Power quality improvement by using DSTATCOM

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Dedicated to

My parents & Guru

Abstract

Distribution system, as the name suggest, is the medium through which power is distributed among the end consumers. Distribution systems are comparatively not as stiff as grid systems, so objectionable voltage drop due to the increase of RL load could be critical for the entire system. Thus DSTATCOM is an effective solution for power systems facing such power quality problems.

This report deals with one of the potential applications of distribution static compensator (DSTATCOM) to industrial systems for mitigation of voltage sag problem.

The model of DSTATCOM connected in shunt configuration to a three phase source feeding RL loads is developed using Simulink of MATLAB software. Simulated results demonstrate that DSTATCOM can be considered as a viable solution for solving such voltage dip problems. This thesis work aims at developing a DSTATCOM for inductive and resistive loads with reduced voltage sag.

Nomenclature

R_f	Filter resistance
L_f	Filter inductance
C_f	Filter capacitance
i_o	Output current
V_i	Output voltage of DSTATCOM
V_s	System voltage
	Power angle
PCC	Point of common coupling
K_p	Proportional gain constant
K_i	Integral gain constant
V_{DC}	DC link voltage
V_{DC}^*	Reference DC link voltage
V_O	PCC voltage
m_{dc}	DC link voltage regulation
m_d	AC side voltage regulation
m_d	AC side voltage regulation

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Chapter 1

Introduction

1.1 Overview

One of the most common power quality problems today is voltage fall/dip at load terminals. A voltage dip is an event which occurs when the operating voltage is less than its actual rating due to excess reactive power consumption by the load. Voltage fall will affect the working of sensitive loads there by decreasing the system performance. In a three-phase system, voltage dip by nature is a three-phase phenomenon, which affects both the phase-to-ground and phase-to-phase voltages. A voltage dip is also caused by a fault in the utility system, a fault within the customer's facility or a large increase of the load current, like starting a motor or transformer energizing.

Improved power quality is the driving force for today's modern industry. Consumer awareness regarding reliable power supply has increased enormously in the last decade. This has led to an additional bump to the development of small distributed generation (DG). Small isolated DG sets have the capability to feed local loads and thus leads to improvement in reliability of power with low capital investment. These systems are also gaining increased importance in isolated areas where transmission using overhead conductors or cables is unrealistic or prohibitive due to excessive cost and other circumstances. Small generation systems in rural areas, islands, hilly terrains, off shore plants, aircrafts etc. can be efficiently utilizing even in developing countries.

However, these DG sets may have to be de-rated if induction motor loads are simultaneously started. One useful choice is to use DSTATCOM in shunt configuration with the main system so that the full capacity of generating sets is efficiently utilized.

DSTATCOM consists of a voltage source converter (VSC) and its internally generates the required capacitive and inductive reactive power. Its control is very fast and has the capability to provide adequate reactive power compensation to the system to which it is connected.

Before DSTATCOM, Thyristor based systems were proposed for reactive power compensation and were used for voltage flicker reduction due to arc furnace loads.

However, due to disadvantages of passive devices such as fixed compensation, large size, possibility of resonance etc., the use of new compensators such as DSTATCOM is growing to solve these power quality problems.

The use of DSTATCOM for solving power quality problems due to voltage fall/dip, flickers, swell etc, has been suggested. The purpose of DSTATCOM is to provide efficient voltage regulation at point of common coupling (PCC) and thus prevent large voltage dips.

1.2. Voltage sag and factors creating of voltage sag

1.2.1. Voltage sag

A voltage sag is an event which occurs when the operating voltage is less than its actual rating due to excess reactive power consumption by the load.This will affect the working of sensitive loads there by decreasing the system performance.

The main symptoms of voltage sag are low voltage profiles, heavy reactive power flows, inadequate reactive support, and heavily loaded systems. The collapse is often precipitated by low-probability single or multiple contingencies. The consequences of collapse often require long system restoration, while large groups of customers are left without supply for extended periods of time. Schemes which mitigate against sag need to use the symptoms to diagnose the approach of the collapse in time to initiate corrective action**.**

1.2.2. Factors creating voltage sag:

1.2.2.1. Short circuit faults

Among Symmetrical and unsymmetrical short circuits, three phase short circuit has the most effect on the voltage. In order to determine the amount of the voltage sag in the radial model of the distribution system, the voltage divider model can be used as illustrated in Fig. 1. In this figure, impedance Z_S is the source impedance at the point of common coupling (PCC) and Z_F is the impedance between the PCC and fault point.

$$V_{sag} = \frac{Z_F}{Z_F + Z_S}$$

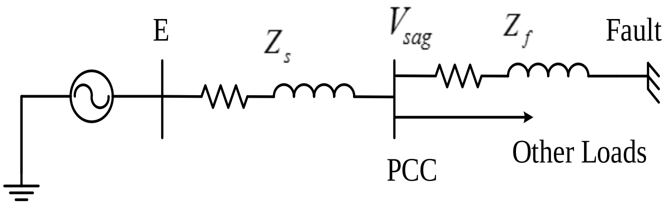


Figure 1.1 Voltage divider model for computing voltage sag in a radial distribution system

1.2.2.2. Starting of the induction motors

The large induction motor start-up is another important factor that affects voltage sag. The starting current during start-up of an induction motor is around 5 to 6 times that of current in the normal operation. In order to explain the start-up phenomenon, the schematic diagram during the induction motor start-up is illustrated in Fig. 2. In the figure, Z_S is the source impedance and Z_M is the motor impedance during the start-up period.

$$V_{sag} = \frac{Z_M}{Z_M + Z_S} E$$

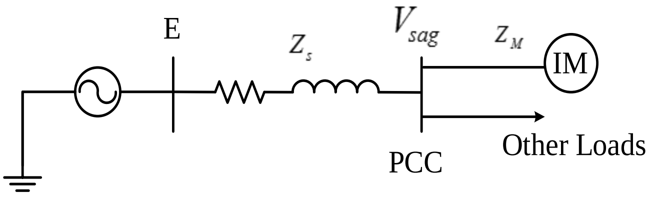


Figure 1.2 The equivalent circuit of the induction motor for the study of voltage sag

1.2.2.3. Distribution transformer energization

When the distribution transformer is energized, the inrush current of the transformer is drawn from the network. The inrush current is firstly huge and after a while it decays and reaches to the small magnetizing current. In order to compute the maximum value of the inrush current and its consequent voltage sag, the equivalent of a single transformer is shown in Fig. 3 Considering Fig. 3, the maximum of inrush current $I_{inrush\,max}$ should not exceed the following current.

$$I_{inrush\,max} = \frac{1}{X + X_P + X_{C,min}} E$$

Where X is the source impedance. The venin reactance at the bus of the energized transformer and $X_{C,min}$ is the minimum magnetizing reactance of the transformer. The impedance $X_{C,min}$ has typically the same value as $2(X_P + X_S)$ or $2X_T$ It is also assumed that X_T is the sum of the primary and secondary leakage reactance's, and it is available from the transformer nameplate. Assuming that the leakage reactance's of the primary and secondary windings are equal, the maximum voltage sag can be computed from:

$$V_{sag} = \frac{X}{X + 2.5X_T} E$$

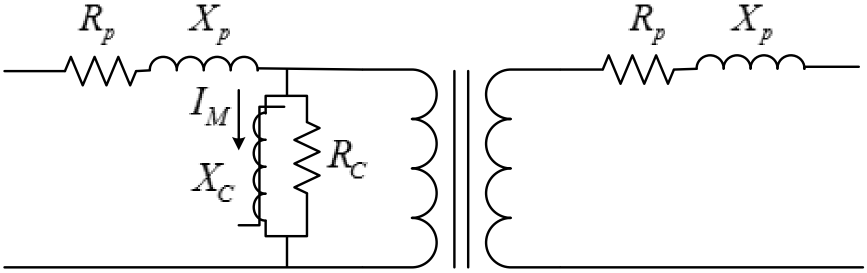


Figure 1.3 The equivalent circuit of the Transformer for the study of voltage sag

1.3 Literature Review

The power electronic devices, due to their intrinsic non-linearity draw reactive power and harmonics from the power supply. In three phase systems, they sometimes also cause unbalance and draw excessive neutral currents. The injected harmonics, reactive power burden, unbalance and excessive neutral currents degrades the system efficiency and poor power factor.

In addition to this, the power system is subjected to various transients like voltage sag, swell, flickers etc. These transients would affect the voltage at distribution levels. Excessive reactive power of loads would increase the generating capacity of generating stations and also increase the transmission line losses and it will also spoil the sensitive loads connected to the distribution system and there by decreases the total system performance. Nowadays, sensitive equipment's are being used in industries and the voltage sag in the power system is not acceptable. Hence supply of reactive power at the load ends becomes essential

Power quality has become an important issue since many loads at various distribution ends like adjustable speed drives, process industries, printers, domestic utilities, computers, microprocessors based equipments etc. have become intolerant to voltage sag, voltage fluctuations, harmonic content and interruptions.

Power quality mainly deals with issues like maintaining a fixed voltage at the PCC for various distribution voltage levels irrespective of voltage fluctuations, maintaining near unity power factor, blocking current unbalance from passing upwards from various distribution levels, reduction of voltage and current harmonics in the system and suppression of excessive supply neutral current.

Conventionally, passive LC filters and fixed compensating devices like thyristor switched capacitor, thyristor switched reactor were employed to improve the power factor of ac loads, but this devices have some demerits of fixed compensation, large size, ageing and resonance. The equipments using power semiconductor devices, generally known as active power filters, active power line conditioners etc., are used for the power quality issues due to their dynamic and adjustable solutions. among these devices STATCOM has turned out to be a promising tool for such quality improvements.

Here the STATCOM we call it as a DSTATCOM because our application is in distribution system, the basic difference between STATCOM and DSTATCOM is, When a STATCOM is employed at the distribution level or at the load end for power factor improvement and voltage regulation alone it is called D-STATCOM. The DSTATCOM which consists of a thyristor/ IGBT-based voltage source inverter, uses to provide voltage stabilization, power factor correction, harmonic control and a host of other power quality solutions for both utility and industrial applications.

The majority of power consumption has been drawn in reactive loads such as fans and pumps etc. These loads draw lagging power factor currents in the distribution systems. These excessive reactive power demand increases feeder losses and reduces the active power flow capability of distribution system which also affects the voltage profile. [1-2]

Voltage sag is the most important power quality problems faced by many industries and utilities. It contributes more than 80% power quality (PQ) problems that exist in power systems. According to definition, voltage sag is a reduction in RMS value in AC voltage at power frequency, for duration of a half cycles to a few seconds. [1]

Voltage sags are not tolerated by sensitive equipments used in modern industrial plants, such as process controllers, programmable logic controllers (PLC), adjustable speed drives (ASD), and robotics. It has been reported that high intensity discharge lamps used for industrial illumination get extinguished at voltage sags of 20% and industrial equipments like PLC and ASD are about 10%. [1-2]

The various factors like short circuit faults, starting of induction motors and transformer energization, creating voltage sag in the distribution system has been discussed. [3]

Various types of reactive power compensation devices like capacitor banks, series compensators, static VAR compensator and STATCOM and its advantages and disadvantages have been discussed. [4]

Control system for a PWM-Based STATCOM has explained the system configuration and modelling [5]

The control strategy of the STATCOM has been explained in the Direct Current Control Method of STATCOM and its Simulation, and Control of VSC-based STATCOM using conventional and direct-current vector control strategies [6-7]

Different types of filter design for the three phase inverter interfacing in distributed generation has been explained [8-9]

Whole control strategy of DSTATCOM with Voltage sourced convertor(VSC), Voltage controller, Current controller, DC link voltage control, Phase locked loop (PLL), abc/dq and dq/abc transformation and sinusoidal pulse width modulation (SPWM) has been explained [10-11]

The concept of Fast acting DC link design has been explained. This fast acting technique enable dc link voltage reach steady state value within no time. [12]

1.4 Objective of the Work

The objective of this work is to study the DSTATCOM and to improve the power quality so that it maintain Voltage magnitude close to nominal value by compensating the required amount of current to the distribution system from the storage element through DSTATCOM. The compensation resulting through operation of the DSTATCOM is to be investigated.

Chapter 2

Power quality

2.1 Introduction

Power quality is defined as the concept of powering and grounding sensitive equipment in a matter that is suitable to the operation of that equipment.

There are many different reasons for the enormous increase in the interest in power quality. Some of the main reasons are as explained below.

Electronics and power electronics equipment has especially become much more sensitive equipment has become less tolerant of voltage quality disturbances, production process have become less tolerant of incorrect of operation of equipment, and companies have become less tolerant of production stoppages. The main perpetrators are interruption and voltage dips, with the emphasis in discussions and in the literature being on voltage dips and short interruptions. High frequency transients do occasionally receive attention as cause of equipment malfunctions.

Equipment produces more current disturbances than it used to do both low and high power equipment is more and more powered by simple power electronic converters which produce a broad spectrum of distortion .there are indications that the harmonics distortion in the power system is rising, but no conclusive results are obtained due to the lack of large scale surveys.

Also energy efficient equipment is a source of power quality disturbance adjustable speed drives and energy saving lamps are both important sources of waveform distortion and are also sensitive to certain type of power quality disturbances. When these power quality problem become a barrier for the large scale introduction of environmentally friendly sources and users' equipment, power quality becomes an environmental issue with much wider consequences than the currently merely economic issues.

The deregulation of the electricity industry has led to an increased need for quality indicators. Customers are demanding, and getting, more information on the voltage quality they can expect.

With the advent of power semiconductor switching devices, like thyristors, GTO's (gate turn off thyristors), IGBT's (insulated gate bipolar transistors) and many more devices, control of electric power has become a reality. such power electronics controllers are widely used to feed electric power to electrical loads, such as adjustable speed drives (ASD's),furnaces, computer power supplies, HVDC system etc.

The power electronic devices due to their inherent non –linearity draw harmonics and reactive power from the supply. In three phase systems, they could also cause unbalance and draw excessive neutral currents. The injected harmonics, reactive power burden, unbalance, and excessive neutral currents cause low system efficiency and poor power factor.

In addition to this, the power system is subjected to various transients like voltage sags, swell, flickers etc. These transients would affect the voltage at distribution levels. Excessive reactive power of loads would increase the generating capacity of generating stations and increase the transmission losses in lines. Hence supply of reactive power at the load ends becomes essential.

Power quality has become an important issue since many loads at various distribution ends like adjustable speed drives, process industries, printers, domestic utilities, computers, microprocessors based equipments etc, have become intolerant to voltage fluctuations, harmonic content and interruptions.

Power quality mainly deals with issues like maintaining a fixed voltage at the point of common coupling for various distribution voltage levels irrespective of voltage fluctuations, maintaining near unity power factor power draw from the supply, blocking and current unbalance from passing upwards from various distribution levels, reduction of voltage and current harmonics in the system and suppression of excessive supply neutral current.

Conventionally, passive LC filters and fixed compensating devices with some degree of variation like thyristors switched capacitors, thyristor switched reactor were employed to improve the power factor of ac loads. Such devices have the demerits of fixed compensation, large size, ageing and resonance. Nowadays equipments using power semiconductor devices, generally known as active power filters, active power line conditioners etc. are used for the power quality issues due to their dynamic and adjustable solutions. The devices like STATCOM, DVR etc., deal with the issued related to power quality using similar control strategies and concepts. Basically, they are different only in the location in a power system where they are deployed and the objectives for which they are deployed.

2.2 Various Power Quality Problems

Power quality problems encompass a wide range of disturbances that can disrupt the operation of sensitive industrial loads and cause a loss of production.

- Voltage fall/dip
- Voltage swells/overvoltage
- Voltage flicker
- Voltage and current harmonic distortion
- Voltage and current transient
- Short interruptions
- Power frequency variation

Voltage fall/dip is sudden reduction in the supply voltage by a value of more than 10% of the reference value followed by a voltage recovery after a short period of time.

Under voltage is a voltage event in which the rms voltage is outside its normal operating margin for a certain period of time, or voltage magnitude event with a magnitude less than the nominal rms voltage, and a duration exceeding 1 minute

Swell it is a momentary increase in the rms voltage or current to between 1.1 and 1.8pu delivered by the mains ,outside of the normal tolerance, with a duration of more than one cycle and less than few seconds

Over voltage is voltage higher than the normal service voltage, such as might be caused from switching and lightning surges or abnormal voltage between two points of a system that is greater than the highest value appearing between the same two points under normal service conditions.

Voltage fluctuation is a special type of voltage variation in which the voltage shows changes in the magnitude and/or phase angle on a time scale of seconds or less. Severe voltage fluctuations lead light flicker

Harmonic distortion is the corruption of the fundamental frequency sine wave at frequencies that are multiple of fundamental (e.g., 180Hz is the third harmonics of a 60 Hz fundamental frequency; 3*60=180).

Current disturbance it is a variation of event during which the current in the system or at the equipment terminal deviates from the ideal sine wave.

Voltage disturbance it is a variation of event during which the voltage in the system or at the equipment terminal deviates from the ideal sine wave.

Voltage transient is a spike of voltage which is caused by a time delay in two devices switching or by noise on the line.

SAG is a decrease in rms voltage or current between 0.1 to 0.9 at the power frequency for duration of 0.5 to 1 minute.

Interruption is the voltage event in which the voltage is zero during a certain (or) a voltage magnitude event with a magnitude less than 10% of the nominal voltage

Power frequency variation is a frequency variations may cause a motor to run faster or slower to match the frequency of the input power.

Voltage tolerances is the immunity of a piece of equipment against voltage magnitude variations (sags, swells and interruption) and short over voltages

Chapter 3

Reactive power compensation

3.1 Introduction:

Reactive power is the power that supplies the stored energy in reactive elements. Power, as we know, consists of two components, active and reactive power. The total sum of active and reactive power is called as apparent power.

In AC circuits, energy is stored temporarily in inductive and capacitive elements, which results in the periodic reversal of the direction of flow of energy between the source and the load. The average power after the completion of one whole cycle of the AC waveform is the real power, and this is the usable energy of the system and is used to do work, whereas the portion of power flow which is temporarily stored in the form of magnetic or electric fields and flows back and forth in the transmission line due to inductive and capacitive network elements is known as reactive power. This is the unused power which the system has to incur in order to transmit power.

Inductors (reactors) are said to store or absorb reactive power, because they store energy in the form of a magnetic field. Therefore, when a voltage is initially applied across a coil, a magnetic field builds up, and the current reaches the full value after a certain period of time. This in turn causes the current to lag the voltage in phase. Capacitors are said to generate reactive power, because they store energy in the form of an electric field. Therefore when current passes through the capacitor, a charge is built up to produce the full voltage difference over a certain period of time. Thus in an AC network the voltage across the capacitor is always charging. Since, the capacitor tends to oppose this change, it causes the voltage to lag behind current in phase.

3.2 Devices used for reactive power compensation:

3.2.1 Capacitor bank
3.2.2 Series compensator
3.2.3 Static VAR compensator

a. Thyristor controlled reactor (TCR)

b. Thyristor switched capacitor (TSC)
c. Fixed capacitor (FC)

3.2.4 STATCOM

3.2.1 Capacitor bank:

Shunt capacitors are mechanically switched or fixed shunt capacitor banks installed at substations or near loads for keeping voltage with the required limit.

The Capacitor bank may be in star or delta connection, they generate leading VAR, hence compensating the lagging VAR, the value of capacitor should suffice the excessive lagging VAR.

Advantages:

1. Much lower cost compared to SVC's
2. Switching speed can be quite fast with current limiting reactors to minimize switching transients.

Disadvantages:

1. Reactive power output drops with the voltage squared
2. For transient voltage instability the switching may not be fast enough to prevent induction motor stalling
3. Precise and rapid control of voltage is not possible (capacitor banks are discrete devices, but they are often configured with several steps to provide a limited amount of variable control)
4. If voltage collapse results in a system, the stable parts of the system may experience damaging overvoltage, immediately following separation

3.2.2 Series compensator:

This kind of compensating technique, the capacitor is connected in series with the load. The voltage of the line inductance is compensated by the capacitor voltage, here the capacitor voltage is inversely proportional to capacitance. Hence the value of capacitance is chosen accordingly.

Advantages:

1. Reduces line voltage drops
2. Limits load dependent voltage drops
3. Influences load flow in parallel lines and increases transfer capability and system stability

Disadvantages:

1. Once capacitor in the line gets damaged, than the entire power flow scheme is interrupted.
2. Maintenance is difficult

3.2.3 Static VAR Compensator (SVC):

Static VAR Compensator is "a shunt-connected static VAR generator or absorber whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific parameters of the electrical power system (typically bus voltage)". SVC is based on thyristors without gate turn-off capability. The operating principal and characteristics of thyristors realize SVC variable reactive impedance. SVC includes two main components and their combination: Thyristor-controlled and Thyristor-switched Reactor (TCR and TSR); and Thyristor-switched capacitor (TSC).

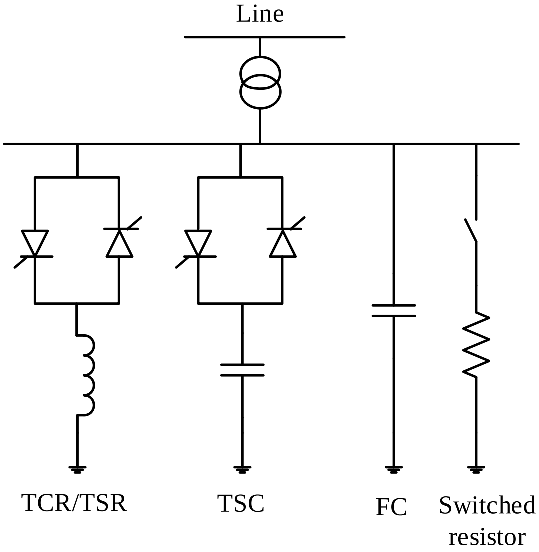


Figure 3.1: Static VAR compensator (SVC): TCR/TSR, TSC, FC and Mechanically switched resistor.

TCR and TSR are both composed of a shunt-connected reactor controlled by two parallel, reverse-connected thyristors. TCR is controlled with proper firing angle input to operate in a continuous manner, while TSR is controlled without firing angle control which results in a step change in reactance.

TSC shares similar composition and same operational mode as TSR, but the reactor is replaced by a capacitor. The reactance can only be either fully connected or fully disconnected zero due to the characteristic of capacitor.

With different combinations of TCR/TSR, TSC and fixed capacitors, a SVC can meet various requirements to absorb/supply reactive power from/to the transmission line.

3.2.4 STATCOM:

It is shunt connected power electronic devices. The major components of a STATCOM are shown in Figure 3.1. It consists of a dc capacitor, three-phase inverter (IGBT, thyristor) module, ac filter, coupling transformer and a control technique. The basic electronic block of the STATCOM is the voltage-sourced convertor that converts an input dc voltage into a three-phase ac output voltage at fundamental frequency in capacitive mode and it converts three phase ac voltage to dc voltage in inductive mode.

Advantages of STATCOM over SVC:

1. Maximum reactive current output will not be affected by the voltage magnitude. Therefore it exhibits constant current characteristics when the voltage is low under the limit.
2. SVC’s reactive power output is proportional to the square of the voltage magnitude, hence reactive power decreases rapidly when the voltage decreases, reducing system stability
3. Speed of response of the STATCOM is faster than SVC
4. Harmonics emission is lower than SVC.
5. In addition, a DSTATCOM device is more compact and requires only a fraction of the land required by an SVC installation.

Chapter 4

DSTATCOM and its components

4.1 Distribution Static Compensator (DSTATCOM)

The DSTATCOM is a three-phase and shunt connected power electronic devices. It is connected near the load of the distribution systems. The major components of a DSTATCOM are shown in Figure 3.1. It consists of a dc capacitor, three-phase inverter (IGBT, thyristor) module, ac filter, coupling transformer and a control technique. The basic electronic block of the DSTATCOM is the voltage-sourced convertor that converts an input dc voltage into a three-phase ac output voltage at fundamental frequency in capacitive mode and it converts three phase ac voltage to dc voltage in inductive mode.

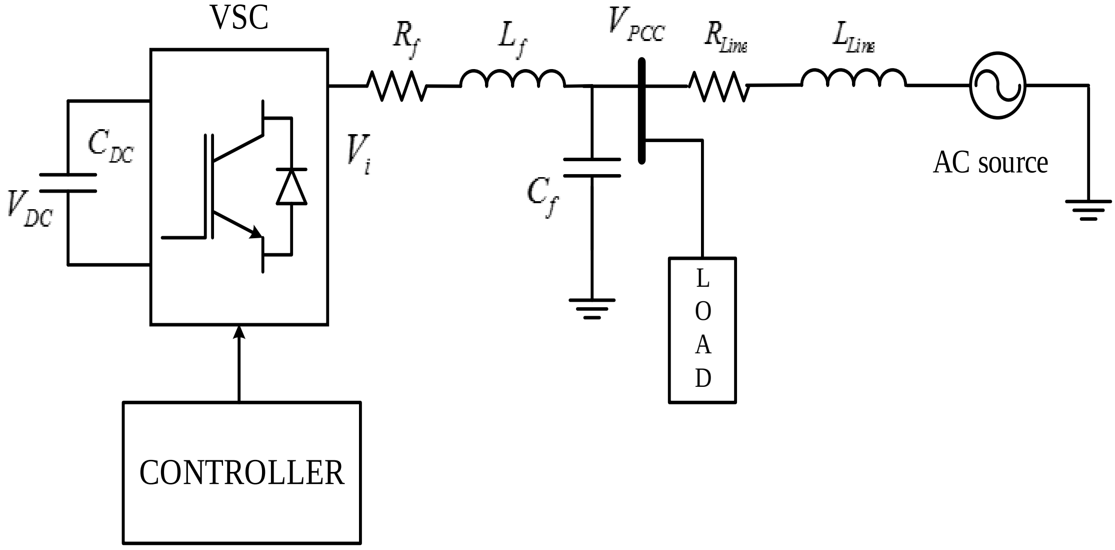


Figure 4.1: Basic building blocks of the DSTATCOM

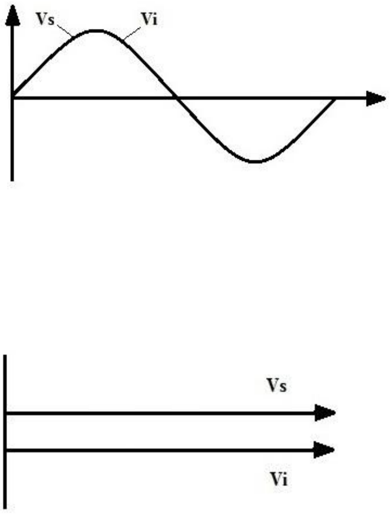
DSTATCOM uses an inverter to convert the DC link voltage V_{DC} on the capacitor to a voltage source of amendable magnitude and phase. Therefore the DSTATCOM can be treated as a voltage-controlled source. The DSTATCOM can also be seen as a current-controlled source.

Figure 3.1 shows the inductance L_f and resistance R_f which represent the equivalent circuit elements of the step-down transformer and the inverter is the main component of the DSTATCOM.

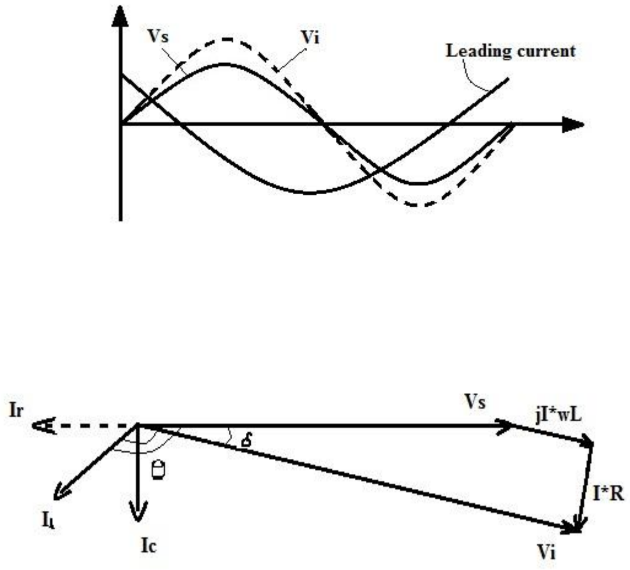
The voltage V_i is the effective output voltage of the DSTATCOM and δ is the power angle. The reactive power output of the DSTATCOM can be either inductive or capacitive depending on the operation mode of the DSTATCOM.

The controller of the DSTATCOM is used to operate the inverter in such a way that the phase angle between the inverter voltage and the line voltage is dynamically adjusted so that the DSTATCOM generates or absorbs the desired VAR at the point of connection. The phase of the output voltage of the IGBT-based inverter, V_i, can be controlled in the same way as the distribution system voltage, V_s.

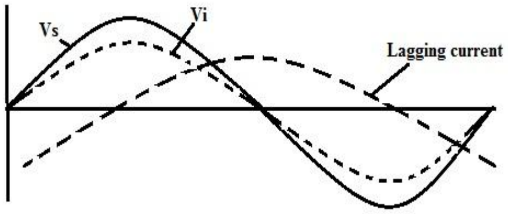
Figure 3.2 shows the three basic operation modes of the DSTATCOM output current (I), which varies depending upon voltage V_i. If V_i is equal to system voltage V_s, the reactive power is zero and the DSTATCOM does not generate or absorb reactive power. When V_i is greater than V_s, the DSTATCOM acts as an inductive reactance connected at its terminal. The current, I, flows through the transformer reactance from the DSTATCOM to the ac system, and the device generates capacitive reactive power. If V_s is greater than $V_i$the DSTATCOM acts as a capacitive reactance connected to its terminal. Then the current flows from the ac system to the DSTATCOM, resulting in the device to absorb inductive reactive power.

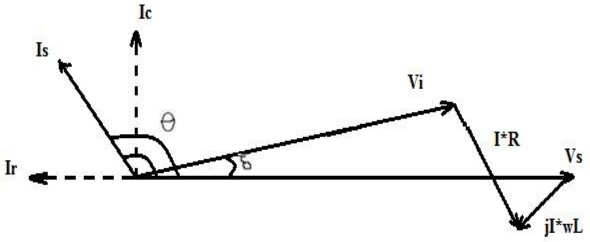


(a) No-Load mode (V_s=V_i)



(b) Capacitive mode (V_i >V_s)





(c) Inductive mode (V_i<V_s)

Figure 4.2: Operation modes of DSTATCOM

4.2 Main Features of DSTATCOM

- Voltage regulation and compensate of reactive power.
- Power factor correction.

4.3 DSTATCOM Controllers

- P controller
- PI Controller
- Hysteresis controller

Chapter 5

Control Architecture

5.1 Basic structure of DSTATCOM:

Figure 5.1 shows the schematic control diagram of DSTATCOM with source and RL load, for providing voltage regulation at the PCC.

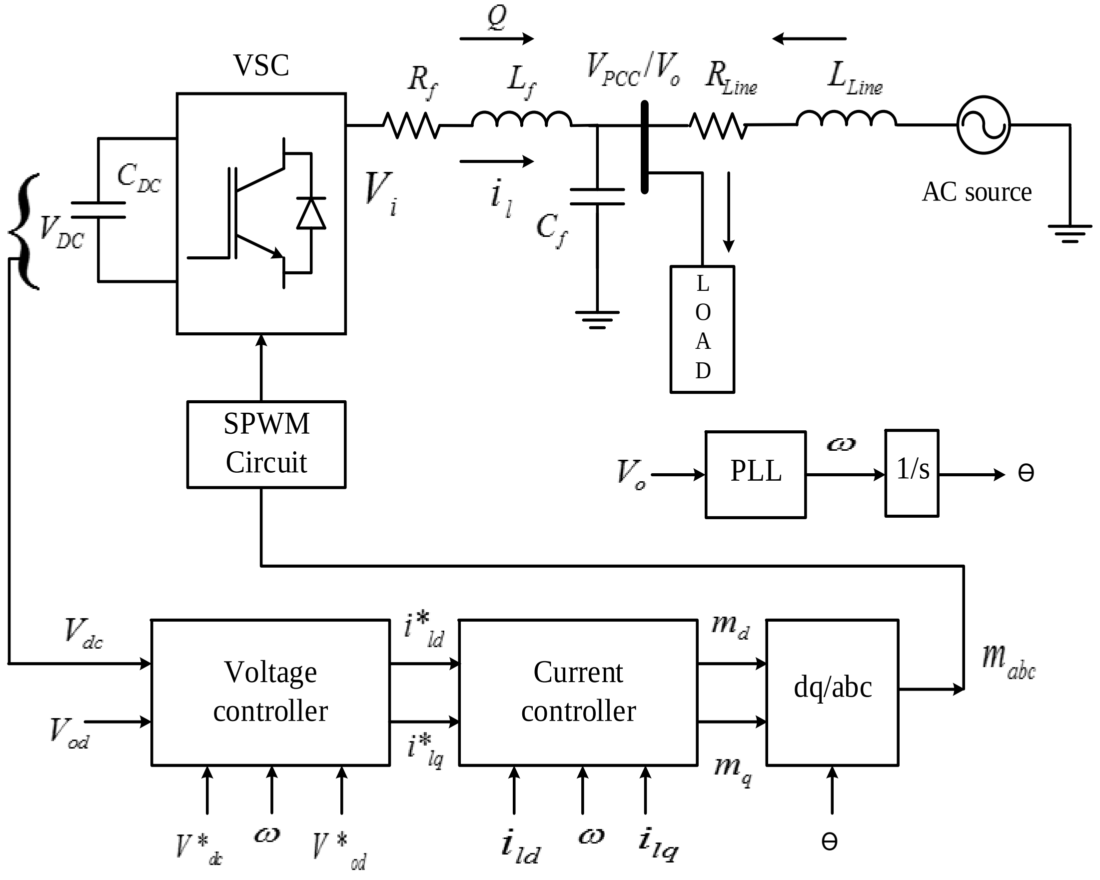


Figure 5.1: Schematic control architecture of DSTATCOM connected to the source and load.

Figure 3.6 shows the basic working diagram of DSTATCOM connected as shunt compensator. It consists of a three-phase, self-commutated inverters using IGBT as current controlled voltage source converter (CC-VSC) and an electrolytic DC capacitor.

The DC bus capacitor in this case is used to provide a self-supporting DC bus. The IGBT inverter with a DC voltage source can be modelled as a variable voltage source

in capacitive mode. AC output terminals of the DSTATCOM are connected through filter reactance or reactance of the connecting transformer. These all together known as DSTATCOM and thus provides fast and efficient reactive power compensation

Here the below figure 5.2 shows the schematic diagram of 3-legged DSTATCOM system which has been used.

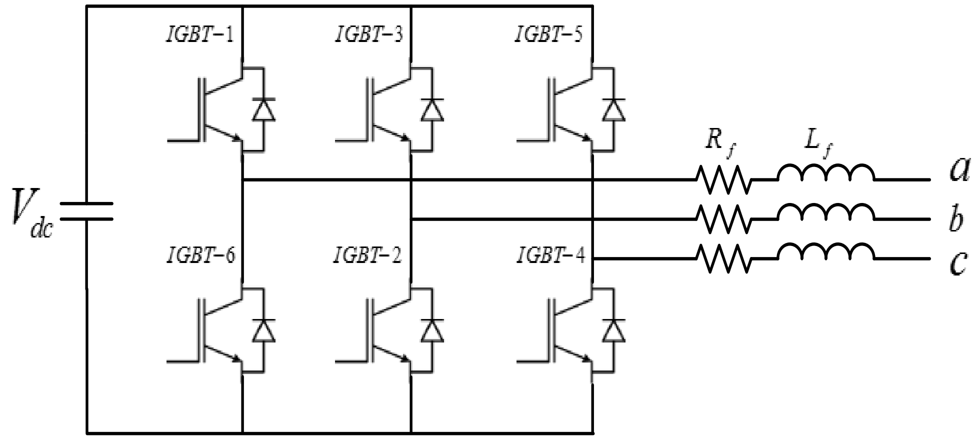


Figure 5.2: Schematic diagram of 3-legged DSTATCOM system

5.2 Control Scheme:

D-STATCOM is similar to the control of an conventional VSC with inner current control and outer voltage control loops. Here, DC link voltage control is required in addition with conventional VSC control.

In steady state, the active and reactive powers injected by the device are 0 and Q_{ref} respectively.

These active and reactive powers are governed by DC link voltage and AC voltage magnitude respectively.

Here for outer voltage control loops we use two PI controllers. One PI controller scheme is realized over the sensed and reference values of dc bus voltage of the DSTATCOM. The second PI controller is realized over the sensed and reference values of ac voltage at PCC.

And for inner current control loops we use two PI controllers. One PI controller scheme is realized over the sensed and reference values of active current component of the DSTATCOM. The second PI controller is realized over the sensed and reference values of reactive current component of the DSTATCOM.

5.3 Filter Design:

Inverter output voltage contains high frequency switching harmonics which are to be filtered before feeding the load. A typical second order low pass filter can be used to avoid harmonics of order of switching frequency or multiples of it. A second order filter gives better attenuation than first order at any given frequency. So, an LC filter is preferred over L filter.

Filter	Order	Attenuation	Resonating Frequency
L	First	-20 dB/decade	----
LC	Second	-40 dB/decade	$f_O = \frac{1}{2\pi\sqrt{LC}}$
LCL	Third	-60 dB/decade	$f_O = \frac{1}{2\pi}\sqrt{\frac{L_1+L_2}{L_1L_2C}}$

Table I: Properties of filter.

The design procedure of LC filter is clearly explained in the below section as follow,

5.3.1 LC Filter:

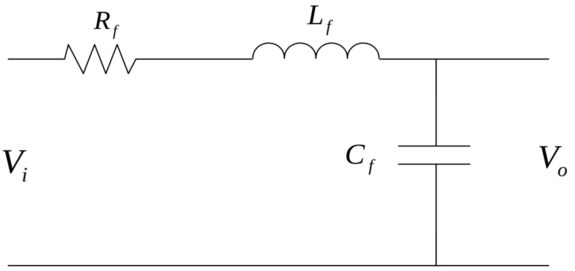


Figure 5.3: Practical LC filter.

Design Procedure:

Transfer function of above system is,

$$G(s) = \frac{V_o(s)}{V_i(s)} = \frac{1}{L_f C_f s^2 + R_f C_f s + 1}$$

Comparing it with standard second order characteristic equation,

$$s^2 + 2\xi w_n s + w_n^2 = s^2 + \frac{R_f}{L_f} s + \frac{1}{L_f C_f}$$

Resonating frequency, $w_o = \frac{1}{\sqrt{L_f C_f}}$, resonant peak, $Q = \frac{1}{R_f}\sqrt{\frac{L_f}{C_f}}$

Voltage drop in the filter is expressed as, $V = L_f \frac{\Delta I}{\delta\, T_s} + (\Delta I) R_f$

Where ΔI is the maximum allowable current ripple in the inductor.

δ is the duty ratio.

T_s is switching time period.

As per IEEE standards 519-1992, the allowable range of ripple is 15 - 20% of rated current.

Rated current of output/load,

$$I = \frac{S}{V}$$

Where S and V are apparent power and voltage rating of load respectively.

Select resonating frequency f_o to be $\frac{1}{10}$ of switching frequency f_s to get 40 dB attenuation.

$$20\log(\frac{w_s}{w_o})^2 = 40$$

Choose ξ in the limits $0 < \xi < 1$ to get stable response.

Inverter specifications:

Rating of inverter = 20 KVA

RMS output voltage = 400 V

Switching frequency = 2 kHz

DC bus voltage = 1200 V

Modulation index = 0.97

AC system frequency = 50 Hz

Duty ratio of pulses = 0.75

Damping ratio = 0.5

Percentage of current ripple = 15%

Calculated filter parameters:

$R_f = 0.29488\ \Omega$

$L_f = 1.47441\ mH$

$C_f = 0.4294963\ mF$

5.4 Current Controller:

The compensator of current controller process the error signal and generates reference voltage signal for inverter operation of DSTATCOM. This reference signal is given the SPWM circuit to generate the required gate pulses. Current controller forms the inner loop with outer voltage control loop in the closed loop control plant. Stability of closed loop plant with both voltage and current control loops is enhanced by proper tuning of voltage and current controllers. This can be done by performing stability analysis using available control techniques. Another important feature of current controller is its inherent capability to limit the DSTATCOM output current.

Current controller will push the error signal to zero in steady state. Therefore, the reference voltage signal is mainly due to feed forward voltage terms. Here, the dq components are decoupled by adjusting the voltages $(I_q w L_f)$ and $(I_d w L_f)$ in V_d and V_q respectively.

The voltage relation of interface filter form the basis for current control.

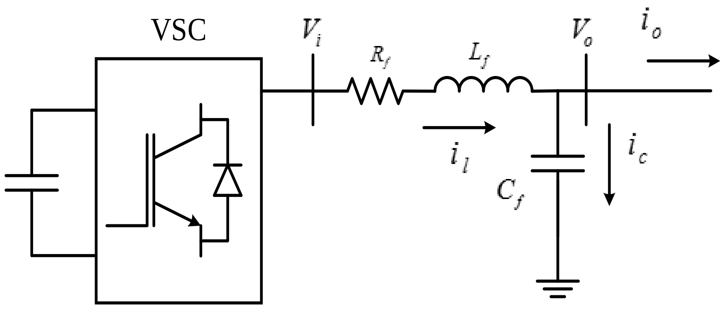


Figure 5.4: Basic diagram of the system

Here we need to control filter inductor current,

$$V_i - V_O = i_l R + L_f \frac{di_l}{dt}$$

Above equation is writing in d-q form as follows,

$$\left(V_{id} + jV_{iq}\right) - (V_{od} + jV_{oq}) = (i_{ld} + ji_{lq})R + L_f \frac{d}{dt}(i_{ld} + ji_{lq})$$

Comparing real and imaginary parts and extracting differential equation for d and q components, we get,

$$\frac{di_{ld}}{dt} = \frac{V_{id} - V_{od} - Ri_{ld} + i_{lq}wL}{L}$$

$$\frac{di_{lq}}{dt} = \frac{V_{iq} - V_{oq} - Ri_{lq} + i_{ld}wL}{L}$$

From the above equations we'll get dq based current controller which is shown in below figure 5.5

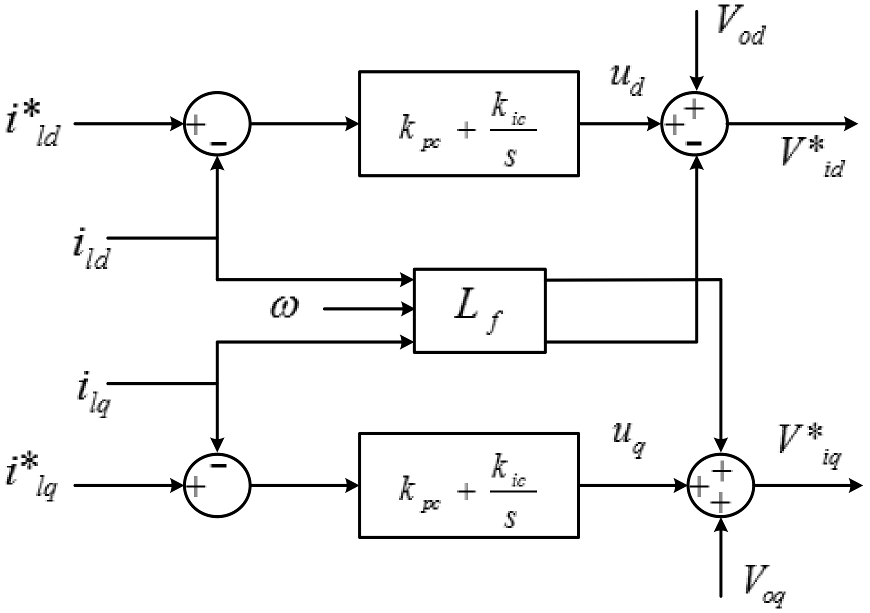


Figure 5.5: Current controller

Proportional Integral (PI) control logic is used to process error signals for getting control variables. The control variables u_d and u_q are further processed with $(V_{od} - i_{lq}wL_f)$ and $(V_{oq} + i_{ld}wL_f)$ to generate V_{id} and V_{iq} respectively. Modulated voltage signals are obtained from the output signals V_{id} and V_{iq} which again converted into abc domain. The final signals in abc domain are used as reference signals in Sinusoidal Pulse Width Modulation (SPWM) to generate gate pulses for VSI.

The below figure shows the control diagram of tuning of PI controller for the current controller,

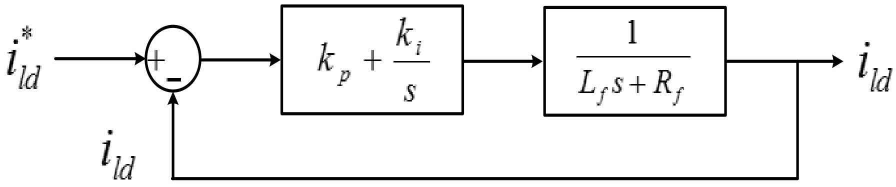


Figure 5.6: d-axis closed loop current controller

The equivalent block diagram of d-axis closed loop controller is shown in above figure. The control circuit for both d and q axes are same. Therefore the compensator gains for both the controllers will be same

The open loop gain of above system is,

$$G(s) = \frac{k_p(s + \frac{k_i}{k_p})}{sL_f(s + \frac{R_f}{L_f})}$$

The open loop system will have a pole at origin and $-\frac{R_f}{L_f}$. The effect of pole at $-\frac{R_f}{L_f}$ will be overcome by keeping zero at same location through pole-zero cancellation.

Therefore, $\frac{R_f}{L_f} = \frac{k_i}{k_p}$

Now, the open loop transfer function is reduced to, $G(s) = \frac{k_p}{sL_f}$

The closed loop transfer function will be in the form of $\left(\frac{1}{1+s\tau_i}\right)$

Where, $\tau_i = \frac{L_f}{k_p}$ is the time constant of the system which will be adequately small in the order of mille seconds.

5.5 Voltage controller:

Voltage controller maintains the actual voltage close to its nominal value. It takes proportional or Proportional Integral (PI) control action over error in voltage signals and generates current reference commands. These reference commands are given to current controller for further control action. Voltage controller is designed using classical control techniques as per system specifications.

5.5.1 Proportional controller/Regulation:

The objective of STATCOM is to deliver required reactive power to the load terminals by taking active power from the system. The consumed active power will appear as energy stored in the DC link capacitor. DC link voltage is controlled from the coupling relation with AC side power. A simple regulation concept is applied between V_{DC} and P_{ac}, V_d and Q_{ref}

It is basically proportional control action over error in DC link voltage. The slope of above characteristics give the regulation coefficient. It is calculated from the basic mathematical relation,

$$m_{dc} = \frac{\Delta V_{dc}}{\Delta P}$$

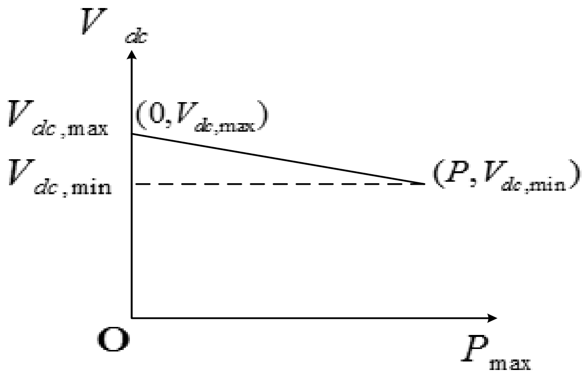


Figure 5.7: Regulation of DC link voltage

When the DC capacior is completely charged with its reference voltage, it will no more take active power from the terminals. It will take energy from the terminals when the charged voltage is zero.

This control phenomena is mathematically expressed as,

$$m_{dc} = \frac{0 - V_{DCmax}}{\frac{1}{2}C_{DC}V_{DC}^2 - 0}$$

DC capacitance is designed based on its voltage and energy storing capacity.

Similarly, reactive power droop coefficient can be calculated as,

$$m_d = \frac{\Delta V_d}{\Delta Q}$$

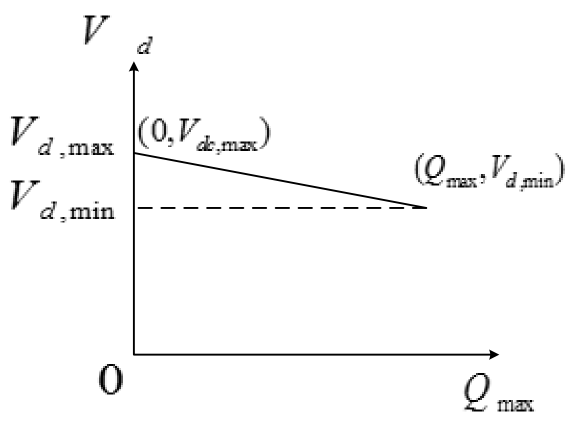


Figure 5.8: Regulation of AC side voltage

And is mathematically expressed as,

$$m_d = \frac{V_{dmax} - V_{dmin}}{0 - Q_{max}}$$

Where Q_{max} is the reactive power rating of VSC

The below figure shows the control diagram of the outer loop voltage control with regulation technique. And its advantages and disadvantages are as follows,

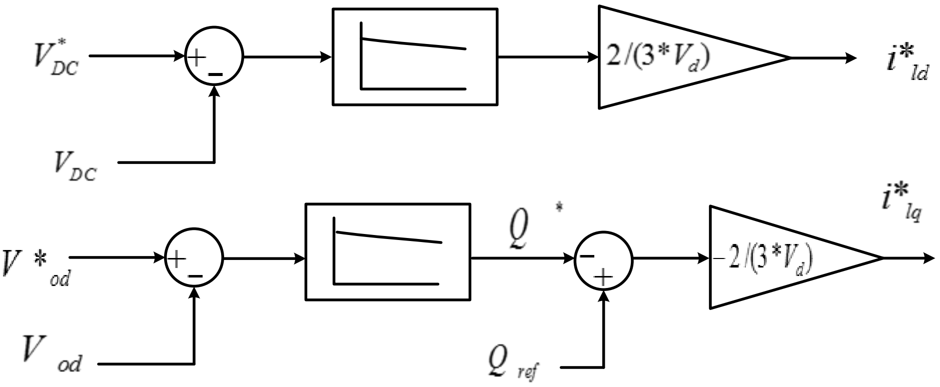


Figure 5.9: DC link voltage and AC side voltage regulation

Advatanges of Proportional Control:

- Ease of implementation and understanding.

Disadvantages of Proportional Control:

- Settling time to reach steady state will be more.

To overcome this disadvantage PI control is implemented.

5.5.2 DC volatge control through PI technique:

Mathematical representation of energy balance is given by

$$P_{DC} = -P_{AC}$$

Energy taken from terminals will be stored as DC energy in the capacitor,

$$P_{DC} = \frac{1}{2} C_{dc} \frac{d}{dt} V_{dc}^2$$

It is related with AC side power in d-q domain.

$$\frac{1}{2} C_{dc} \frac{d}{dt} V_{dc}^2 = -(v_d i_d + v_q i_q)$$

$$C_{dc} V_{dc} \frac{d}{dt} V_{dc} = -(v_d i_d + v_q i_q)$$

$$\frac{d}{dt} V_{dc} = \frac{-(v_d i_d + v_q i_q)}{C_{dc} V_{dc}}$$

We can implement PI controller in two possible ways,

The error input to the PI controller can be taken as,

(1) $\Delta V_{dc}^2 = (V_{dcref}^2 - V_{dc}^2)$

(2) $\Delta V_{dc} = (V_{dcref} - V_{dc})$

Tuning of PI controller for ΔV_{dc}^2 is easy by applying classical control technique's.

Tuning of PI controller for ΔV_{dc} error is made from trial and error approach.

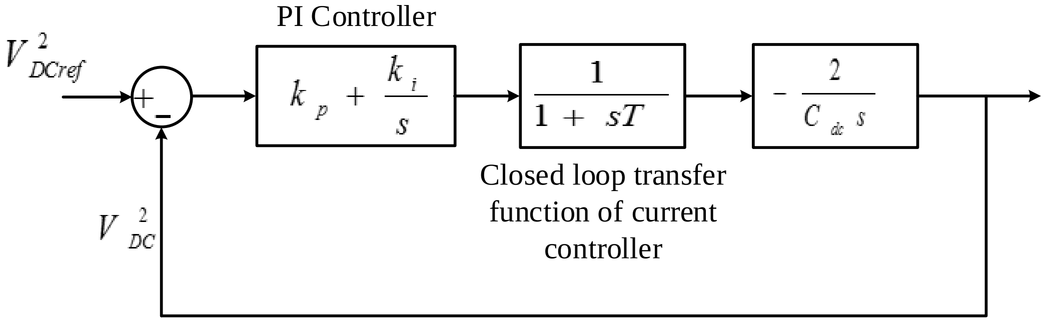


Figure 5.10: Tuning of PI controller for ΔV_{dc}^2

Figure 5.11 shows the control diagram of the outer loop voltage control with PI controller technique. And its advantages and disadvantages are as follows,

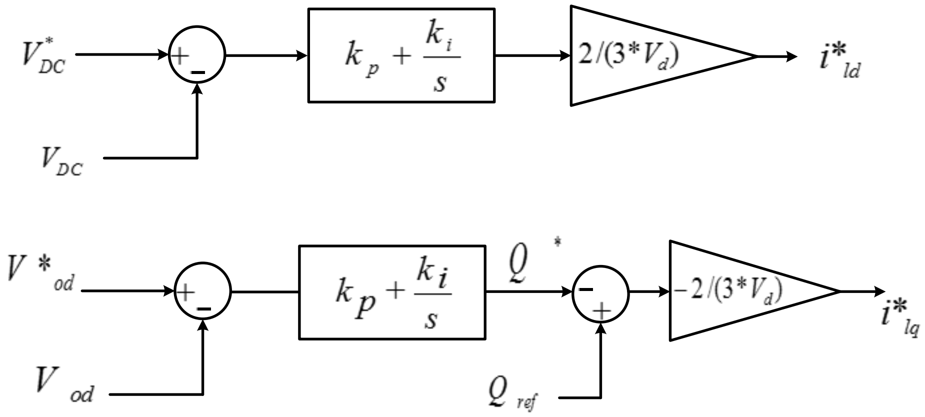


Figure 5.11: Voltage Controller with PI control

Advantages of PI controller:

- Settling time to reach steady state will be less.

Disadvantages of PI controller:

- It will work for linear systems. For non-linear systems, system is linearized around equilibrium and PI control is applied.

5.6 Reference currents generation:

The below figure shows the different ways of generating reference currents. The droop controller and PI controller techniques are explained in the above sections, here the $2/(3 * V_d)$ gain in the figure comes from the below equation as follows,

$$P = \frac{3}{2}(V_d i_d + V_q i_q)$$

$$Q = \frac{3}{2}(-V_d i_q + V_q i_d)$$

Making V_q=0 by using PLL and the above equation becomes as follows,

$$i_d = \frac{2}{(3 * V_d)} P$$

$$i_q = -\frac{2}{(3 * V_d)} Q$$

Here in this system by using PLL we are making V_q=0 and also generating w and Θ for current controller and abc to dq transformation.

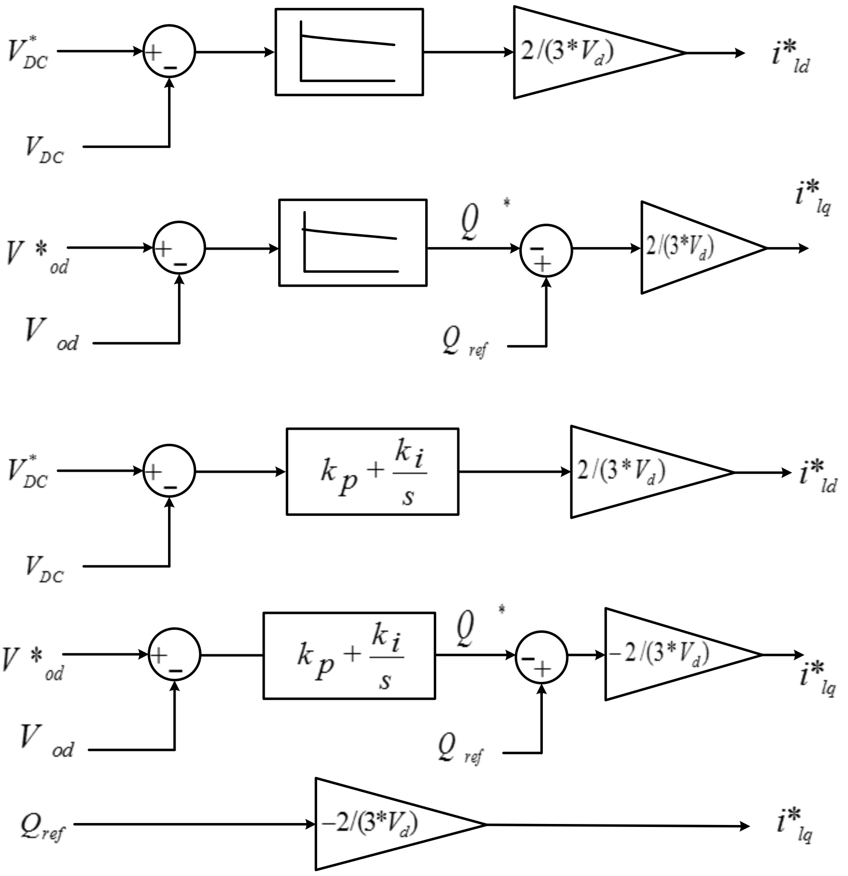


Figure 5.12: Reference currents generation.

Here in one of the control technique for reference currents generation in the above figure q-component of reference current component is being generated by using Q_{ref} and it is calculated in the below MATLAB program as follows,

5.7 Calculation of Q_{ref}:

```
clc
clear all

Nbus     = 2;
Nline    = 1;
lined    = [0.5290 1.5870];
busd     = [0 230 16e3 12e3];
r        = lined(:,1);                % Resistance, R...
x        = lined(:,2);                % Reactance, X...
Zline    = complex(r,x);              % line impedance
Pl       = busd(:,3);                 % load active power
Ql       = busd(:,4);                 % load reactive power
BMva     = 20e3;                      % Base KVA
V1       = busd(:,2);                 % voltage at bus 1
V2a      = busd(:,2);                 % voltage at bus 2
delta1   = busd(:,1);                 % voltage angle of bus 1

Zload         = ((3*V1^2)/(complex(Pl,-Ql)));
R             = real(Zload);
X             = imag(Zload);
Iline         = V1/complex((r+R),(x+X));
V2            = V1-(Iline*Zline);
del2          = angle(V2);
V2            = V2a.*complex(cos(del2),sin(del2))
S2            = V2*conj(Iline);
Q2            = imag(S2)
```

Chapter 6

Results and discussion

6.1 Performance of Three Phase Source with RL Loads without DSTATCOM for high ($\frac{X}{R}$) ratio line.

Figure 6.1 shows the three phase source feeding RL load through line impedance without DSTATCOM.

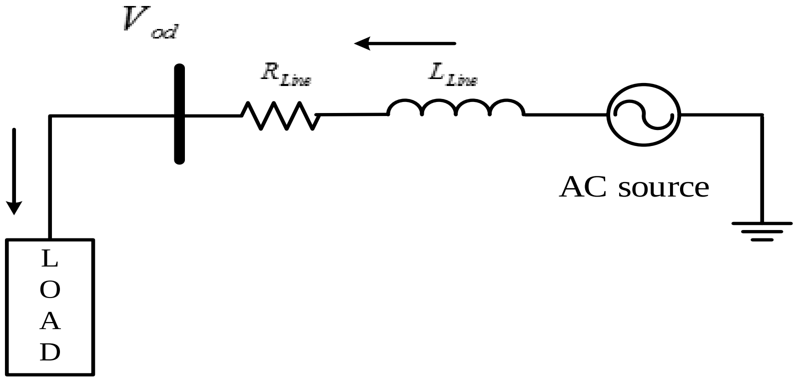


Figure 6.1: Three phase source feeding RL loads without DSTATCOM

The load is applied at t = 0 sec and the simulated results in Figure 6.1 (a) show that voltage dip. Voltage dips from the reference value of 230V to 183V, which is 20% voltage dip for high ($\frac{X}{R}$) ratio line impedance with P controller.

Figure 6.1 (b) show that voltage dip. Voltage dips from the reference value of 230V to 183V, which is 15% voltage dip for high ($\frac{X}{R}$) ratio line impedance with PI controller.

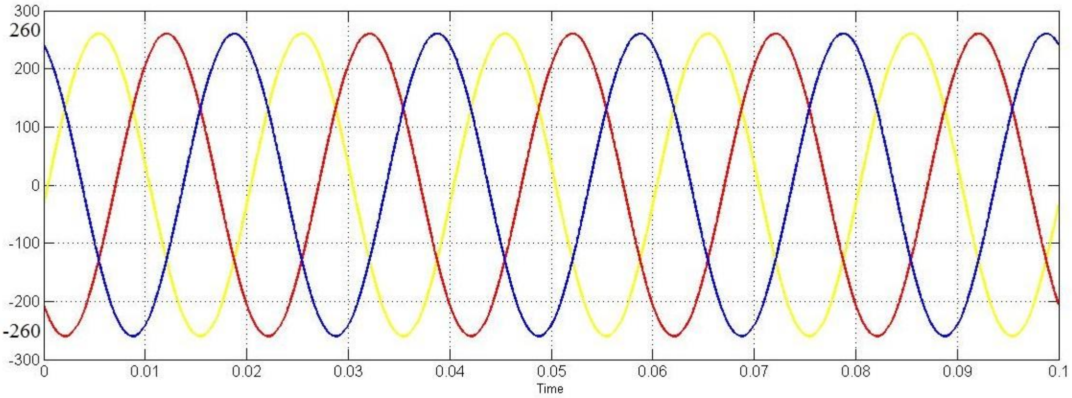


Figure 6.1 (a): Three phase voltage waveform for P controller

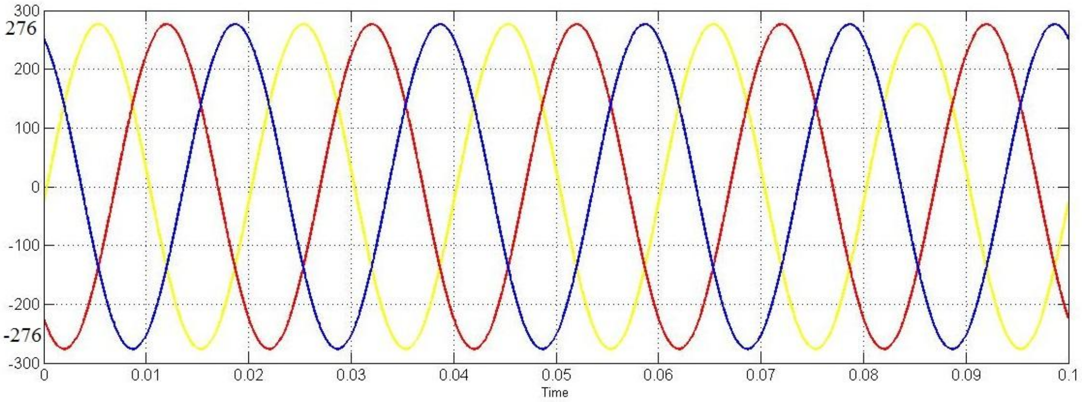


Figure 6.1 (b): Three phase voltage waveform for PI controller

6.2 Performance of Three Phase Source with RL Loads with DSTATCOM for high ($\frac{X}{R}$) ratio

Figure 6.2 shows the three phase source feeding RL load with DSTATCOM. An IGBT based PWM voltage source inverter as DSTATCOM which is connected in shunt with the main system via transformer impedance (R_C , L_C). The controller block uses voltage and current inputs and generates gating pulses for IGBT switches of VSC. The RL load is applied at t = 0 sec and observed voltage dip at PCC.

However, DSTATCOM system is able to reduce the sag. Here two Proportional (P) controllers are used, one regulate the DC link voltage and the other one is to regulate the ac terminal voltage at PCC. And also by replacing the two Proportional (P) controllers with Proportional-integral (PI) and observed the outputs.

Figure 6.2 (a,.s) shows the various output wave forms of the system with high $(\frac{X}{R})$ ratio line impedance with DSTATCOM by using P and PI controllers.

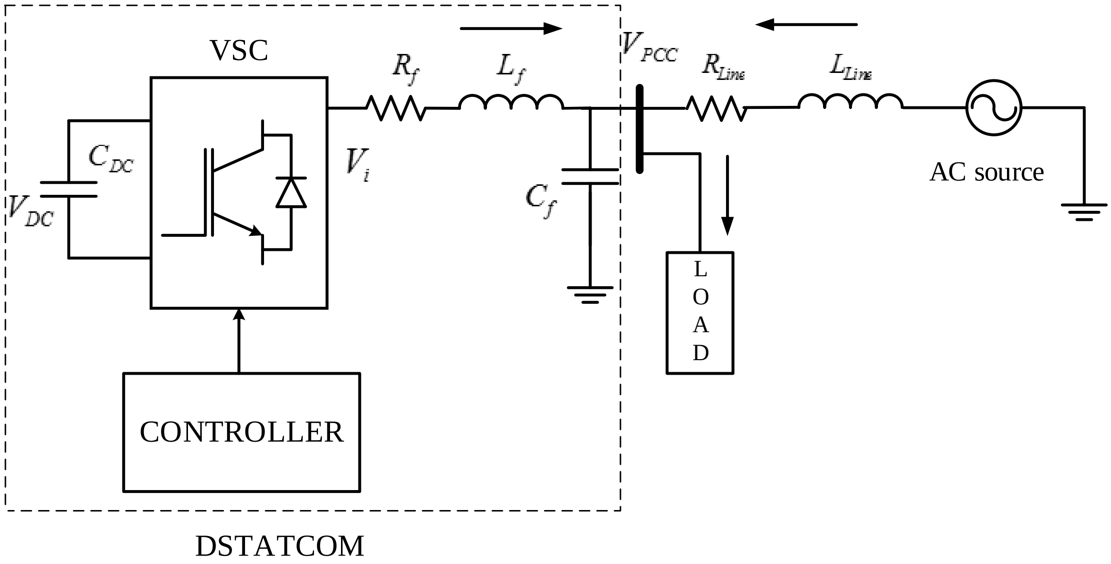


Figure 6.2: Three Phase source feeding RL loads with DSTATCOM

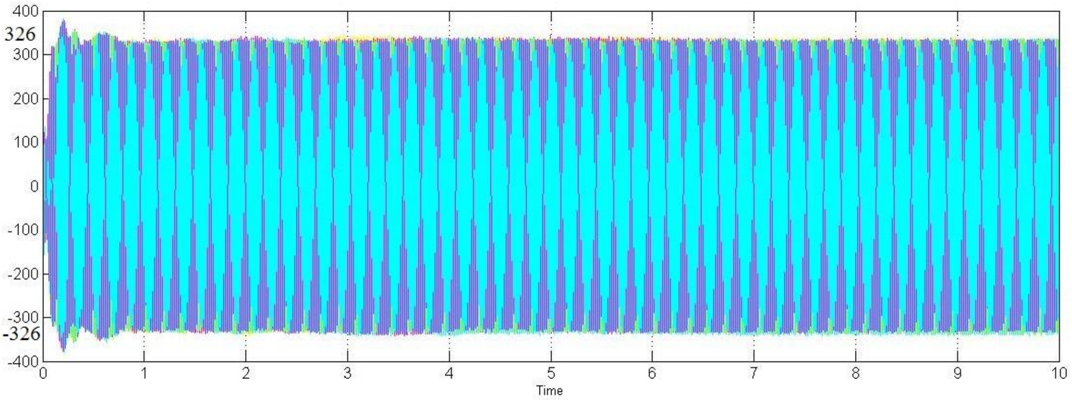


Figure 6.2 (a): Three phase voltage waveform at PCC with P controller

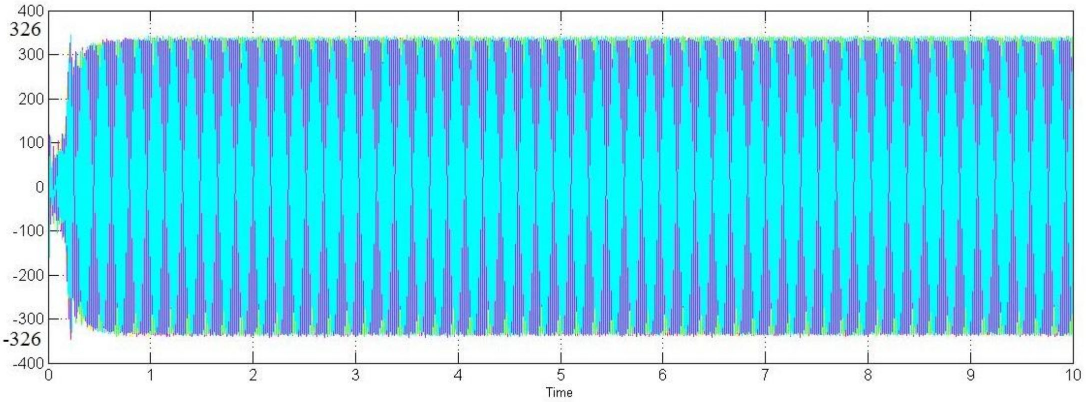


Figure 6.2 (b): Three phase voltage waveform at PCC with PI controller

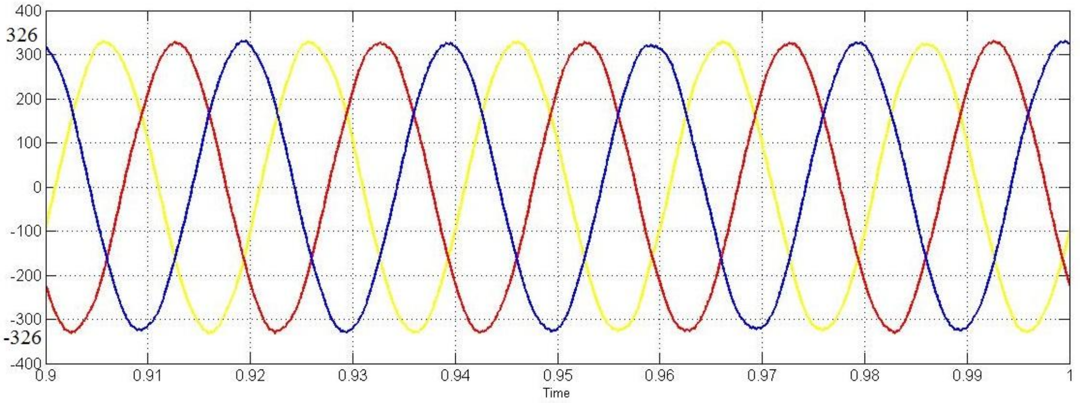


Figure 6.2 (c): Zoomed view of Three phase voltage waveform with P and PI controller

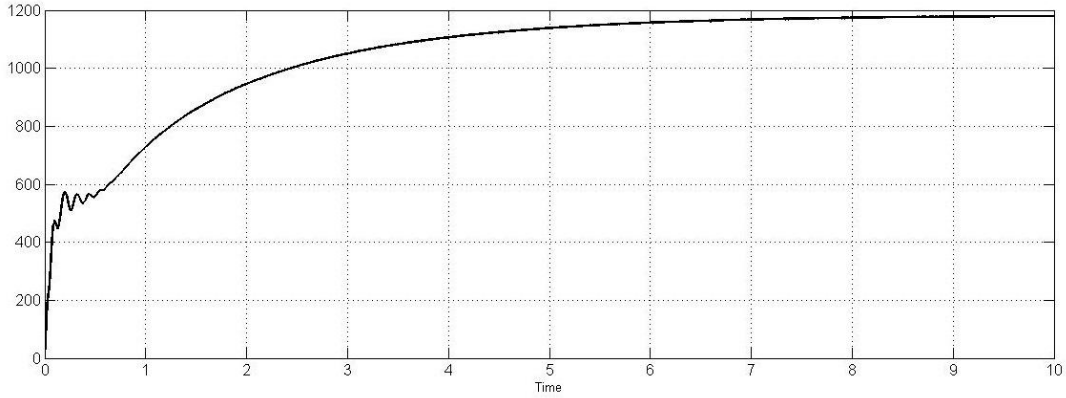


Figure 6.2 (d): DC link voltage waveform of DSTATCOM with P controller

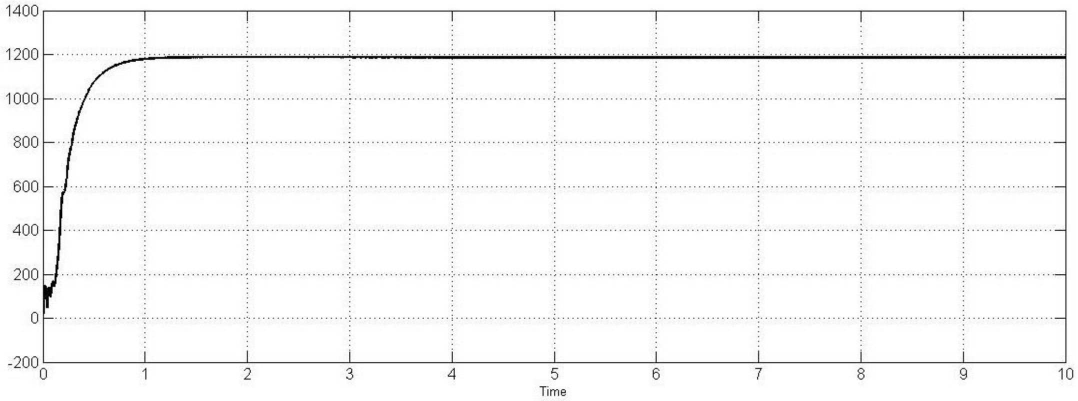


Figure 6.2 (e): DC link voltage waveform of DSTATCOM with PI controller

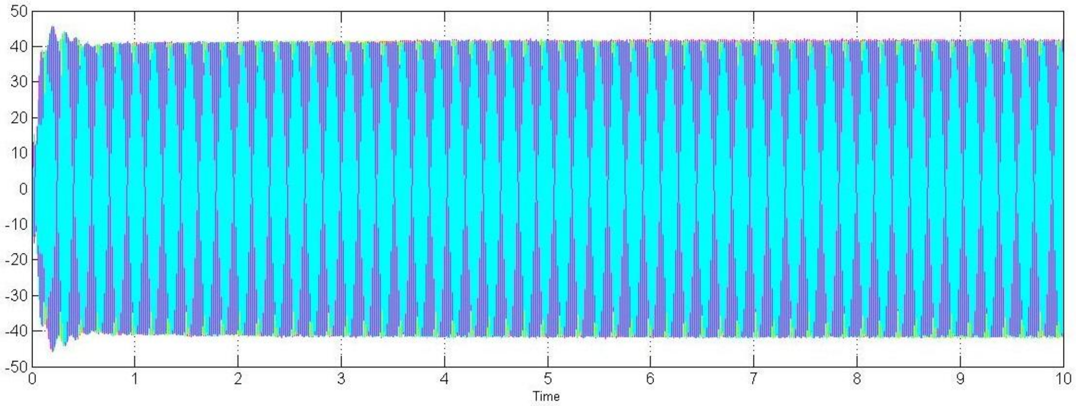


Figure 6.2 (f): Three phase load current waveform for P controller.

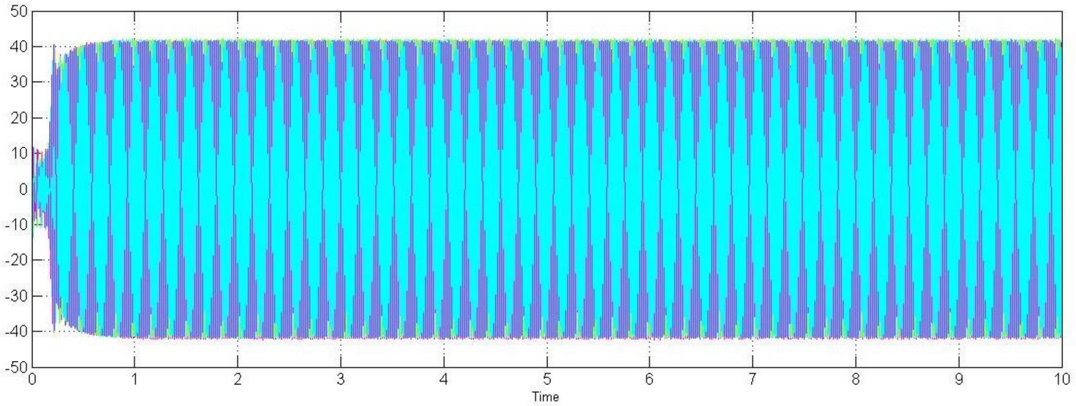


Figure 6.2 (g): Three phase load current waveform for PI controller.

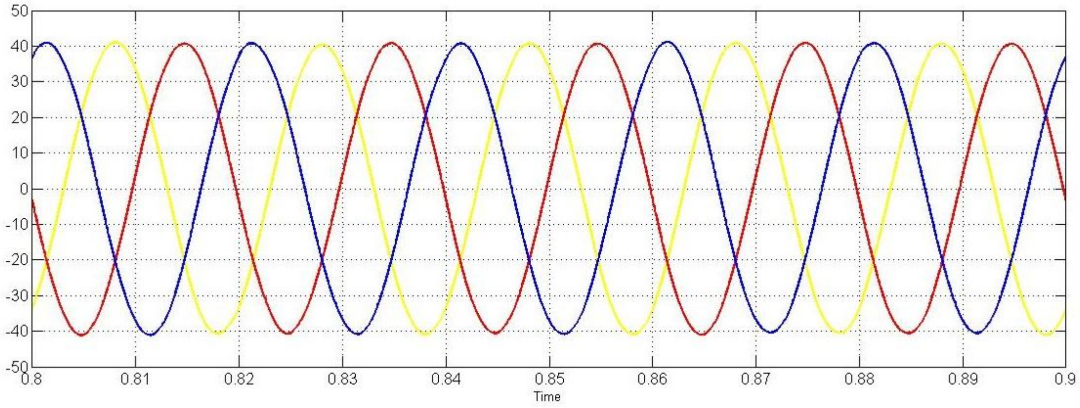


Figure 6.2 (h): Three phase zoomed view of load current waveform with P and PI controller.

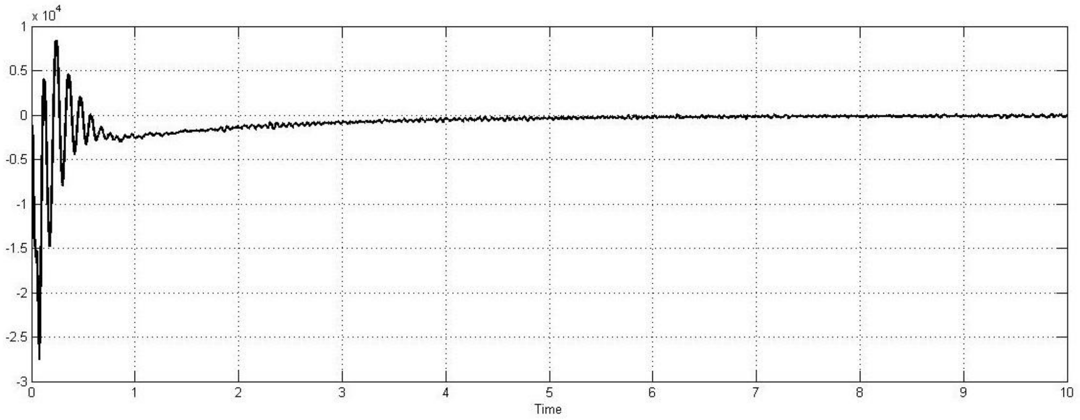


Figure 6.2 (i): Active power output waveform of the DSTATCOM with P controller.

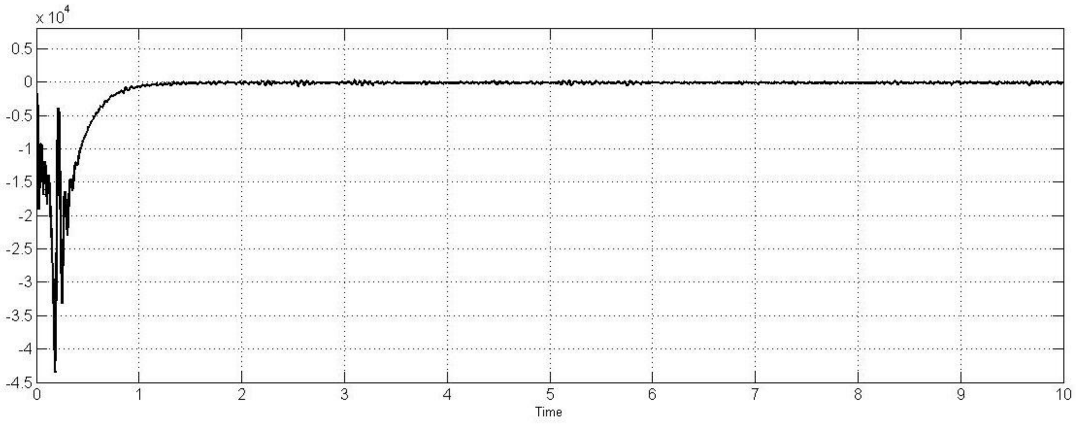


Figure 6.2 (j): Active power output waveform of the DSTATCOM with PI controller.

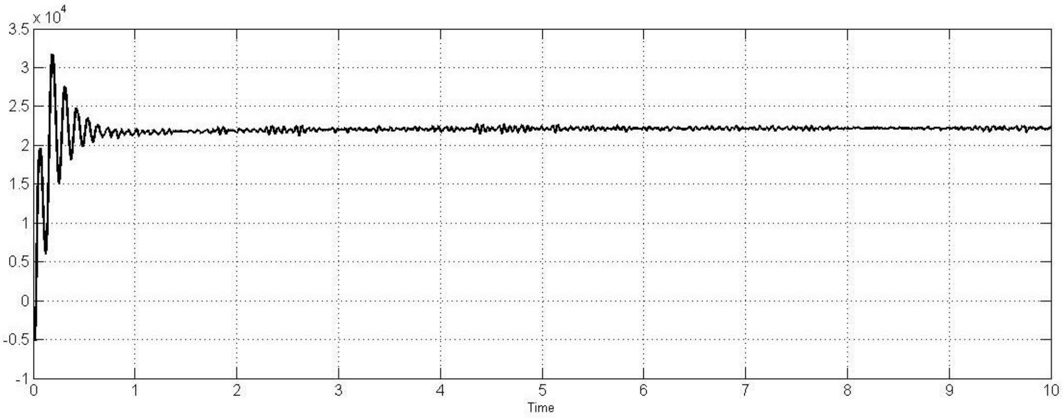


Figure 6.2 (k): Reactive power output waveform of the DSTATCOM with P controller.

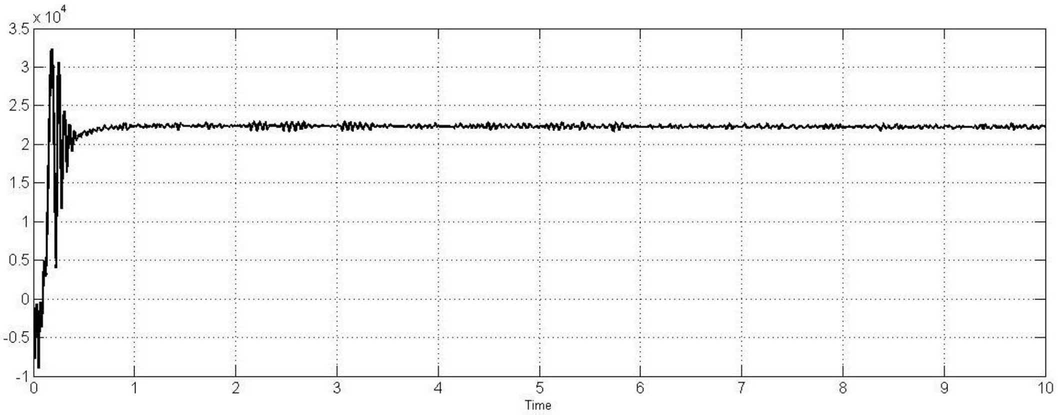


Figure 6.2 (l): Reactive power output waveform of the DSTATCOM with PI controller.

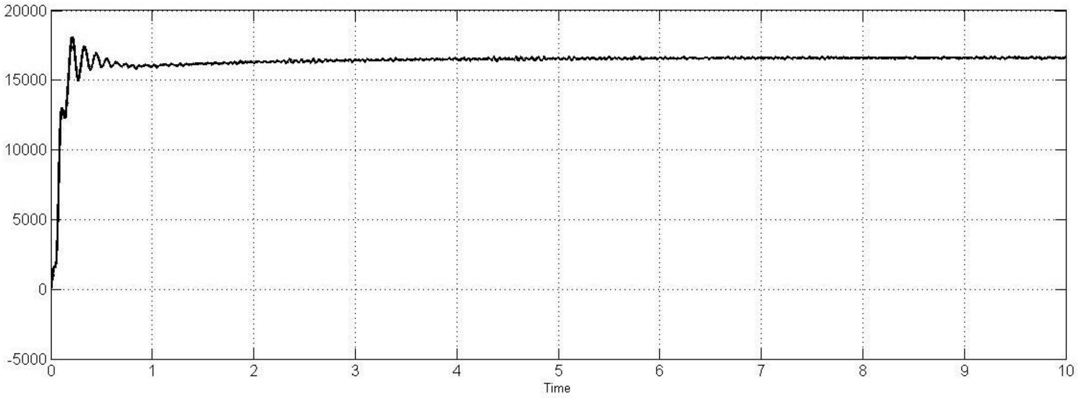


Figure 6.2 (m): Waveform of the active power load of a system with P controller.

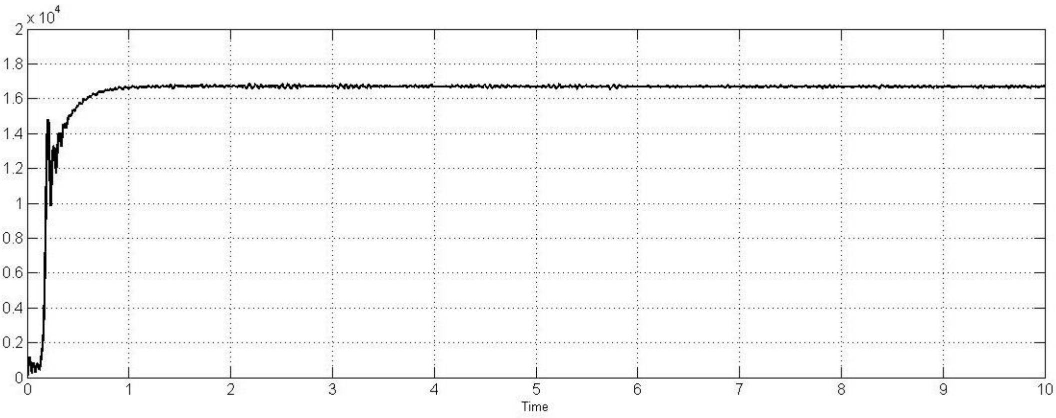


Figure 6.2 (n): Waveform of the active power load of a system with PI controller.

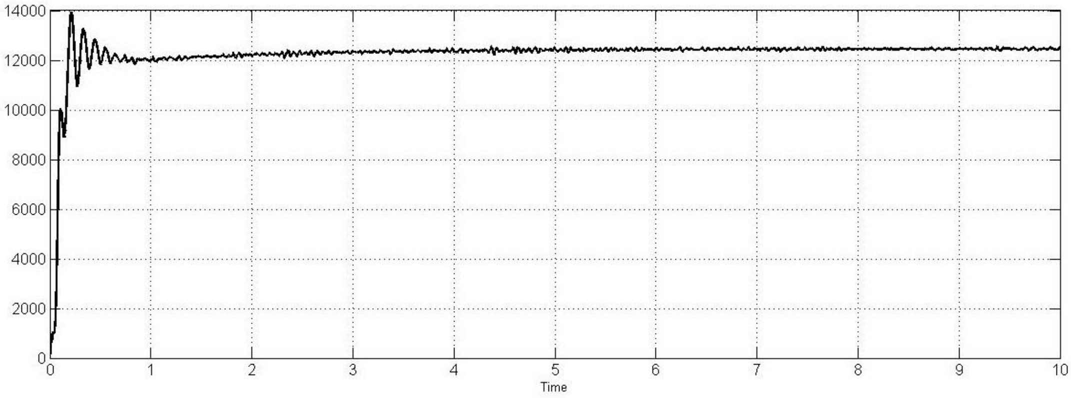


Figure 6.2 (o): Waveform of the reactive power load of a system with P controller.

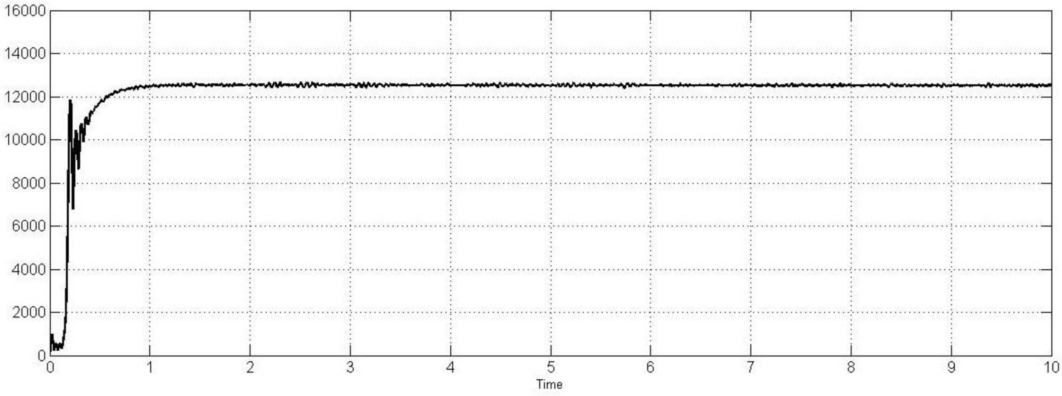


Figure 6.2 (p): Waveform of the reactive power load of a system with PI controller.

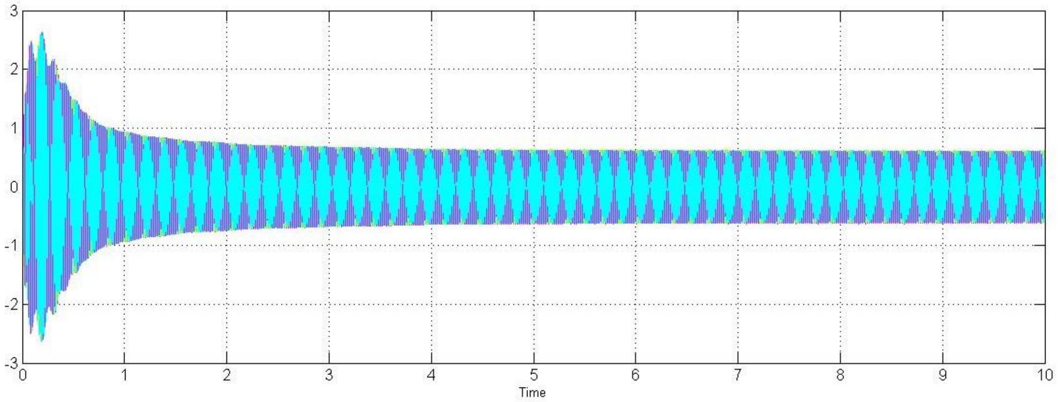


Figure 6.2 (q): Waveform of three phase reference currents to the DSTATCOM with P controller.

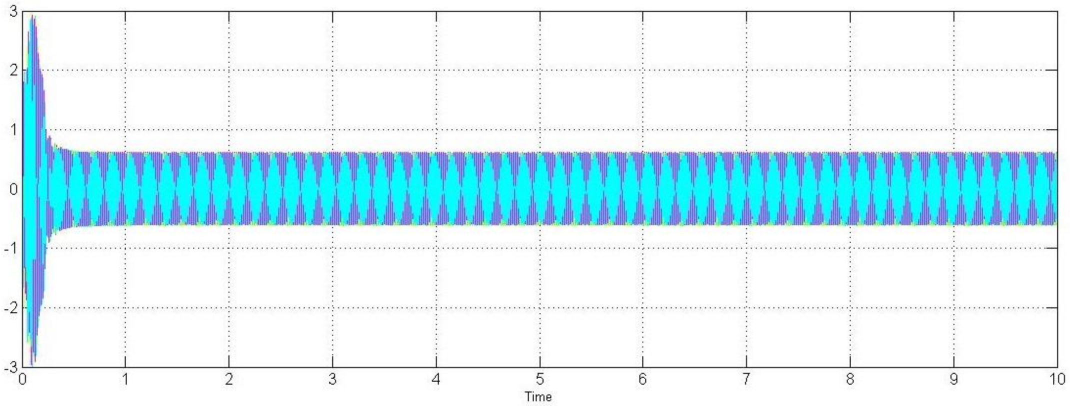


Figure 6.2 (r): Waveform of three phase reference currents to the DSTATCOM with PI controller.

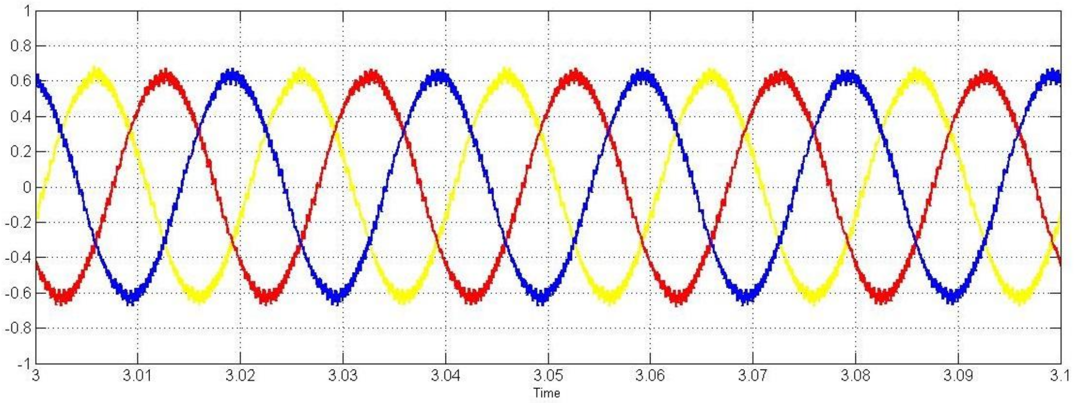


Figure 6.2 (s): Zoomed viewed waveform of the three phase reference currents to the DSTATCOM with P and PI controller.

6.3 Performance of Three Phase Source with RL Loads with DSTATCOM for high $\left(\frac{R}{X}\right)$ ratio:

Figure 6.3 (a,..s) shows the various output wave forms of the system with high $\left(\frac{R}{X}\right)$ ratio line impedance with DSTATCOM by using P and PI controllers. Figure 6.3 show that voltage dip. Voltage dips from the reference value of 230V to 200V, which is 13% voltage dip for high $\left(\frac{R}{X}\right)$ ratio line impedance with DSTATCOM by using P and PI controllers.

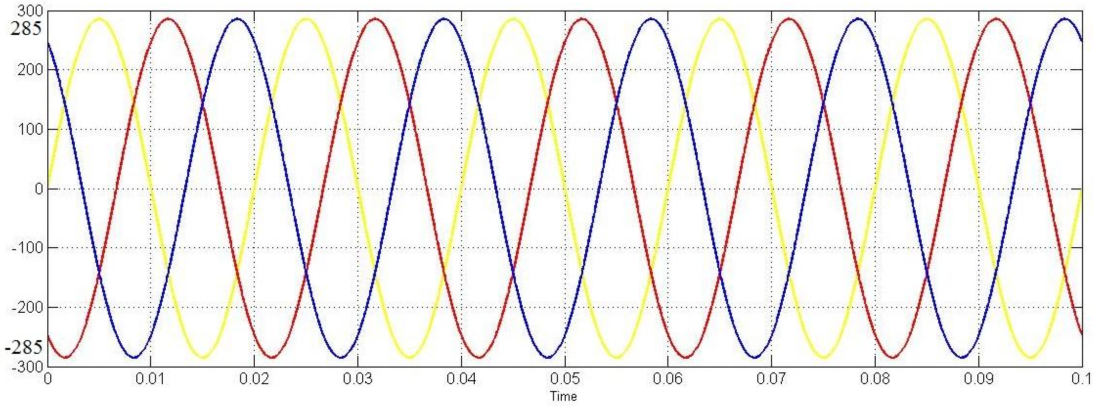


Figure 6.3: Three phase voltage waveform of without DSTATCOM with P and PI controller

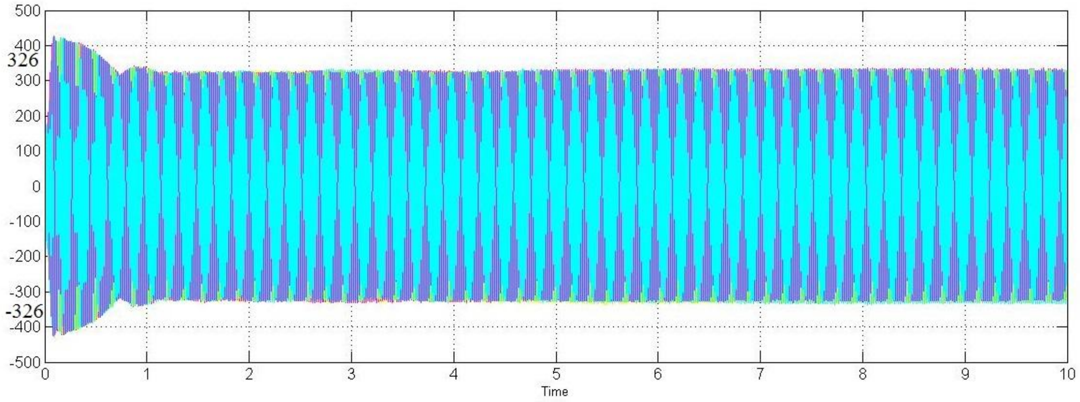


Figure 6.3 (a): Three phase voltage waveform at PCC with P controller

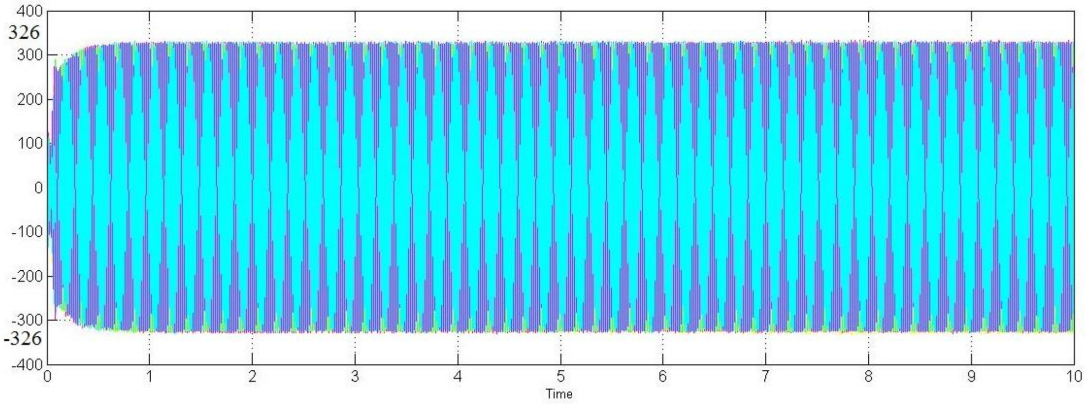


Figure 6.3 (b): Three phase voltage waveform at PCC with PI controller

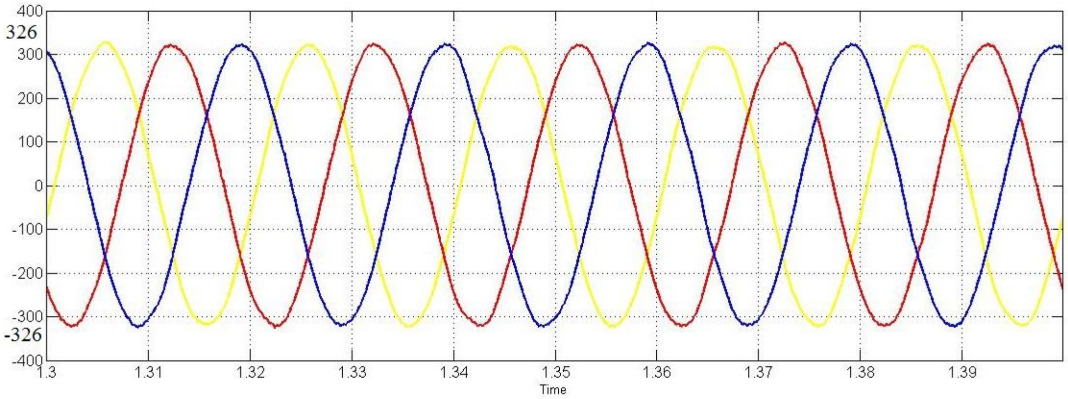


Figure 6.3 (c): Zoomed view of three phase voltage waveform with P and PI controller

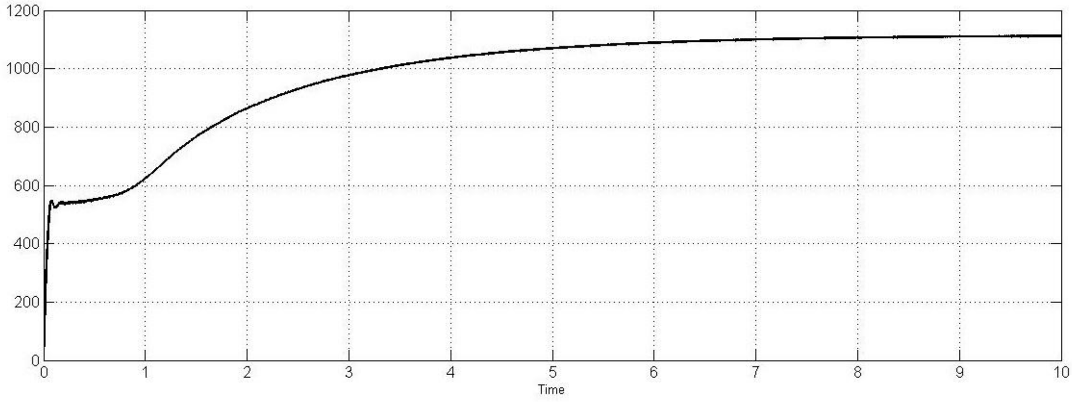


Figure 6.3 (d): DC link voltage waveform of DSTATCOM with P controller

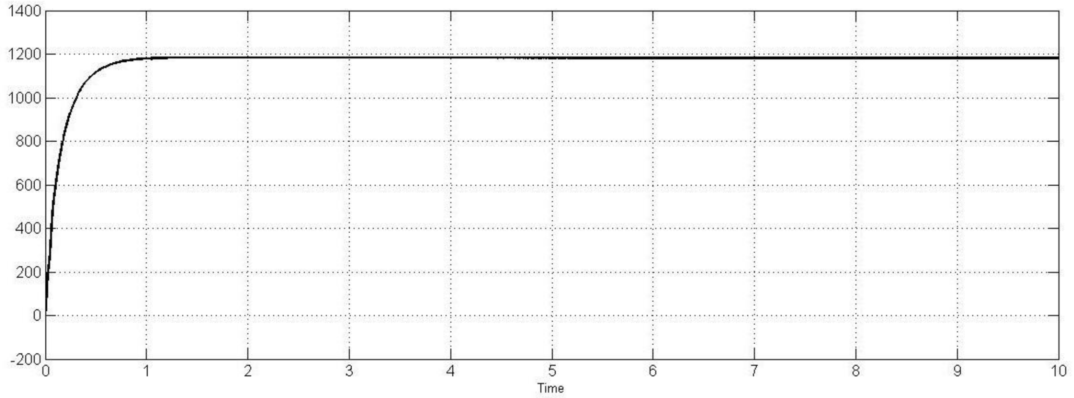


Figure 6.3 (e): DC link voltage waveform of DSTATCOM with PI controller

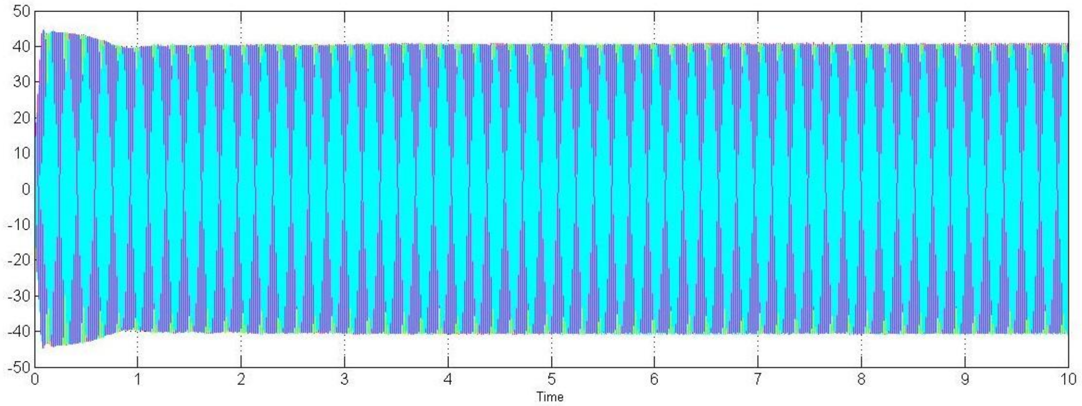


Figure 6.3 (f): Three phase load current waveform with P controller.

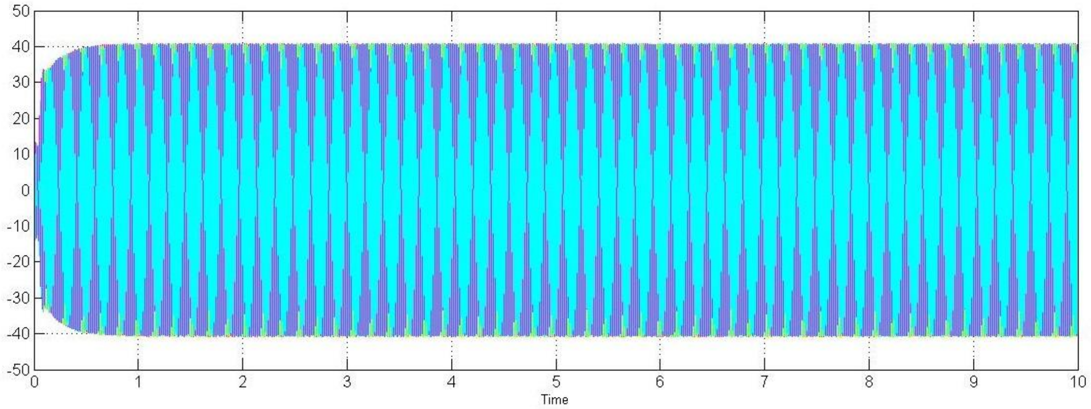


Figure 6.3 (g): Three phase load current waveform with PI controller.

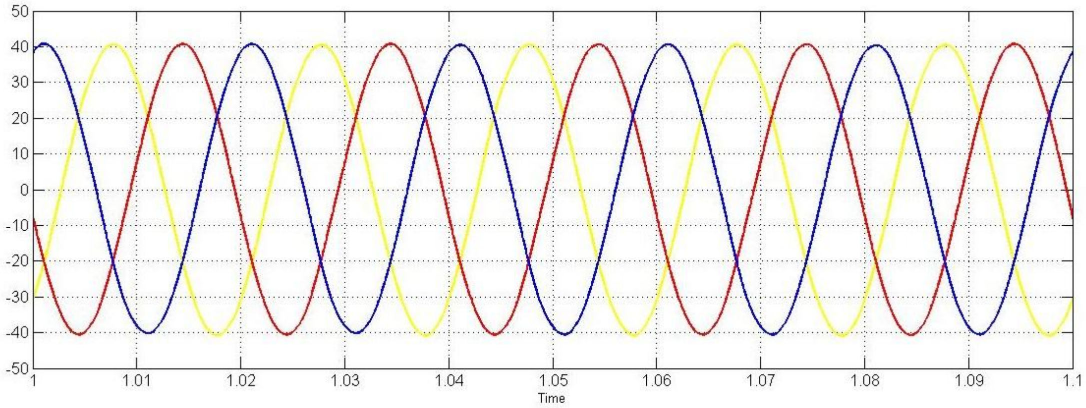


Figure 6.3 (h): Three phase zoomed view waveform of the load current with P and PI controller.

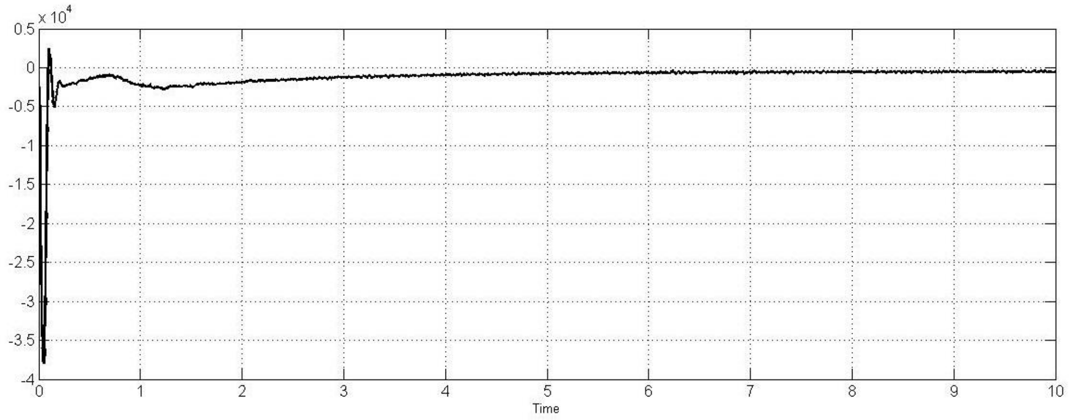


Figure 6.3 (i): Active power output waveform of the DSTATCOM with P controller.

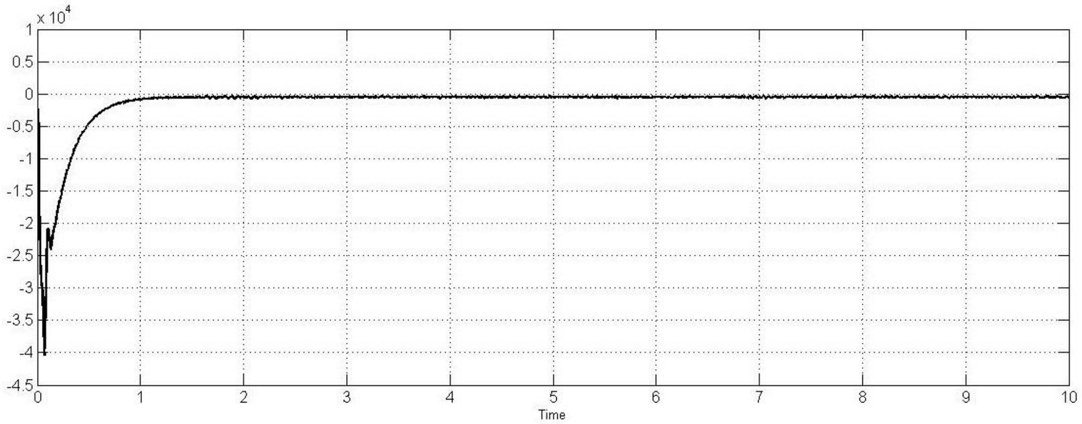


Figure 6.3 (j): Active power output waveform of the DSTATCOM with PI controller.

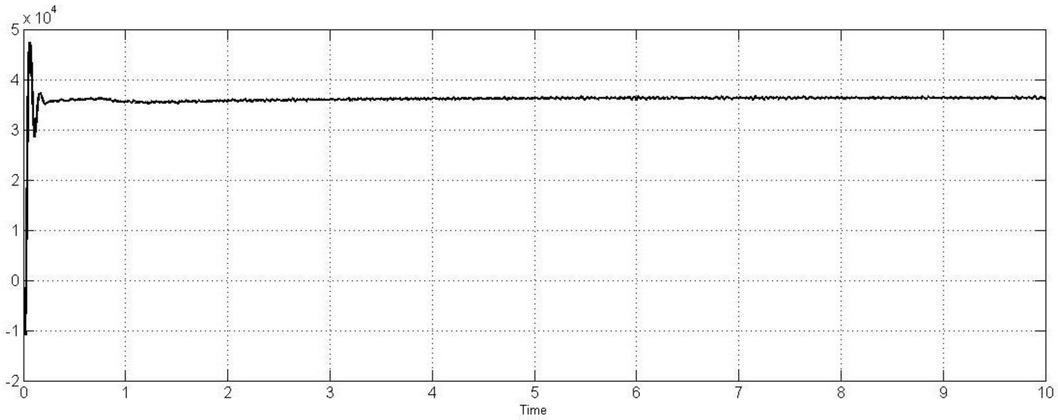


Figure 6.3 (k): Reactive power output waveform of the DSTATCOM with P controller

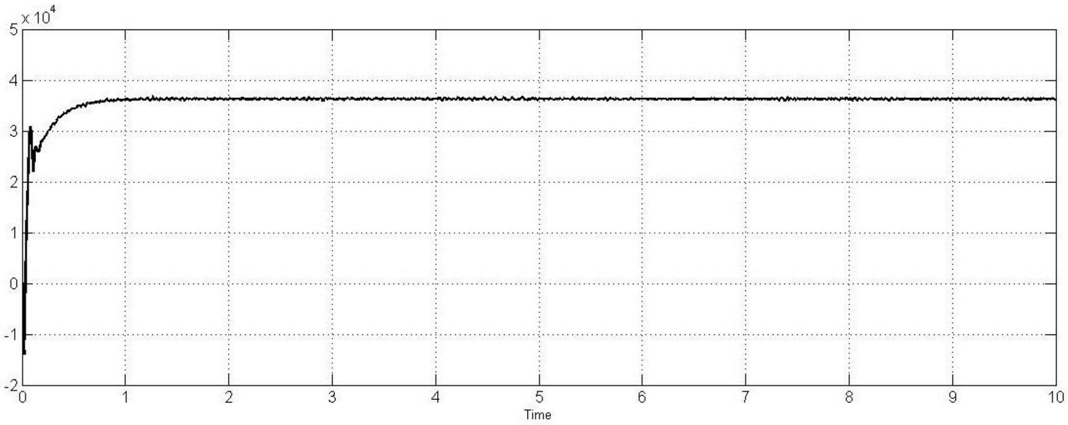


Figure 6.3 (l): Reactive power output waveform of the DSTATCOM with PI controller

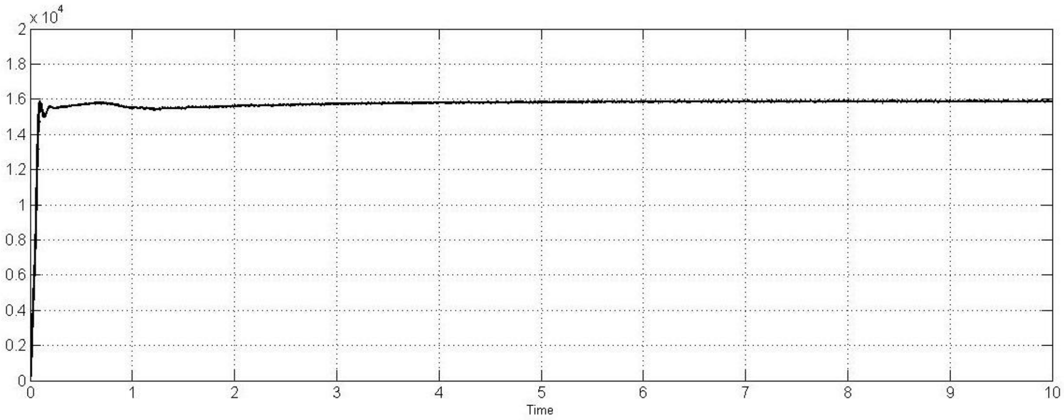


Figure 6.3 (m): Waveform of Active power load of the system with P controller.

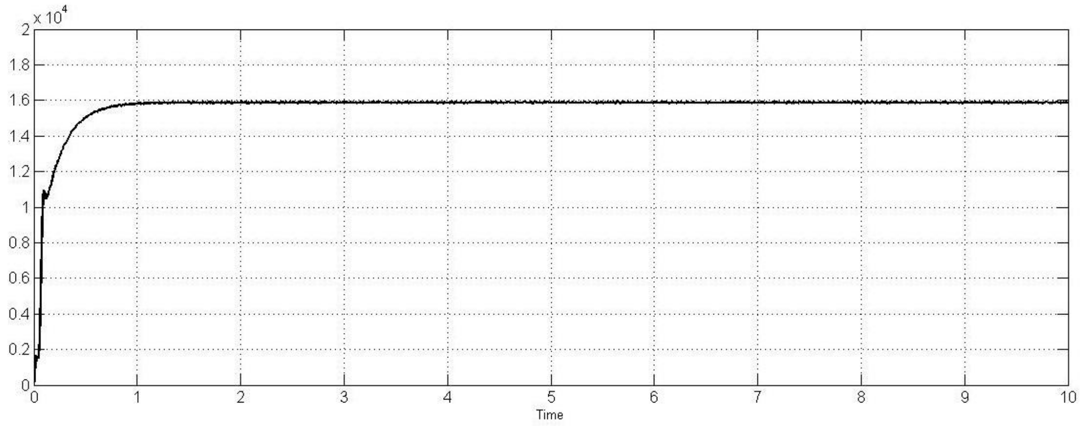


Figure 6.3 (n): Waveform of Active power load of the system with PI controller.

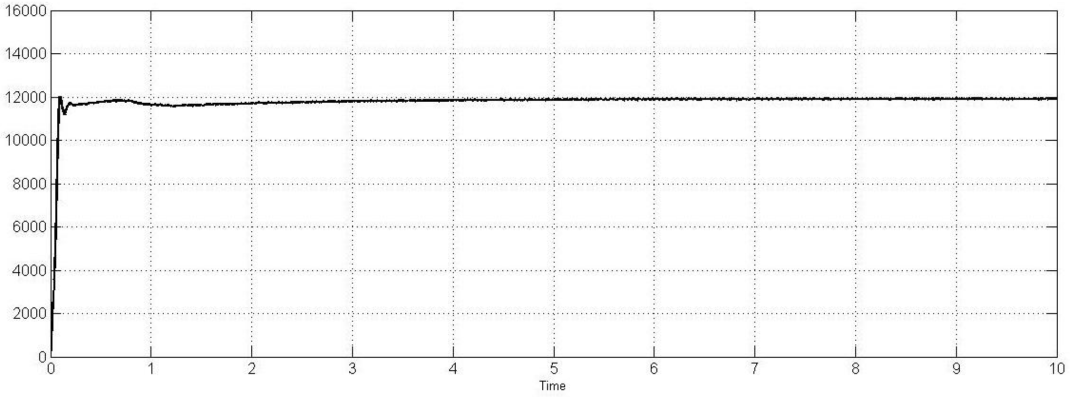


Figure 6.3 (o): Waveform of the Reactive power load of the system with P controller.

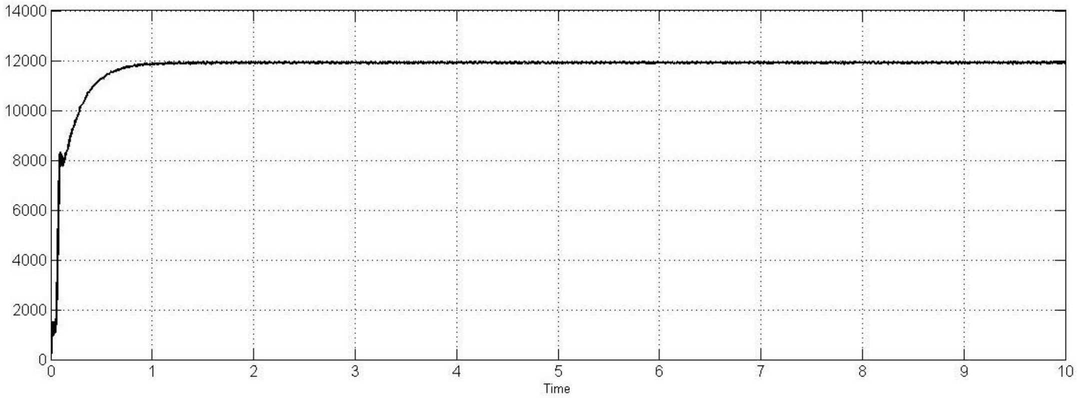


Figure 6.3 (p): Waveform of the Reactive power load of the system with PI controller.

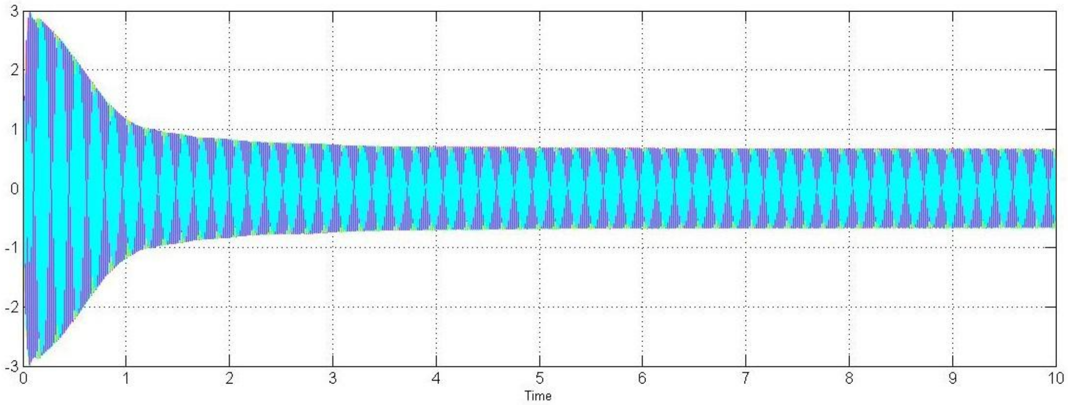


Figure 6.3 (q): Waveform of Three phase reference currents to the DSTATCOM with P controller.

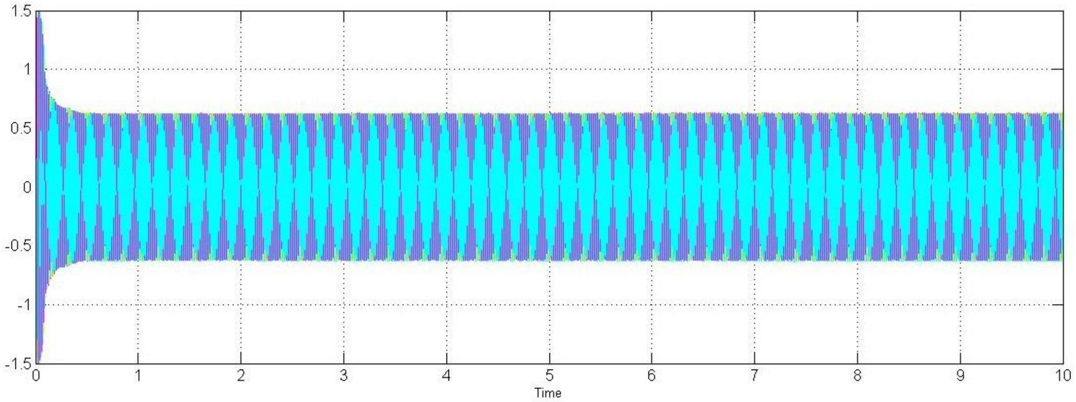


Figure 6.3 (r): Waveform of three phase reference currents to the DSTATCOM with PI controller.

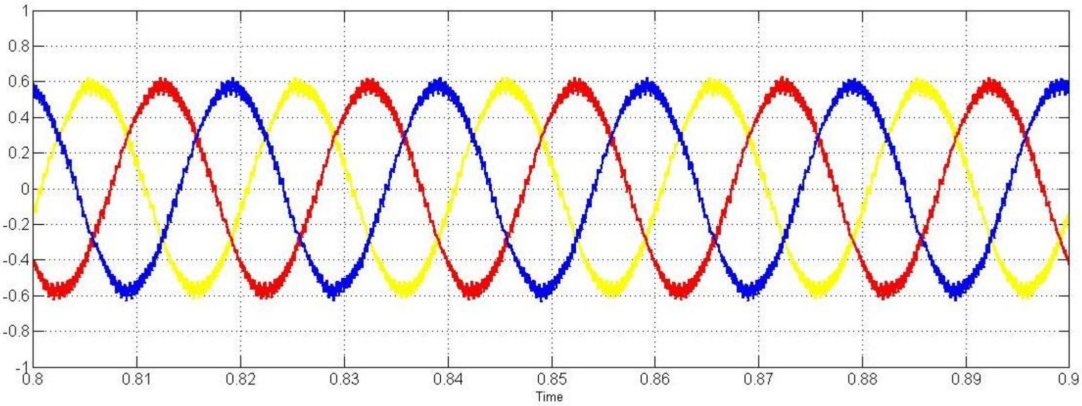


Figure 6.3 (s): Zoomed viewed waveform of the three phase reference currents to the DSTATCOM with P and PI controller.

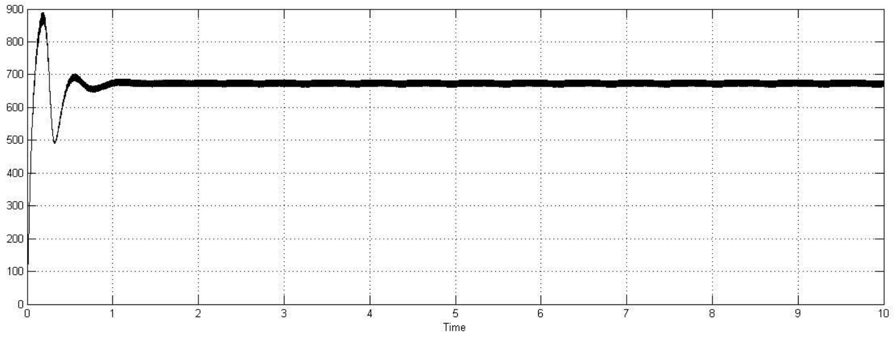


Figure 6.4: Waveform of the DC link voltage for tuned PI controller.

Here from the above figure we observed that by using P controller Settling time to reach steady state will be more and by using PI controller the DC link voltage of the system reached its steady state value much faster than that of P controller and also AC side voltages are controlled, even for the system with resistive dominating.

Figure 6.4 shows the DC link voltage for tuned PI controller. The DC link voltage is controlled by using this technique and also AC side voltages are not controlled properly. Further improvement in control strategy is required for the AC side voltage control.

Chapter 7

Conclusion

Control of D-STATCOM for high X/R ratio and high R/X ratio system is verified in the present work. Voltage magnitude close to nominal value can be ensured for consumers by using DSTATCOM. DC-link voltage control and AC side voltage control has been implemented by using proportional and proportional integral (PI) control techniques. The results reveal that the control objective can be achieved with both the techniques. Control strategy need to be further improved such that it works even for unbalanced and non-linear loads.

Appendix

System parameters used in simulation:

- Three Phase Source:
  400V (Phase to Phase) rms voltage, 50Hz

- DSTATCOM parameters:
  Rating of inverter = 20 KVA
  Switching frequency = 2 KHz
  DC bus voltage = 1200 V
  Filter resistance = 0.29488 Ω
  Filter inductance = 1.47441 mH
  Filter capacitance = 0.42949 mF

- P Controller parameters:
  DC link voltage regulation, m_{dc} = -6
  AC side regulation, m_d = -36
- PI Controller parameters:
  DC link voltage, K_p = -58
  K_i = 1.9
  AC side voltage, K_p = -34
  K_i = 2.1

References

[1] R. C. Dugan, M. F. McGranaghan, and H. W. Beaty, *Electric Power Systems Quality,* New York: 2nd Edition, McGraw Hill, 2006.

[2] K. R. Padiyar, *FACTS Controllers in Power Transmission and Distribution*, New Delhi: New Age International (P) Limited, 2007.

[3] H. Rahmat Allah, B. Mahdi, and A. Mostafa, “Voltage sag Mitigation using a new Direct control in DSTATCOM for Distribution systems,” in *Proc.* U.P.B. Sci. Bull., Series C *Conf.,* Iran: *2009,* vol. 71, Iss. 4.

[4] D. P. Kothari and I. J. Nagarath, *Modern Power systems Analysis,* New Delhi: 3nd Edition, McGraw Hill, 2009.

[5] P. Garica Gonzalez and A. Garcia Cerrada, "Control system for a PWM-based STATCOM," *IEEE Trans. Power Delivery.,* vol. 15, no.4, pp. 1252-1257, Oct. 2000.

[6] Li. Shengqing, Li. Weizhou, Xu. Wenxiang and Zeng. Huanyue, “The Direct Current Control Method of STATCOM and its Simulation,” in *Proc. Intelligent System Design and Engineering Applications (ISDEA), Third International Conf.,* Jan 16-18. 2013, vol. no. pp.1426-1429.

[7] Li. Shuhui, Xu. Ling, and A. Haskew Timothy. “Control of VSC-based STATCOM using conventional and direct-current vector control strategies,” *IEEE Trans. International Journal of Electrical Power & Energy Systems.,* vol. 45 pp. 175-186, 2013.

[8] K. H. Ahmed, S. J. Finney, and B. W. Williams, "Passive Filter Design for Three-Phase Inverter Interfacing in Distributed Generation," in *Proc. Compatibility in Power Electronics, CPE Conf.,* May 29 2007-Jun. 1 2007, vol. 7, pp.1-9.

[9] P. A. Dahono, A. Purwadi, and Qamaruzzaman, "An LC filter design method for single-phase PWM inverters," in *Proc. Int. Power Electronics and Drive System Conf.,* Feb. 21-24 1995, vol. 2, pp. 571-576.

[10] M. B. Delghavi and A. Yazdani, "A control strategy for islanded operation of a Distributed Resource (DR) unit," in *Proc. Power & Energy Society General Meeting, PES IEEE Conf.,* 2009, vol., no, pp. 1-8.

[11] A. Yazdhani and R. Iravani, *Voltage-Sourced Converters in Power Systems. IEEE Press,* Canada: Wiley, Jan. 2010.

[12] M. K. Mishra, K. Karthikeyan, "A Fast-Acting DC-Link Voltage Controller for Three Phase DSTATCOM to Compensate AC and DC Loads," *IEEE Trans. Power Delivery.*, vol. 24, no. 4, pp. 2291-2299, Oct. 2009.