "unified" here means that the dc terminals of all the controller converters are all connected together for real power transfer.

2.2.4 Combined Series-Shunt Controller

[Figure 2.1 and figure 2.2]. This could be a combination of separate shunt and series controllers, which are controlled in a coordinated manner [figure 2.4].

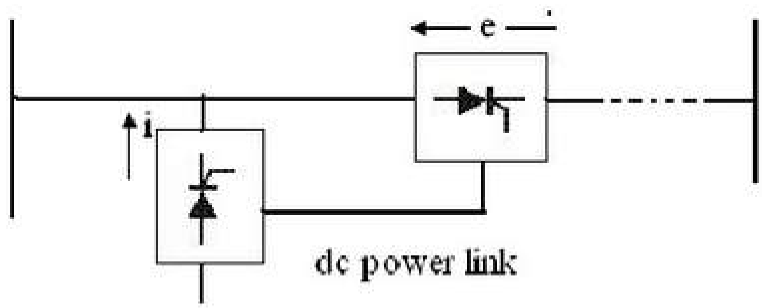


Figure 2.4: Combined series-shunt controller

In principle, combined shunt and series controllers inject current into the system with the shunt part of the controller and voltage in series in the line with the series part of the Controller. However, when the shunt and series controllers are unified, there can be a real power exchange between the series and shunt Controllers via the power link.

Depending on the power electronic devices used in the control, the FACTS controllers can further be classified as:

- Variable impedance type
- VSC based.

a. The variable impedance type based FACTS controllers include

  - SVC, (shunt connected)

- TCSC, (series connected)
- TCPST of Static PST, (combined shunt and series)

b. The VSC based FACTS controllers include

- STATCOM, (shunt connected)
- SSSC, (series connected)
- IPFC, (combined series-series)
- UPFC, (combined shunt-series)

Some of the special purpose FACTS controllers are

- Thyristor Controller Braking Resistor (TCBR)
- Thyristor Controlled Voltage Limiter (TCVL)
- Thyristor Controlled Voltage Regulator (TCVR)
- Inter-phase Power Controller (IPC)

The FACTS controllers based on VSC have several advantages over the variable impedance type. For example,

- STATCOM is much more compact than a SVC for similar rating and is technically superior.
- It can supply required reactive current even at low values of the bus voltage and can be designed to have in built short term overload capability.
- Also, a STATCOM can supply active power if it has an energy source or large energy storage at its DC terminals.

The only drawback with VSC based controllers is the requirement of using self commutating power semiconductor devices such as GTO, IGBT, IGCT. Thyristors do not have this capability and cannot be used although they are available in higher voltage ratings and tend to be cheaper with reduced losses.

However, the technical advantages with VSC based controllers coupled will emerging power semiconductor devices using silicon carbide technology are expected to lead to the wide spread use of VSC based controllers in future. It is interesting to note that while SVC was the first FACTS controllers (which utilized the thyristor valves developed in connection with HVDC line commutated convertors) several new FACTS controller based on VSC have been developed. This has led to the introduction of VSC in HVDC transmission for ratings up to 300MW.

2.3 Benefits with the Application of FACTS Controllers

Primarily, the FACTS controllers provide voltage support at critical buses in the system (with shunt connected controllers) and regulate power flow in critical lines (with series connected controllers). Both voltage and power flow are controlled by the combined series and shunt controller (UPFC). The power electronic control is quite fast and this enables regulation both under steady state and dynamic conditions (when the system is subjected to disturbances).

The benefits due to FACTS controllers are listed below.

- They contribute to optimal system operation by reducing power losses and improving voltage profile.
- The power flow in critical lines can be enhanced as the operating margins can be reduced due to fast controllability. In general, the power carrying capacity of lines can be increased to values up to the thermal limits (imposed by current carrying capacity of the conductors).
- The transient stability limit is increased thereby improving dynamic security of

the system and reducing the incidence of blackouts caused by cascading outages.

- The steady state or small signal stability region can be increased by providing auxiliary stabilizing controllers to damp low frequency oscillations.
- FACTS controllers such as TCSC can counter the problem of Sub-synchronous Resonance (SSR) experienced with fixed series capacitors connected in lines evacuating power from thermal power stations (with turbo generators).
- The problem of voltage fluctuations and in particular, dynamic over-voltages can be overcome by FACTS controllers.

The capital investment and the operating costs (essentially the cost of power losses and maintenance) are offset against the benefits provided by the FACTS controllers and the 'payback period' is generally used as an index in the planning.

The major issues in the deployment of FACTS controllers are:

- the location
- ratings (continuous and short term) and
- control strategies required for the optimal utilization.

Here, both steady-state and dynamic operating conditions have to be considered. Several systems studies involving power flow, stability, short circuit analysis are required to prepare the specifications. The design and testing of the control and protection equipment is based on Real Time Digital Simulator (RTDS) or physical simulators. It is to be noted that a series connected FACTS controller (such as TCSC) can control power flow not only in the line in which it is connected, but also in the parallel paths (depending on the control strategies).

Chapter 3

STATCOM

3.1 Introduction to STATCOM

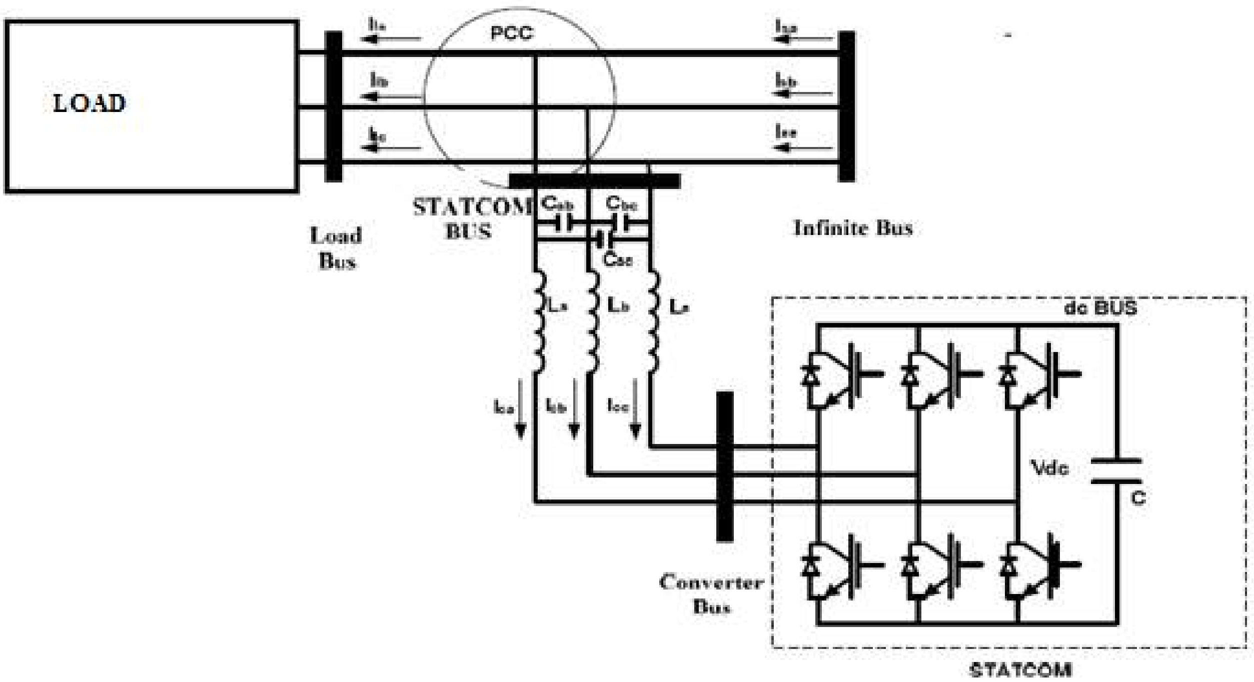


Figure 3.1: STATCOM compensation

A STATCOM is basically a VSC shunt connected bidirectional converter based device which can act as generalized impedance converter to realize either inductive or capacitive reactance by changing its output voltage levels. By proper tracking of the load current the converter can generate such voltages and currents so that the harmonics and oscillations generated by the load current do not get transmitted to the supply side.

A state of art DSTATCOM is capable of canceling or suppressing; the effect of poor load power factor, the effect of poor voltage regulation, the harmonics introduced by the load, the dc offset in loads such that the current drawn from the source has no offset, the effect of unbalanced loads such that the current drawn from the source is balanced, and if provided with an energy storage system, it can perform load leveling when the source fails.

A general schematic of the system with STATCOM compensation is shown in figure 3.1.

A STATCOM is connected in shunt with the ac system as shown above which provides a multifunctional topology which can be used for up to three quite distinct purposes:

- Voltage regulation and compensation of reactive power,
- Correction of power factor and
- Elimination of current harmonics.

The concept that an inverter can be used as a generalized impedance converter to realize either inductive or capacitive reactance has been widely used to mitigate power quality issues of distribution networks. One such device is the STATCOM which is connected in shunt at the load end. The heart of the STATCOM is a converter.

3.2 Comparison of SVC and STATCOM

This shunt connected static compensator was developed as an advanced static VAR compensator where a VSC is used instead of the controllable reactors and switched capacitors. Although VSCs require self-commutated power semiconductor devices such as GTO, IGBT, IGCT, MCT, etc (with higher costs and losses) unlike in the case of variable impedance type SVC which use thyristor devices, there are many technical advantages of a STATCOM over a SVC. These are primarily:

- Faster response,
- Requires less space as bulky passive components (such as reactors) are eliminated,
- Inherently modular and re-locatable,
- It can be interfaced with real power sources such as battery, fuel cell or SMES (superconducting magnetic energy storage) and
- A STATCOM has superior performance during low voltage condition as the reactive current can be maintained constant (In a SVC, the capacitive reactive current drops linearly with the voltage at the limit (of capacitive susceptance). It is even possible to increase the reactive current in a STATCOM under transient conditions if the devices are rated for the transient overload. In a SVC, the maximum reactive current is determined by the rating of the passive components- reactors and capacitors.

3.3 Applications of STATCOM

The primary objective of applying a STATCOM in transmission networks is the fast regulation of voltage at a load or an intermediate bus. This will also increase the power transfer capacity of the network and thus enhance ATC (Available Transfer Capacity).

The use of multi-pulse and/or multilevel converters eliminates the need for harmonic filters in the case of a STATCOM. However, the costs increase not only due to the increased costs of magnetics and self-commutated devices (such as GTO, thyristors, IGBTs), but also resulting from increased losses. (The total losses can vary from 0.5 to 1.0 %). The new developments in power semiconductor technology are expected to bring down the costs and losses. The voltage and power ratings are expected to increase. At present, the use of STATCOM in distribution systems has become attractive, not only for voltage regulation, but also for eliminating harmonics and improving power quality. Utilizing an auxiliary controller with Thevenin voltage signal as input, it is possible to damp both low frequency oscillations and sub-synchronous oscillations.

A STATCOM is a shunt-connected reactive-power compensation device that is capable of generating and/ or absorbing reactive power and in which the output can be varied to control the specific parameters of an electric power system. It is in general a solid-state switching converter capable of generating or absorbing independently controllable real and reactive power at its output terminals when it is fed from an energy source or energy-storage device at its input terminals. A STATCOM can improve power-system performance in such areas as the following:

- The dynamic voltage control in transmission and distribution systems;
- The power-oscillation damping in power-transmission systems;
- The transient stability;
- The voltage flicker control;
- The control of not only reactive power but also (if needed) active power in the connected line, requiring a dc energy source.

Furthermore, a STATCOM does the following:

- It occupies a small footprint, for it replaces passive banks of circuit elements by compact electronic converters;
- It offers modular, factory-built equipment, thereby reducing site work and commissioning time;
- It uses encapsulated electronic converters, thereby minimizing its environmental impact.

A STATCOM is analogous to an ideal synchronous machine, which generates a balanced set of three sinusoidal voltages, at the fundamental frequency, with controllable amplitude and phase angle. This ideal machine has no inertia, is practically instantaneous, does not significantly alter the existing system impedance, and can internally generate reactive (both capacitive and inductive) power.

A STATCOM controller provides voltage support by generating or absorbing reactive power at the point of common coupling without the need of large external reactors or capacitor banks.

3.4 Principle of Operation

A STATCOM is comparable to a Synchronous Condenser (or Compensator) which can supply variable reactive power and regulate the voltage of the bus where it is connected. It provides the desired reactive-power generation and absorption entirely by means of electronic processing of the voltage and current waveforms in a voltage-source converter (VSC). A single-line STATCOM power circuit is shown in figure 3.2, where a VSC is connected to a utility bus through magnetic coupling.

In figure 3.3, a STATCOM is seen as an adjustable voltage source behind a reactance- meaning that capacitor banks and shunt reactors are not needed for reactive-power generation and absorption, thereby giving a STATCOM a compact design, or small footprint, as well as low noise and low magnetic impact.

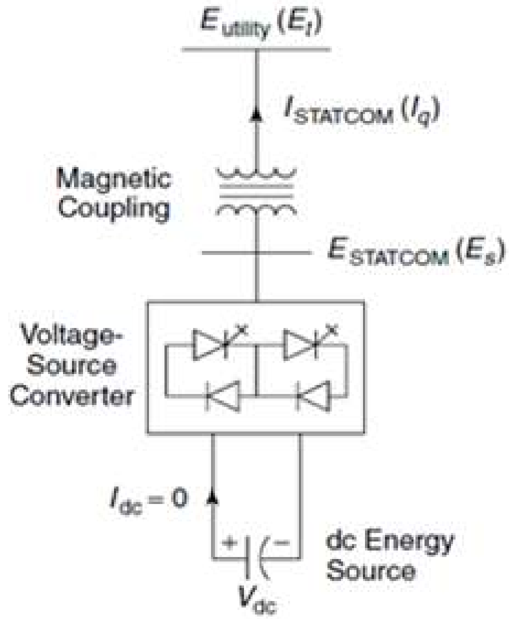


Figure 3.2: STATCOM principle - Power circuit

The exchange of reactive power between the converter and the ac system can be controlled by varying the amplitude of the 3-phase output voltage, E_s, of the converter, as illustrated in figure 3.4.

The basic principle behind the transfer of reactive power between STATCOM and grid can be explained by following condition:

- Whenever grid voltage is equal to STATCOM voltage ($E_s = E_t$) no power flow will occur between STATCOM and grid, in these case STATCOM is said to be in floating state.

- Whenever the grid voltage is higher than STATCOM voltage ($E_s > E_t$), STATCOM absorbs reactive power from the grid. Hence reactive power is inductive in nature.

- Whenever grid voltage is less than STATCOM voltage ($E_s < E_t$), STATCOM supplies reactive power. Hence reactive power is capacitive in nature.

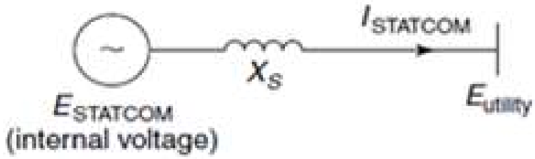


Figure 3.3: STATCOM principle - An equivalent circuit

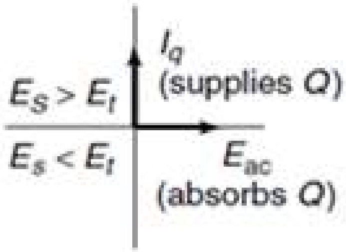


Figure 3.4: STATCOM principle - Power exchange

3.5 Power Exchange Between STATCOM and AC system

Adjusting the phase shift between the converter- output voltage and the ac system voltage can similarly control real-power exchange between the converter and the ac system. In other words, the converter can supply real power to the ac system from its dc energy storage if the converter-output voltage is made to lead the ac-system voltage. On the other hand, it can absorb real power from the ac system for the dc system if its voltage lags behind the ac-system voltage.

A STATCOM provides the desired reactive power by exchanging the instantaneous reactive power among the phases of the ac system. The mechanism by which the converter internally generates and/ or absorbs the reactive power can be understood by considering the relationship between the output and input powers of the converter.

The converter switches connect the dc-input circuit directly to the ac-output circuit. Thus the net instantaneous power at the ac output terminals must always be equal to the net instantaneous power at the dc-input terminals (neglecting losses).

Assume that the converter is operated to supply reactive-output power. In this case, the real power provided by the dc source as input to the converter must be zero. Furthermore, because the reactive power at zero frequency (dc) is by definition zero, the dc source supplies no reactive power as input to the converter and thus clearly plays no part in the generation of reactive-output power by the converter. In other words, the converter simply interconnects the three output terminals so that the reactive-output currents can flow freely among them. If the terminals of the ac system are regarded in this context, the converter establishes a circulating reactive-power exchange among the phases. However, the real power that the converter exchanges at its ac terminals with the ac system must, of course, be supplied to or absorbed from its dc terminals by C_{dc} link. Although reactive power is generated internally by the action of converter switches, a C_{dc} capacitor must still be connected across the input terminals of the converter. The primary need for the capacitor is to provide a circulating-current path as well as a voltage source. The magnitude of the capacitor is chosen so that the dc voltage across its terminals remains fairly constant to prevent it from contributing to the ripples in the dc current. The VSC-output voltage is in the form of a staircase wave into which smooth sinusoidal current from the ac system is drawn, resulting in slight fluctuations in the output power of the converter. However, to not violate the instantaneous power-equality constraint at its input and output terminals, the converter must draw a fluctuating current from its dc source. Depending on the converter configuration employed, it is possible to calculate the minimum capacitance required to meet the system requirements, such as ripple limits on the dc voltage and the rated-reactive power support needed by the ac system.

The VSC has the same rated-current capability when it operates with the capacitive- or inductive-reactive current. Therefore, a VSC having a certain MVA rating gives the STATCOM twice the dynamic range in MVAR (this also contributes to a compact design). A dc capacitor bank is used to support (stabilize) the controlled dc voltage needed for the operation of the VSC. The reactive power of a STATCOM is produced by means of power electronic equipment of the VSC type. The VSC may be a 2-level or 3-level type, depending on the required output power and voltage. A number of VSCs are combined in a multi-pulse connection to form the STATCOM. In the steady state, the VSCs operate with fundamental frequency switching to minimize converter losses. However, during transient conditions caused by line faults, a PWM mode is used to prevent the fault current from entering the VSCs. In this way, the STATCOM is able to withstand transients on the ac side without blocking.

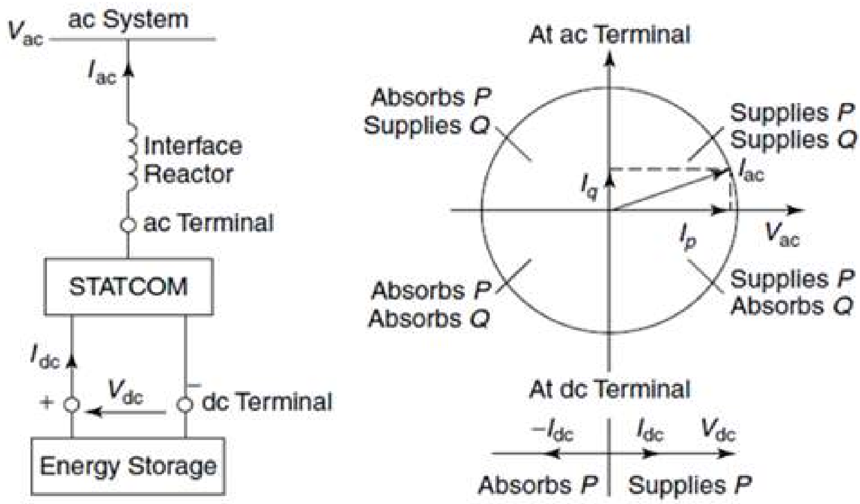


Figure 3.5: Power exchange between the STATCOM and the AC system

The reactive and real power exchange between the STATCOM and the ac system can be controlled independently of each other. Any combination of real power generation or absorption with var generation or absorption is achievable if the STATCOM is equipped with an energy-storage device of suitable capacity, as depicted in figure 3.5. With this capability, extremely effective control strategies for the modulation of reactive and real output power can be devised to improve the transient and dynamic system stability limits.

3.6 Power Flow Calculation in the STATCOM

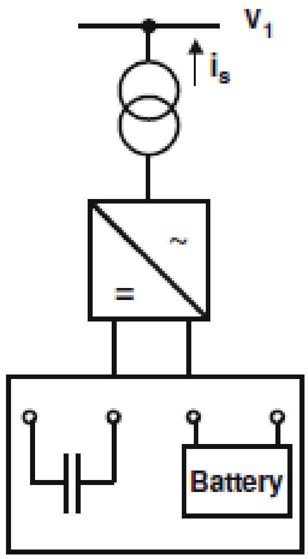


Figure 3.6: General STATCOM circuit

Figure 3.6 and figure 3.7 shows STATCOM general scheme and its equivalent circuit. In the derivation, it is assumed that (a) harmonics generated by the STATCOM are neglected; (b) the system as well as the STATCOM are three phase balanced. Then the STATCOM can be equivalently represented by a controllable fundamental frequency positive sequence voltage source V_{sh}.

According to the equivalent circuit of the STATCOM shown in figure 3.7, Suppose,

$$V_{sh} = V_{sh} \angle \Theta_{sh} \tag{3.1}$$

$$V_i = V_i \angle \Theta_i \tag{3.2}$$

then the power flow constraints of the STATCOM are

$$P_{sh} = V_i^2 g_{sh} - V_i V_{sh} [g_{sh} cos(\Theta_i - \Theta_{sh}) + b_{sh} sin(\Theta_i - \Theta_{sh})] \tag{3.3}$$

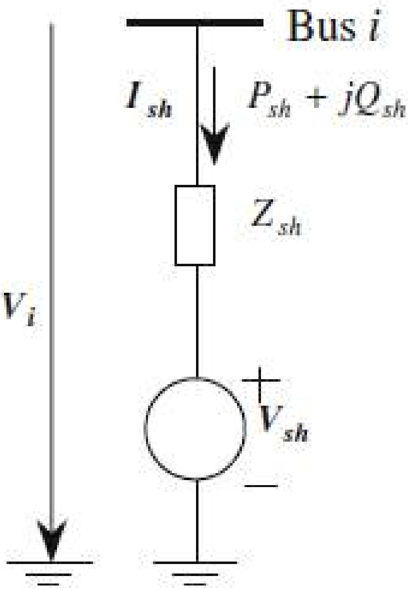


Figure 3.7: Equivalent circuit

$$Q_{sh} = -V_i^2 b_{sh} - V_i V_{sh}[g_{sh} sin(\Theta_i - \Theta_{sh}) - b_{sh} cos(\Theta_i - \Theta_{sh})] \tag{3.4}$$

where,

$$g_{sh} + jb_{sh} = 1/Z_{sh} \tag{3.5}$$

The operating constraint of the STATCOM is the active power exchange via the DC-link as described by

$$PE = Re(V_{sh} I_{sh}^*) = 0 \tag{3.6}$$

where,

$$Re(V_{sh} I_{sh}^*) = V_{sh}^2 g_{sh} - V_i V_{sh}[g_{sh} cos(\Theta_i - \Theta_{sh}) - b_{sh} sin(\Theta_i - \Theta_{sh})] \tag{3.7}$$

The reactive power generated by the STATCOM is controlled to a reactive power injection reference. Mathematically, such a control constraint is described as follows

$$Q_{sh} - Q_{sh}^{spec} = 0 \tag{3.8}$$

where Q_{sh}^{spec} is the specified reactive power injection control reference. Q_{sh} which is given by equation 3.4, is the actual reactive power generated by the STATCOM.

3.6.1 Capacitive Compensation

In this control mode, a STATCOM is used to control the magnitude of the current I_{sh} of the STATCOM to a specified current magnitude control reference. The control constraint may be represented by,

$$I_{sh} - I_{sh}^{spec} = 0 \tag{3.9}$$

However it is found that there are two solutions corresponding to this control constraint. Due to the problem incurred, the power flow solution with such a constraint may arbitrarily converge to one of the two solutions.

In order to avoid the above non-unique solution problem, an alternative formulation of the current magnitude control is introduced here. Since $I_{sh} = I_{sh}^{spec}$, if further assume I_{sh} leads V_{sh} by 90° , then

$$I_{sh} = I_{sh}^{spec} \angle(\Theta_{sh} + 90°) \tag{3.10}$$

I_{sh} can also be defined by,

$$I_{sh} = \frac{V_i - V_{sh}}{Z_{sh}} \tag{3.11}$$

then we have,

$$I_{sh}^{spec} \angle(\Theta_{sh} + 90°) = \frac{V_i - V_{sh}}{Z_{sh}} \tag{3.12}$$

Mathematically, such a control mode can be described by one of the following equations,

$$Re[I_{sh}^{spec}\angle(\Theta_{sh}+90°)] = Re[\frac{V_i - V_{sh}}{Z_{sh}}] \tag{3.13}$$

or

$$Im[I_{sh}^{spec}\angle(\Theta_{sh}+90°)] = Im[\frac{V_i - V_{sh}}{Z_{sh}}] \tag{3.14}$$

The formulation of equation 3.13 and equation 3.14 can force the power flow to converge to one of the two solutions. This control mode has a clear physical meaning. Since I_{sh} leads V_{sh} by 90°, this control mode provides capacitive reactive power compensation while keeping the current magnitude constant.

3.6.2 Inductive Compensation

In order to circumvent the same problem mentioned above, new formulation of the current control constraint needs to be introduced. In this control mode, the STATCOM is used to control the magnitude of the current I_{sh} of the STATCOM while I_{sh} lags V_{sh} by 90 degrees. Mathematically, such a control mode may be described by

$$Re[I_{sh}^{spec}\angle(\Theta_{sh}-90°)] = Re[\frac{V_i - V_{sh}}{Z_{sh}}] \tag{3.15}$$

or

$$Im[I_{sh}^{spec}\angle(\Theta_{sh}-90°)] = Im[\frac{V_i - V_{sh}}{Z_{sh}}] \tag{3.16}$$

The formulation of equation 3.15 and equation 3.16 can force the power flow to converge to the other one of the two possible solutions. This control mode also has a clear physical meaning, that is, it provides inductive reactive power compensation while keeping the current magnitude constant.

3.7 Design of DC link Capacitor

The charging of the capacitor is referred is to the reactive power in the system. The capacitor charged when the current in the system is higher than in the STATCOM and is discharged when the current is lower. For inverter the most important part is the sequences of operation of the IGBTs. The difference in current between the current before and after the fault is considered as current faults. A suitable range of DC capacitor is needed to store the energy to mitigate the voltage sag. The DC capacitor, C_{dc} is used to inject reactive power to the STATCOM when the voltage is in sag condition. In the design, the harmonic effects must be considered because the load is inductive and this may affect the value of C_{dc}. The following equation is used to calculate C_{dc},

$$\frac{1}{2}C_{DC}[V_{c_{MAX}}^2 - V_{DC}^2] = \frac{1}{2}V_{SM}.\Delta I_L.T \tag{3.17}$$

above equation is used for harmonic mitigation in single phase system but for a three phase system the equation is given by

$$C_{DC} = 3 \times \frac{V_S.\Delta I_L.T}{V_{c_{MAX}}^2 - V_{DC}^2} \tag{3.18}$$

where,

V_s = peak phase voltage of the supply

I_L = step- drop of load current

T = period of one cycle of voltage and current

$V_{c_{MAX}}$ = preset upper limit of the energy storage C(per phase)

V_{DC} = voltage across C (DC link) (per-phase).

The value of ΔI_L can be found by measuring the load current before and during the voltage sag. The value of V_{DC} is given form by,

$$V_{DC} = \frac{3\sqrt{3}.V_S.\cos\alpha}{\pi} \tag{3.19}$$

where, α = delay angle,

if $\alpha = 0$, the equation becomes

$$V_{DC} = \frac{3\sqrt{3}.V_S}{\pi} \tag{3.20}$$

The value of $V_{c_{MAX}}$ is the present upper limit of C_{dc} , and is two or three times of the V_{DC}.

3.8 Presently Installed STATCOM

3.8.1 India - Kolkata

RXPE provides Reactive Compensator solution for improving power quality, optimizing control, and saving energy in power generation, transmission and distribution. We have the largest installed base of SVC in the world, have supplied world's largest 320 MVAR STATCOM, and have a $80,000m^2$ of state of the art manufacturing and testing facilities to manufacture more than 1000 units per year.

- Input Voltage: 6 kV to 500 kV
- Power Range: 1.5 MVAR to 750 MVAR

It has been widely proved that STATCOM can greatly improve the transmission and distribution performance of electric system. STATCOM's can be installed at various locations along the network to achieve the effect of stabilizing voltage, reducing transmission loss, improving transmission capability, increasing transient stabilization limit and damping small inference, strengthening voltage control and attenuating power oscillation.

Figure 3.8: STATCOM at India - Kolkata

3.8.2 China

Jul. 31, 2013 By Hong Rao and Shukai Xu, Electric Power Research Institute of China Southern Power. The Chuxiong UNHDC converter station is part of the China Southern Power Grid that supplies power to the Pearl River Delta region.

The largest and most important power centre in terms of total energy consumption supplied by China Southern Power Grid is the Pearl River Delta region. The economics and industry in this region, still developing at an increasing rate, play an important role in China. The four main large cities in this region are Guangzhou, Shenzhen, Dongguan and Foshan, and the demand in each city exceeds 10,000 MW.

For the Pearl River Delta region, China Southern Power Grid (CSG) has constructed a long-distance ultrahigh-voltage (UHV) hybrid alternating-current/direct-current (AD/DC) power grid comprising eight 500-kVAC overhead lines, four high-voltage DC (HVDC) links (500 kV, 3,000 MW) and one 1,418-km (881-mile) UHVDC link (800 kV, 5,000 MW), which have, in total, a west-to-east load-transfer capacity of more than 25,000 MW. Therefore, dynamic reactive power demand and voltage stability are paramount to ensuring the supply of electrical energy to this region.

As the electric utility industry is developing rapidly to keep pace with China's growing economy, there is an increasing demand for high-quality services. CSG's response is to establish a strategy to provide a source of energy that is intelligent, efficient, reliable and generated by renewable energy, that is, green power.

Figure 3.9: STATCOM at China

For CSG's load center in the East, a STATCOM could significantly help with voltage recovery following faults in the eastern sector of the CSG service territory and also prevent failure of the HVDCs' serial commutation.

Control and reliability studies were required to determine the optimum location for installing a STATCOM and what the capacity of the unit should be. The Electric Power Research Institute of CSG (EPRI-CSG) undertook in-depth, detailed studies that considered different operational modes, system development and hybrid AC/DC

Figure 3.10: China Southern Power Grid service area and STATCOM location

operation. The studies revealed the most severe system fault that could occur was a three-phase fault where a link circuit breaker failed to open.

The studies indicated that the best place for a STATCOM to be installed was either in the 500-kV Dongguan substation or in the 500-kV Hengli substation. When determining the required capacity of the STATCOM, CSG had to consider the conditions of each substation as well as the age of its equipment. After much consideration, CSG decided to install a 200-MVAR STATCOM in its 500-kV Dongguan substation.

From 2007 to 2010, CSG, along with Rongxin Power Electronic Co. and Tsinghua University, established a consortium project to undertake the research and development of the 200-MVAR STATCOM.

3.8.3 VELCO STATCOM

STATCOM system at Vermont electric power Co.'s Essex 115kV substation was installed to compensate for heavy increases in summer time electric usage.

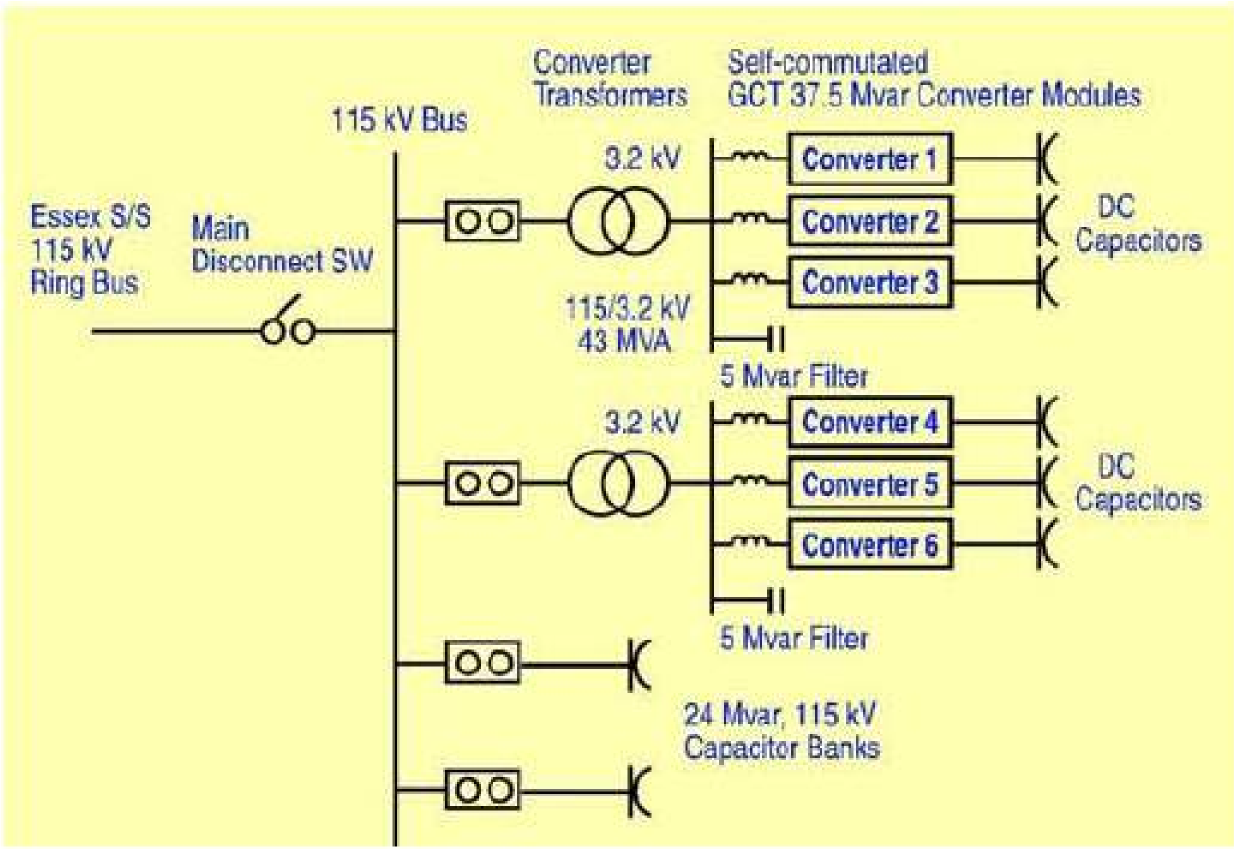


Figure 3.11: Essex projects- single line diagram

The STATCOM system has a rated capacity of +133/-41 MVA. It consists of two groups of 43 MVA voltage source converters (VSCs) and two sets of 24 MVA shunt capacitors.

Each VSC group consists of three sets of 12.5 MVA VSC modules and a small 5 MVA harmonic filter, with a nominal phase-to-phase AC voltage of 3.2kV and a DC link voltage of 6kV. The 43 MVA STATCOM groups of VSCs connect to the 115kV system via two 43 MVA, 3.2kV to 115kV 3-phase inverter transformers. The 24 MVA

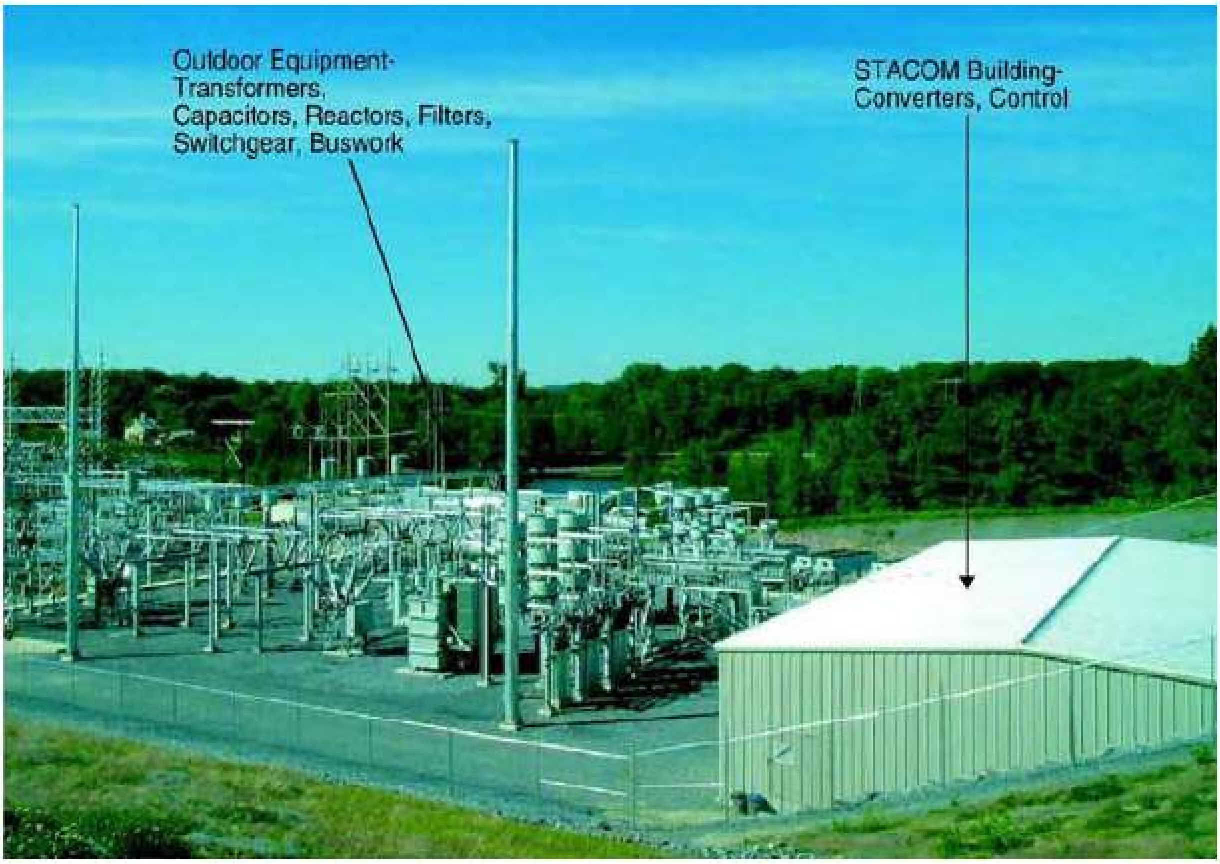


Figure 3.12: Essex project- external view +133/-41 MVA, 115 kV STATCOM system

shunt capacitors are connected directly at the 115kV level.

3.8.4 SDG&E Talega STATCOM / B2B project

-100 to +100Mvar dynamic range, 138kV ac system

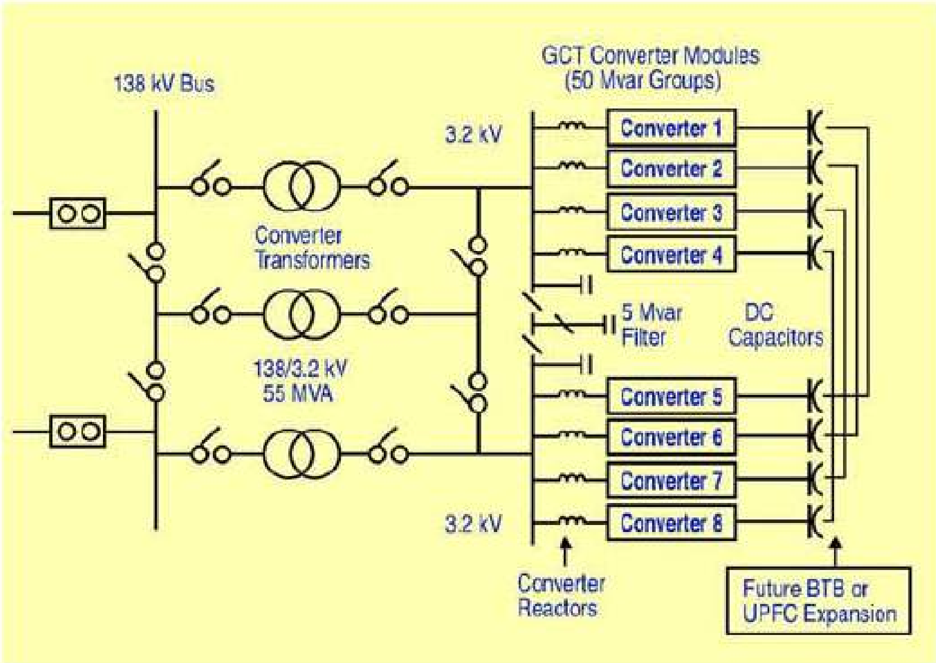


Figure 3.13: Talega - single line diagram

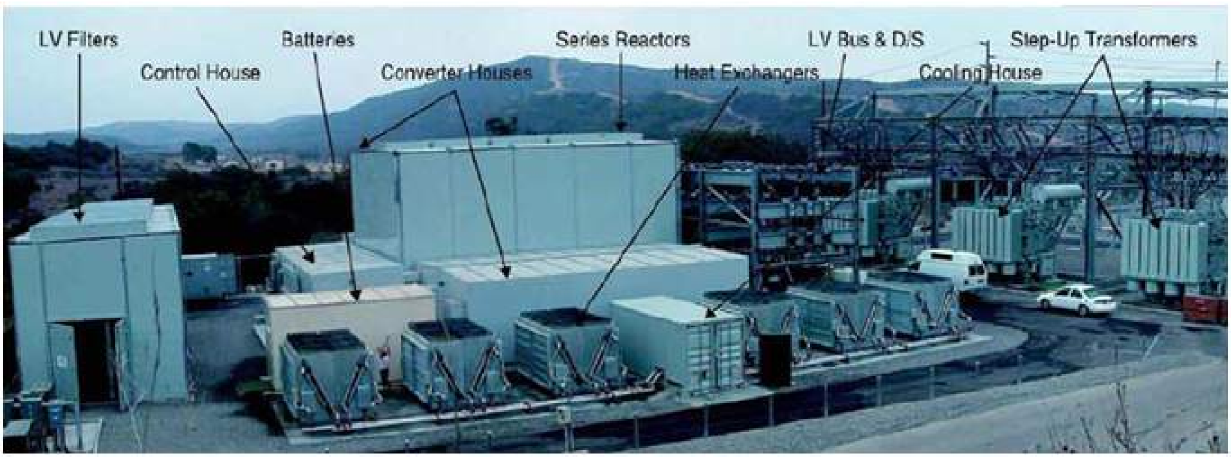


Figure 3.14: External view at Talega

3.8.5 Seattle Iron & Metals Corp. D-STATCOM Project

0 to +5 Mvar dynamic range, 4.16kV/26.4kV ac system

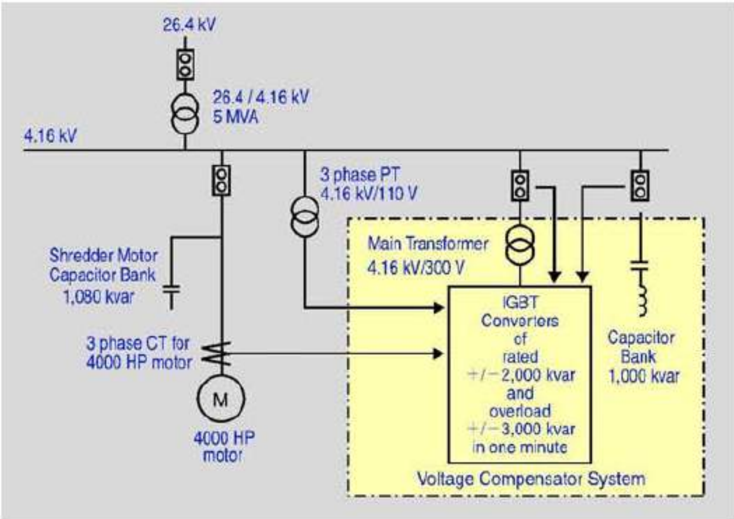


Figure 3.15: Single line diagram

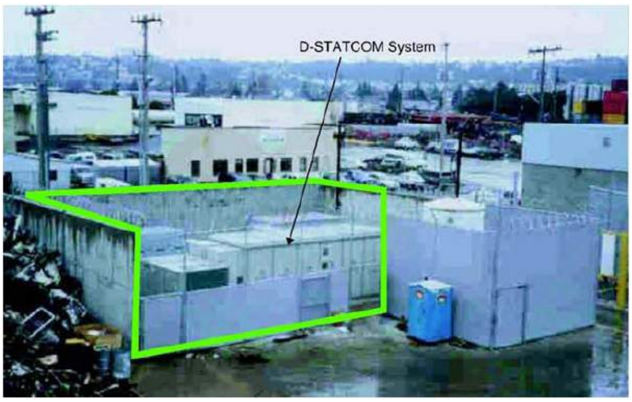


Figure 3.16: External view at steel recycle facility

Chapter 4

Control Techniques Used in STATCOM

4.1 Basic Control Techniques

The basic controlling Technique used by STATCOM is that, it adjusts it's the terminal voltage, in such a way that reactive power is absorbed or injected to the grid to maintain the grid voltage to its nominal value. That is If the grid voltage is equal to nominal grid voltage, STATCOM terminal voltage will get adjusted to grid voltage by adjusting the firing angle of gates used in VSC (assuming that grid voltage and STATCOM voltage are in phase).

The operation of STATCOM is based on controlling STATCOM terminal voltage. For controlling STATCOM terminal voltage, we need a control unit. The main parts of a STATCOM are:

- Voltage Source Converter
- Control unit for STATCOM
- PWM Generator

4.2 Voltage Source Converter (VSC)

Three phases VSC consist of six switches connected as shown in figure 4.1. The switches connected to same leg of the inverter (S1 and S4, S3 and S6, or S5 and S2) cannot be switched on simultaneously because this would result in a short circuit across the dc link voltage supply. Similarly, in order to avoid undefined states in the VSC, the switches of any leg of the inverter cannot be switched off simultaneously. By using six switches we can have eight switching topology. Out of eight valid states, two of them produce zero ac line voltages in this case the ac line currents freewheel through either the upper or lower components. The selection of the states in order to generate the required waveform is done by the modulating technique.

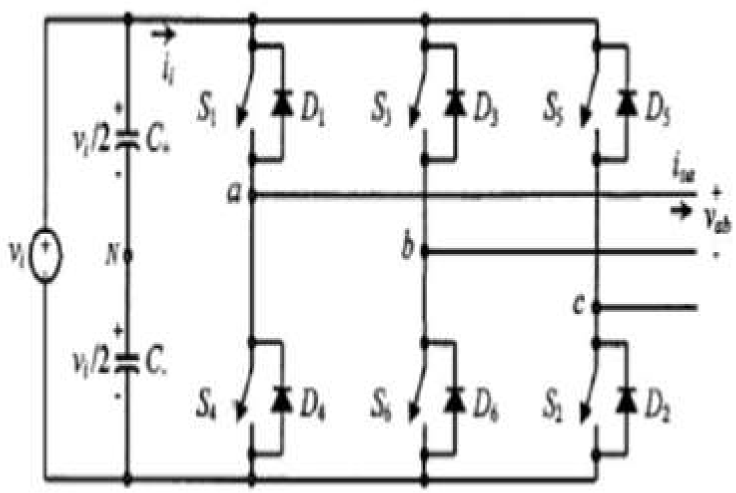


Figure 4.1: Voltage source converter

The switches of VSC are GTOs (they could be IGBTs, IGCTs, or other self-commutating switches) with an anti-parallel connected diode, which will operates with a unidirectional voltage-blocking capability and a bidirectional current flow.

4.3 Control Unit for STATCOM

Control unit forms the brain of STATCOM. Parameters selected for controlling STATCOM terminal voltage are grid voltage, grid current and STATCOM input DC voltage (across capacitor or DC link voltage).Here we use a DC capacitor which acts as DC source for VSC. To maintain the DC input voltage of VSC, a constant value (voltage across capacitor), DC voltage across the capacitor is taken as one of the parameter for controlling. By adjusting the firing angle of the converter, STATCOM terminal voltage can be varied. So the setting of firing of STATCOM forms the key part of STATCOM controller design.

Following are the main parts of STATCOM control unit.

- ABC to DQ conversion algorithm
- Phase look loop (PLL)
- Regulator

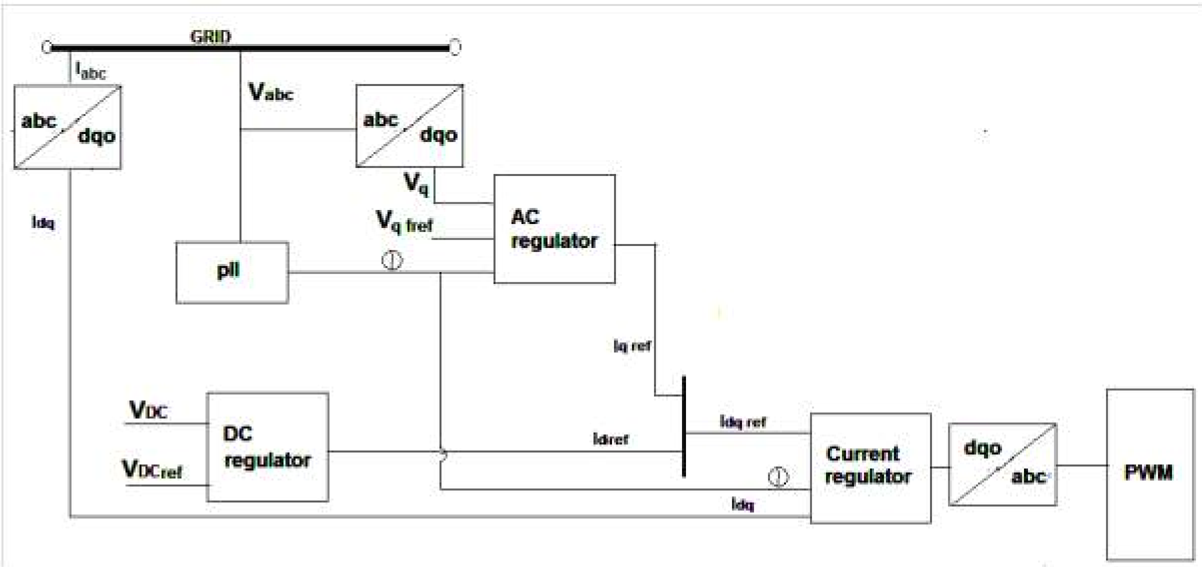


Figure 4.2: Control unit of STATCOM

4.3.1 ABC to DQ Conversion Algorithm

Normally STATCOM is complex to design. One of the reasons is that during design procedure we have to consider each phase separately and during transients there will be harmonics in all the three phases, which in turn make the analysis complex. Secondly, the circuit will become more complex. Some of these limitations can be overcome by mathematical transformation of three phase AC vectors in to two phase rotating dq axis vector. In dq-frame under steady-state conditions, the signals are assumed to have DC waveforms.

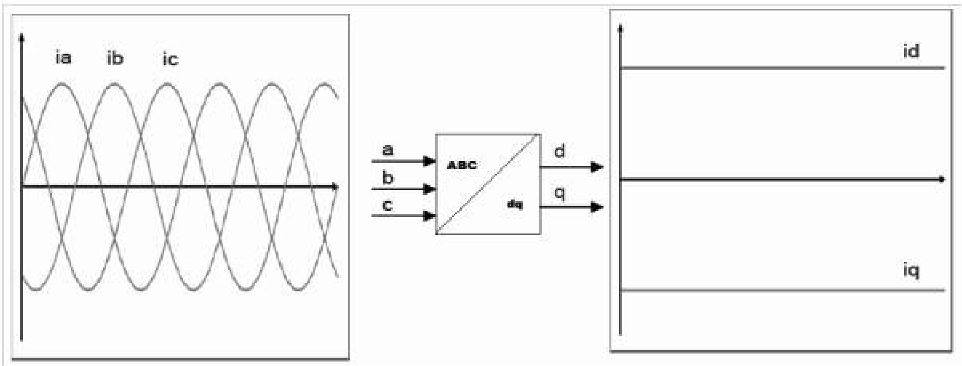


Figure 4.3: Wave forms in ABC and dq axis

In dq transformation, vectors in ABC reference axis which is displaced by 120° are transformed in two perpendicular axis and both the axis itself is assumed to be rotating at the same speed of supply frequency hence the name synchronous rotating frame. Since both d axis and q axis are rotating at the same speed of supply frequency, vectors in those axis will be having constant magnitude and phase, hence appears to be DC. Whenever there is any disturbance in AC, DC waveform in dq axils will gets disturbed. Hence analysis and control can be done easily in synchronous rotating frame. And reduction of three parameter (in abc axis) to two parameter (in dq axis) reduces the complexity in circuit.

Transformation algorithm is given by

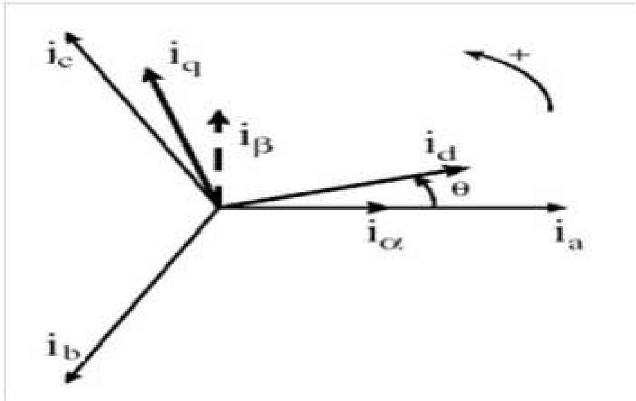


Figure 4.4: Vector diagram in abc and dq axis

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \frac{2}{3} \times \begin{bmatrix} \sin\theta & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \end{bmatrix} \times \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (4.1)$$

4.3.2 PLL

The PLL adjusts the phase of locally generated signal to match the phase of an input signal. This is used to synchronise control unit with grid parameter. The basic scheme of PLL consists of three block units:

- PD, It generates signal proportional to the phase difference between input signal and the signal generated by internal oscillator called VCO.
- The task of LF, it is to attenuate the high-frequency components from PD output.
- VCO, it generates a periodic signal, whose frequency is shifted with respect to a given basic frequency. It forms the output of PLL.

Due to voltage variations phase detection by direct methods can lead to significant errors. PLL in natural coordinates are not sufficiently immune to grid voltage

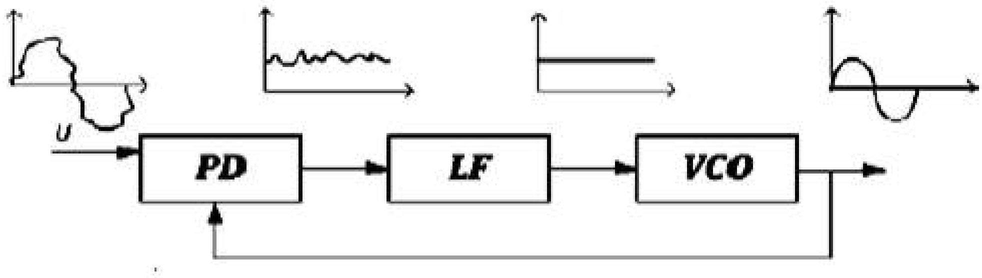


Figure 4.5: Basic PLL structure

variations a hence coordinates transformation to dq coordinates are done, which assures proper filtration from distortions. PLL in dq coordinates is called Synchronous Rotation Frame PLL.

4.3.3 Regulator

In the control circuit we can find three regulators:

- AC voltage regulator
- DC voltage regulator
- Current regulators

AC Voltage regulator will set quadrature axis reference current and DC voltage regulator sets direct axis reference current. And current regulator will form the input for PWM. These regulators will be normally PI controller, PID controller or any artificial intelligence control technique like fuzzy controller, neuro-fuzzy etc.

DC link voltage is kept constant by controlling the active power flowing to/from the converter. DC link voltage is compared with the DC link voltage reference and DC link voltage error is processed in DC voltage regulator. Therefore DC voltage regulator determines the phase angle of the converter voltage with respect to source voltage. DC link voltage is determined according to highest STATCOM fundamental voltage in the operation.

4.4 PWM Generator

Pulse width modulation, PWM of a signal source involves the modulation of its duty cycle, to control the amount of power sent to a load. The gating signals are generated by comparing a rectangular reference signal of the amplitude A_r with triangular carrier wave of amplitude A_c, by varying A_r from 0 to A_c, the pulse width can be varied from 0 to 100%.

The ratio of A_r to A_c is the control variable and defined as the modulation index. The frequency of the triangular voltage (f_s, carrier frequency) determines the converter switching frequency and the frequency of the control voltages determine the fundamental frequency of the converter voltage f1, modulating frequency). Hence, modulating frequency is equal to supply frequency in STATCOM. Reactive power of STATCOM is varied by controlling the modulation index. Modulation signal is obtained by changing the phase angle and amplitude of this fixed amplitude sine wave. Thus by varying the modulation index PWM generator will produce suitable firing signals to the switches in VSC and generate required voltage at the STATCOM terminal there by enabling exchange of reactive power between STATCOM and grid, hence enhancing transient stability.

4.5 Actual Multi-level Control Scheme

The proposed multi-level control scheme for the STATCOM device, consisting of an external, middle and internal level, is based on concepts of instantaneous power on the synchronous-rotating dq reference frame. Rotating reference frame is used because it offers higher accuracy than stationary frame-based techniques.

4.5.1 External Level Control

The external level control (left side in figure 4.6) is responsible for determining the active and reactive power exchange between the enhanced custom power device and the

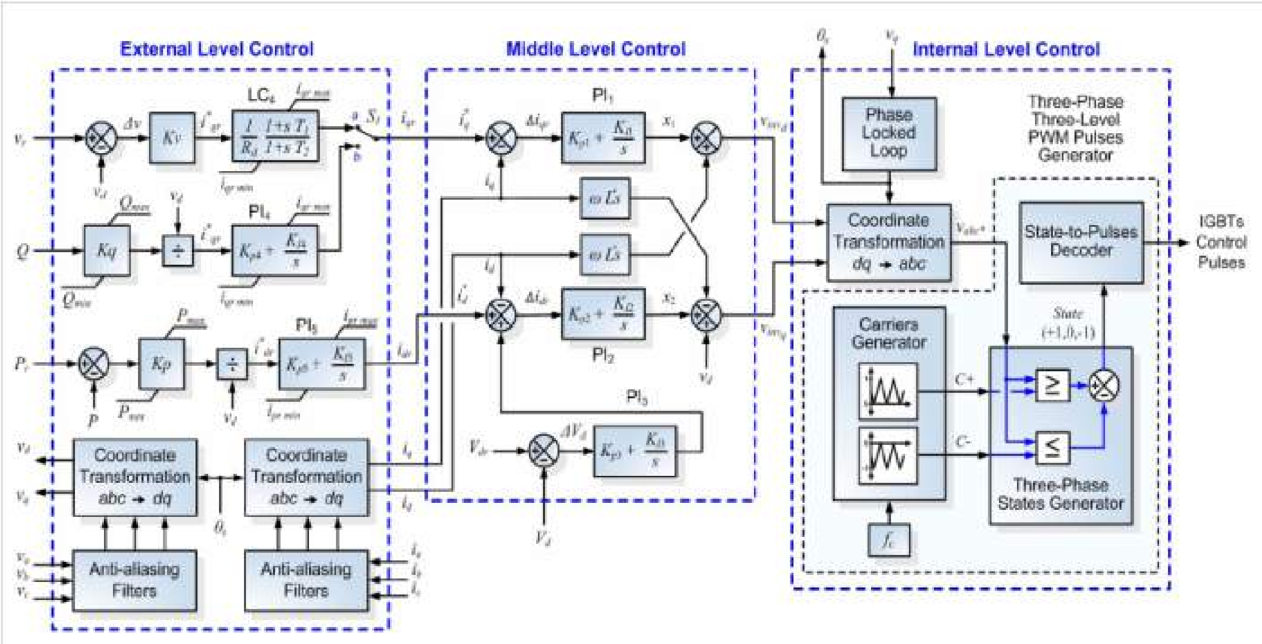


Figure 4.6: STATCOM control scheme

utility system. The proposed external level control scheme is designed for performing three major control objectives, that is the voltage control mode (VCM), which is activated when switch S1 is in position a, the power factor control mode (PFCM), activated in position b, and the active power control mode (APCM) that is always activated. The standard control loop of the external level consists in controlling the voltage at the PCC of the STATCOM through the modulation of the reactive component of the output current. To this aim, the instantaneous voltage at the PCC is computed by using a synchronous-rotating orthogonal reference frame. Thus, by applying Park's transformation, the instantaneous values of the three-phase ac bus voltages are transformed into dq components, v_d and v_q respectively. This operation permits to design a simpler control system than using abc components, by employing PI compensators. A voltage regulation droop (or slope) R_d is included in order to allow the terminal voltage of the STATCOM to vary in proportion with the compensating reactive current. In this way, a higher operation stability of the integrated device is obtained in cases that more fast-response compensators are operating in the area. As a result, the PI controller with droop characteristics becomes a simple phase-lag compensator (LC).

The PFCM corresponds to a variation of the reactive power control mode, being the last controller similar to the APCM but changing active components by reactive ones. In the power factor control mode, the reactive power reference is set to zero in order to provide all the reactive power demand at the consumer Side and thus being able to maintain unity power factor. The reactive power measurement is carried out at the customer supply side and is used as a reference for the PFCM. A standard PI compensator is included to eliminate the steady-state error in the reactive current reference computation. The integral action gives the controller a large gain at low frequencies that results in eliminating the post-transient current offset. The APCM allows controlling the active power exchanged with the electric system. This control mode compares the reference power set with the actual measured value in order to eliminate the steady-state active current offset via a PI compensator. In this way, the active power exchange between the STATCOM and the PS can be controlled so as to force the batteries to absorb active power when P_r is negative, or to inject active power when P_r is positive. The active power limits have been established with priority over the reactive power ones. In this way, P_{max} and P_{min} dynamically adjust in real-time the reactive power available from the STATCOM device, through constrains Q_{max} and Q_{min}. As during a fault or a post-fault transient of the electric system, the instantaneous voltage vector in the PCC, vd may greatly reduce its magnitude, the controllers will tend to raise the output active and reactive currents. Therefore the current ratings need to be independently restricted.

4.5.2 Middle Level Control

The middle level control makes the expected output to dynamically track the reference values set by the external level. In order to derive the control algorithm for this block, a dynamic model of the integrated STATCOM controller needs to be set up. For this purpose, a simplified scheme of the STATCOM equivalent circuit is used, that is depicted in Fig above The STATCOM is considered as a voltage source that is shunt-connected to the network through the inductance L_s, accounting for the equivalent leakage of the step-up coupling transformer and the series resistance R_s, representing the transformers winding resistance and VSI semiconductors conduction losses.

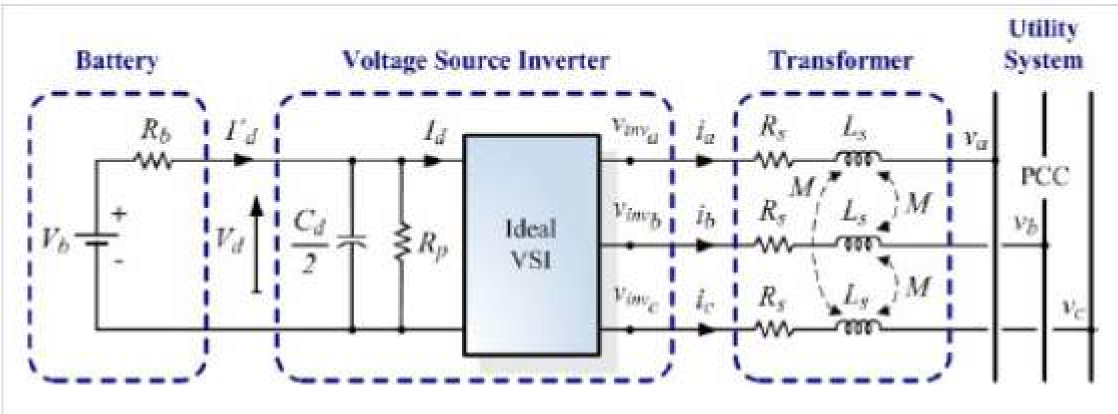


Figure 4.7: STATCOM equivalent circuit

The mutual inductance M represents the equivalent magnetizing inductance of the step-up transformers. In the dc side, the equivalent capacitance of the two dc bus capacitors is described by $C_{d/2}$ whereas the switching losses of the VSI and power loss in the capacitors are considered by R_p. The Energy Storage System is represented by an ideal dc voltage source V_b, and a series resistance R_b, accounting for the battery internal resistance. The self-discharge and leakage as well as the capacity of batteries are represented by a parallel combination of a resistance and a capacitor. Both values are included into R_p and $C_{d/2}$, respectively. The dynamics equations governing the instantaneous values of the three-phase output voltages in the ac side of the STATCOM and the current exchanged with the utility grid are given by equations 4.2, 4.3, 4.4 and 4.5.

$$\begin{bmatrix} v_{inv_a} \\ v_{inv_b} \\ v_{inv_c} \end{bmatrix} - \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = (\mathbf{R}_s + s\mathbf{L}_s) \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{4.2}$$

where,

$$s = \frac{d}{dt} \tag{4.3}$$

$$\mathbf{R}_s = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \tag{4.4}$$

$$\mathbf{L}_s = \begin{bmatrix} L_s & M & M \\ M & L_s & M \\ M & M & L_s \end{bmatrix} \tag{4.5}$$

Under the assumption that the system has no zero sequence components, all currents and voltages can be uniquely transformed into the synchronous-rotating dq reference frame. Thus, the new coordinate system is defined with the d-axis always coincident with the instantaneous voltage vector ($v_d = |\mathrm{v}|$, $v_q = 0$). Consequently, the d-axis current component contributes to the instantaneous active power and the q-axis current component represents the instantaneous reactive power. By applying Park's transformation equation 2.1 can be transformed into the dq reference frame as follows:

$$\begin{bmatrix} v_{inv_d} - v_d \\ v_{inv_q} - v_q \\ v_{inv_0} - v_0 \end{bmatrix} = \mathbf{K}_s \begin{bmatrix} v_{inv_a} - v_a \\ v_{inv_b} - v_b \\ v_{inv_c} - v_c \end{bmatrix} \tag{4.6}$$

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \mathbf{K}_s \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{4.7}$$

Then by neglecting zero sequence component, above equations can be derived as

$$\begin{bmatrix} v_{inv_d} \\ v_{inv_q} \end{bmatrix} - \begin{bmatrix} v_d \\ v_q \end{bmatrix} = (\mathbf{R}_s + s\mathbf{L'}_s) \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} -\omega & 0 \\ 0 & \omega \end{bmatrix} \mathbf{L'}_s \begin{bmatrix} i_q \\ i_d \end{bmatrix} \tag{4.8}$$

where,

$$\mathbf{R}_s = \begin{bmatrix} R_s & 0 \\ 0 & R_s \end{bmatrix} \tag{4.9}$$

$$\mathbf{L'}_s = \begin{bmatrix} L'_s & 0 \\ 0 & L'_s \end{bmatrix} = \begin{bmatrix} L_s - M & 0 \\ 0 & L_s - M \end{bmatrix} \tag{4.10}$$

The STATCOM ac and dc sides are related by the power balance between the input and the output on an instantaneous basis, as described by equations 4.11 and 4.12.

$$P_{ac} = P_{dc} \tag{4.11}$$

$$\frac{3}{2}(v_{inv_d} i_d + v_{inv_q} i_q) = (\frac{V_b - V_d}{R_d}) - \frac{C_d}{2} V_d \frac{dV_d}{dt} - \frac{V_d^2}{R_p} \tag{4.12}$$

The VSI of the STATCOM basically generates the ac voltage (V_{inv}) from the dc voltage (v_d). Thus, the connection between the dc-side voltage and the generated ac voltage can be described by using the average switching function matrix S and the factor K_{inv}, as given by equations 4.13, 4.14 and 4.15.

$$\begin{bmatrix} v_{inv_d} \\ v_{inv_q} \end{bmatrix} = k_{inv} \begin{bmatrix} S_d \\ S_q \end{bmatrix} V_d \tag{4.13}$$

With the factor,

$$k_{inv} = \frac{1}{2} ma \tag{4.14}$$

where, m = Modulation index, m belongs to [0,1]. a = n2/n1, Voltage ratio of coupling transformer and the average switching factor matrix for dq reference frame.

$$\begin{bmatrix} S_d \\ S_q \end{bmatrix} = \begin{bmatrix} \cos\alpha \\ \sin\alpha \end{bmatrix} \tag{4.15}$$

with, α = phase-shift of the converter output voltage from the reference position. Essentially, equations 4.8 to 4.15 can be summarized in the state-space as follows.

$$s \begin{bmatrix} i_d \\ i_q \\ V_d \end{bmatrix} = \begin{bmatrix} \frac{-R_s}{L_s'} & \omega & \frac{K_{inv} S_d}{L_s'} \\ -\omega & \frac{-R_s}{L_s'} & \frac{K_{inv} S_q}{L_s'} \\ -\frac{3}{C_d} K_{inv} S_d & -\frac{3}{C_d} K_{inv} S_q & -\frac{2}{C_d}\left(\frac{R_b R_p}{R_b + R_p}\right) \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ V_d \end{bmatrix} - \begin{bmatrix} \frac{v}{L_s'} \\ 0 \\ \frac{-2V_b}{R_b C_d} \end{bmatrix} \tag{4.16}$$

As can be observed, equation 4.16 defines the simplified state-space model of the STATCOM controller in the dq reference frame. This model is used as a basis for designing the middle level control, which is depicted in Fig (middle side). Inspection of equation 4.16 shows a cross-coupling of both components of the STATCOM output current. Therefore, in order to achieve a decoupled active and reactive power control, it is simply required to decouple the control of i_d and i_q. Thus, by generating the appropriate control signals x_1 and x_2 derived from setting to zero derivatives of currents in the upper part (ac side) of equation 4.16, the middle level control algorithms are obtained. In order to achieve this condition in steady-state, conventional PI controllers with proper feedback of STATCOM output current components are introduced, yielding equation 4.17 as follows.

$$s\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \frac{-R_s}{L_s'} & 0 \\ 0 & \frac{-R_s}{L_s'} \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} - \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \tag{4.17}$$

As can be noticed from previous equation, i_d and i_q respond to x_1 and x_2 respectively with no cross coupling. In this way, the introduction of these new control variables allows to obtain a full model (ac side) reduced to two first-order functions, which considerably improves the control system performance. From equation 4.16, it can be seen the additional coupling resulting from the dc capacitors voltage V_d, as much in the dc side (lower part) as in the ac side (upper part). This difficulty demands to maintain the dc bus voltage as constant as possible, in order to decrease the influence of the dynamics of V_d. The solution to this problem is obtained by using another PI compensator which allows laminating the steady-state voltage variations at the dc bus, by forcing a small active power exchange with the electric grid.

4.5.3 Internal Level Control

The internal level is responsible for generating the switching signals for the six valves of the three-level VSI, according to the control mode (sinusoidal PWM) and types of valves (IGBTs) used. Figure 4.6 shows a basic scheme of the internal level control of the STATCOM. This level is mainly composed of a line synchronization module and a three-phase three-level PWM firing pulses generator for the STATCOM VSI. The line synchronization module consists mainly of a phase locked loop (PLL). This circuit is a feedback control system used to automatically synchronize the STATCOM device switching pulses; through the phases of the inverse coordinate transformation from dq to abc components, with the positive sequence components of the ac voltage vector at the PCC (v_q). The design of the PLL is based on concepts of instantaneous power theory in the dq reference frame. Coordinate transformations from abc to dq components in the voltage and current measurement system are also synchronized through the PLL. In the case of the sinusoidal PWM pulses generator block, the controller of the VSI generates pulses for the carrier-based three-phase PWM inverter using three-level topology. thus, the expected sinusoidal-based output voltage waveform $V_{abc}*$ of the STATCOM, which is set by the middle level control, is compared to two positive and negative triangular signals generated by the carriers generator for producing three state PWM vectors (1, 0, -1). These states are decoded by the states-to-pulses decoder via a look-up-table that relates each state with the corresponding firing pulse for each IGBT of the four ones in each leg of the three-phase three-level VSI.

Chapter 5

Simulations and Results

5.1 Matlab Model of STATCOM

A Static Synchronous Compensator (STATCOM) is used to regulate voltage on a 25kV network. Two feeders (21 km and 2 km) transmit power to loads connected at buses B2 and B3. The 600V load connected to bus B3 through a 25kV/600V transformer represents a plant absorbing continuously changing currents, similar to an arc furnace, thus producing voltage flicker. The variable load current magnitude is modulated, so that its apparent power varies approximately between 1 MVA and 5.2 MVA, while keeping a 0.9 lagging power factor. This load variation will allow you to observe the ability of the STATCOM to mitigate voltage flicker.

The STATCOM regulates bus B3 voltage by absorbing or generating reactive power. This reactive power transfer is done through the leakage reactance of the coupling transformer by generating a secondary voltage in phase with the primary voltage (network side). This voltage is provided by a voltage-sourced PWM inverter. When the secondary voltage is lower than the bus voltage, the STATCOM acts like an inductance absorbing reactive power. When the secondary voltage is higher than the bus voltage, the STATCOM acts like a capacitor generating reactive power.

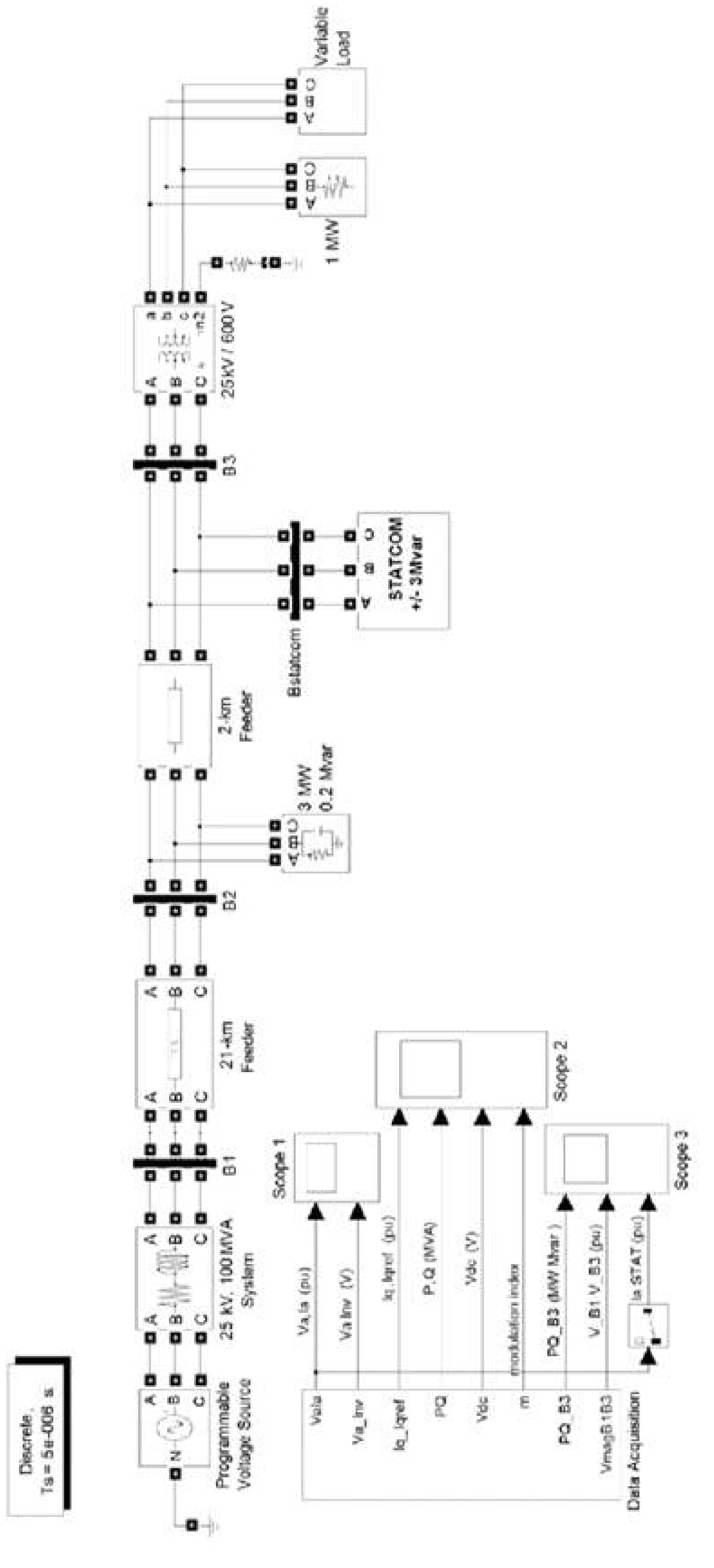


Figure 5.1: Matlab Simulation model

5.2 STATCOM Consists of the Following Components

- A voltage-sourced PWM inverter consisting of two IGBT bridges. The inverter modulation frequency is $28 \times 60 = 1.68$ kHz so that the first harmonics will be around 3.36 kHz, where m = modulation index = 28.
- LC damped filters connected at the inverter output where, L = 800μH and C = 100μF.
- A $C_{dc} = 10000\mu$F capacitor acting as a DC voltage source for the inverter.
- A PWM pulse generator using a modulation frequency of 1.68 kHz.
- $K_{pd} = 0.001$, $K_{id} = 0.15$.
- $K_{pa} = 0.55$, $K_{ia} = 250$

5.3 STATCOM Controller Consists of Several Functional Blocks

- A Phase Locked Loop (PLL). The PLL is synchronized to the fundamental of the transformer primary voltages.
- Two measurement systems. V_{meas} and I_{meas} blocks compute the d-axis and q-axis components of the voltages and currents by executing an abc-dq transformation in the synchronous reference determined by sin(ωt) and cos(ωt) provided by the PLL.
- An inner current regulation loop. This loop consists of two proportional-integral (PI) controllers that control the d-axis and q-axis currents. The controllers outputs are the V_d and V_q voltages that the PWM inverter has to generate. The

V_d and V_q voltages are converted into phase voltages V_a,V_b and V_c which are used to synthesize the PWM voltages. The I_q reference comes from the outer voltage regulation loop. The I_d reference comes from the DC-link voltage regulator.

- A DC voltage controller which keeps the DC link voltage constant to its nominal value (Vdc = 2.4 kV).

5.4 STATCOM Dynamic Response

During this test, the variable load will be kept constant and you will observe the dynamic response of a STATCOM to step changes in source voltage. Check that the modulation of the Variable Load is not in service (Modulation Timing [Ton Toff] = [0.15 1] X 100 > Simulation Stop time). The Programmable Voltage Source block is used to modulate the internal voltage of the 25-kV equivalent. The voltage is first programmed at 1.077 pu in order to keep the STATCOM initially floating (B3 voltage=1 pu and reference voltage Vref = 1 pu). Three steps are programmed at 0.2s, 0.3s, and 0.4s to successively increase the source voltage by 6%, decrease it by 6% and bring it back to its initial value (1.077 pu).

Start the simulation. Observe on Scope1 the phase A voltage and current waveforms of the STATCOM as well as controller signals on Scope2. After a transient lasting approximately 0.15sec., the steady state is reached. Initially, the source voltage is such that the STATCOM is inactive. It does not absorb nor provide reactive power to the network.

At t = 0.2s, the source voltage is increased by 6%. The STATCOM compensates for this voltage increase by absorbing reactive power from the network (Q=+2.7 Mvar on trace 2 of Scope2).

At t = 0.3s, the source voltage is decreased by 6% from the value corresponding to Q = 0. The STATCOM must generate reactive power to maintain a 1 pu voltage (Q changes from +2.7 MVAR to -2.8 MVAR).

Note that when the STATCOM changes from inductive to capacitive operation, the modulation index of the PWM inverter is increased from 0.56 to 0.9 (trace 4 of Scope2) which corresponds to a proportional increase in inverter voltage. Reversing of reactive power is very fast, about one cycle, as observed on STATCOM current.

5.5 Results of Simulation Model

5.5.1 Simulation Result of Scope 1

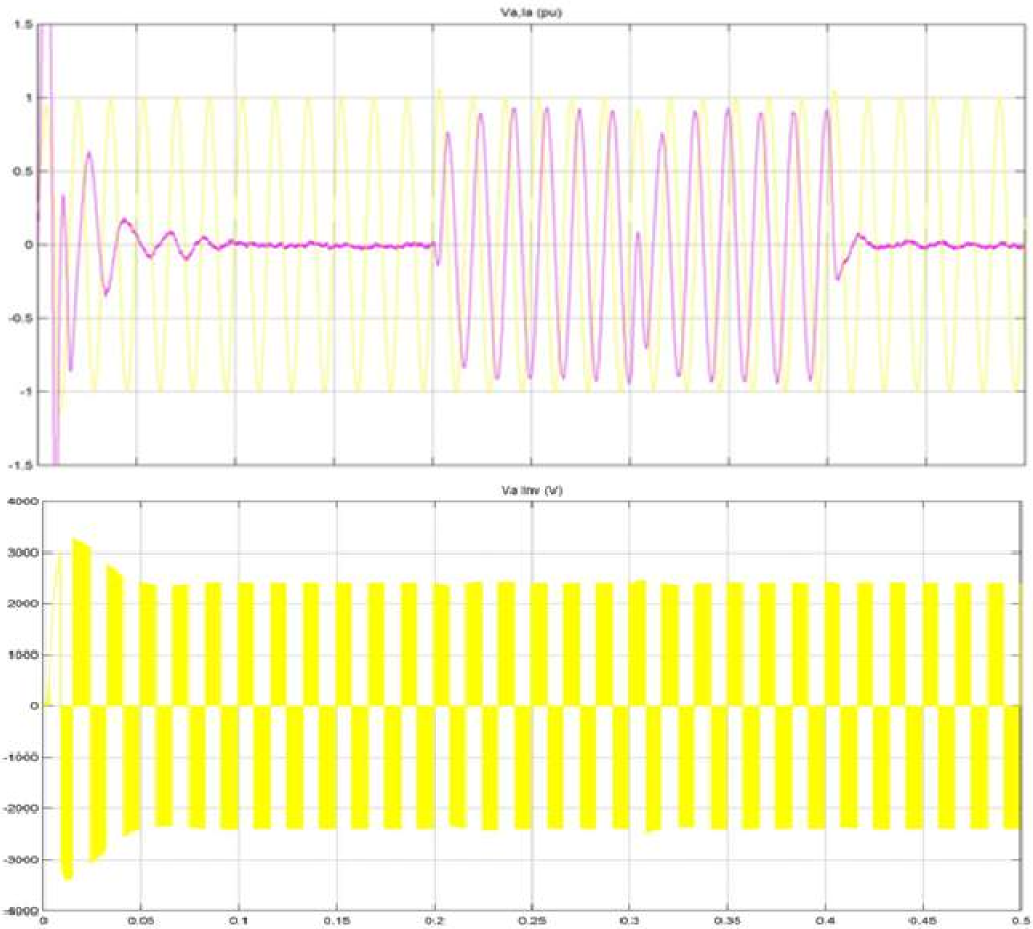


Figure 5.2: Phase A voltage and current (pu) and STATCOM(inverter) output of Phase A

5.5.2 Simulation Result of Scope 2

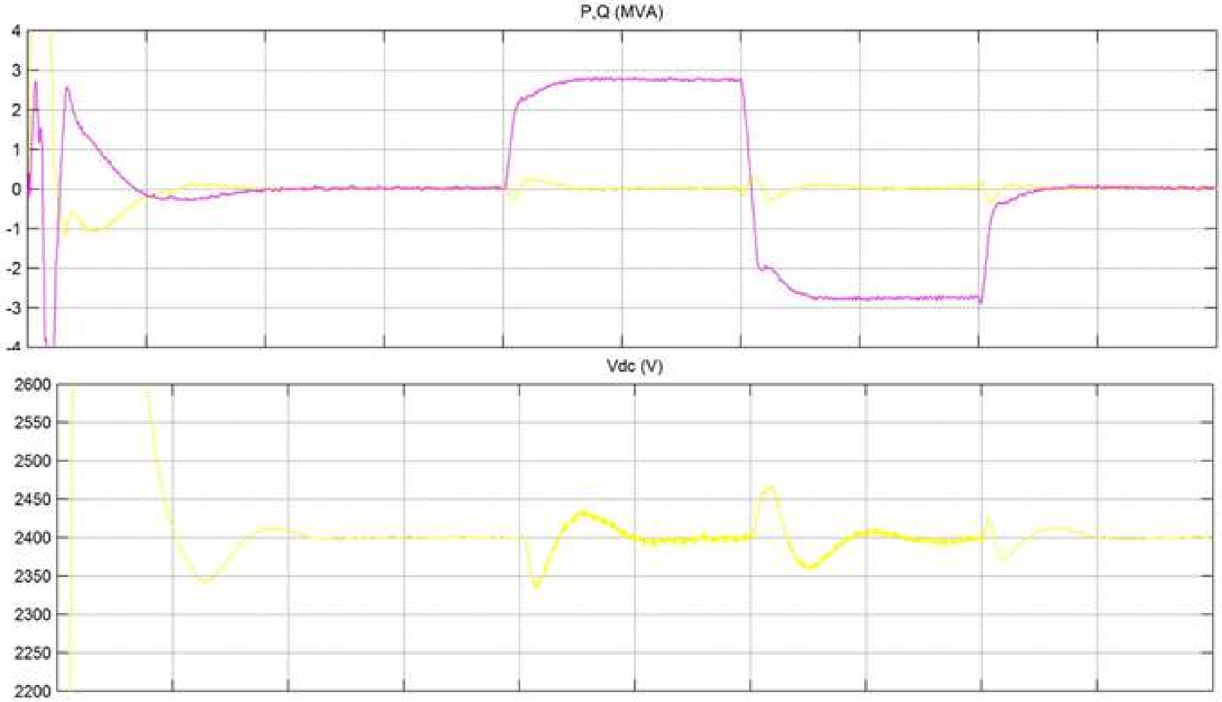


Figure 5.3: PQ (MVA) and DC link voltage, Vdc (V)

5.5.3 Simulation Result of Scope 3

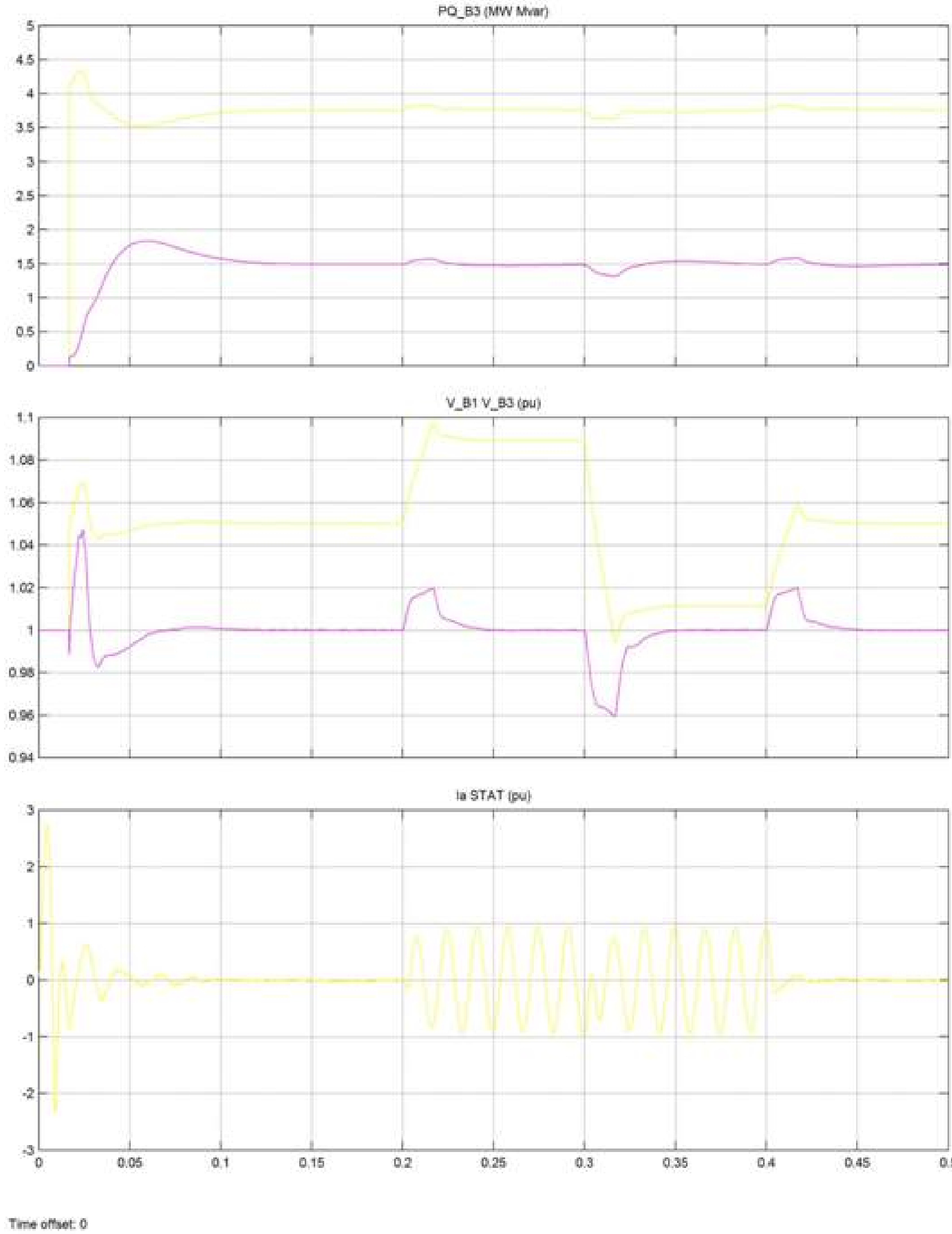


Figure 5.4: Variations of P and Q at bus B3 & V & Istat of Bus B1,B3

5.6 Power from the Simulation Model Graph

Receiving End Active Power, P = 3.761MW

Receiving End Reactive Power, Q = 1.488Mvar

Total Apparent Power, S = $\sqrt{MW^2 + Mvar^2}$

Power Factor = $\frac{MW}{MVA}$

(with STATCOM)

PF = 3.761 / $\sqrt{3.761^2 + 1.488^2}$ = 0.9298

(without STATCOM)

PF = 127.12 / $\sqrt{127.12^2 + 219.9^2}$ = 0.5005

Chapter 6

Introduction to Arm Cortex M4 Controller

The ADSP-CM40x family of mixed-signal control processors is based on the ARM Cortex-M4TM processor core with floating point unit operating at frequencies up to 240 MHz and integrating up to 384KB of SRAM memory, 2MB of flash memory, accelerators and peripherals optimized for motor control and photo-voltaic (PV) inverter control and an analog module consisting of two 16-bit SAR-type ADCs and two 12-bit DACs. The ADSP-CM40x family operates from a single voltage supply (VDD_EXT/VDD_ANA), generating its own internal voltage supplies using internal voltage regulators and an external pass transistor.

This family of mixed-signal control processors offers low static power consumption and is produced with a low-power and low voltage design methodology, delivering world class processor and ADC performance with lower power consumption.

By integrating a rich set of industry-leading system peripherals and memory, the ADSP-CM40x mixed-signal control processors are the platform of choice for next-generation applications that require RISC programmability, advanced communications and leading-edge signal processing in one integrated package. These applications span a wide array of markets including power/motor control, embedded industrial,

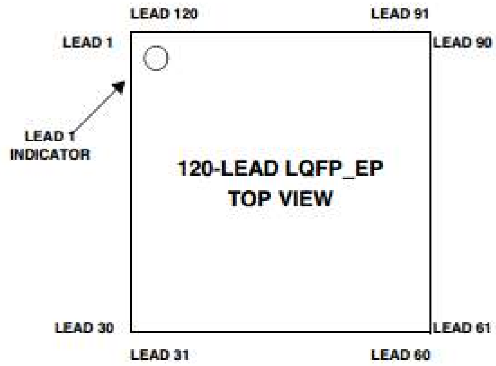


Figure 6.1: 120-Lead LQFP Package Lead Configuration (Top View)

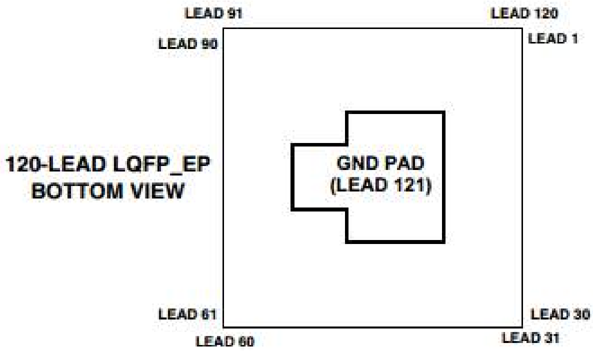


Figure 6.2: 120-Lead LQFP Package Lead Configuration (Bottom View)

instrumentation, medical and consumer.

Each ADSP-CM40x family member contains the following modules

- 8 GP timers with PWM output
- 3-Phase PWM units with up to 4 output pairs per unit
- 2 CAN modules
- 1 two-wire interface (TWI) module
- 3 UARTs

6.1 System Features

- 100 MHz to 240 MHz ARM Cortex-M4 with floating-point unit
- 128k Byte to 384k Byte zero-wait-state L1 SRAM with 16k Byte L1 cache
- Up to 2M Byte flash memory
- 16-bit asynchronous external memory interface
- Enhanced PWM units
- Four 3rd/4th order SINC filters for glueless connection of isolated ADCs
- Harmonic analysis engine
- 10/100 Ethernet MAC
- Full Speed USB On-the-Go (OTG)
- Two CAN (controller area network) 2.0B interfaces
- Three UART ports
- Two Serial Peripheral Interface (SPI-compatible) ports
- Eight 32-bit general-purpose timers
- Four Encoder Interfaces, 2 with frequency division
- Single power supply
- ANALOG SUBSYSTEM FEATURES
    a. ADC controller (ADCC) and DAC controller (DACC)
    b. Two 16-bit SAR ADCs with up to 24 multiplexed inputs, supporting dual simultaneous conversion in 380 ns (16-bit, no missing codes, 3.5LSB INL)
    c. Two 12-bit R-string DACs, with output rate up to 50 kHz

- Two 2.5 V precision voltage reference outputs

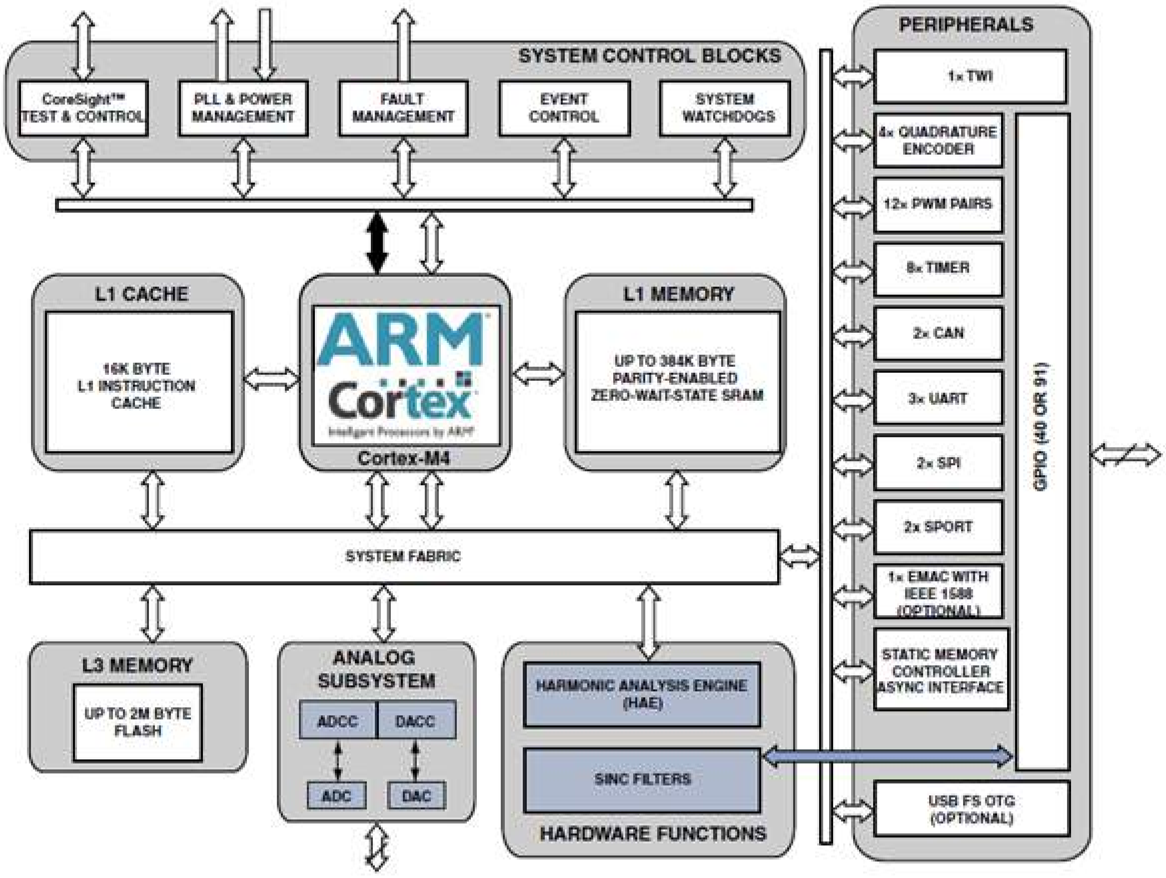


Figure 6.3: Block Diagram of ARM Cortex M4 Controller

6.2 Memory Architecture

The ADSP-CM40x processor provides sufficient memory to support processor based applications. It includes 384k bytes of internal SRAM that can be partitioned in to blocks of code and data (64k bytes of configurable memory blocks).

It also includes a static memory controller for interface to external devices or memories. Apart from the above, there is support for two SPI-based flash memories (one inside the package and the other externally supported) that can be memory-mapped for high performance code execution through SPI Quad/Dual I/O read modes. Further inclusion of an internal 16k byte code cache improves the execute-in-place (XiP) functionality of flash memories significantly.

The ADSP-CM40x Processor Functional Block Diagram in the Introduction shows a number of system control blocks. Some of these blocks provide system control operations, such as event handling and managing the memory sub-system interface. The following sections provide information on managing the memory sub-system interface of the ADSP-CM40x processor.

6.2.1 Memory Architecture Features

- An internal memory sub-system supporting:
    a. Up to 384K bytes of zero wait state and configurable SRAM
    b. 16K bytes of zero wait state code cache
    c. 32K bytes of boot ROM
- A high performance bus architecture involving:
    a. Cortex core internal bus matrix
    b. Memory bus matrix that connects to the Cortex core over the I-Code, D-Code, and SYS buses
- Cacheable external-memory interfaces, which support:
    a. 32M byte x up to 4 banks of static memory control connected to asynchronous memories (SRAM, flash, FPGA)
    b. 2M bytes of internal SPI flash (within ADSP-CM40x package)
    c. Up to 16M bytes of external SPI flash

6.3 3 Phase PWM Units

The Pulse Width Modulator (PWM) module is a flexible and programmable waveform generator. With minimal CPU intervention the PWM peripheral is capable of generating complex waveforms for motor control, Pulse Coded Modulation (PCM), Digital to Analog Conversion (DAC), power switching and power conversion. The PWM module has 4 PWM pairs capable of 3-phase PWM generation for source inverters for AC induction and DC brushless motors.

6.3.1 PWM Features

The two 3-phase PWM generation units each feature

- 16-bit center-based PWM generation unit
- Programmable PWM pulse width
- Single/double update modes
- Programmable dead time and switching frequency
- Twos-complement implementation which permits smooth transition to full ON and full OFF states
- Dedicated asynchronous PWM shutdown signal.

6.4 Architectural Concepts

The PWM Controller is driven by a clock, whose period is tSCLK. The PWM generator produces four pairs (four high-side and four low-side) of PWM signals on the eight PWM output pins. Each high and low pair constitutes a channel. For example PWM_AL/PWM_AH make up channel A, and PWM_BL/PWM_BH make up channel B and so on. Each pair of channel outputs can be produced with reference to either

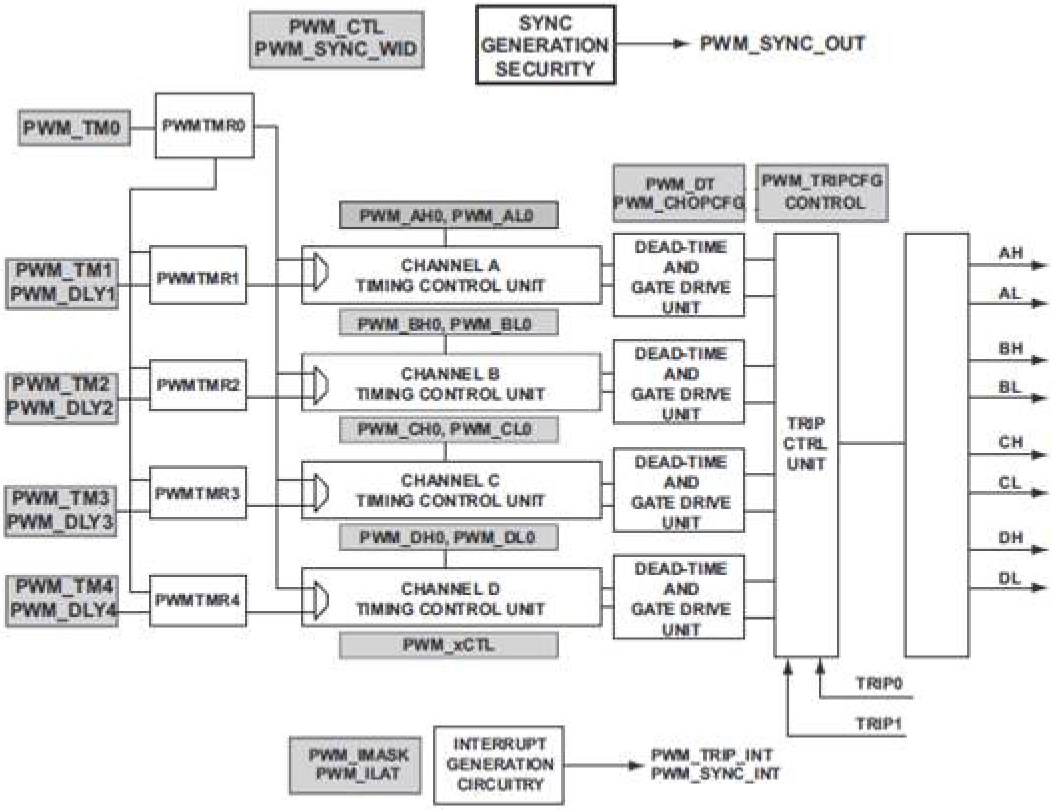


Figure 6.4: PWM Block Diagram

a main timer or to an independent timer. These timers operate on a switching frequency determined by the PWM_TM0 registers. There are 2 duty registers for every PWM output, which enable generation of symmetrical or asymmetrical waveforms that produce lower harmonic distortion in three-phase PWM inverters, with minimal CPU intervention.

6.4.1 PWM Block Diagram

The following figure shows a block diagram that represents the main functional blocks of the PWM controller.

The primary blocks are described below.

- Each pair of PWM signals is referenced either to the main timer or to the independent timer.

- PWMTMR0 is the main timer and can trigger the delayed start of the other timers.
- Timing Control Units, one for each channel, which together form the core of the PWM, generate the required complex waveforms on the high side and low side outputs for the respective channel.
- Dead Time insertion is done after the ideal PWM output pair is generated.
- The Gate Drive Unit generates the high-frequency chopping signal and subsequently mixes it with the requisite PWM output signals.
- The PWM Shutdown and Interrupt Controller manages the various PWM shutdown modes
- For the timing unit and generates the requisite interrupt signals.
- The PWM Sync Pulse Control Unit generates the internal PWMSYNC pulse and also controls whether the external PWMSYNC input pulse is used.

6.5 Control Algorithm

The PWM scheme used to switch the Three phase Inverter (STATCOM) is Unipolar-pulse width modulation. The algorithm is described briefly in the flowchart.

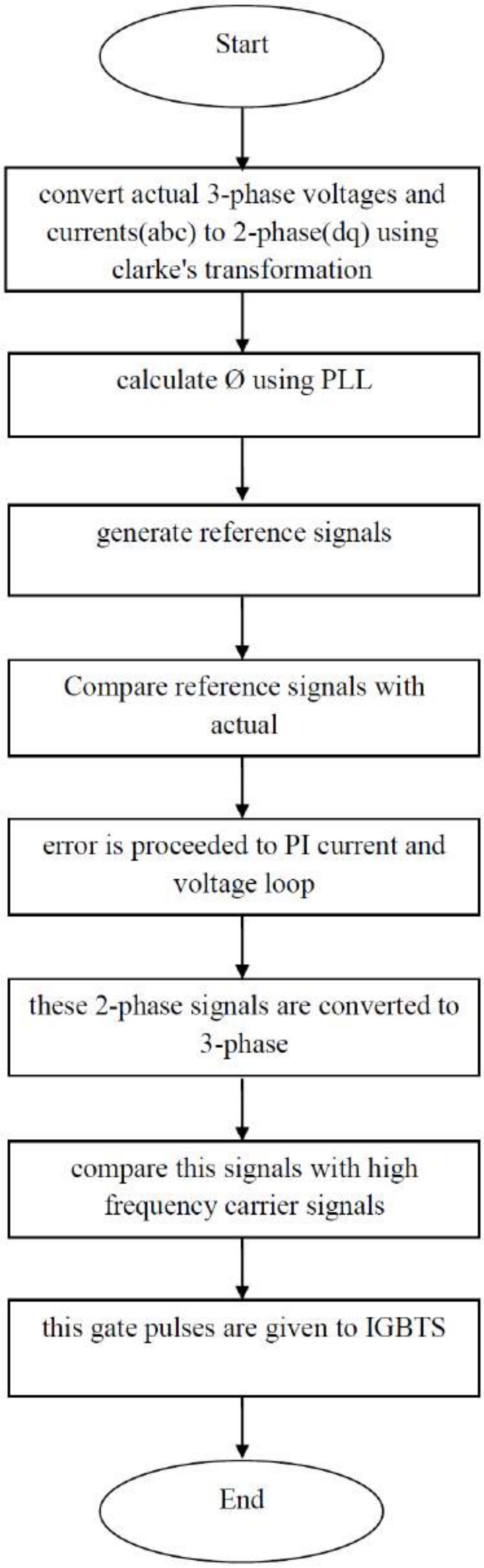


Figure 6.5: Control algorithm for STATCOM

6.6 Control Signals

Comparing a reference signals generated with high frequency signal, gate pulses are generated. Fig., below shows the gate pulses of 3.040sec deadband of the single leg.

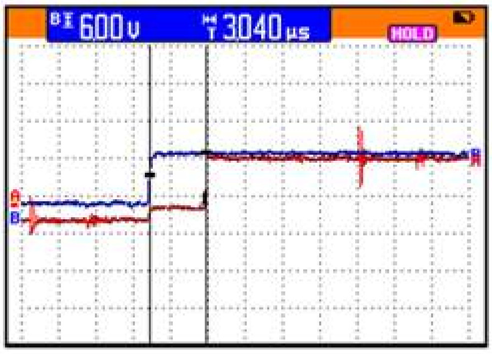


Figure 6.6: Dead band between the gate pulses of the single leg

Chapter 7

Hardware

In the previous chapters the selected topology of the STATCOM is simulated and simulation results are analyzed. But before the actual implementation of hardware, the components are to be selected very carefully considering, voltage rating, current rating & power rating.

7.1 Component Selection

Now since the DC link is 2400V the IGBTs chosen has the rating of 3400V & 100A of Mitsubhishi of 1.68kHz switching frequency. Another important quantity whose value is to be decided wisely is capacitors.

The value of capacitors is decided on the basis of voltage ripple to be allowed in the capacitors. Assuming 7 % ripple in the capacitance voltage. The value of the DC link capacitor comes out to be 10,000μF. And the value of the LC filter is, L = 800μH and C = 100μF.

7.2 Power calculation

Conversion of V_{abc} and I_{abc} to dq,

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \sqrt{\frac{2}{3}} \times \begin{bmatrix} 1 & \frac{1}{2} & \frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \times \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{7.1}$$

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \sqrt{\frac{2}{3}} \times \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \times \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{7.2}$$

Instantaneous Power

$$P = v_d \cdot i_d + v_q \cdot i_q \tag{7.3}$$

$$P = v_q \cdot i_d - v_d \cdot i_q \tag{7.4}$$

7.2.1 Power Factor Calculation

As we know,

Reactive power,

$$P = V \times I \times \sin\phi, kVAR \tag{7.5}$$

Active Power,

$$Q = V \times I \times \cos\phi, kW \tag{7.6}$$

Apparent Power,

$$S = \sqrt{P^2 + Q^2}, kVA \tag{7.7}$$

Power Factor,

$$PF = \cos\phi \tag{7.8}$$

$$PF = \frac{kW}{kVA} \tag{7.9}$$

For the power factor calculation, there are two ways to be used:

- Quadrature mode (ph-ph)
- In phase mode (ph-N)

7.2.2 Quadrature Mode (ph-ph)

In this mode, any two phases (either a-b, b-c, c-a) voltages are sensed. And remaining phase current is sensed. e.g., phase a-b voltage are sensed and phase c current is sensed. This sensed voltage and current are 90° phase shifted as shown below.

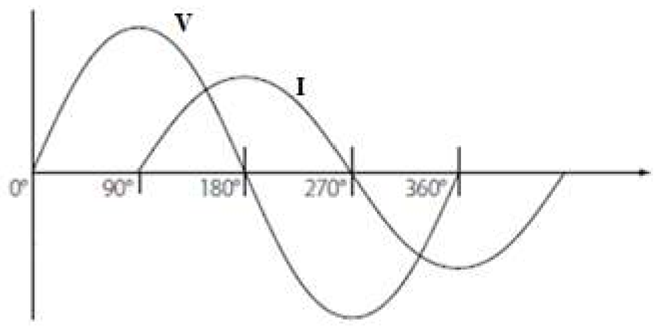


Figure 7.1: Quadrature mode

So, in this mode we directly get;

$$V \times I = kVAR \tag{7.10}$$

Then getting both V and I in phase as shown in figure 7.2;
Now we will get,

$$V \times I = kW \tag{7.11}$$

from equation 7.10 and 7.11; we get

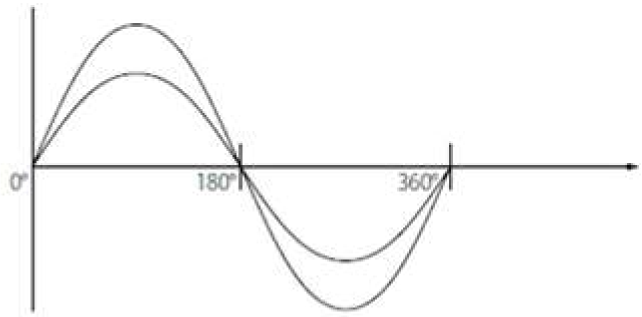


Figure 7.2: In phase mode

$$KVA = \sqrt{kVAR^2 + kW^2} \tag{7.12}$$

and power factor

$$PF = \frac{kW}{kVA} \tag{7.13}$$

7.2.3 In Phase Mode(ph-N)

In this mode, phase to neutral voltage & current are sensed. In these sensed voltage and current are in phase. So, in this mode we directly get;

$$V \times I = kW \tag{7.14}$$

and after phase shifting current by 90°, we will get,

$$V \times I = kVAR \tag{7.15}$$

from equation 7.14 and 7.15; we get

$$KVA = \sqrt{kVAR^2 + kW^2} \tag{7.16}$$

and power factor

$$PF = \frac{kW}{kVA} \tag{7.17}$$

7.3 Algorithm

a. Using user interface, take frequency of triangular wave (f_c = 1.68kHz).

b. Based on above frequency, generate samples of triangular wave or it could be in a look up table.

c. Read frequency of sine wave using comparator circuit. Take digital input pin or external interrupt pin with edge trigger. When it goes from low to high, it gives interrupt to the system. In ISR start timer. When it switched from high to low, note timer value, which is ON time and reset timer and start it again. When transition happens from low to high, note timer value, which is off time.

d. Add ON and OFF time give time period for one cycle. Divide it by 256, we will get time period for single sample. This is the trigger point for generating samples of Mains current and voltage.

e. Enable ADC and get values of current and voltage. Take total 256 samples.

f. Calibrate it (multiply it with current gain constant and voltage gain constant, add offsets and the phase corrections. All these calibrated values will be stored at the time of calibration)

g. Calculate following parameters:

   (1) Active Power(P) = $(\int Vn.In.dt)/256$; where n=1 to 256

   (2) Reactive power (IQ) = $(\int Vn.I(n+64).dt)/256$; where n=1 to 256

   (3) Apparent power (S) = $\sqrt{(P^2+Q^2)}$

   (4) Where dt = $1/\Delta f$ = T/256.

h. Using reactive power values (kVAR) find out whether current is leading or lagging (kVAR is -ve or kVAR is +ve resp.)

i. Get values of phase angle and amplitude by implementing PLL logic.

j. PLL logic will generate sine wave based on frequency, phase angel and amplitude. Sine wave with unity amplitude samples will be available in the look up table. $y(t) = A \sin(\omega t + \phi)$. The PLL logic will give the values of "A", "ωt and ϕ".

k. Compare sine wave samples with triangular wave samples. This is extreme fast process and at least in one mains cycle 25,600 comparisons has to be achieved.

l. If sine wave sample > triangular wave sample, then we will get PWM ON time.

m. Else PWM off time. (Note that the commutation time for IGBT switching would be taken care by IGBT driver ICs)

n. Trigger PWM unit ON or OFF time.

o. Take feedback of how much kVAR is pumped by STATCOM using acquiring its information and try to minimize gap of actual and to be pumped in values.

p. Take feedback of DC link. If it is less then control phase angle offset of sine wave to be generated and repeat sr. no. j.

7.4 Testing of the Controller with CALMET

Calibrator / tester C300 is used for adjusting, checking and verification of measuring instruments used in power engineering. These include electricity meters, frequency, voltage and current protective relays, current transformers and clamps, active and reactive power meters, phase meters, frequency meters, ammeters, voltmeters, transducers, monitoring systems and power quality analyzers.

Calibrator C300 is three phase source of AC current and voltage with accuracy class 0.05% and programmable value of harmonics. It generates voltage up to 560V in sub ranges 70-140-280-560V, current up to 120A in sub ranges 0.5-6-20-120A, frequency in range 40-500Hz and phase shift in range 0360°. In one phase connection it can generate current up to 360A.

Calibrator C300 is controlled by means of personal computer with installed software Calpro 300 in Windows operating system.

7.4.1 Main Connections

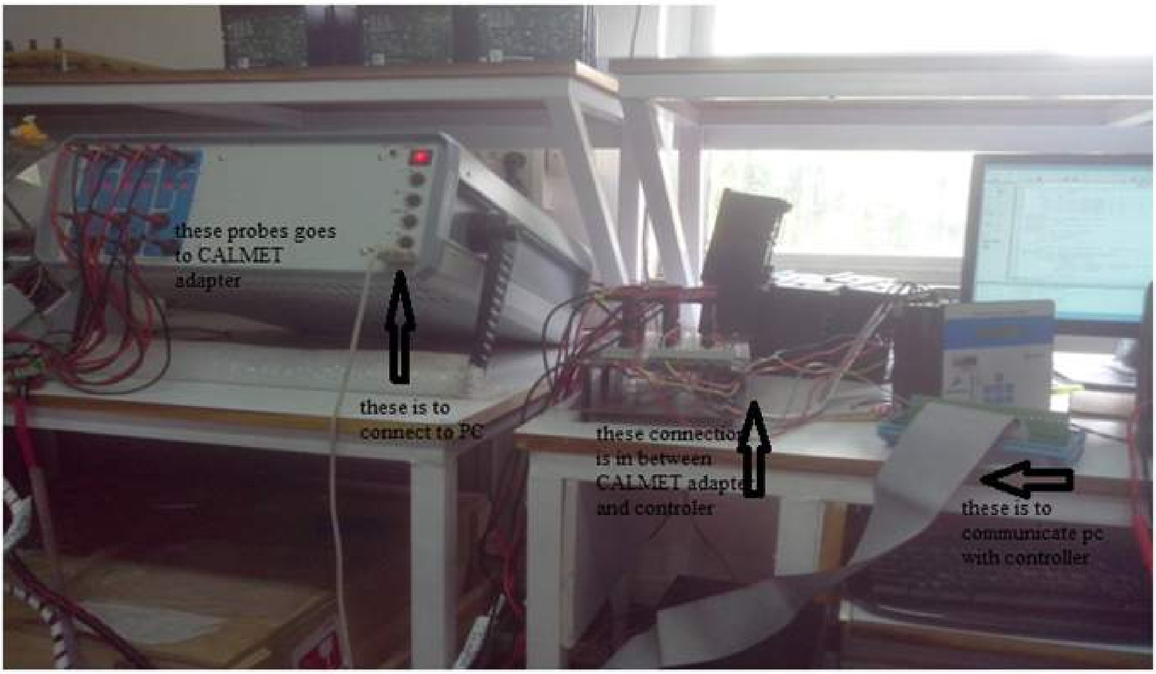


Figure 7.3: testing of controller using CALMET with 254V, 1A and 50Hz.

Connect the CALMET to CALMET adapter by probes, other connection of the CALMET adapter goes to controller via connecting wires.

One of the connection of the CALMET goes to PC via serial cable shown in fig. below. similarly, one connetion of the controller is made with PC.

7.4.2 Working of the CALMET with Controller

- First enter the required value of Voltage, current and cos (phase angle) in the Calpro 300 software in Computer.
- Those set values goes to CALMET via cable connected to it.
- These values are given to controller as CALMET is connected to it.
- then its calibrated and results are shown below: (for varying phase angle what are the values of active and reactive powers).

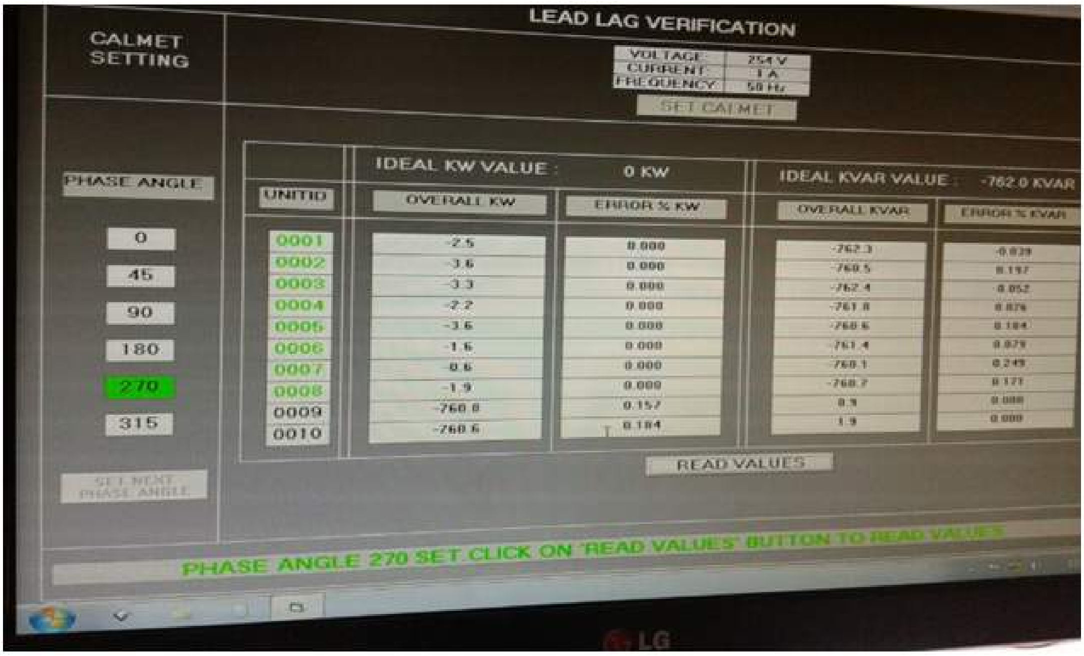


Figure 7.4: lead-lag verification for phase angle = 270°, no active power is generated

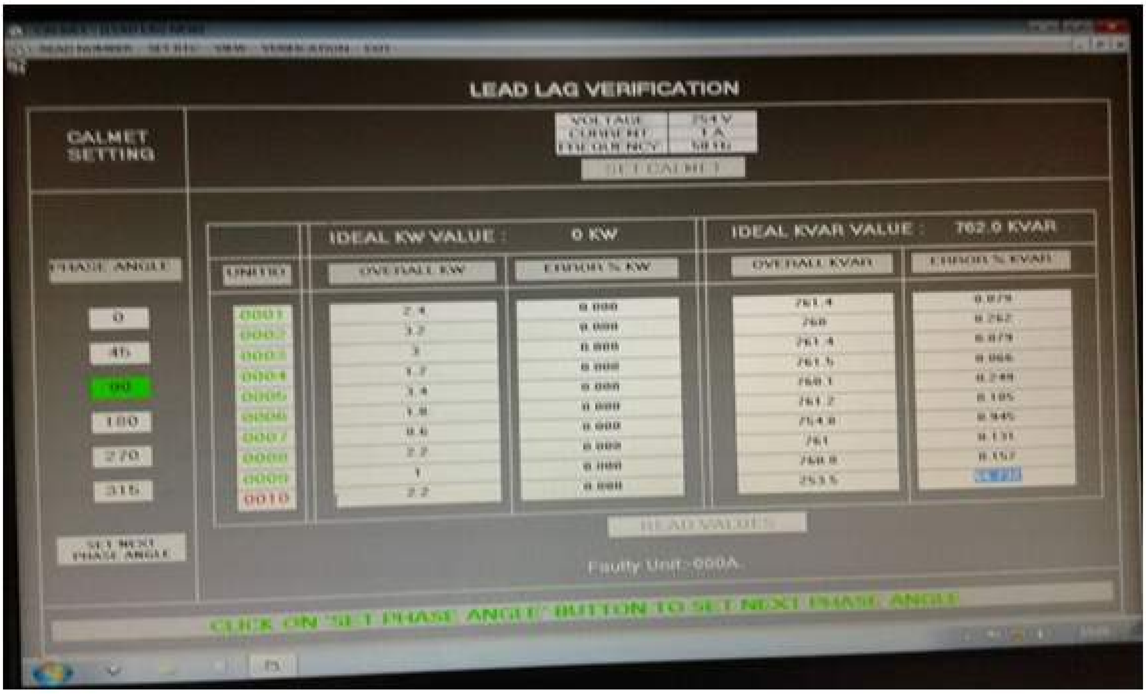


Figure 7.5: lead-lag verification for phase angle = 90°, no active power is generated

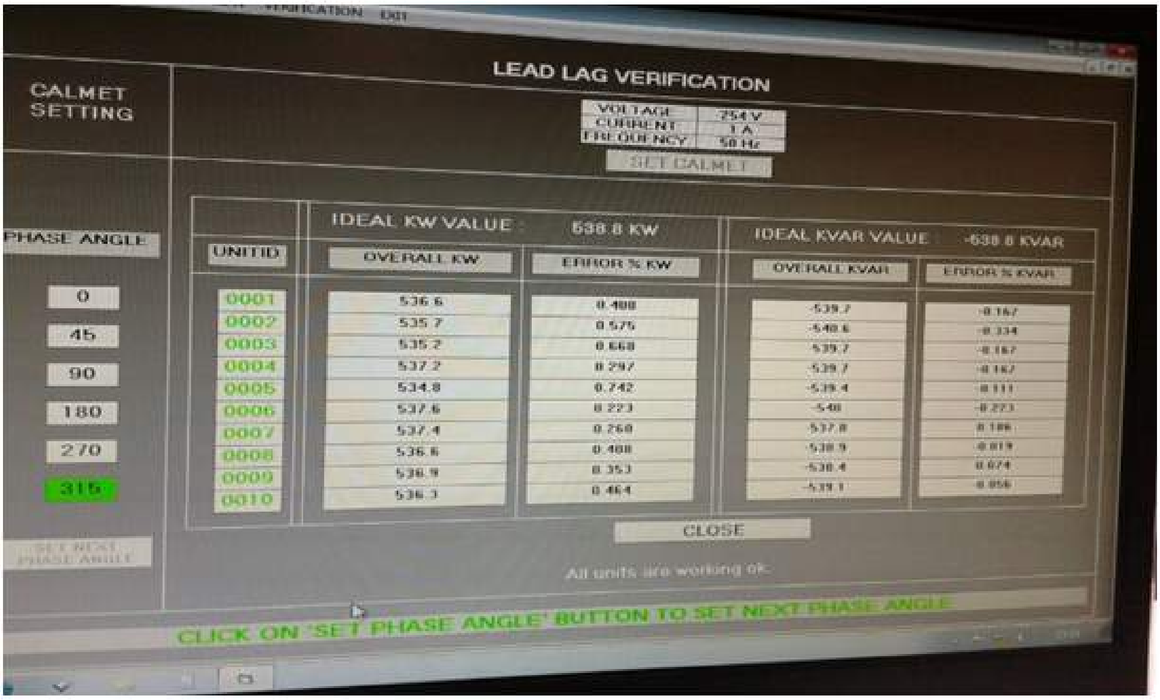


Figure 7.6: lead-lag verification for phase angle = 315°

7.4.3 Interchanging the Requirement of the Power

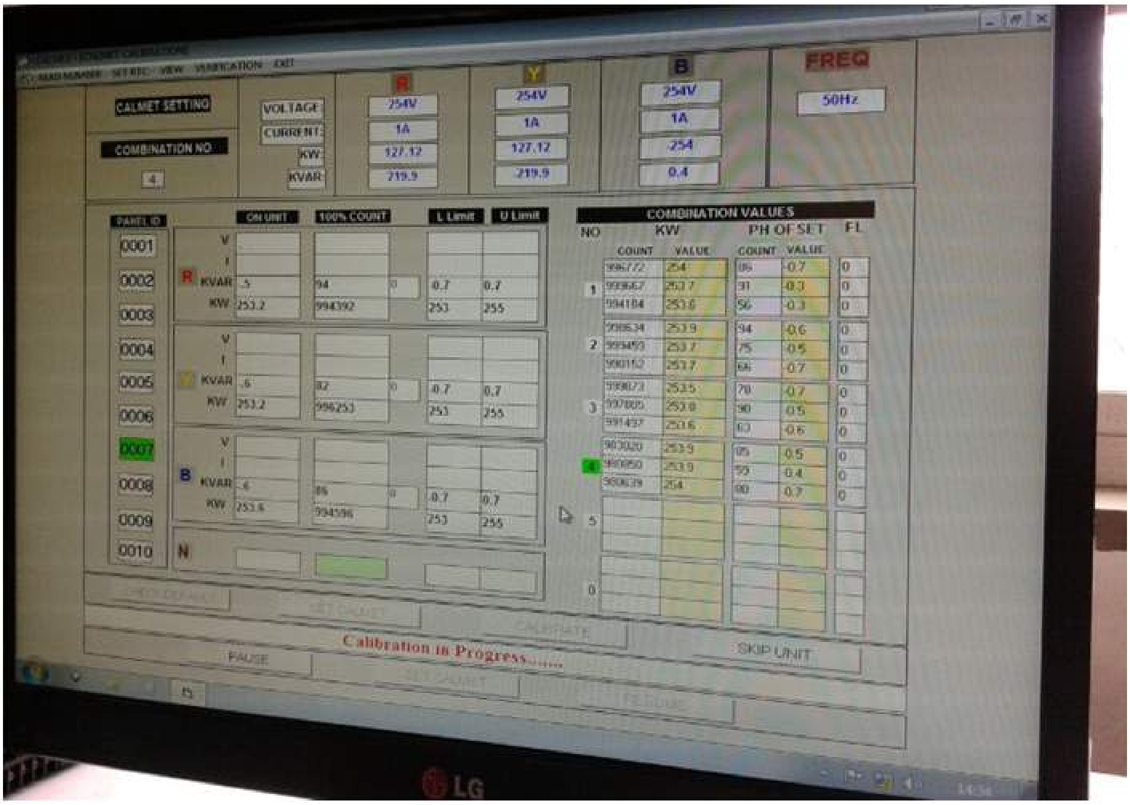


Figure 7.7: R-Y-B phase power: 127.12:127.12:-254(kW)

Figure 7.8: R-Y-B phase power: : -254:127.12:127.12(kW)

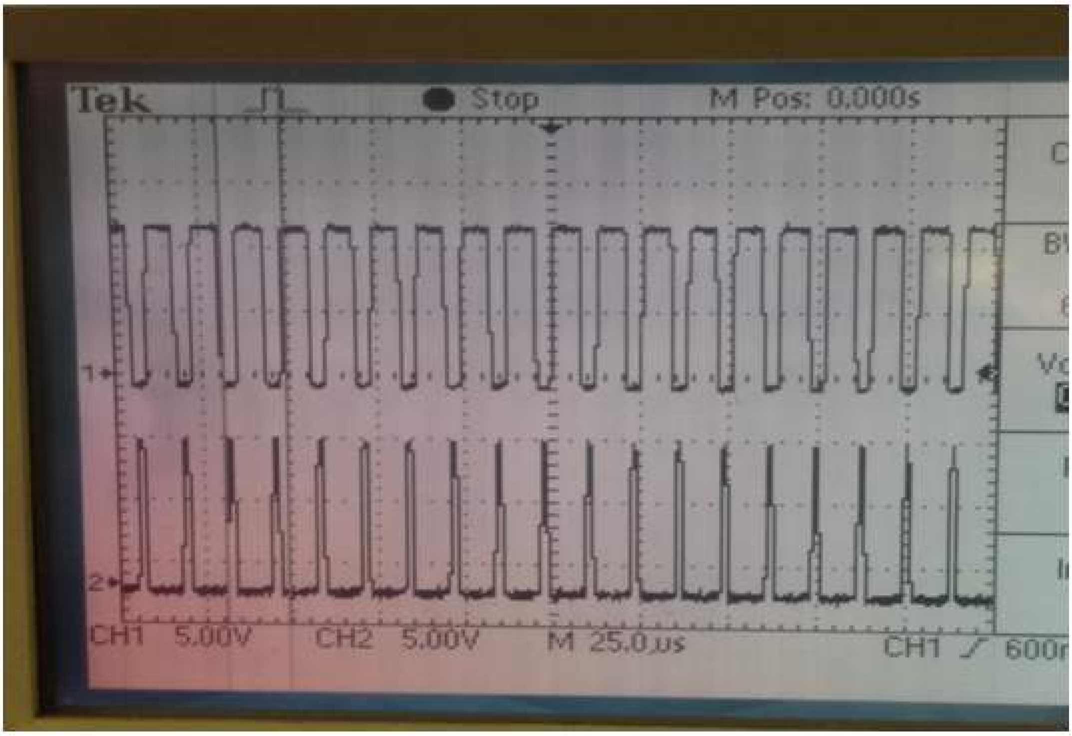


Figure 7.9: gate signals for single leg

Chapter 8

Conclusion and Future Work

8.1 Conclusion

From the Simulation and hardware implementation of STATCOM it can be seen that, from simulation Power Factor improves from 0.5005 to 0.9298 and using ARM-Cortex controller a dead band of 3.040μ sec is generated.

From the Hardware implementation and testing with it with CALMET software by varying phase angle, reactive power is compensated and power factor is improved. And required gate signals are also generated.

The voltage source is created from a DC capacitor and therefore a STATCOM has very little active power capability. However, its active power capability can be increased if a suitable energy storage device is connected across the DC capacitor. The reactive power at the terminals of the STATCOM depends on the amplitude of the voltage source.

The response time of a STATCOM is shorter than that of an SVC, mainly due to the fast switching times provided by the IGBTs of the voltage source converter. But a STATCOM has better characteristics than a SVC. The STATCOM also provides better reactive power support at low AC voltages than an SVC, since the reactive power from a STATCOM decreases linearly with the AC voltage (as the current can be maintained at the rated value even down to low AC voltage). In addition, the speed of response of a STATCOM is faster than that of an SVC and the harmonic emission is lower. On the other hand STATCOM typically exhibit higher losses and may be more expensive than SVC.

8.2 Future Work

- Completing the whole unit assembling and testing the unit on site. Regulate the voltage against sag/swell.
- Using ARM-Cortex implement for the harmonic analysis.

Appendix A
Hardware Setup View

Figure (a) - CALMET with 3-Phase Voltage & Current probe

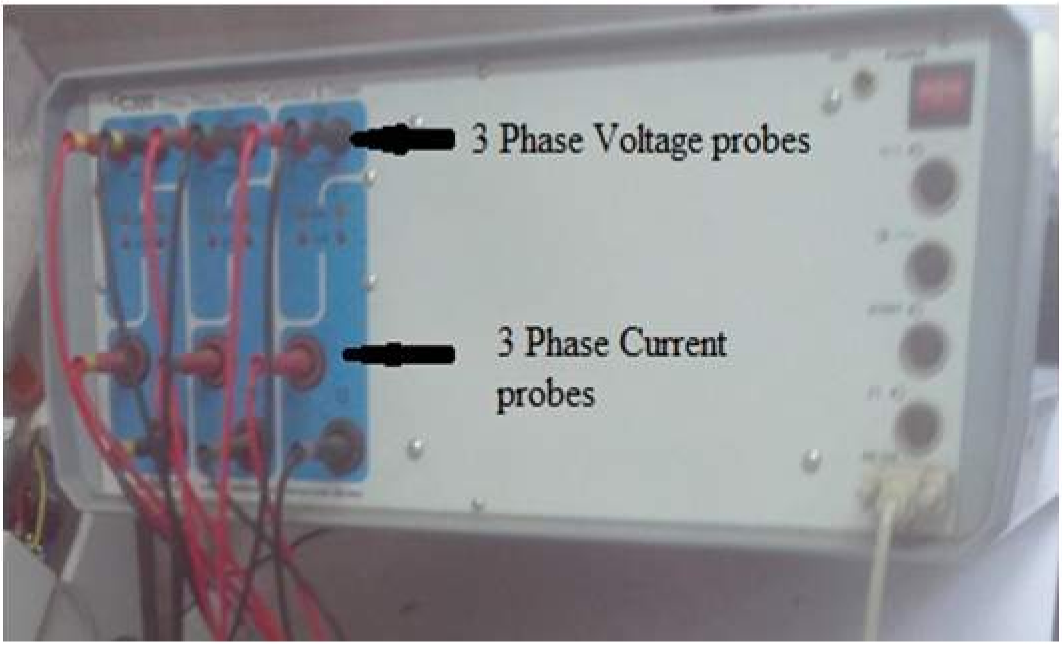


Figure (b) - Setup of ARM cortex M4 Calibrating with CALMET and its adapter

Figure (c) - CALMET adapter Card

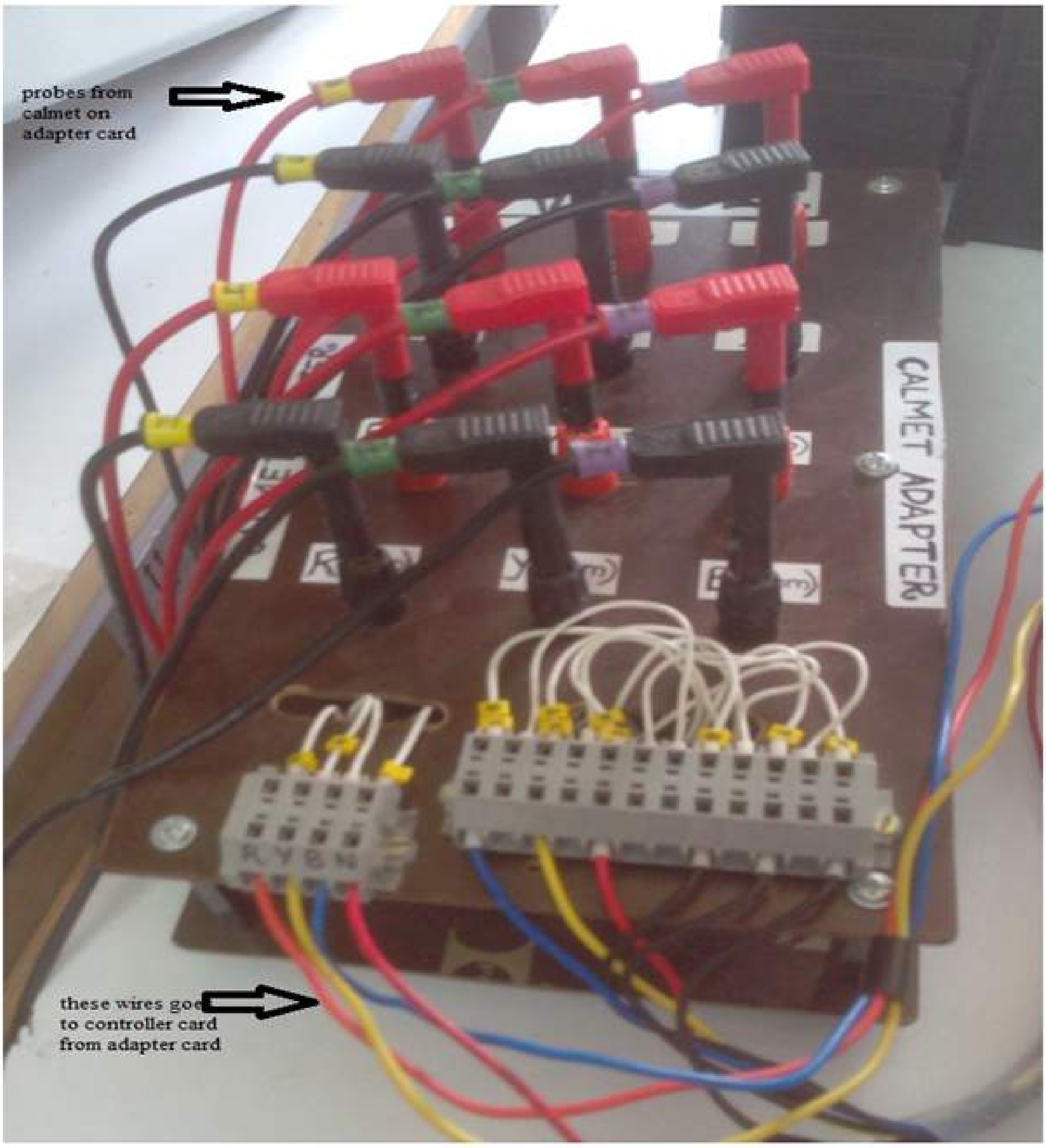
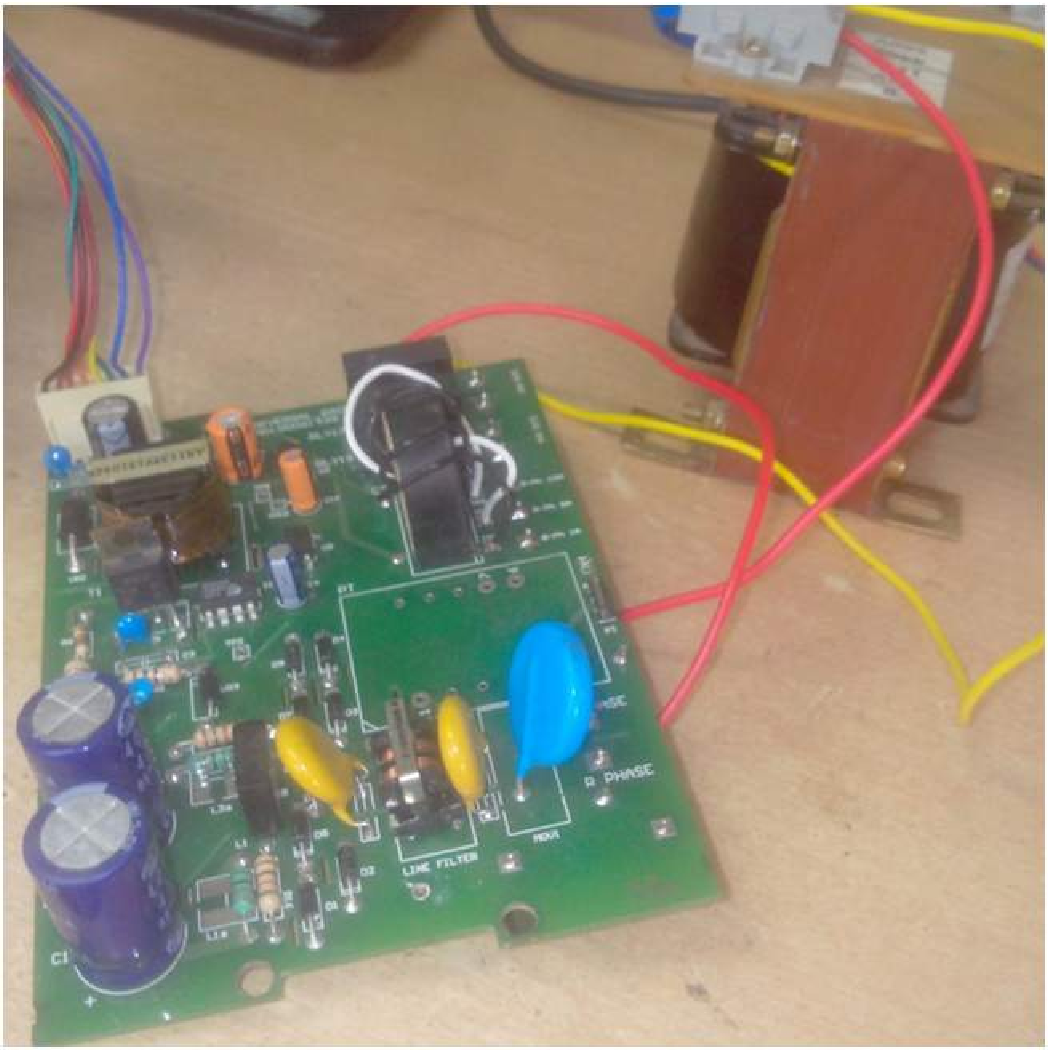
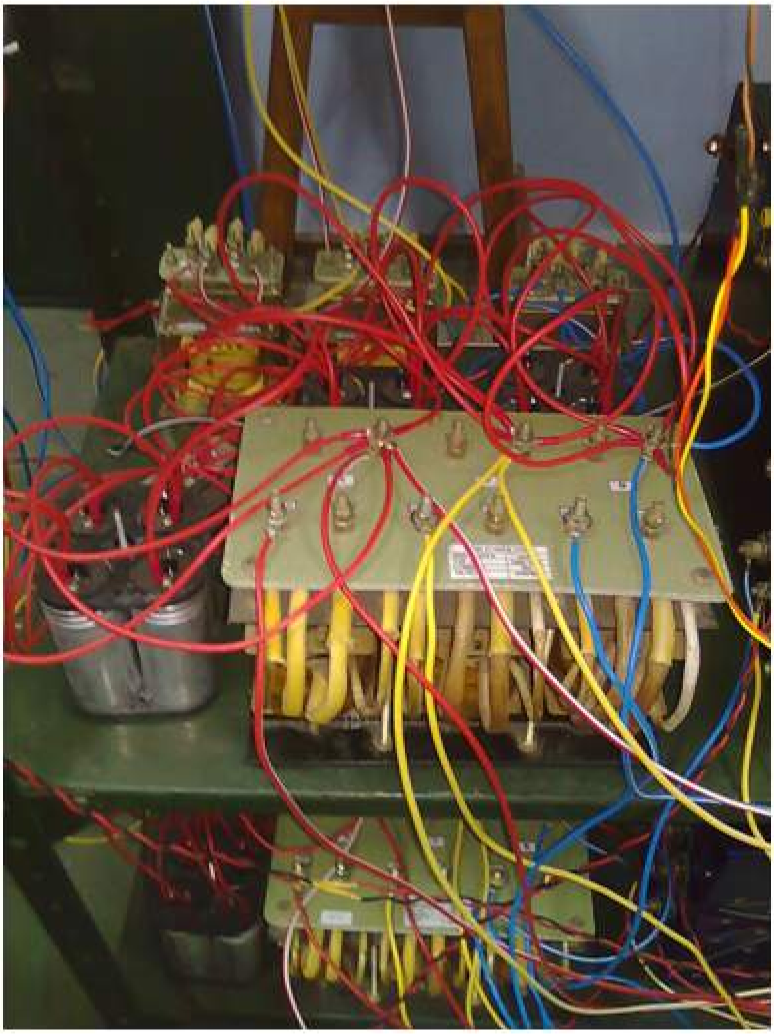


Figure (d) - Supply card(SMPS) for ARM controller



This SMPS is of 8.4 Watts, only one secondary winding of 5.6V. This SMPS is using TNY278PN (tiny switch), Mosfet IRFBC20/IRF840, TL431

Figure (e) - IGBT setup for single stack



Appendix B
IC's Used

B.1 - IGBT Modules

(collector emitter voltage, Vces = 1700V; collector current, Ic =100A)

Maximum Ratings (T_j=25°)

Symbols	Parameter	condition	Ratings	Unit
V_{CES}	Collector-emitter voltage	G-E short	1700	V
V_{GES}	Gate-emitter voltage	C-E short	+/- 20	V
I_C	Collector current	T_c= 25°C	100	A
I_{CM}	Collector current	Pulse (Note2)	200	A
I_E (Note1)	Emitter current	T_c= 25°C	100	A
I_{EM} (Note1)	Emitter current	Pulse (Note2)	200	A
P_C (Note3)	Maximum collector dissipation	T_c= 25°C	890	W
T_j	Junction temperature		-40 ~ +150	°C
T_{stg}	Storage voltage		-40 ~ +150	°C
V_{sio}	Isolation voltage	Terminals to base plate, f= 60Hz, AC 1 minute	3500	V_{rms}
-	Torque strength	Main terminals M6 screw Mounting M6 screw	3.5 4.5 3.5 4.5	N.m N.m
-	Weight	Typical value	400	G

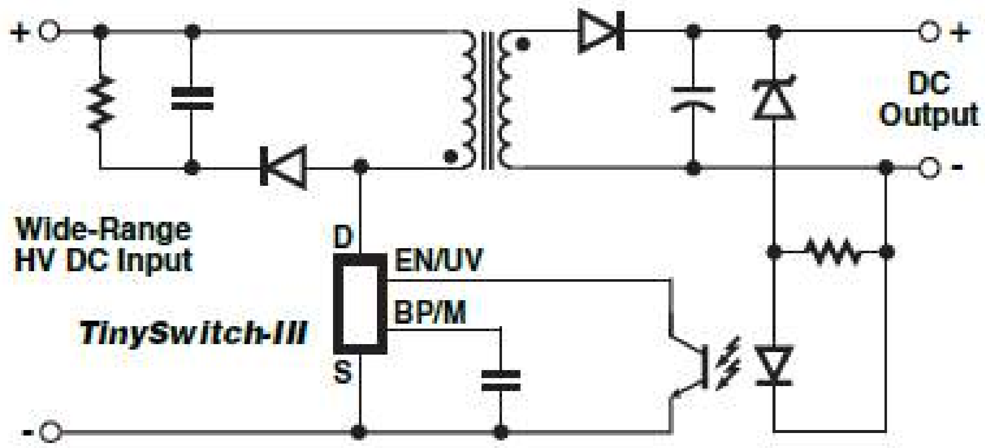
Electrical Characteristics (T_j=25°)

Symbols	Parameter	Test condition	Limits Min	Limits type	Limits Max	Unit
I_{CES}	Collector cut off current	V_{CE}= V_{CES}, V_{GE}= 0V	-	-	1	mA
$V_{GE(th)}$	Gate-emitter threshold voltage	I_C= 10mA, V_{CE}= 10V	4	5.5	7	V
I_{GES}	Gate leakage current	+/-V_{GE}= V_{GES}, V_{CE}=0V	-	-	0.5	µA
$V_{CE(sat)}$	Collector- emitter saturation voltage	I_C= 100A, V_{GE}= 15V; Tj= 25°C/125°C	- -	3.2 3.8	4.0 -	V
C_{ies}	Input capacitance	V_{CE}= 10V, V_{GE}= 0V	-	-	14	nF
C_{oes}	Output capacitance	V_{CE}= 10V, V_{GE}= 0V	-	-	2.4	nF
C_{res}	Reverse transfer capacitance	V_{CE}= 10V, V_{GE}= 0V	-	-	0.75	nF
Q_G	Total gate charge	V_{CC}= 1000V, I_C= 100A, V_{GE}=15V	-	450	-	nC
$t_{d(on)}$	Turn-on delay time	V_{CC}= 1000V, I_C= 100A V_{GE}= +/-15V R_G= 3.1Ω, inductive load I_E= 100A	-	-	350	ns
t_r	Turn-on rise time	V_{CC}= 1000V, I_C= 100A V_{GE}= +/-15V R_G= 3.1Ω, inductive load I_E= 100A	-	-	150	ns
$t_{d(off)}$	Turn-off delay time	V_{CC}= 1000V, I_C= 100A V_{GE}= +/-15V R_G= 3.1Ω, inductive load I_E= 100A	-	-	550	ns
t_f	Turn-off fall time	V_{CC}= 1000V, I_C= 100A V_{GE}= +/-15V R_G= 3.1Ω, inductive load I_E= 100A	-	-	800	ns
$t_{rr(note1)}$	Reverse recovery time	V_{CC}= 1000V, I_C= 100A V_{GE}= +/-15V R_G= 3.1Ω, inductive load I_E= 100A	-	-	600	ns
$Q_{rr(note1)}$	Reverse recovery charge	V_{CC}= 1000V, I_C= 100A V_{GE}= +/-15V R_G= 3.1Ω, inductive load I_E= 100A	-	5.8	-	µC
$V_{CE(note1)}$	Emitter- collector voltage	I_E= 100A, V_{GE}= 0V; (Tj=25° / 125°)	- -	- 2.2	4.6 -	V
$R_{th(j-c)}Q$	Thermal resistance	IGBT part (1/2 module)	-	-	0.14	k/W
$R_{th(j-c)}R$	Thermal resistance	FWDi part (1/2 module)	-	-	0.24	k/W
$R_{th(c-f)}$	Contact thermal resistance	Case to heat sink, thermal compound applied (1/2 module)	-	0.04	-	k/W
$R_{th(j-c')}Q$	Thermal resistance	Case temperature measured point is just under the chips	-	-	0.09	k/W

B.2 - TNY278PN (tiny switch)

Lowest System Cost with Enhanced Flexibility:

- Simple ON/OFF control, no loop compensation needed
- Selectable current limit through BP/M capacitor value
  - Higher current limit extends peak power or, in open frame applications, maximum continuous power
  - Lower current limit improves efficiency in enclosed adapters/chargers
  - Allows optimum TinySwitch-III choice by swapping devices with no other circuit redesign
- Tight I2f parameter tolerance reduces system cost
  - Maximizes MOSFET and magnetics power delivery
  - Minimizes max overload power, reducing cost of transformer, primary clamp & secondary components
- ON-time extension - extends low line regulation range/hold-up time to reduce input bulk capacitance
- Self-biased: no bias winding or bias components
- Frequency jittering reduces EMI filter costs
- Pin-out simplifies heatsinking to the PCB
- SOURCE pins are electrically quiet for low EMI



Enhanced Safety and Reliability Features:

- Accurate hysteretic thermal shutdown protection with automatic recovery eliminates need for manual reset
- Improved auto-restart delivers less than 3% of maximum power in short circuit and open loop fault conditions
- Output overvoltage shutdown with optional Zener
- Line under-voltage detect threshold set using a single optional resistor
- Very low component count enhances reliability and enables single-sided printed circuit board layout
- High bandwidth provides fast turn on with no overshoot and excellent transient load response

- Extended creepage between DRAIN and all other pins improves field reliability

B.3 - Mosfet IRFBC20/IRF840

Product Summary:

$V_{DS} = 500V$

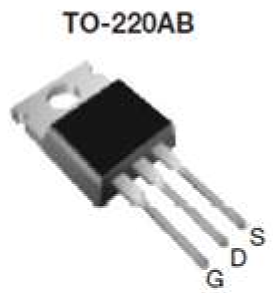
$R_{DS(on)}$, $V_{GS} = 10V$; 0.85Ω

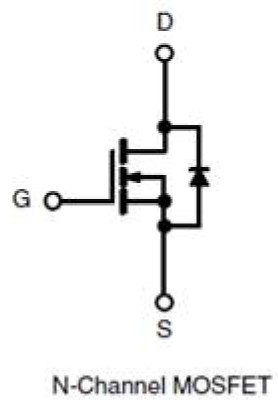
Q_g (Max) $= 63nC$

$Q_{gs} = 9.3nC$

$Q_{gd} = 32nC$

Configuration - Single





Features:

- Dynamic dV/dt Rating
- Repetitive Avalanche Rated
- Fast Switching

- Ease of Paralleling
- Simple Drive Requirements
- Compliant to RoHS Directive 2002/95/EC

Description:

Third generation Power MOSFETs from Vishay provide the designer with the best combination of fast switching, ruggedized device design, low on-resistance and cost-effectiveness. The TO-220AB package is universally preferred for all commercial-industrial applications at power dissipation levels to approximately 50 W. The low thermal resistance and low package cost of the TO-220AB contribute to its wide acceptance throughout the industry.

B.4 - TL431/TL431A (Programmable Shunt Regulator)

Features:

- Programmable Output Voltage to 36 Volts
- Low Dynamic Output Impedance 0.2Ω Typical
- Sink Current Capability of 1.0 to 100mA
- Equivalent Full-Range Temperature Coefficient of 50ppm/^{o}C Typical
- Temperature Compensated For Operation Over Full Rated Operating Temperature Range

- Low Output Noise Voltage
- Fast Turn-on Response

1. Ref 2. Anode 3. Cathode

Description:

The TL431/TL431A are three-terminal adjustable regulator series with a guaranteed thermal stability over applicable temperature ranges. The output voltage may be set to any value between VREF (approximately 2.5 volts) and 36 volts with two external resistors These devices have a typical dynamic output impedance of 0.2?. Active output circuitry provides a very sharp turn-on characteristic, making these devices excellent replacement for zener diodes in many applications.

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