Mitigation of Voltage Sag for Motor Loads in Distribution Systems using DSTATCOM

Thesis submitted in partial fulfilment of the requirement for the award of degree of

Master of Engineering
in
Power System and Electric Drives

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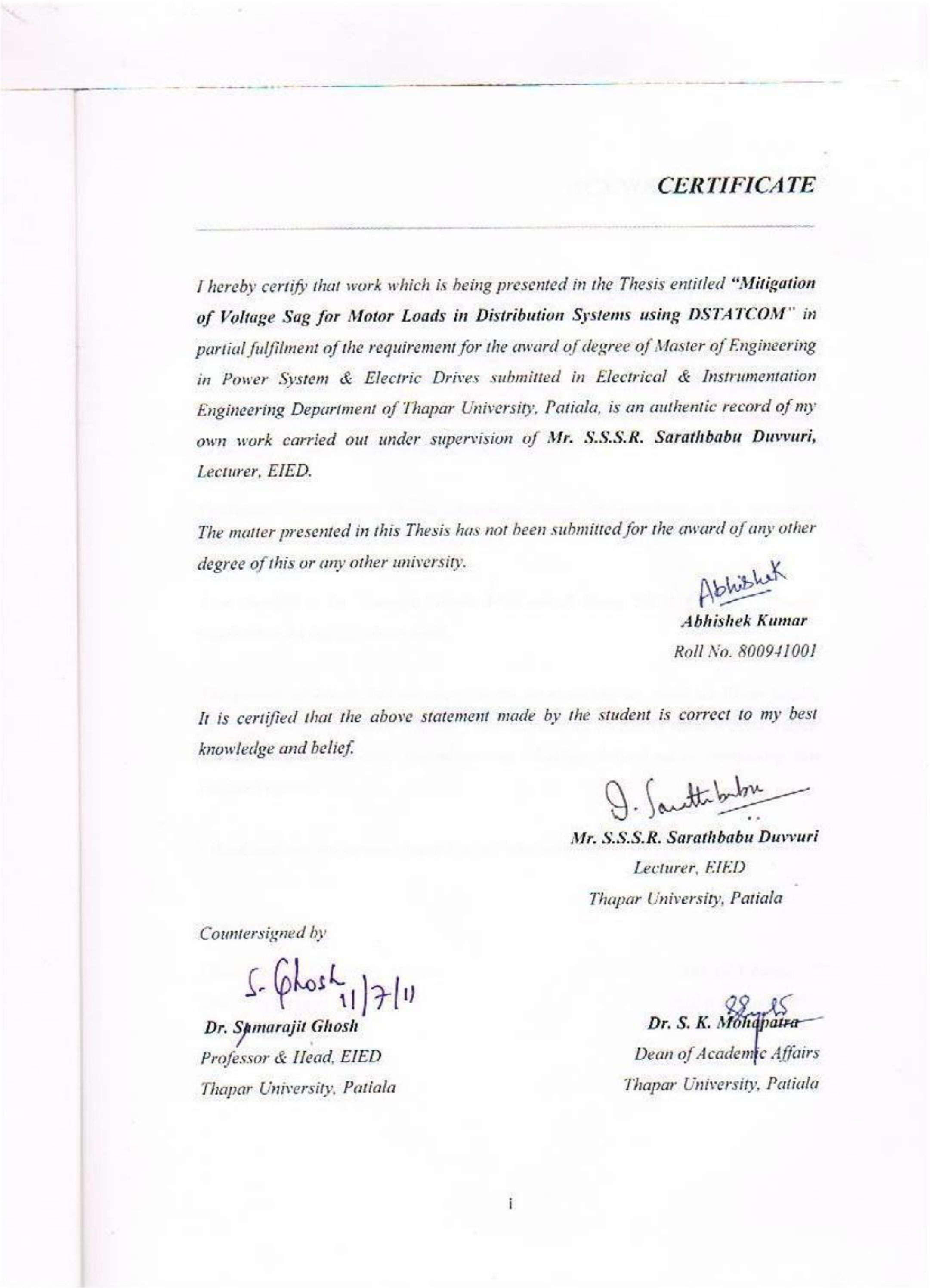

CERTIFICATE

I hereby certify that work which is being presented in the Thesis entitled ***"Mitigation of Voltage Sag for Motor Loads in Distribution Systems using DSTATCOM"*** *in partial fulfilment of the requirement for the award of degree of Master of Engineering in Power System & Electric Drives submitted in Electrical & Instrumentation Engineering Department of Thapar University, Patiala, is an authentic record of my own work carried out under supervision of* ***Mr. S.S.S.R. Sarathbabu Duvvuri,*** *Lecturer, EIED.*

The matter presented in this Thesis has not been submitted for the award of any other degree of this or any other university.

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It is certified that the above statement made by the student is correct to my best knowledge and belief.

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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 large starting currents and objectionable voltage drop during the starting of an induction motor 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 dip problem. The dip in voltage is generally encountered during the starting of an induction motor.

The model of DSTATCOM connected in shunt configuration to a three phase source feeding dynamic motor 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 induction machines with reduced voltage dip.

ORGANIZATION OF THE THESIS

The complete project thesis is divided in to five chapters as follows.

Chapter 1 provides the introduction of the power quality problem compensated by DSTATCOM. It also gives the brief of the literature review of the work done in past in this area and finally defines the objective of the work.

Chapter 2 provides a brief summary explaining about the power quality, assets and improvement techniques. It also introduces about the various power quality problems.

Chapter 3 deals with operational concepts of DSTATCOM and its controller. It also tells us how it compensates the reactive power.

Chapter 4 provides the simulation diagram and results for the three phase source with motor load with and without DSTATCOM.

Chapter 5 leads us to the conclusion of the thesis and future scope in this area.

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ABBREVIATIONS

DSTATCOM	Distribution Static Compensator
PI	Proportional Integral
PWM	Pulse Width Modulation
PPP	Premium Power Park
IRP	Instantaneous Reactive Power
SRF	Synchronous Reference Frame
VSC	Voltage Source Convertor
PCC	Point of Common Coupling
PBT	Power Balance Theory
NPC	Neutral Point Clamped
IM	Induction Motor
FCML	Flying Capacitor Multilevel Inverter
DCML	Diode-Clamped Multilevel Inverter
VSI	Voltage Source Inverter
CSI	Current Source Inverter
CC-DS	Current Control DSTATCOM
VC-DS	Voltage Control DSTATCOM
ASD	Adjustable Speed Drive
AIS	Artificial Immune System
PSO	Particle Swarm Optimization

SMC	Sliding Mode Controller
EAF	Electrical Arc Furnace
BESS	Battery Energy Storage System
SVPWM	Space Vector Pulse Width Modulation
HVDC	High Voltage Direct Current
IGBT	Insulated Gate Bipolar Transistor
GTO	Gate Turn on Thyristor
PSB	Power System Block-set
AC	Alternating Current
DC	Direct Current

NOMENCLATURE

R	Resistance
L	Inductance
Ii	Output current
Vi	Output voltage
Vs	System voltage
δ	Power angle
I_c	Capacitive current
I_L	Inductive current
Ir	Reference current
Kp	Proportional gain constant
Ki	Integral gain constant
v_{dc}	Direct current voltage
v_{dcr}	Reference direct current voltage
V_o	Output voltage
w_a, w_b, w_c	Quadrature unit current vectors
u_a, u_b, u_c	Phase unit current vectors
v_{tm}	Voltage at point of common coupling
vt_a, vt_b, vt_c	Terminal voltages
i_{sadr}, i_{sbdr}, i_{scdr}	Phase component of reference supply current
i_{saqr},i_{sbqr},i_{scqr}	Quadrature component of reference supply current

i_{sar}, i_{sbr}, i_{scr}	Reference supply current
Rs	Stator resistance
Rr	Rotor resistance
Lm	Mutual inductance
Lls	Stator inductance
Llr	Rotor inductance
h_b	Hysteresis band
Rc, Lc	Transformer impedance

CHAPTER 1

INTRODUCTION

1.1 Overview

One of the most common power quality problems today is voltage dip. A voltage dip is a short time (10 ms to 1 minute) event during which a reduction in rms voltage magnitude occurs. It is often set only by two parameters, depth/magnitude and duration. The voltage dip magnitude ranges from 10% to 90% of nominal voltage (which corresponds to 90% to 10% remaining voltage) and with a duration from half a cycle to 1 min. 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 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 tremendously in the last decade. This has lead to an additional thrust to the development of small distributed generation. Small isolated DG sets have the capability to feed local loads and thus lads 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. Small generation systems in hilly terrains, islands, off shore plants, power distribution in rural areas, aircrafts etc. can be efficiently utilized even in developing countries.

However, these DG sets may have to be de-rated if induction motor loads are simultaneously started. One useful option is to use DSTATCOM in shunt configuration with the main system so that the full capacity of generating sets is efficiently utilized. DSTATCOM employs a voltage source converter (VSC) and generates capacitive and inductive reactive power internally. Its control is very fast and has the capability to provide adequate reactive compensation to the system.

DSTATCOM can be effectively utilized to regulate voltage for one large rating motor or for a series of small induction motors starting simultaneously. Induction motor loads draw large starting currents (5- 6times) of the full rated current and may affect working of sensitive loads.

Thyristor based systems were initially 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 large size, fixed compensation, possibility of resonance etc., the use of new compensators such as DSTATCOM is growing to solve power quality problems.

The use of DSTATCOM for solving power quality problems due to voltage sags, flickers, swell etc has been suggested. The purpose of DSTATCOM is to provide efficient voltage regulation during short duration of induction motor starting and thus prevent large voltage dips.

1.2 Literature Review

The power electronic devices, due to their inherent non-linearity draw harmonics and reactive power 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 lead to 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 like thyristor switched capacitor, 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. Now a day's equipments using power semiconductor devices, commonly known as active power filters, active power line conditioners etc. are used for the power quality issues due to their dynamic and adjustable solutions. Out of these devices DSTATCOM has turned out to be a promising tool for such quality improvements. DSTATCOM deals with the issues related to power quality using similar control strategies and concepts. Thus to mitigate this voltage dip problem, DSTATCOM with two controllers proportional integral and hysteresis is used.

B.N. Singh *et al*. [1] considered that the problem of voltage dip is caused due to starting of an induction motor. DSTATCOM with two PI controllers are used for mitigating this voltage dip problem. One PI controller is realized over the sensed and reference values of dc bus voltage of the DSTATCOM and the second PI controller is realized over the sensed and reference values of ac voltage at PCC. A hysteresis PWM controller is employed over the sensed supply currents and instantaneous reference supply currents to generate six gating pulse for DSTATCOM.

R. Chiumeo *et al*. [2] have proposed a possible configuration of a premium power park and developed a model using ERSE provided an adequate basis for a general methodology to study the theoretical design of premium power park based on custom power devices and also focuses on the analysis of the D-STATCOM control system structure and its behaviour in the PPP in absence of network disturbance and when a fault occurs.

Bhim singh *et al*. [3] have proposed a DSTATCOM which is used for the compensation of reactive power and unbalance caused by various loads in distribution system. Three different methods are designed to derive reference currents for a DSTATCOM. DSTATCOM is controlled using IRP and SRF theories for compensation of reactive power and unbalance, and these methods are compared with a new adaline based control algorithm and also presents the control of DSTATCOM for reactive power, harmonics and unbalanced load current compensation of a diesel generator set for an isolated system. The PI controller is used to maintain a constant voltage at the dc-bus of a VSC working as a DSTATCOM.

Byung-Moon Han *et al*. [4] have described modelling and AC voltage direct control technique of DSTATCOM and analyzed the dynamic characteristics of distribution system such as sag, harmonics, re-closer operation, actual line model and transformer saturation characteristics during system fault.

Dinesh Kumar *et al*. [5] considered the problem of voltage compensation at PCC. He described the modelling and analysis of DSTATCOM which is capable of compensating sinusoidal or non-sinusoidal load currents. A detailed state space model of the compensator is derived.

M.G. Molina, *et al*. [6] discussed the dynamic performance of a DSTATCOM coupled with an energy storage system for improving the power quality of distribution system and demonstrated the effectiveness of the proposed multi-level control approaches in the synchronous rotating d-q reference frame and presented a detailed model. The fast response device proved to be very effective in enhancing the distribution capacity control, voltage control and power factor correction.

Sunil Kumar *et al*. [7] have proposed the control algorithm based on PBT which is modified to control the DSTATCOM. A 3-leg VSC with a zigzag transformer is used as a DSTATCOM for compensation of the reactive power, harmonics currents, unbalance loads and the neutral current in three-phase four wire distribution system. The modified PBT based control algorithm is used for extracting the reference source currents for the voltage regulation at PCC.

Gerard Ledwich *et al*. [8] discussed the issues for the correction of load unbalance and distortion at a weak ac bus using DSTATCOM. It has been shown that for weak ac buses, DSTATCOM may introduce distortion in the line current or the voltage at the PCC.

Juan Segundo-Ramirez *et al*. [9] have presented the stability analysis of the DSTATCOM in current control mode based on bifurcation theory using this they proposed a simplified DSTATCOM model. The state-space approach has been used to for DSTATCOM.

Zhang Dongliang *et al*. [10] have presented modelling of DSTATCOM based on switch function. They also designed a control method of three-level converter tracking and DC current voltage balance. DSTATCOM can rapidly compensate load reactive power, and it has good dynamic var compensation, using the direct current control method.

R. S. Bajpai *et al*. [11] discussed the sliding mode control of the DSTATCOM to mitigate the effect of harmonics, sub-harmonics and inter-harmonics distortion and controls the PCC voltage close to sinusoidal wave-shape. The control scheme maintains the power balance at the PCC and regulates the terminal voltage in the presence of disturbances either from the load or from the source side.

Jovia V. Milanovic *et al*. [12] have presented the influence of induction motors on voltage sag propagation, accounting for the change in sag characteristics and then presented a completely automated procedure for the accounting of the effects of IMs on voltage sag performance at low-voltage distribution network buses.

Anshuman Shukla *et al*. [13] have proposed the design of a state feedback switching controller for a five-level inverter-based DSTATCOM. The state feedback switching controller uses linear quadratic regulator design that tracks the reference state trajectories. The DSTATCOM is connected to a system having balanced source supplying an unbalanced and non-linear load through a long feeder.

Two different DSTATCOM structures are considered –one based on FCMLI and the other based on DCMLI. A comparative study of their performances has been presented when the DSTATCOMs, in conjunction with a feeder side filter capacitor, are used for improving the power quality of the distribution system and the other aspects of the proposal are having balanced dc-link voltages for the DCMLI and balanced flying capacitor voltages for the FCMLI, while ensuring the desired tracking using the proposed switching control scheme.

Walmir Freitas, *et al*. [14] discussed a dynamic study about the influence of ac generator (induction and synchronous machines) and distribution static synchronous compensator devices on the dynamic behaviour of distribution network. The performance of a DSTATCOM as a voltage controller or a power factor controller has been analyzed. DSTATCOM voltage controller can improve the stability performance of induction generators and the DSTATCOM power factor controller may badly affect the stability performance of synchronous generator.

Mahesh K. Mishra *et al*. [15] have proposed a deadbeat control algorithm to operate distribution static compensators as voltage regulators to maintain the voltage of a specified bus. A closed loop control scheme has been used consisting of an outer dc capacitor voltage loop and an inner load angle control loop. A DSTATCOM can be used at this bus to reduce harmonics and balance the bus voltages.

G. Ledwich *et al*. [16] discussed the control technique of a distribution static compensator that can be operated flexibly in the voltage or current control mode. In voltage control mode, the DSTATCOM can force the voltage of a distribution bus to balance sinusoids. In the current control mode, it can cancel distortion caused by the load, such that current drawn by the compensated load is pure balanced sinusoid.

Hendri Masdi *et al*. [17] discussed the design of a prototype distribution static compensator for voltage sag mitigation in an unbalanced distribution system. For fast response requirement, the feedforward compensation scheme is employed to enable the DSTATCOM to mitigate voltage sag and at the same time to correct the power factor, thus acting as a load compensator.

Rahmat-Allah HOOSHMAND *et al*. [18] considered the problem of power quality, the voltage sag and temporary voltages due to three phase short circuit, starting of induction motor and transformer-energizing. Then influence of voltage sag compensation by means of distribution static compensator and direct control is presented for DSTATCOM.

Mohamed A. Eldery *et al*. [19] have proposed the model for the VSI and CSI-based ASD as well as the CC and VC DSTATCOM and discussed the DSTATCOM effects on the ASD stability boundaries. The VC-DS can improve the stability limits at low speeds of both VSI and CSI-based ASD. The CC-DS has no influence on the stability limits of both the current and the voltage source inverter-based ASD.

Pinaki Mitra *et al*. [20] considered the problem of power quality in electric ship power system. They discussed the control strategy for a DSTATCOM based on AIS. Innate immunity to common disturbances is achieved using a controller whose optimal parameters are determined using PSO algorithm.

J.R.P Gupta *et al*. [21] discussed different control strategies for power quality improvement of DSTATCOM for a three-phase, three wire distribution system. A three-leg VSI configuration with a dc bus capacitor has been used as DSTATCOM. The hysteresis as well as PWM current controllers have been designed, analyzed and compared for PI controller and SM controller.

B.P. Muni *et al*. [22] discussed a model of EAF and control algorithm for DSTATCOM for voltage flicker mitigation. The EAF was modelled as a current source controlled by a non-linear resistance and the DSTATCOM controller's performance is evaluated using both p-q and d-q theories for voltage flicker mitigation caused by V-I characteristic based EAF model.

Su Chen *et al*. [23] considered the problem of power quality voltage flicker and harmonics. In this DSTATCOMs are implemented using two cascaded loops, an ac current control loop and a dc-bus voltage loop. They discussed an alternative control structure based on the simultaneous control of line current and dc-link voltage by the means of instantaneous power control.

Deepika Masand *et al*. [24] discussed the comparative study of three different algorithms used for the control of DSTATCOM with linear and nonlinear loads. DSTATCOM is used for complete reactive power compensation, power factor correction and voltage regulation.

Vasudeo Virulkar *et al*. [25] discussed the performance of a DSTATCOM coupled with BESS for mitigation of voltage flicker and detailed modelling of DSTATCOM with BESS and its control strategies have been analyzed.

Bishnu P. Muni *et al*. [26] have proposed SVPWM based control logic, the PWM converter output voltages are controlled such that the reactive power generated by the DSTATCOM closely follow the reference reactive power and the DC link voltage is maintained at a desired value. SVPWM switched DSTATCOM has been used for power factor correction and voltage sag compensation.

J. Sun *et al*. [27] considered the problem of voltage flicker. They have proposed the modelling and control scheme of DSTATCOM for voltage flicker mitigation. PWM controllers have been used for DSTATCOM.

K. Aodsup *et al*. [28] presents the design, control and analysis of a DSTATCOM enhanced with an energy storage device when combined with a wind farm comprising fixed speed induction generators. DSTATCOM, controlled via a decoupled vector control technique, proved to be an effective way of reducing voltage flicker emissions at the PCC, removing the wind speed fluctuations and improving the transient stability of wind farm.

Sumate Naetiladdanon [29] has explained various the design considerations of DSTATCOM for voltage sag compensation without the possible interactions and the voltage sag compensation performance with different current injection schemes and the interaction.

Alka Adya *et al*. [30] considered the problem of power quality aspects like power factor correction, voltage regulation and load balancing of linear load. The power quality improvement with DSTATCOM on a small, isolated alternator feeding a three-phase, three wire distribution system was performed.

A.P. Mittal *et al*. [31] have proposed the design, analysis of neural network based DSTATCOM controller with respect to PI controllers for power factor correction and load balancing.

Adib Abrishamifar *et al*. [32] have proposed a direct power control of three-phase pulse width modulation inverter without the application of voltage line sensors to a distribution static compensator for power quality improvement.

1.3 Objective of the Work

Objective of this present work is to study of DSTATCOM and to improve the power quality of a distribution system by injecting 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 a, 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 thr power quality issues due to their dynamic and adjustable solutions. Flexible ac transmission systems and custom power products 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 dip
- Voltage swells/overvoltage
- Voltage flicker
- Voltage and current harmonic distortion
- Voltage and current transient
- Short interruptions
- Power frequency variation

Voltage dip is sudden reduction in the supply voltage by a value of more than 10% of the reference value fallowed 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.

Balanced Sag is an equal drop in the r.m.s. value of voltage in the three phases of a three phase system or ar the terminals of three phase equipment for duration up to a few minutes.

Interruption is the voltage event in which the voltage is zero during a certain time. The during which the voltage is zero is to as the “duration of the interruption.(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 it is the immunity of a piece of equipment against voltage magnitude variations (sags, swells and interruption) and short over voltages

Unbalanced fault is a circuit or open circuit fault in which not all three phases are equally involved.

Critical distance is at when a short-circuit fault will lead to a voltage sag of a given magnitude for a given load position.

Recovery time is the time interval needed for the voltage or current to return to its normal operating value, after a voltage or current event.

Fault is an event occurs on the power system and it effects the normal operation of the power system.

CHAPTER 3

DSTATCOM AND FUNCTIONS OF ITS CONTROLLER

3.1 Distribution Static Compensator (DSTATCOM)

The DSTATCOM is a three-phase and shunt connected power electronic devices. It is connected near the load at 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 inverter that converts an input dc voltage into a three-phase output voltage at fundamental frequency.

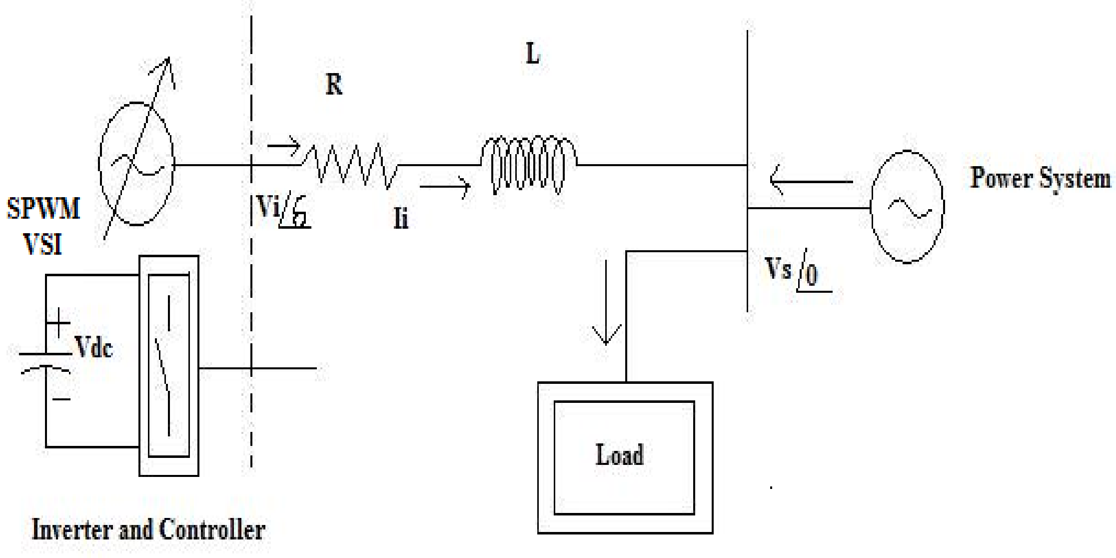
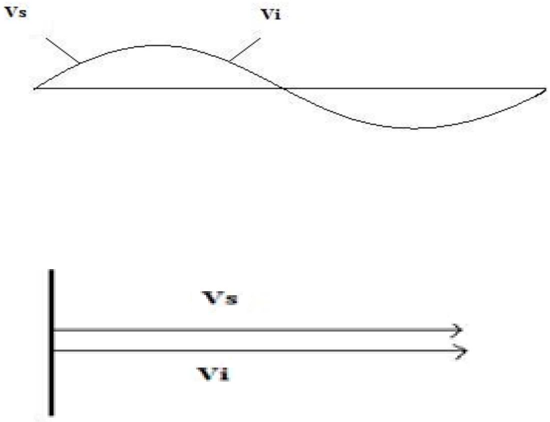


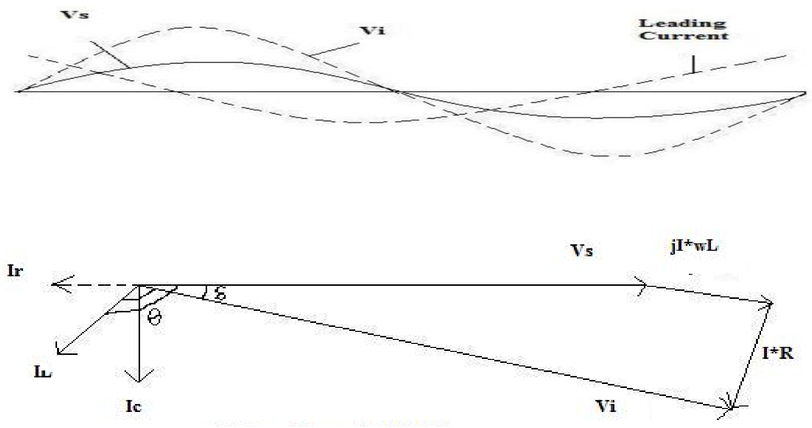
Figure 3.1: Basic building blocks of the DSTATCOM

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.

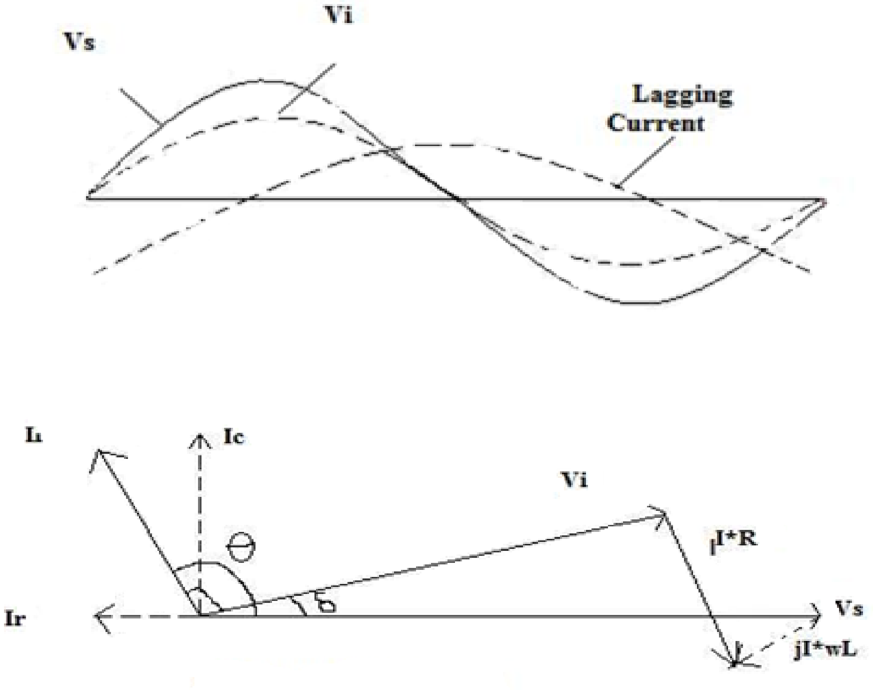
Figure 3.1 shows the inductance *L* and resistance *R* which represent the equivalent circuit elements of the step-down transformer and the inverter is the main component of the DSTATCOM. The voltage *Vi* is the effective output voltage of the DSTATCOM and δ is the power angle. The reactive power output of the DSTATCOM can be either inductive or capacitive depending on the operation mode of the DSTATCOM. Referring to Figure 3.2, 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 thyristor-based inverter, Vi, can be controlled in the same way as the distribution system voltage, Vs. Figure 3.2 shows the three basic operation modes of the DSTATCOM output current (I), which varies depending upon voltage Vi. If Vi is equal to system voltage Vs, the reactive power is zero and the DSTATCOM does not generate or absorb reactive power. When Vi is greater than Vs, 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 Vs is greater than Vi, 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 (Vs=Vi)



(b) Capacitive mode ($V_i > V_s$)



(c) Inductive mode ($Vi<Vs$)

Figure 3.2: Operation modes of DSTATCOM

3.2 Main Features of DSTATCOM

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

3.3 DSTATCOM Controllers

- PI Controller
- Hysteresis Controller

3.3.1 Design of PI Controller

PI controller is shown in Figure 3.3. PI controller is one of the most widely required controller in the industry as it is the simplest to design. In proposed system, one PI controller is developed over the DC link voltage of DSTATCOM. The DC bus voltage is filtered and then compared with the reference value. Thus the resulting error signal ($v_{e\,(n)} = V_{dcr} - V_{dc(n)}$) is obtained and the output $V_{o(n)}$ is obtained as:

$$V_{o\,(n)} = V_{o(n-1)} + K_p \left(V_{e(n)} - V_{e(n-I)}\right) + K_i\, V_{e(n)}$$

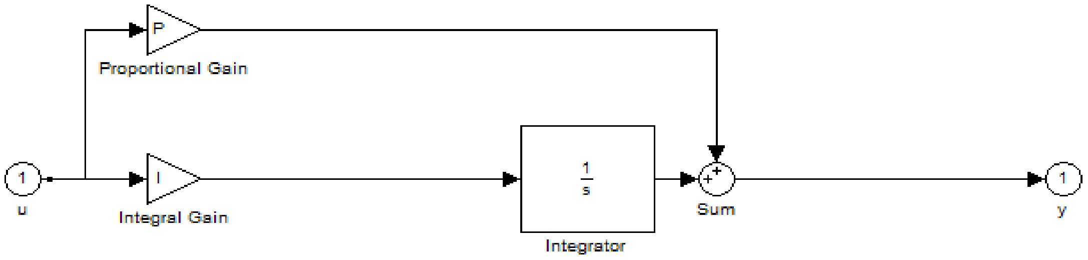


Figure 3.3: PI controller

where K_p and K_i are the proportional and integral gain constants respectively for the used PI controller. The output $V_{o\,(n)}$ is taken as amplitude of I_{spdr} after limiting it to a safe value.

3.3.2 Design of Hysteresis Controller

Hysteresis controller for the tracking of reference source currents is shown in Figure 3.4. The error signals of the reference and the actual (instantaneous) source currents are calculated and compared within a small hysteresis band which is generally 1% to 5% of the current level. The control logic used is given as $i_{sa} < i_{sa}^* - h_b$, then the upper switch of VSC is turned OFF and lower switch is turned ON. The upper and the lower switching device (IGBT in our model) are switched ON and OFF in a complementary fashion. The hysteresis band h_b can be varied. A narrow hysteresis band results in very good and fast tracking of currents but switching frequency may become too high. A wide hysteresis band may not provide effective tracking thus leading to the system becoming unstable.

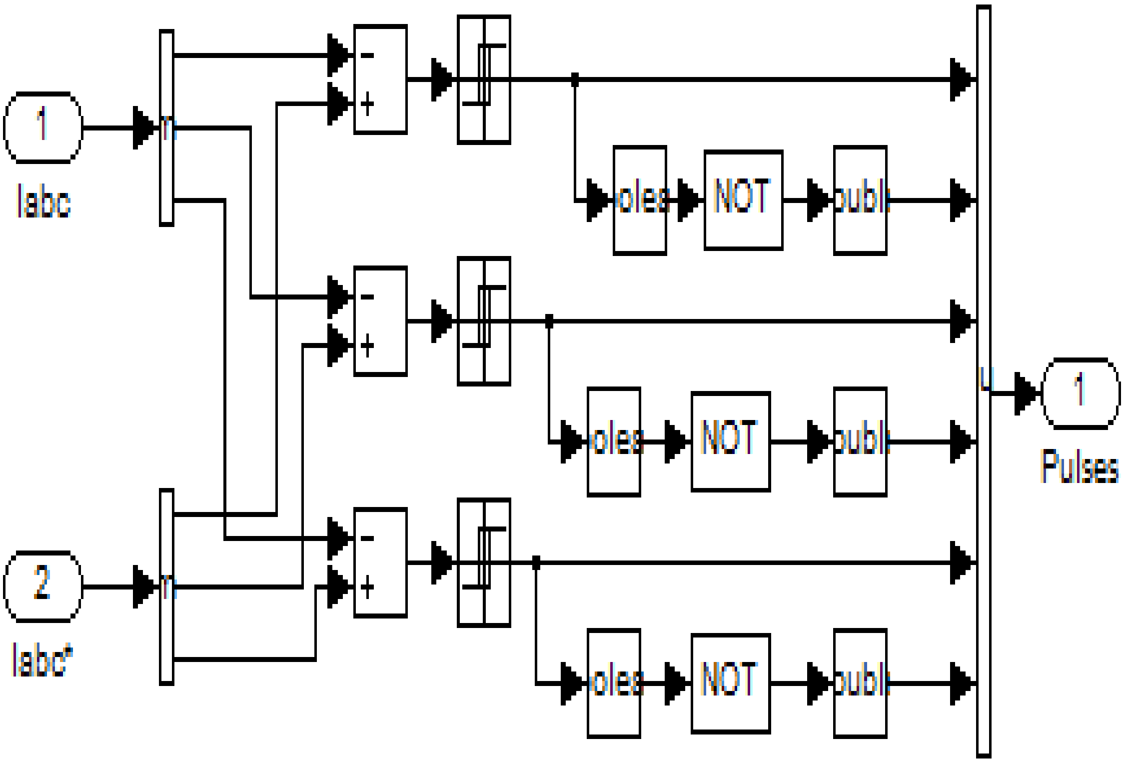


Figure 3.4: Schematic representation of PWM hysteresis control

3.4 System Configuration

Figure 3.5 shows the schematic diagram of DSTATCOM for providing voltage regulation. The three phase source feeds the induction motor load.

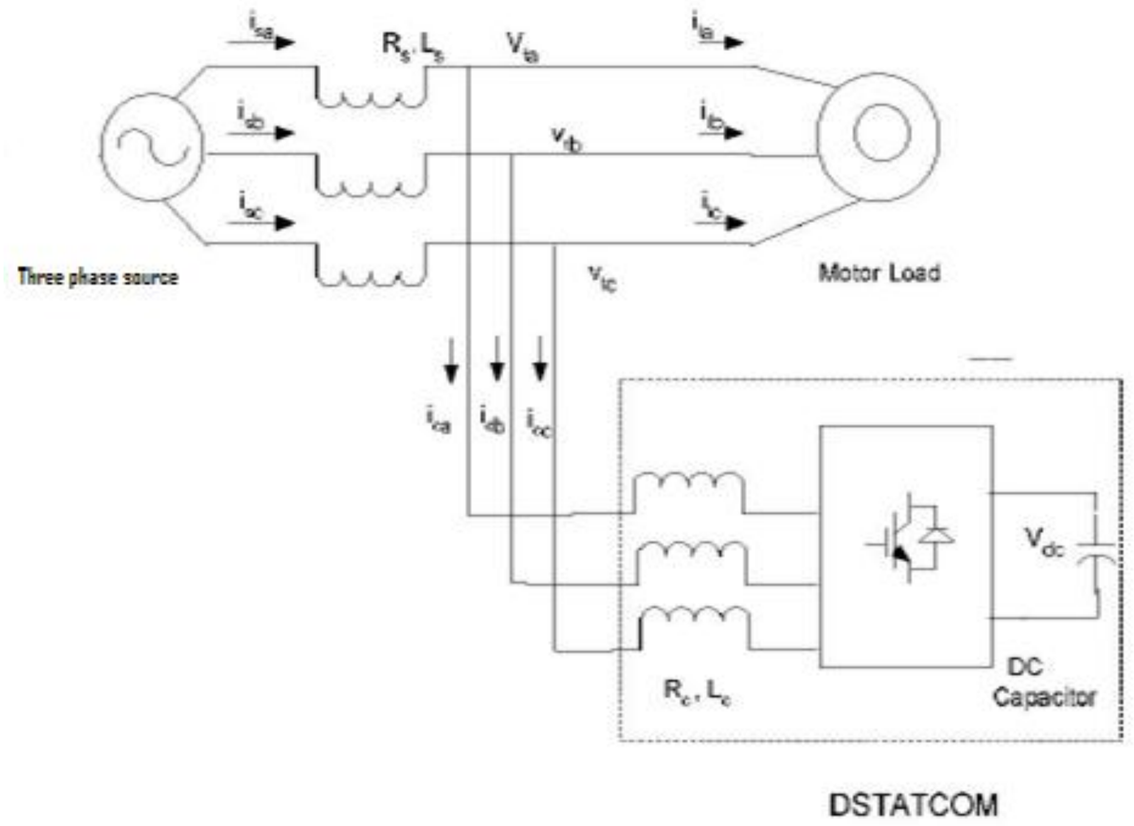


Figure 3.5: Schematic Diagram of DSTATCOM system connected to three phase source

Figure 3.6 shows the basic working diagram of DSTATCOM connected as shunt compensator. It consists of a three-phase, 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. AC output terminals of the DSTATCOM are connected through filter reactance or reactance of the connecting transformer. DSTATCOM thus provides fast and efficient reactive power compensation.

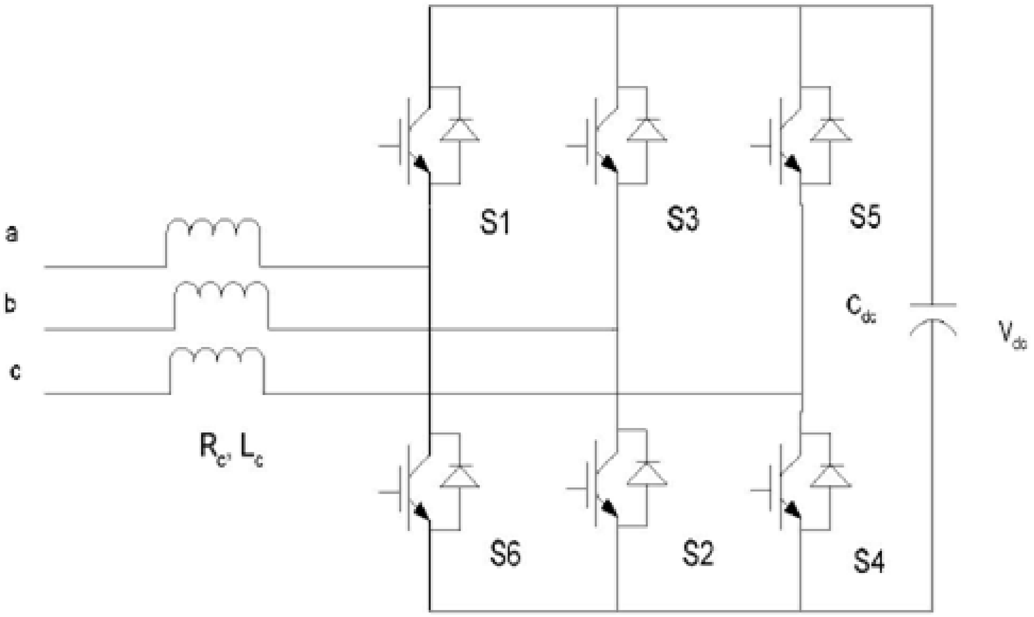


Figure 3.6: Schematic diagram of 3-legged DSTATCOM system

3.4.1 Control Scheme

Figure 3.7 shows the control scheme for voltage regulation of the motor. Here 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.

The output of the first PI controller (I_{spdr}) is considered as amplitude of in-phase components of reference supply currents and the output of second PI controller (I_{spqr}) is considered to be the amplitude of quadrature components of reference supply currents. A set of in-phase unit vectors (u_a, u_b and u_c) are calculated by dividing the terminal voltages (v_{ta}, v_{tb} and v_{tc}) by their amplitude (v_{tm}). Another set of three-phase quadrature unit current vectors (w_a. w_b and w_c) are calculated using in-phase unit current vectors (u_a, u_b and u_c).

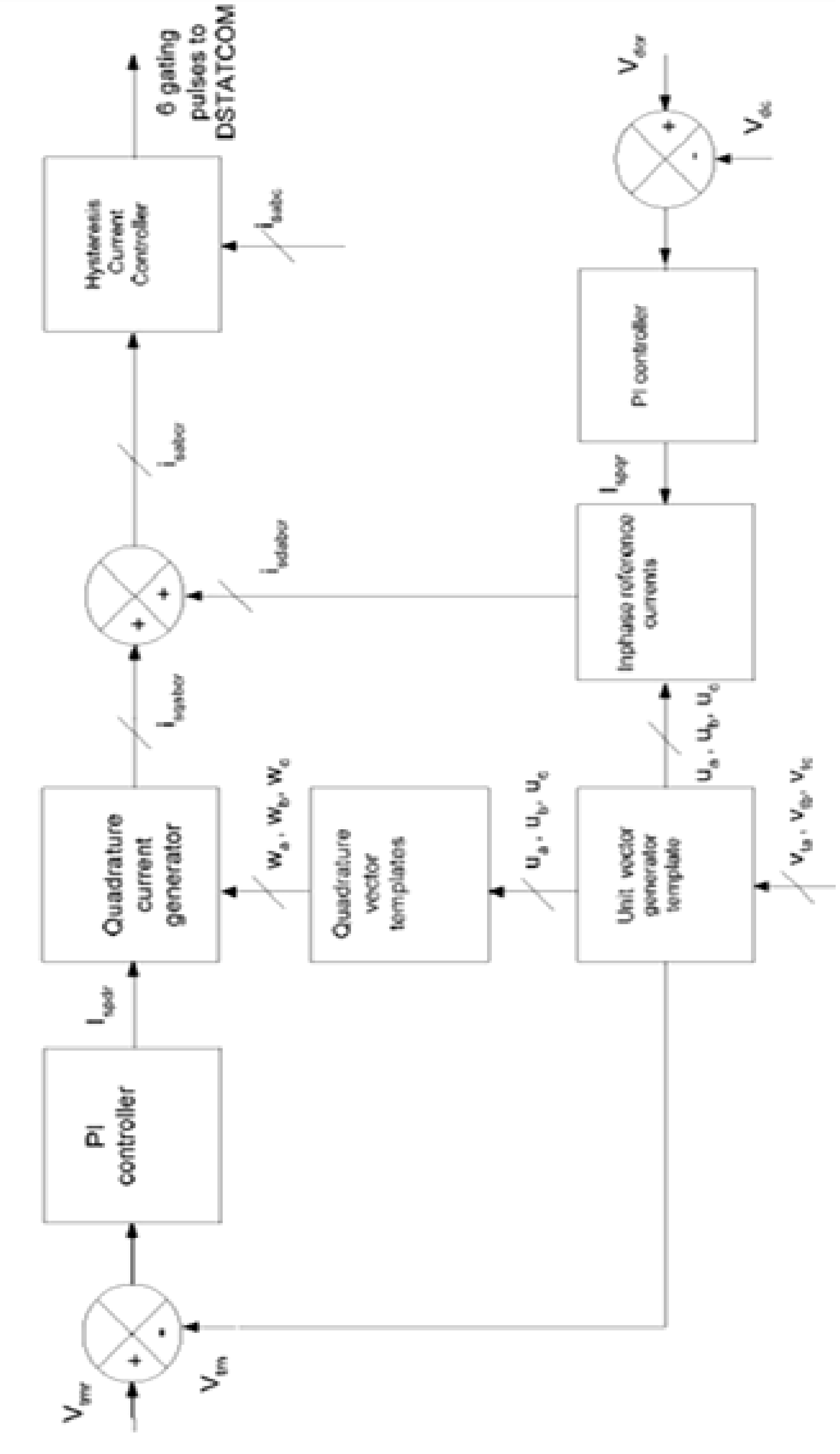


Figure 3.7: Schematic diagram of DSTATCOM control scheme

The multiplication of in-phase amplitude with in-phase unit current vectors results in-phase components (i_{sadr}, i_{sbdr} and i_{scdr}) of three-phase reference supply currents and similarly multiplication of quadrature amplitude with quadrature unit current vectors results in the quadrature components (i_{saqr}, i_{sbqr} and i_{scqr}) of three-phase reference supply currents. Algebraic sum of these in-phase and quadrature components results in the three-phase reference supply currents ($i_{sar,}$ i_{sbr}, and i_{scr}). These three-phase reference supply currents are calculated using three-phase supply voltages and dc bus voltage of the DSTATCOM.

(a) Computation of In-Phase Components of Reference Supply Currents

The amplitude of in-phase component of reference supply currents (I_{spdr}) can be calculated using first PI controller over the average value of dc bus voltage of the DSTATCOM and its reference counterpart**.**

$$I_{spdr(n)} = I_{spdr(n-1)} + K_{pd}\{v_{de(n)} - v_{de(n-1)}\} + K_{id}\, v_{de(n)} \tag{1}$$

where $v_{de(n)} = v_{dcr} - v_{dca(n)}$ denotes the error in v_{dc} calculated over reference v_{dcr} and average value of v_{dc} and K_{pd} and K_{id} are proportional and integral gains of the dc bus voltage PI controller.

The output of this PI controller gives the amplitude of in-phase component of the reference supply currents. Three phase components of the reference supply currents are computed using their amplitude and in-phase unit current vectors are derived from the supply voltages. The amplitude of the supply voltage is calculated as following:

$$v_{tm}^2 = 2/3(v_{ta}^2 + v_{tb}^2 + V_{tc}^2) \tag{2}$$

The unit vectors (u_a, u_b, u_c) are calculated as:

$$\begin{gathered} u_a = v_{ta}/\, v_{tm}, \\ u_b = v_{tb}/\, v_{tm}, \\ u_c = v_{tc}/\, v_{tm} \end{gathered} \tag{3}$$

The in-phase magnitudes of reference currents (i_{sadr}, i_{sbdr}, i_{scdr}) are calculated as:

$$\begin{gathered} i_{sadr} = l_{spdr}\, u_{a,} \\ i_{sbdr} = l_{spdr}\, u_{b,} \\ i_{scdr}=l_{spdr}\, u_c \end{gathered} \tag{4}$$

(b) Computation of Quadrature Components of Reference Supply Currents

The amplitude of quadrature component of reference supply currents (I_{spqr}) is computed using second PI controller over the average values of the amplitude of supply voltage and its reference counterpart.

$$I_{spqr(n)} =I_{spqr(n-l)} + K_{pq}\{v_{ae(n)-}\, v_{ae(n\ 1)\}} + K_{iq}\, v_{ae(n)} \tag{5}$$

where $v_{ae(n)=}\ v_{tmr}$- $v_{tm(n)}$ denotes the error in v_{tm} calculated over reference v_{tmr} and average value of V_{tm} and K_{pq} and K_{iq} are the proportional and integral gains of the second PI controller. The quadrature unit current vectors (w_a, w_b, w_c) are derived from in-phase unit current vectors (u_a, u_b, u_c) as:

$$\begin{gathered} w_a=\{-u_b + u_c\}I/\ (3)^{1/2} \\ w_b=\{u_a(3)^{1/2} + (u_b\text{-}u_c)\ \}/\ 2(3)^{1/2} \\ w_c=\{-u_a(3)^{1/2}+(u_b\text{-}u_c)\}/2(3)^{1/2} \end{gathered} \tag{6}$$

(c) Computation of Total Reference Supply Currents

The total reference currents are calculated by the addition of respective in-phase and quadrature current components as:

$$i_{sar} = i_{sadr} + i_{saqr}$$

$$i_{sbr} = i_{sbdr} + i_{sbqr}$$

$$i_{scr} = i_{scdr} + i_{scqr}$$

(7)

A PWM hysteresis controller is applied over the sensed (i_{sa}, i_{sb} and i_{sc}) and the reference values of supply currents (i_{sar}, i_{sbr} and i_{scr}) to generate six gating pulses for the six IGBT switches used in the DSTATCOM.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Performance of Three Phase Source with Motor Loads without DSTATCOM

Figure 4.1 shows the simulation model of three phase source feeding motor loads without DSTATCOM. A 7.5kW induction motor is connected at the end of three phase source.

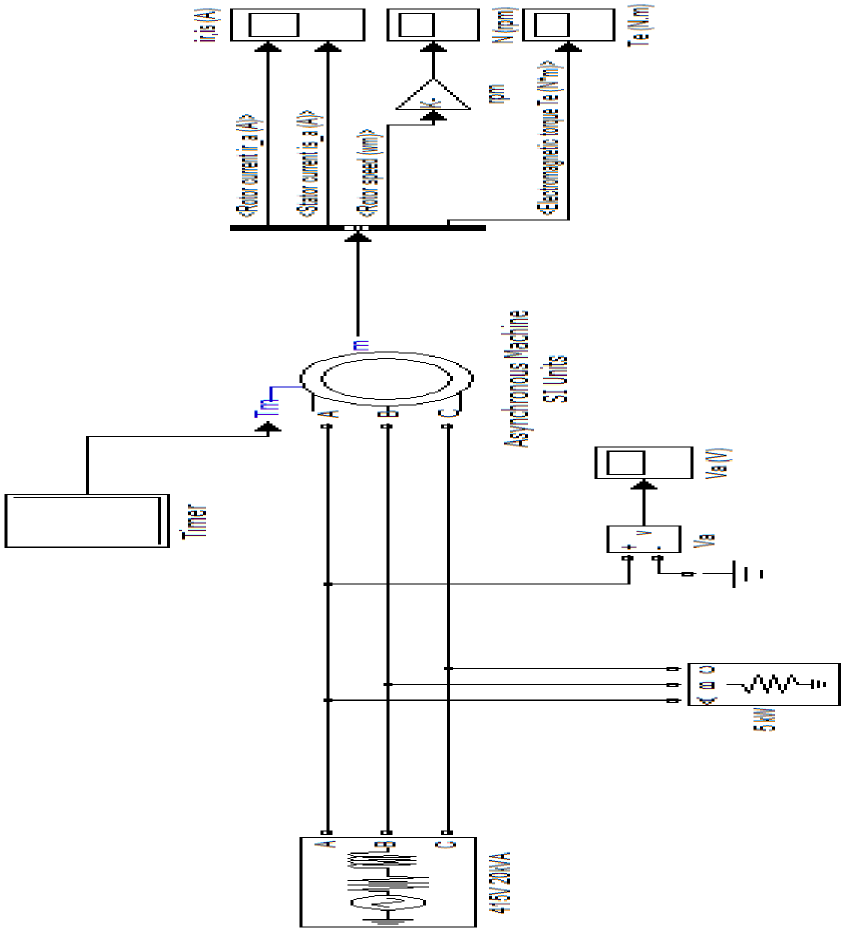


Figure 4.1: Simulation model of three phase source feeding motor loads without DSTATCOM

The motor load is applied at t = 0 sec and the simulated results in Figure 4.2 (c) show that voltage dips instantaneously. Voltage dips from the reference value of 160V to 70V, which is 56.3% voltage dip. This large voltage dip is encountered at the starting of induction motor as the motor draws 5-6 times the full load currents (Figure 4.2 (a)) during this duration. The motor now develops rated speed, as shown by Figure 4.2(d) and it is put on full load at 5 sec. However, the voltage dip is now within limits as the motor is already started and is drawing normal full rated current. Figure 4.2 (a, b, c, d, e) respectively shows the stator current, rotor current, load voltage, speed, electromagnetic torque with respect to time.

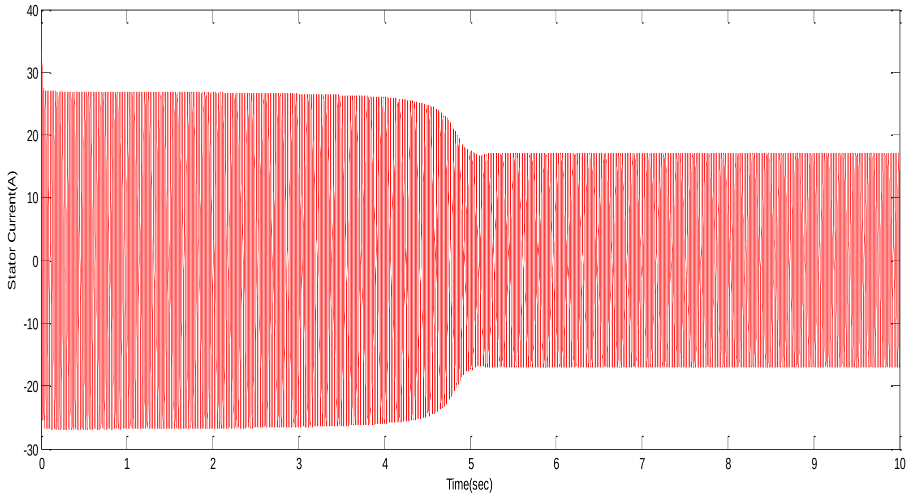


Figure 4.2(a): Stator Current (A) Vs Time (sec)

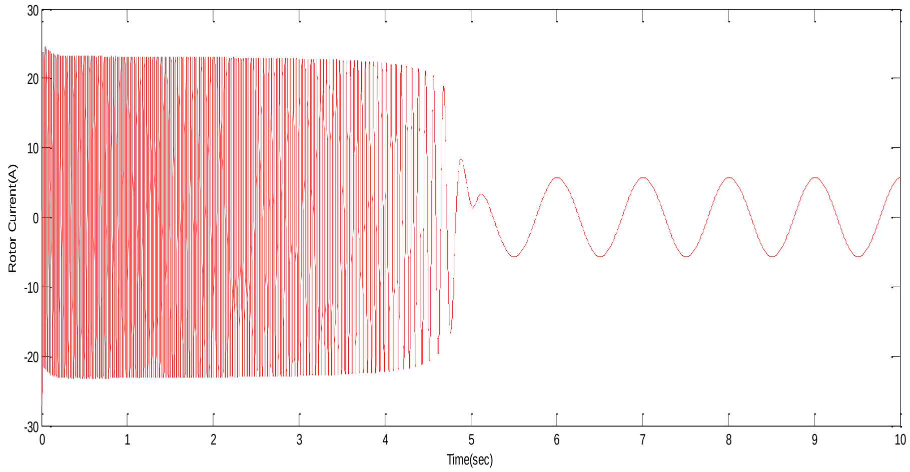


Figure 4.2(b): Rotor Current (A) Vs Time (sec)

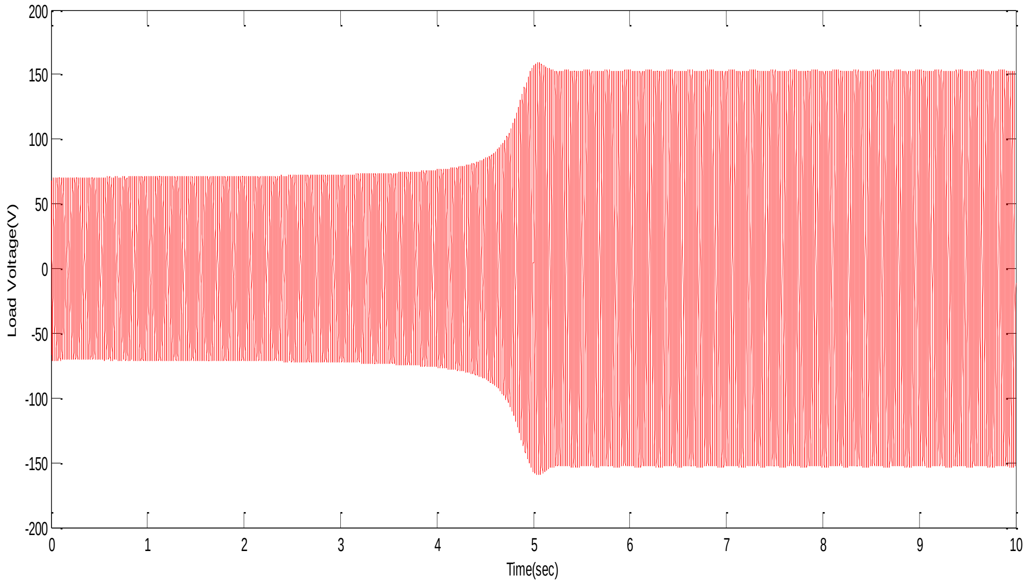


Figure 4.2(c): Load Voltage (V) Vs Time (sec)

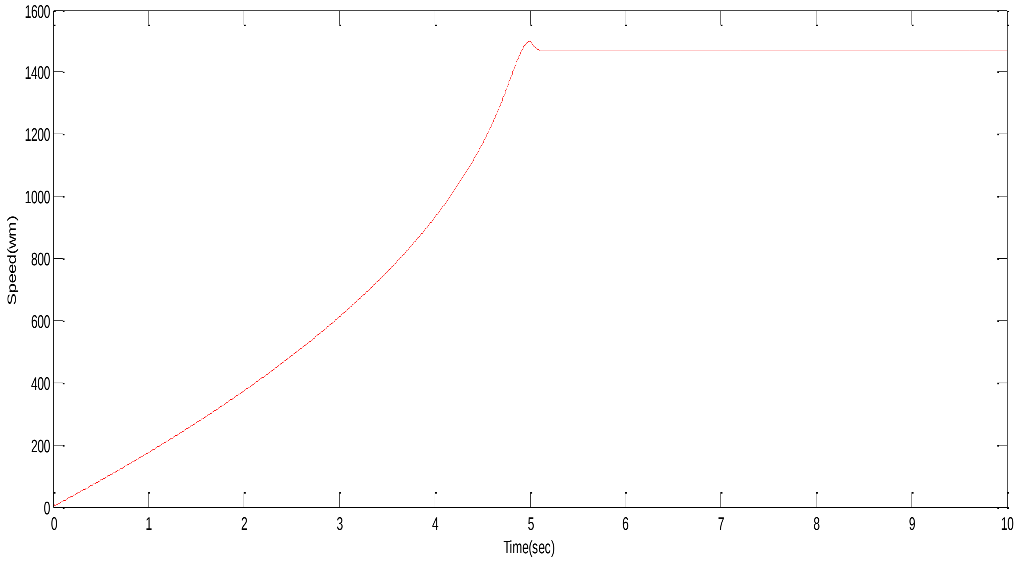


Figure 4.2(d): Speed (rpm) Vs Time(sec)

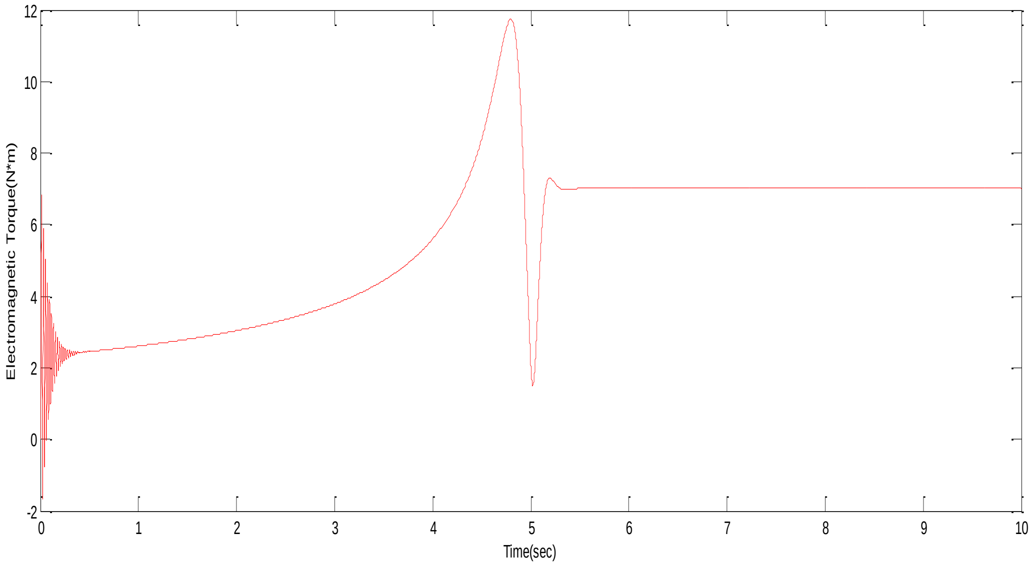


Figure 4.2(e): Electromagnetic Torque Vs Time (sec)

Figure 4.2: Performance of three phase source feeding motor loads without DSTATCOM

4.2 Performance of Three Phase Source with Motor Loads with DSTATCOM

Figure 4.3 shows the simulation model of three phase source feeding motor loads with DSTATCOM. A 7.5kW induction motor is connected at the other end of three phase source.

An IGBT based PWM voltage source inverter as DSTATCOM is implemented using Universal bridge block from Power Electronics subset of Power System Block-set. It is connected in shunt with the main system via transformer impedance (R_c, L_c). The current regulator block uses voltage inputs and generates gating pulses for IGBT switches of VSC. The motor load is applied at t = 0 sec and it is observed that the voltage at PCC dips.

However, DSTATCOM system is able to reduce the dip from 160V to 95V (Figure 4.5(c)) two PI controllers are used one regulate the DC link voltage and the other one is to regulate the ac terminal voltage at PCC. The momentary voltage dip is approximately 40.7% which is much less as compared to three phase system without DSTATCOM. The full load on motor is applied at t = 5sec and the voltage at PCC is regulated nearly to reference value of 160V.

4.2.1 Control Scheme

Figure 4.4 shows the PI control scheme model of DSTATCOM developed using MATLAB. This figure shows the generation of terminal voltage, unit in-phase current templates and unit quadrature current templates. The figure 4.4 (a, b, c) shows the subsystem detailed simulink diagrams of the unit vectors used in the main control scheme for the generation of reference current. This reference current evaluated using the phase components and quadrature components of reference currents. The in-phase components of reference currents are responsible for the power factor correction of load and the quadrature components of the supply reference currents are responsible for the regulation of the AC system at PCC. The reference supply currents are generated using the indirect current control scheme as illustrated using equations (1)-(7).

A hysteresis PWM controller is designed over the sensed supply currents (i_{sa}, i_{sb}, i_{sc}) and instantaneous reference supply currents (i_{sar}, i_{sbr}, i_{scr}) to generate six gating pulses for the switching of DSTATCOM. The PWM current controller controls the supply currents in a band around the desired reference current values. If the current in phase 'A' is less than reference current in the same phase, then upper IGBT for leg 'A' is turned 'OFF' and lower IGBT is turned 'ON'. Similar logic is applied to the other two legs.

The controller controls the supply currents in a band (h_b) around the desired reference current values. The hysteresis controller generates appropriate switching pulses for six IGBTs of the VSI inverter. Figure 4.5(a, b, c, d, e) respectively show stator current, rotor current, load voltage, speed and electromagnetic torque with respect to time.

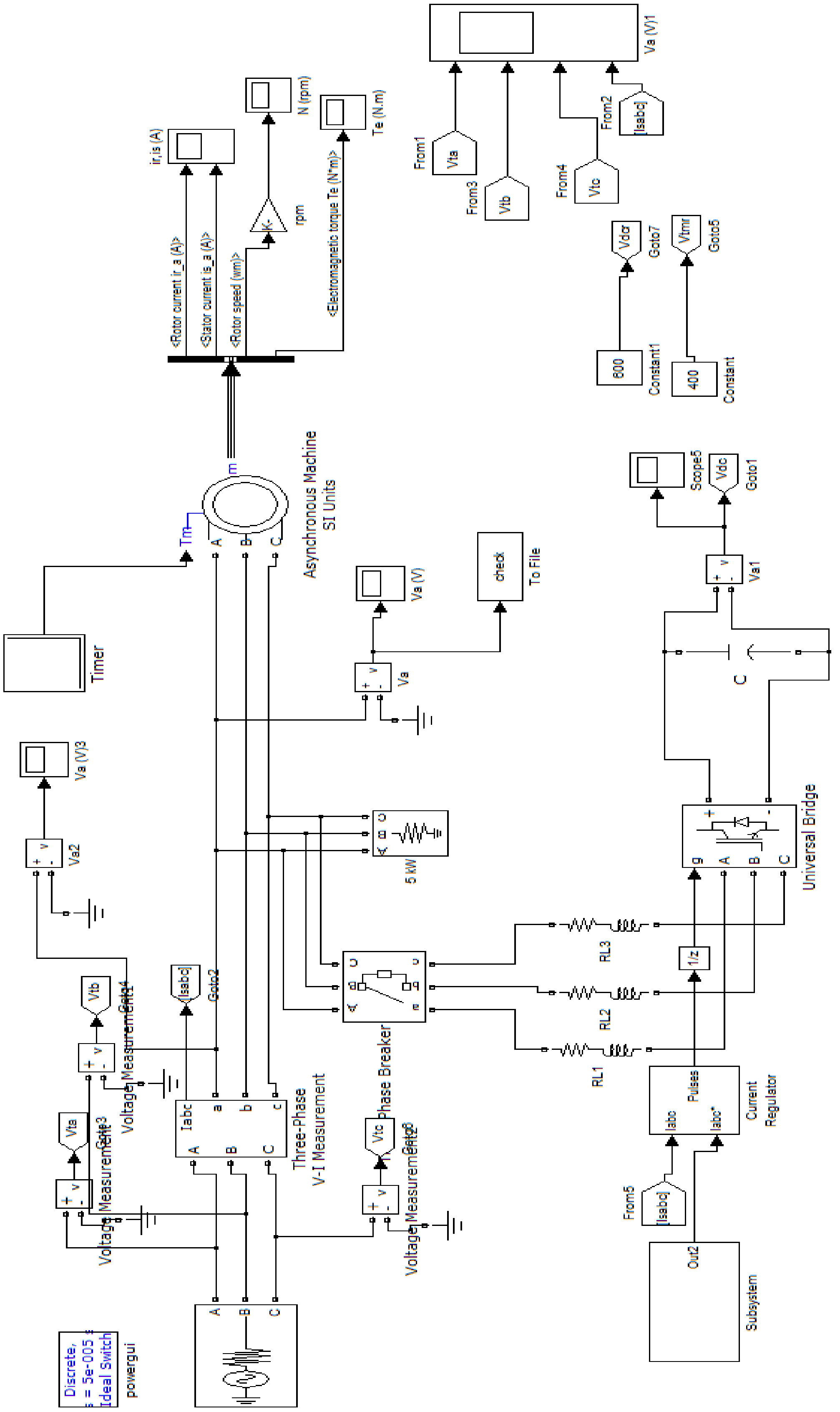


Figure 4.3: Simulation model of three Phase source feeding motor loads with DSTATCOM

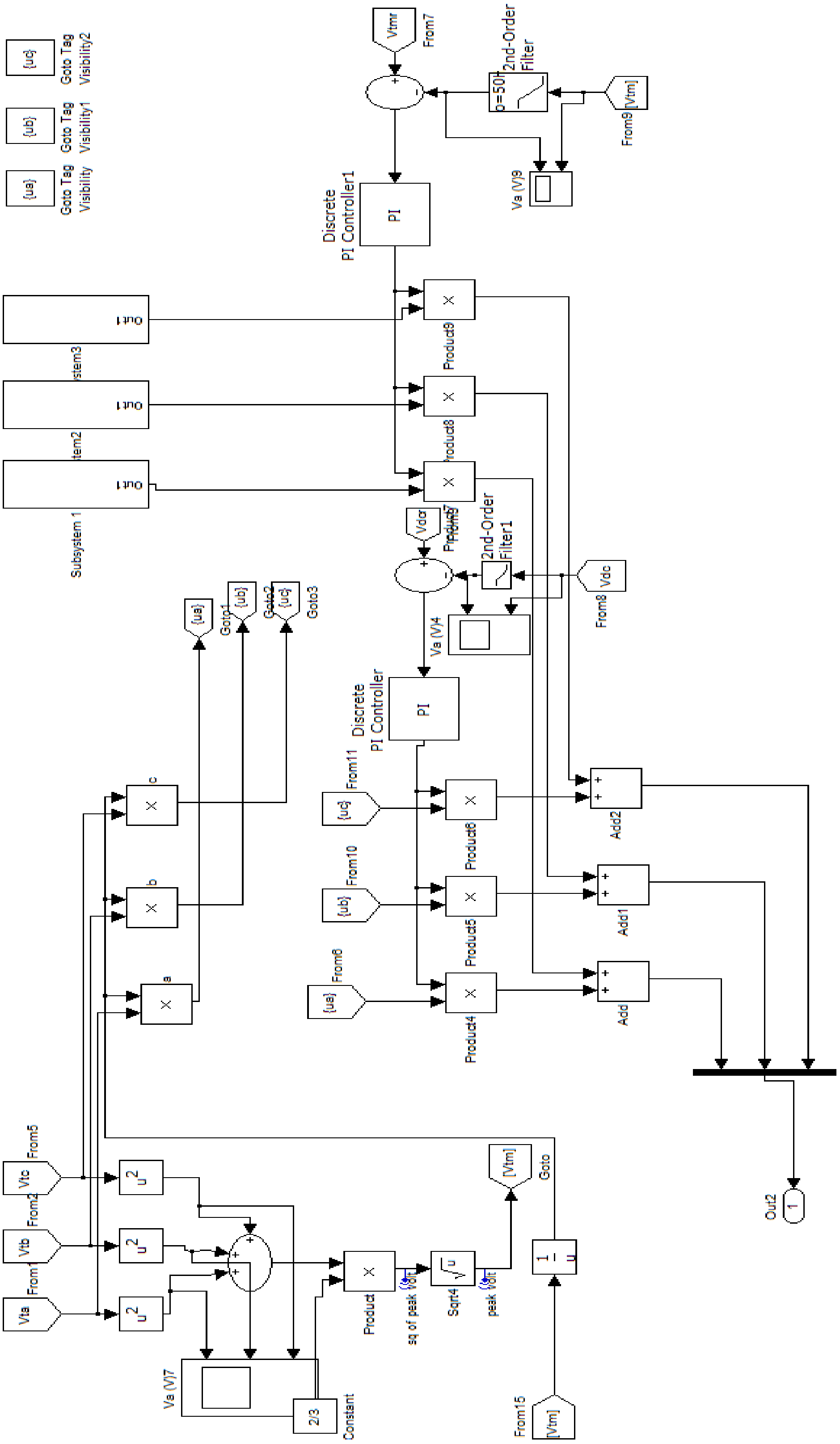


Figure 4.4: Matlab based model of control scheme for generation of reference current

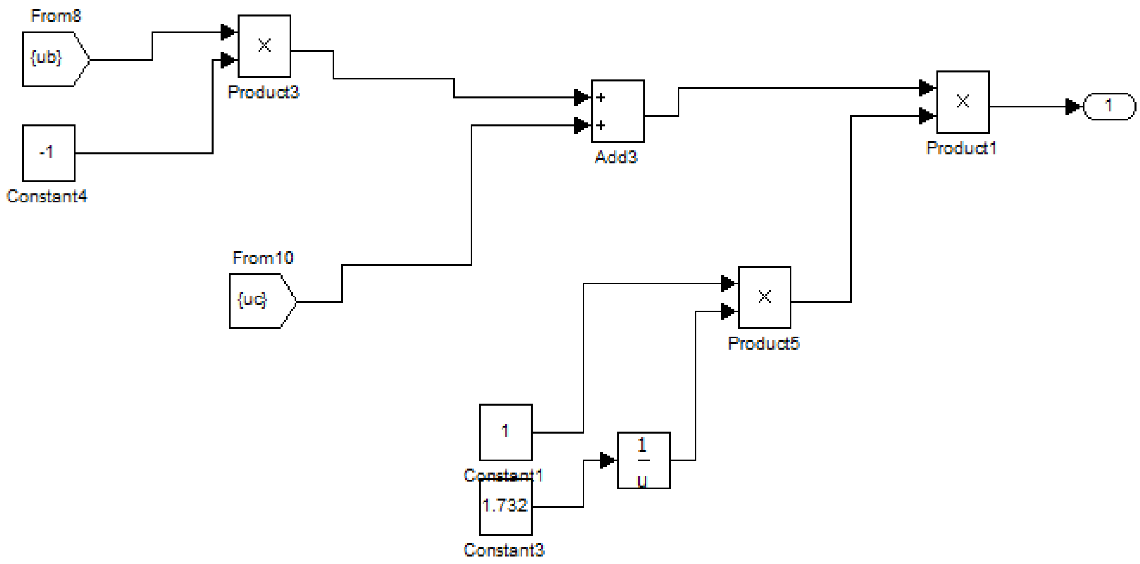


Figure 4.4(a): Subsystem 1

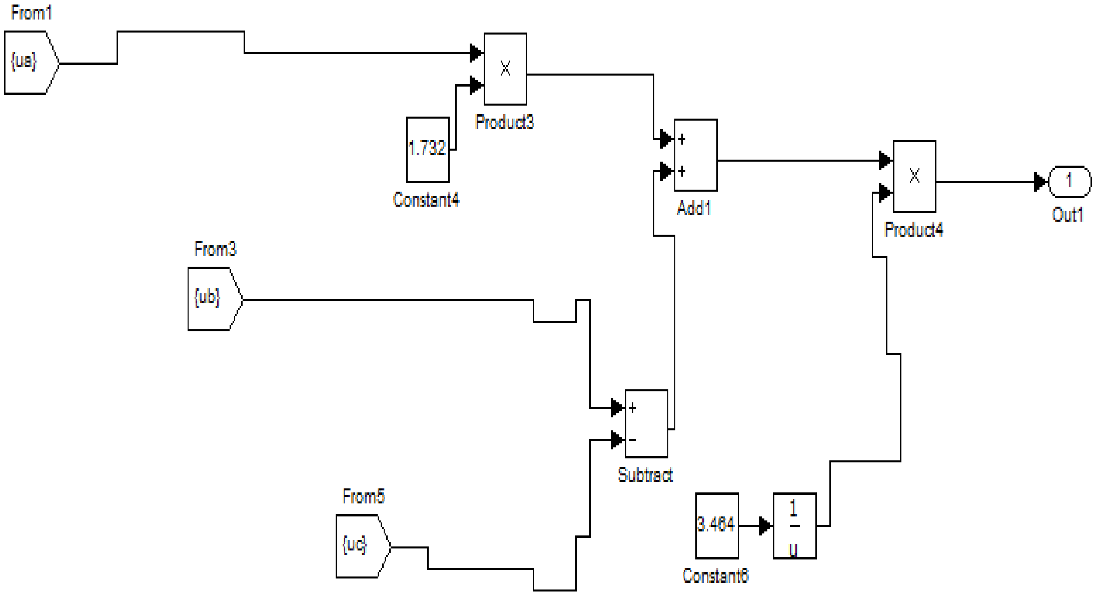


Figure 4.4(b): Subsystem 2

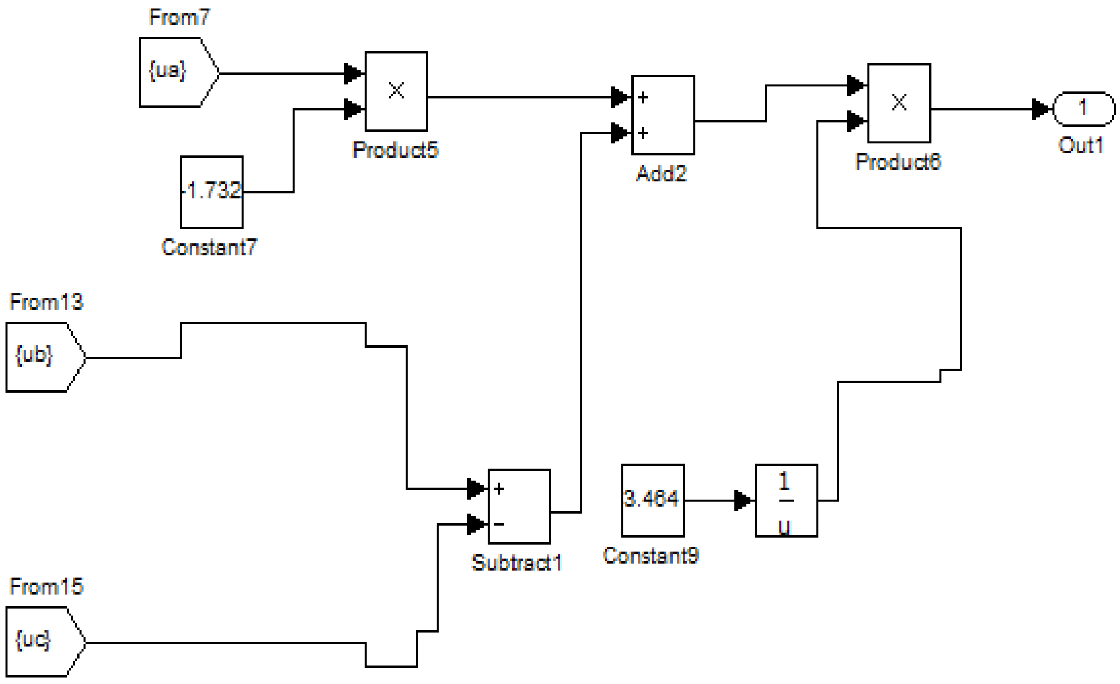


Figure 4.4(c): Subsystem 3

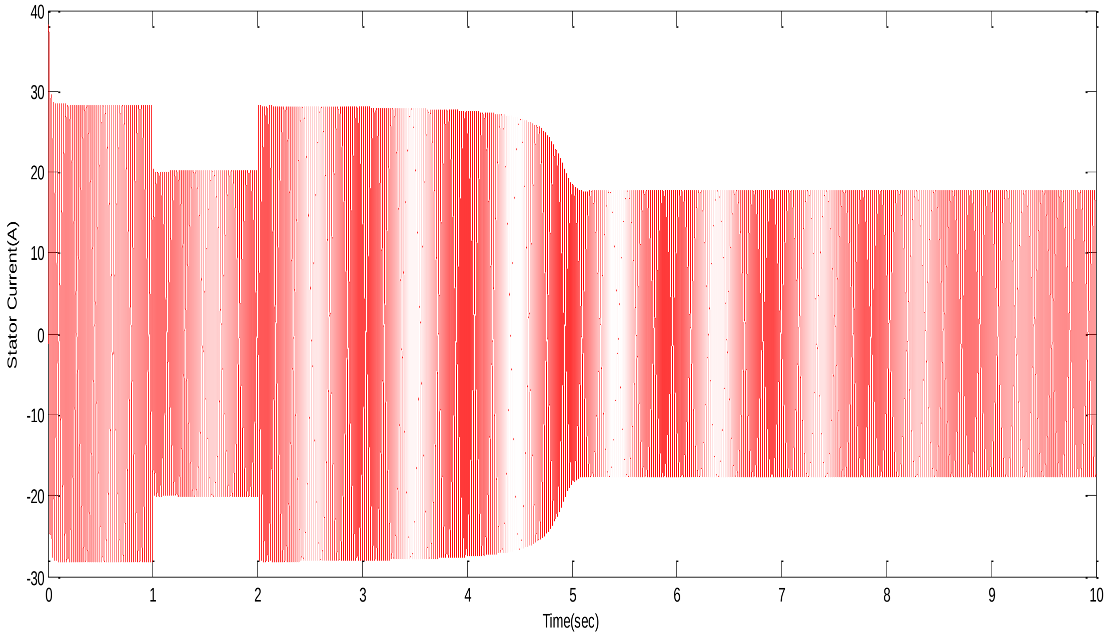


Figure 4.5(a): Stator Current(A) Vs Time(sec)

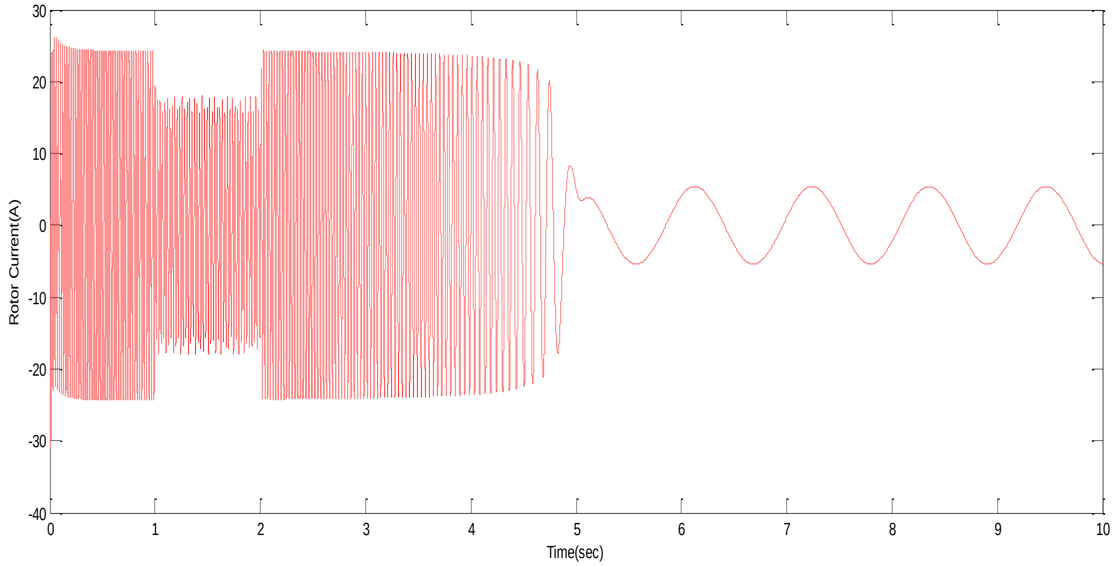


Figure 4.5(b): Rotor Current(A) Vs Time(sec)

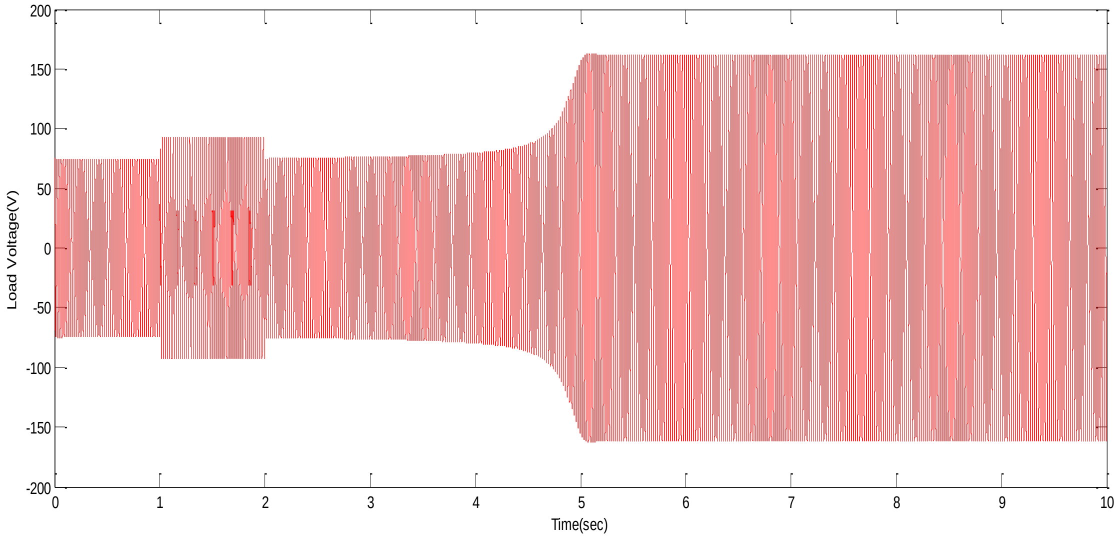


Figure 4.5(c): Load Voltage(V) Vs Time(sec)

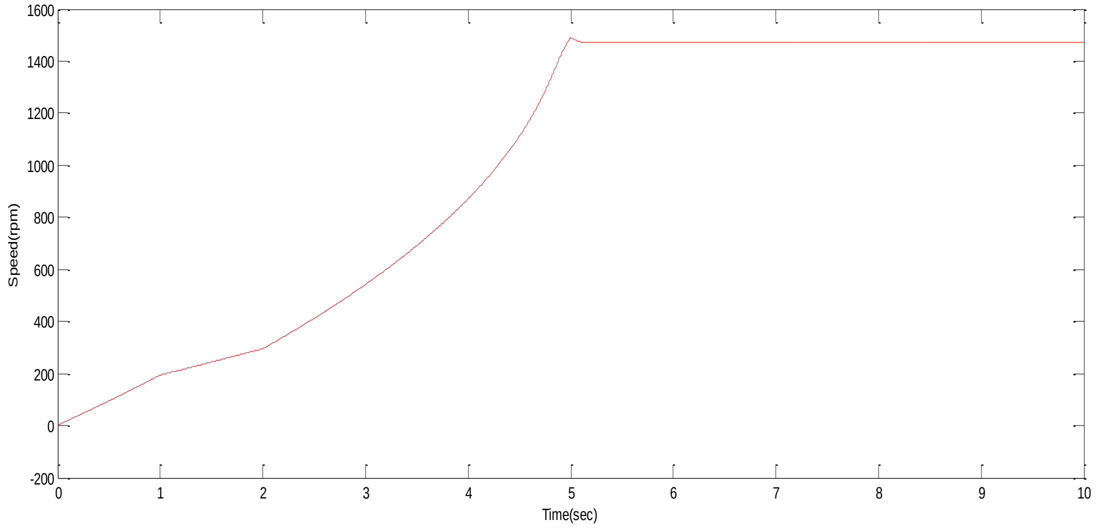


Figure 4.5(d): Speed(rpm) Vs Time(sec)

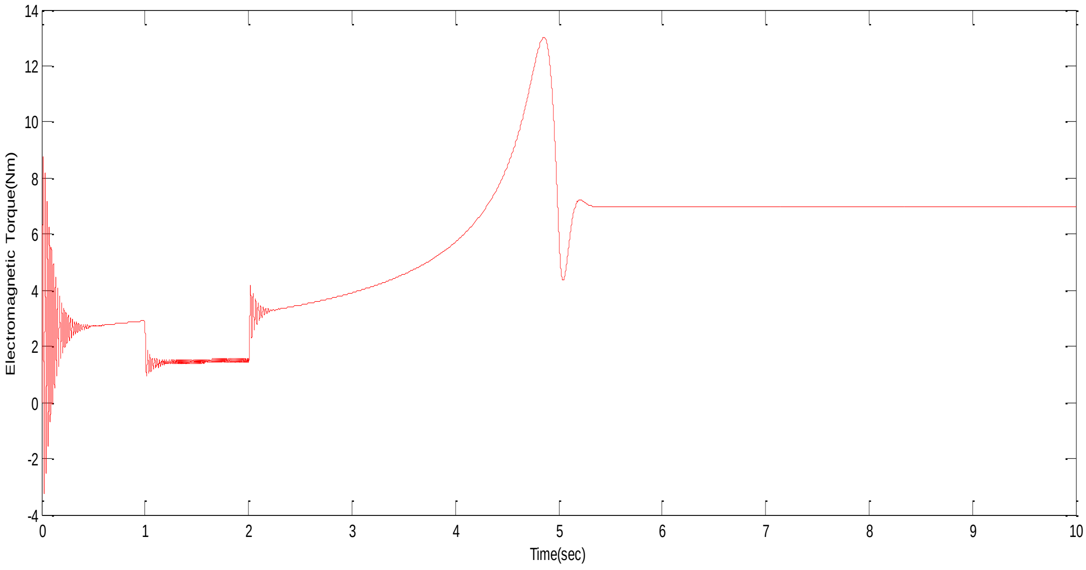


Figure 4.5(e): Electromagnetic Torque(Nm) Vs Time(sec)

CHAPTER 5

CONCLUSIONS AND FUTURE SCOPE

5.1 Conclusions

A model of three phase source feeding motor loads has been developed using PSB and Simulink of standard MATLAB software. Sudden application of an induction motor load results in large starting currents which results in sudden dip in ac terminal voltage at PCC. The extent of voltage dip with and without DSTATCOM controller is compared. This voltage dip is of the order of 56.3% without any controller. This dip is very large and it may affect the functioning of other sensitive equipment connected at PCC .Model of DSTATCOM system applied in shunt configuration has been developed. The DSTATCOM control utilizes two PI controllers for regulating DC link voltage and also the ac terminal voltage at PCC. The Simulated results have shown that DSTATCOM application reduces the momentary dip to from 56.3% to 40.7% only. The voltage dip can be reduced by proper tuning of PI controllers and use of fixed value of AC capacitor.

5.2 Future scope

(1) The application of fuzzy logic approach can be used for power factor correction, Load balancing, voltage regulation, harmonics filtering.
(2) Neural logic controller can be used for mitigation of harmonics in Non-linear load.

Appendix

System parameters used in simulation:

- Three Phase Source:
  415V (Phase to Phase) rms voltage, 50Hz

- Motor load parameters:
  8.5kW, 3-phase, 400V,
  Rs = 0.6387,
  Rr = 0.451,
  L1s = 0.004152,
  Llr = 0.004152,
  Lm = 0.1486 (all in pu)

- DSTATCOM parameters:
  Rc = 0.2,
  Lc = 7.5mh
  C_{dc} = 15uf,
  h_b=0.2A

- PI Controller parameters:
  Kpd = 0.15,
  Kid = 0.9
  Kpa = 0.14,
  Kia= 1.4

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