DISTRIBUTED REACTIVE POWER COMPENSATION FOR RADIAL FEEDER

A DISSERTATION

submitted in partial fulfillment of the requirement for the degree of
Master of Technology
in
Power Systems
By
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(2k11/PSY/05)

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CERTIFICATE

This is to certify that the project entitled, "**DISTRIBUTED REACTIVE POWER COMPENSATION FOR RADIAL FEEDER**", submitted by **Ms. Bhavna Rathore**, University Roll No. 2k11/PSY/05, student of Master of Technology (Power System) in Electrical Engineering department from Delhi Technological University (Formerly Delhi college of Engineering), is a dissertation work carried out by her under my guidance during session 2012-2013 towards the partial fulfillment of the requirements for the award of the degree of Master of Technology in Power system.

I wish her all the best in her endeavours.

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DECLARATION

I, hereby declare that the work being presented in this Project Report entitled **“DISTRIBUTED REACTIVE POWER COMPENSATION FOR RADIAL FEEDER”** is an original piece of work and an authentic report of my own work carried out during the period of 4th Semester as a part of my major project.

The model developed and results presented in this report is an outcome of the work carried out during the above said period and is also compiled as thesis for my Major Project for completing the requirements of Master‘s Degree of Examination in Power System Engineering, as per Delhi Technological University curriculum.

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ABSTRACT

Voltage regulation of distribution lines is a challenging problem, particularly when it is not economic to upgrade the entire feeder system. The distribution networks supplying rural areas are often quite weak because of the long distances involved and the high R/X ratio of the lines that are used. Hence, as demand increases on these networks, power quality issues such as poor voltage regulation and voltage sags often become a significant problem. Lumped compensation by power electronic converters is reported in literature to have the potential to improve supply quality and increase line utilisation in weak distribution networks. But widespread use of this technology has been limited due to costly power electronics processing for high power rating and reliability concerns. This thesis illustrates the concept of distributive approach for realizing the cost effective solution and more effective functionality of Power Electronics converters for proposed distributed solution. Low cost electronic devices, power electronics and communication technologies if distributedly applied, entire subtransmission and distribution network may be covered more effectively and cost effective power flow control can easily be done by Distributive Compensation. Often under such configurations the central control approach is quite complex and require large communication setup and coordination of sensors, and often the basic theme of simplicity of distributive compensation is lost. This thesis explores the use of Distributed Shunt compensators based on autonomous control to achieve stable steady state and dynamic compensation of the voltage profile along a radial distribution system under widely varying load conditions. The proposed scheme allows independent operation of each unit, such that each unit has to compensate the voltage drop of its preceding section of line by supplying the requisite reactive power. This autonomous control along the radial feeder with proposed autonomous distributed control technique is shown working effectively by improving voltage profile, operating at unity power factor and by compensation of load reactive power. A decentralized control strategy is also used under grid connected mode to compensate reactive demand of load under widely varying condition. Simulated results under MATLAB environment are presented to validate the effectiveness of the proposed control schemes for distributed compensation under load perturbations.

Keywords: *DSTATCOM, Distributed Power Flow Controlling Devices, Reactive Power, Voltage Source Converter.*

TABLE OF CONTENT

LIST OF FIGURES

Page No.

LIST OF TABLES

ACRONYMS

AFU	Active Power Filter Unit
ANN	Artificial Neural Network
APF	Active Power Filter
CLC	Central Limit Control
DAFS	Distributed Active Filter System
DC	Direct Current
DG	Distributed Generation
D-FACTs	Distributed Flexible AC transmission system
DLC	Distributed Load Control
DPFC	Distributed Power Flow Controller
DSF-PLL	Distributed Synchronous Frame - Phase Locked Loop
DSI	Distributed Series Inductor
DSSC	Distributed Static Series Compensation
D-STATCOM	Distributed Static Shunt Compensation
DVR	Distributed Voltage Restorer
EHV	Extra High Voltage
EPLL	Evolutionary Phase Locked Loop
FACTs	Flexible Alternating Current Transmission System
HV	High Voltage
IGBT	Insulated Gate Bipolar Transistor
IRPT	Instantaneous Real Power Theory
KVA	Kilo Volt Ampere
MOSFET	Metal Oxide Semiconductor Field Effect Transistors
MSC	Master Slave Control
NN	Neural Network
PCC	Point of Common Coupling
PE	Power electronics
PFCD	Power Flow Controlling Device
PI	Proportional Plus Integral
PLL	Phase Locked Loop
PQ-PLL	Active Reactive Power - Phase Locked Loop
PWM	Pulse Width Modulation

SPWM	Sinusoidal Pulse Width Modulation
SRF	Synchronous Reference Frame
SRF-PLL	Synchronous Reference Frame - Phase Locked Loop
STATCOM	Static Shunt Compensation
UPFC	Unified Power Flow Controller
UPS	Uninterruptable Power Supply
VAR	Volt Ampere Reactive
VSC	Voltage Source Converter
VSG	Voltage Source generator

CHAPTER-1

INTRODUCTION

1.1General:

The automation of modern industry has harnessed the expectation level of reliability of power and therefore to cater to the needs, power grid is becoming more and more networked in order to fulfill the growing demand of power with acceptable quality and costs. This restructuring of power grid has uncertainties in system operation resulting in various vital issues like uneven line loading, lack of power flow control, voltage stability, and depleting margin of operational currents matching short circuit current level etc. In the meshed network, the occurrence of contingency can result the sudden increase/decrease in the power flow. This in turn can result in overloading of the line and increase the risk of cascading outages and blackouts.

During the last twenty years, due to growing consumption together with variety of loads populated in power system, the behaviour of the electricity market and the inception of renewable energy sources and the operation of power systems has changed tremendously. The concept of distributed generation and smart grid has emerged very strongly to maximise the efficiency of the power system making the system extremely complex, but user friendly and bidirectional.

Power system, particularly the distribution system is a great change in terms of bidirectional power flow due to inception of distributing generation sources. In the conventional power systems, the power flow in has a fixed direction; it always flows from the point of generation through the transmission network to the distribution network. In our country the legacy has been inherited from UK, which has developed the major power infra-structure during pre-independence era. Accordingly the distribution system in India is radial type. It is the least expensive in terms of equipment first-cost. However, it is also the least reliable since it incorporates only one utility source and in case of the loss of the utility source, transformer, or the service or distribution equipment will result in a loss of service. Further, the loads must be shut down in order to perform maintenance on the system.

Without making a total makeover the problem can be solved by including Distributed Generation with radial distribution Network. Distributed Generation (DG) are probably connected only at small and medium power levels that are connected near the load centres in the distribution side of the power system. Many DG units are based on renewable energy sources such as solar and wind. But introducing a large number of such generators on the distribution side often leads to big changes in the power flow of the distribution networks. First, the direction of the power flow becomes unpredictable and, when DG units in one area feed loads in other areas; there will be reverse power flow from causing great concern to the protection system employed. Second, the output energy of renewable sources depends on weather conditions therefore is highly intermittent. With the increasing percentage of renewable energy sources in use, a large amount of power has to be controlled to enable the power system to quickly switch between the renewable sources and stand-by power generation. Therefore, stand-by power, which can be provided by near-by power plants or energy storages, should be available when renewable energy is insufficient to supply the connected load. This leads to an increased need for power flow control methods.

Majority of the time in distribution and subtransmission system the receiving end voltage is lesser than sending voltage due to line impedance drop and reactive demand of the load. To compensate this voltage drop and to improve power capacity and stability various static devices has been used in lumped configurations, but widespread use of this technology has been limited due to costly power electronics processing for high power rating and reliability concerns.

Recently Distributed Flexible AC transmission system (D-FACTs) has been introduced to overcome most of the problem surfaced in subtransmission systems. D-FACTs devices are modular, small in size and light in weight. Generally modules are rated about 10 KVA to 15KVA [1] [2]. For instance the series devices may be clamped on the transmission line and can be controlled so as to increase or decrease the line impedance of line, which in turn control active power flow and regulate system voltage. But these devices have slow operation due to the transformer and mechanical parts of the module, which form a complete magnetic circuit only after the module is clinched around the conductor. The difficulties experienced during the employment of Thyristor based series compensators prompted researchers to explore distributed compensation where IGBT based voltage source converters can be used to get fast response.

1.2 Distribution System

Power systems are comprised of 3 basic electrical subsystems.

- Generation subsystem
- Transmission subsystem
- Distribution subsystem

The subtransmission system is also sometimes designated to indicate the portion of the overall system that interconnects the HV transmission system to the low voltage distribution system.

The power system is often demarcated by voltage levels as follows:

- Generation: 1kV-30 kV
- EHV Transmission: 500kV-765kV
- HV Transmission: 230kV-400kV
- Subtransmission system: 66kV-169kV
- Distribution system: 220V-33kV

Our focus in the thesis is on the distribution system. About 40% of investment in the power system is in the distribution system equipment as against 40% in generation and 20% in transmission. The distribution system receives power from one or more transmission or subtransmission lines at the corresponding voltage level and feeds the power to one or more distribution feeders that originate from the substation and thus from the primary distribution network. Most feeders emanate radially from the substation to supply the load. A generalized single line diagram for a power system network is shown in fig. 1.1.

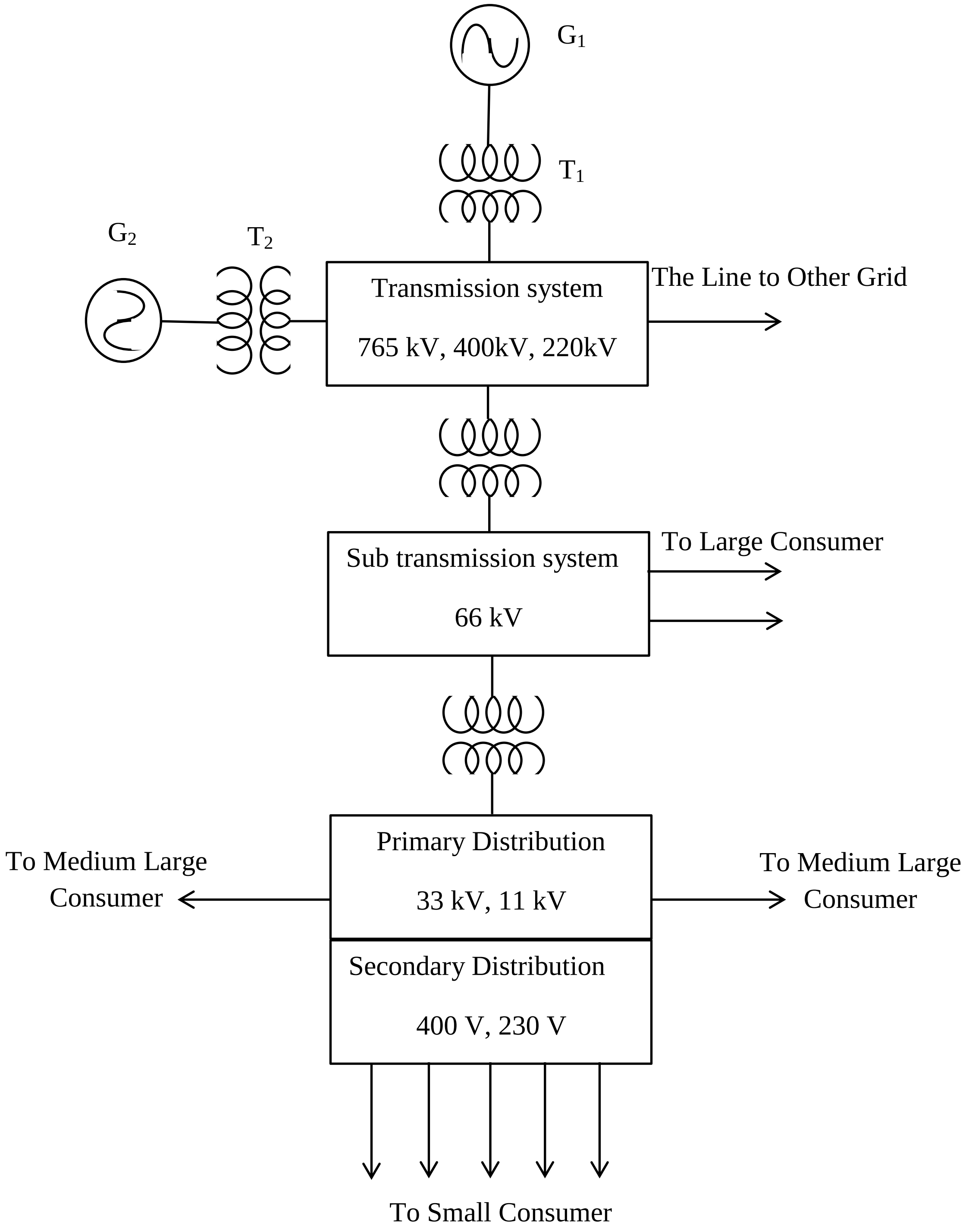

Fig.1.1: Single line power system network

The distribution of electrical energy is done at the constant voltage according to the scheme which may be classified as:

- Radial Distribution System
- Parallel Distribution System
- Ring main Distribution System
- Interconnected Distribution System

1.2.1 Radial Distribution System:

Figure 1.2 shows a typical radial system of distribution. The subtransmission substation supplies the primary distribution system feeders radiating from the substation bus. They feed the distribution transformer of substations which step down the voltage to distribution voltage and supply various loads through distributors. The radial system is the simplest and lowest in first cost but has poorest service and reliability.

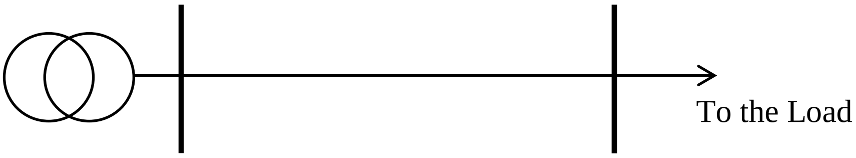

Fig.1.2: Radial Distribution System

1.2.2 Parallel Distribution System:

In parallel distribution systems as shown in fig. 1.3 utilizes two radial feeders originating from the same or different secondary substations and are run in parallel. Each feeder is capable of supplying the entire load and shares the total load equally in normal conditions. Though this system is expensive, but enjoys increased reliability as in case of fault on one feeder, the total load can be supplied by the healthy feeder. Interruption of supply is experienced by the connected loads only for the time duration taken in transferring the load from the faulty feeder to healthy one either by manual or automatic switches. Such a system is employed wherever the continuity of supply is of greater importance.

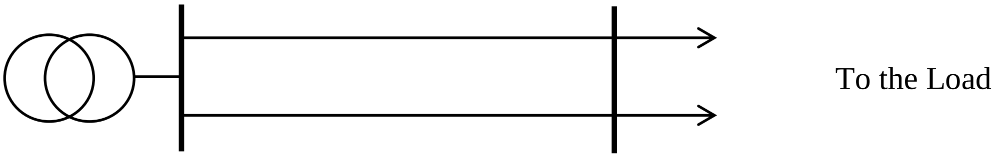

Fig.1.3: Parallel Distribution System

1.2.3 Ring main Distribution System:

Fig. 1.4 depicts the ring main distribution system, where the primaries of distribution transformer form a loop through the bus-bars in the substation for the area to be served. The system is very reliable as each distributer is fed via two feeders. In the event of fault on any section of the feeder, the continuity of supply is maintained. Very less voltage fluctuations are experienced at consumer’s end under such scheme.

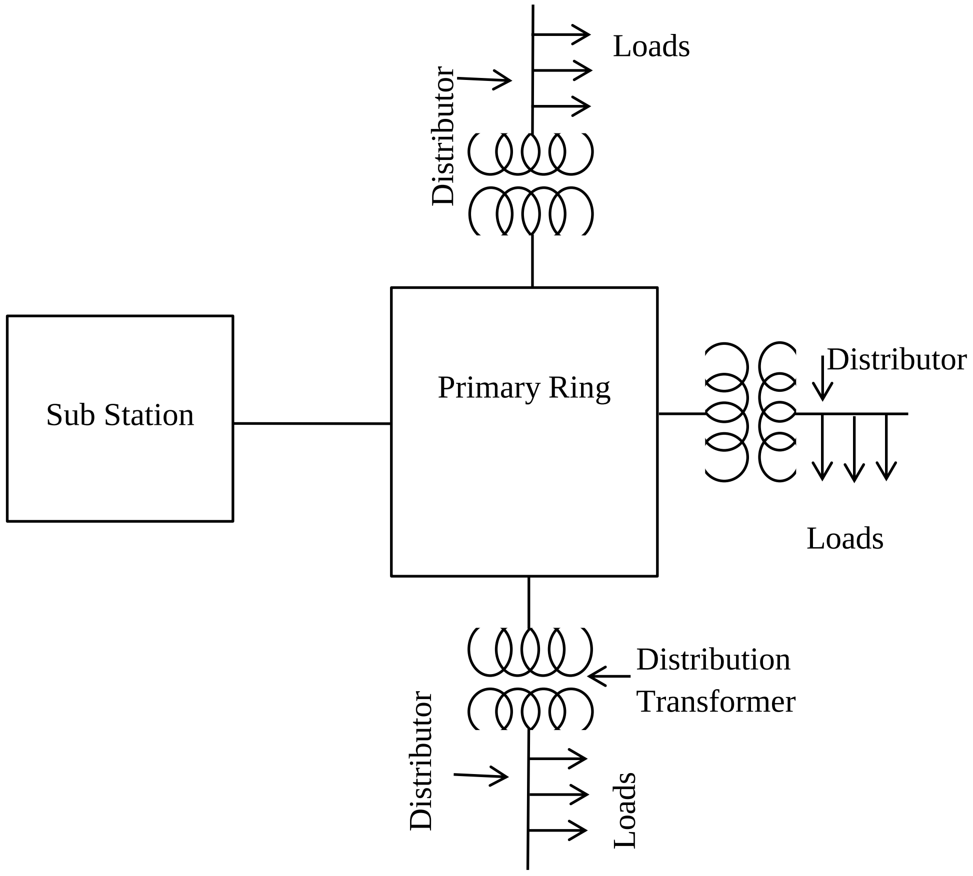

Fig.1.4: Ring main Distribution System

1.2.4 Inter-connected Distribution System:

When the feeder ring is energised by two or more than two generating station or substation, it is called inter-connected system. Fig.1.5 shows the single line diagram of inter-connected system. This type of system is applicable in large distribution areas with large loads and where the system has to be made even more reliable for continuity of supply. This is true for primary distribution systems as well as in some applications to secondary distribution systems. An inter-connected distribution system is also used where loads are heavy as in small crowded commercial areas. This distribution system gives the maximum possible flexibility, reliability of the continuity of the advantage of diversity between loads, etc.

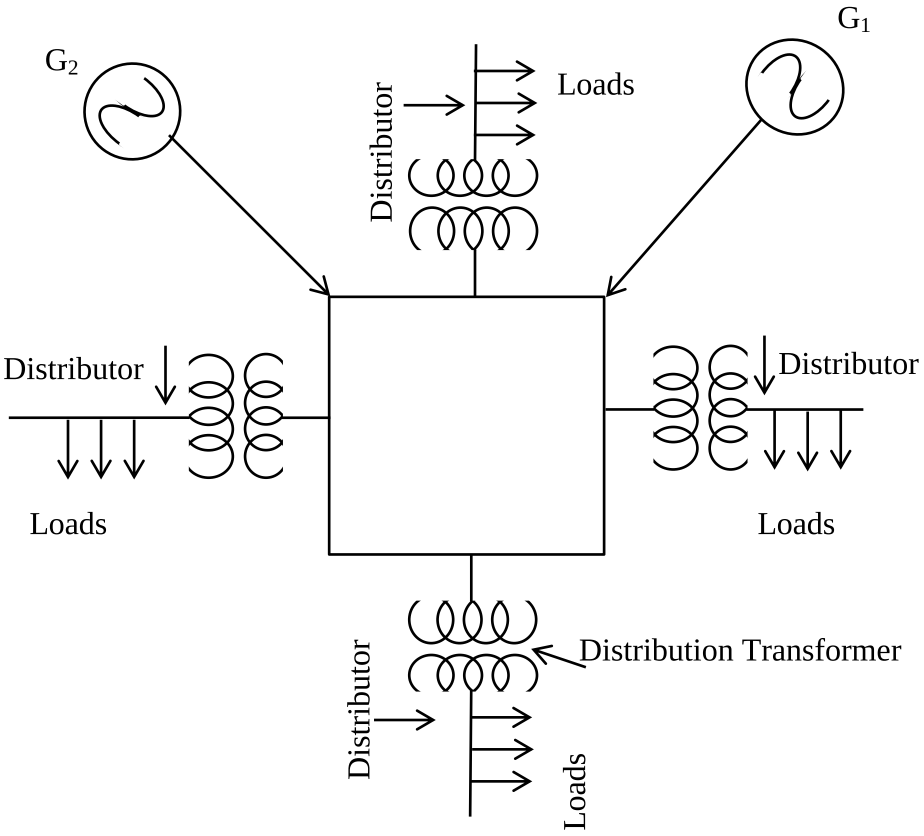

Fig. 1.5: Inter-connected Distribution System

Previously in India, radial types of feeders were used for power distribution, but due to its disadvantages these were replaced by inter-connected system. The network with interconnected distribution system gives better voltage regulation and less possible outages to consumers as compare to radial system. The size of the substations required is also smaller compared to that required in radial system. The circuits in the primary networks are fed at both ends and hence give better voltage regulation. In the case of radial distribution, the length of the feeders is larger than in case of inter-connected system.

Voltage regulation of long weak distribution lines is a challenging problem, particularly when it is not economic to upgrade the entire feeder system. Power flow controlling devices (PFDs) offer an attractive alternative, with their potential to provide both steady state and transient voltage compensation for a limited capital investment. However, operation of these systems with weak networks and/or with multiple distributed installations needs careful attention to avoid unexpected interactions and to achieve optimum regulation performance. This thesis explores the use of distributed static (D-STATCOM) compensators to achieve stable steady state and dynamic compensation of the voltage profile along a radial distribution network for rural electrification under widely varying load conditions.

1.3 Power Flow Controlling Devices:

Power flow is controlled by adjusting the parameters of a system, such as voltage magnitude, line impedance and transmission angle. Power Flow Controlling Device (PFCD) are capable of system parameters to control the power flow Depending on how devices are connected in systems, PFCDs can be divided into shunt devices, series devices, and combined configuration (both in shunt and series with the system).

(a) Shunt Device: A shunt device as shown in fig. 1.6(A) connects between the grid and the ground. For controlling the voltage magnitude shunt devices generate or absorb reactive power at the point of connection. As the bus voltage magnitude can only be varied within certain limits, controlling the power flow in this way is limited and shunt devices mainly serve other purposes. For example, the voltage support provided by a shunt device at the midpoint of a long subtransmission line can boost the power transmission capacity. Another application of shunt devices is to provide reactive power locally, thereby reducing unwanted reactive power flow through the line and reducing network losses. Also, distribution side shunt devices can improve power quality, especially during large demand fluctuations.

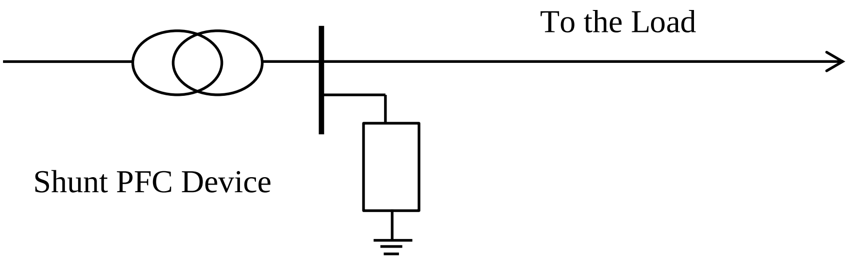

Fig.1.6 (a): Simplified diagram of shunt PFCD

(b) Series Device: Series PFCD as shown in fig. 1.6(b) is connected in series with the transmission line is referred to as a ‘series device’. Series devices generally are operated to affect the impedance of transmission lines. The line impedance can be changed by inserting a reactor or capacitor. A capacitor can be inserted in the line to reduce the line impedance for compensating the inductive voltage drop. By decreasing the inductive impedance of the line, series devices are also used to limit the current flowing through certain lines and prevent overheating.

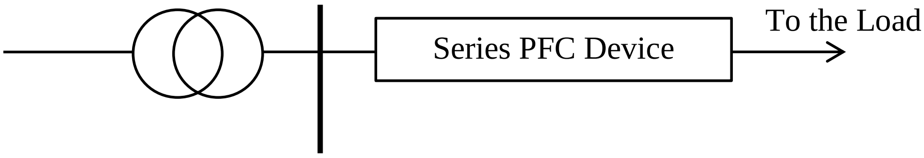

Fig.1.6 (b): Simplified diagram of series PFCD

(c) Combined Device: A combined PFCD as depicted in fig. 1.6(c) is a two-port device, which is connected to the grid, both as a shunt and in a series, to enable active power exchange between the shunt and series parts. Combined devices are suitable most for power flow control because they can simultaneously vary multiple system parameters, such as the transmission angle, the bus voltage magnitude and the line impedance.

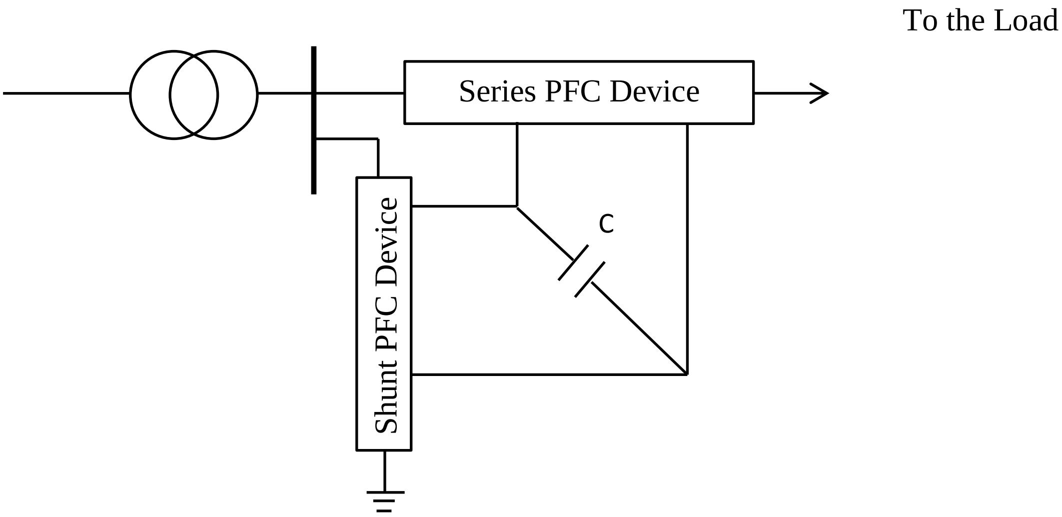

Fig.1.6(c): Simplified diagram of Combined PFCD

Based on the devices used and the use of semiconductor switches, the PFCDs can be further categorized into

- Mechanical-based devices and
- Power electronics (PE)-based devices.

1.3.1 Mechanical-based devices:

Mechanical Power Flow Controlling Devices consist of fixed or mechanical interchangeable passive components, such as inductors or capacitors, together with transformers. Typically, mechanical PFCDs have relatively low cost and high reliability. Due to their relatively low switching speed (from several seconds to minutes) and step-wise adjustments of mechanical PFCDs, they have relatively poor control capability and thus are not suitable for complex networks in the future.

1.3.2 Power electronics (PE)-based devices:

Tyristor based PFCDs also contain passive components, but include additional power electronics switches to achieve smaller steps and faster response. Power electronics based PFCD devices can be further subcategorized into two types according to the applied switch technologies: thyristor-based devices and Voltage Source Converter (VSC) based devices.

Thyristor PFCDs use inverse-parallel thyristors in series or in parallel with passive components. By controlling the firing angle of the thyristors, the impedance of the device can be adjusted. A thyristor can be controlled to turn on but turn off automatically when the current goes negative. Consequently, the thyristor PFCD can only be turned on once within one cycle. Thus the switching frequency of thyristor based PFCDs is therefore limited to the system frequency (50/60Hz), resulting in low switching losses but moderate response. Because thyristors can handle larger voltages and currents than other power semiconductors, the power level of thyristor PFCDs are also higher and therefore find application in transmission lines. However, the waveforms of voltages and currents generated by thyristor PFCDs contain a large amount of harmonics, thereby requiring large filters.

VSC based PFCDs employ advanced switch technologies, such as Insulated Gate Bipolar Transistors (IGBT), Insulated Gate Commutated Thyristors (IGCT), or Metal Oxide Semiconductor Field Effect Transistors (MOSFET) to build converters. Because these switches have very fast turn-on and turn-off capability, the output voltage of a VSC is independent from that of power frequency. Consequently, it is possible to turn the switches on and off within the VSC multiple times within one cycle of fundamental frequency. Several types of VSCs have been developed, such as multi-pulse converters, multi-level converters, square-wave converters, etc.

These VSCs have proved a free controllable voltage both in magnitude and phase. Due to their relatively high switching frequency, VSC PFCDs make practically instant control (less than one cycle) possible. High switching frequencies also reduce low frequency harmonics of the outputs and even enable PFCDs to compensate disturbances from networks. Therefore, VSC PFCDs are the most suitable devices for future power systems particularly for subtransmission and distribution system.

On the other hand, there are few challenges ahead of VSC PFCDs. Firstly, because large amounts of switches are connected in series or in parallel to allow the high voltage and high current through, the VSC PFCDs may be expensive. In addition, due to their higher switching frequency and higher on-state voltage the losses are higher as well. However, with developments in power electronics, VSC PFCDs can become more feasible and cost-effective in the future.

According to the above considerations of different types of PFCDs, it can be concluded that VSC based PFCDs have the best control capability among all PFCDs. They inherit the advantages of fast and effective control and combined PFCDs, which is the fast adjustment of multiple system parameters.

1.4 Problem Definition:

Although the PE PFCDs has superior capability to control power flow, but wide spread use of this technology is limited due to a number of reasons:-

- High power rating devices are required in high power rating system which resulted in increased installation cost [5]. A PE PFCDs cost around 120-150 $ per kVA, compared to 15-20 $ per kVA for static capacitors [1-7]. If a single unit of higher rating is used for compensation in subtransmission and distribution system it requires complex processing, multiple feedback, complex protections etc.
- Due to the lumped nature of PE PFCDs, these are located at specific point (not in wide area) of transmission line. So failure at that point leaves entire system to shut down [5]. To gain the desired reliability, complex protections (bypass circuit) and redundant backups (backup transformers and capacitor banks) are always provided for the combined PE PFCDs, further raising the cost. Moreover, the essence of compensation is not near ideal when compared with distributed compensation.
- As the PFCD devices are installed at different locations for different purposes, each of them is unique. As a result, each PFCD requires custom design and manufacturing, which may leads to a long building cycle and high cost.

Due to these three major drawbacks, the PE DPFCs are not widely accepted in practice.

1.5 Objective and Approaches:

There is a great demand of power electronics based power flow control devices in power systems in the future. However, due to the cost and the reliability issues as discussed above, there are many hurdles for its widespread application. Accordingly the main objectives of this thesis can be summarized as:

To develop a new distributed PFCD that has the following characteristics:

- Having fast response with acceptable switching losses.
- Acceptable cost to electric utilities.
- Acceptable reliability for power systems.
- Has smart solution with co-ordinated control.
- Provide multirole in the system with multiple compensation.

The approach to develop such a device consists of the following steps:

- Review the fundamentals of power-flow-control theory and the state-of-art of PFCDs with respect to operating principles, advantages and limitations.
- Find ways to reduce the cost and increase the reliability of PFCD devices.
- Generate a new concept of a power flow controlling device according to these points. The new concept presented in this thesis is called ‘Distributed static shunt Compensator (DSTATCOM)’. It is a device, which has taken a STATCOM as its starting point. The DSTATCOM has the same control capability as the STATCOM; independent control of active and reactive power, control of the transmission angle and the bus voltage. By employing the Distributed FACTS concept [7] the cost can greatly reduce due to the small rating of the components in the converters. Also, the reliability of the DSTATCOM will be improved because of the redundancy provided by the multiple shunt compensators. Once in the following chapters the DSTATCOM concept is presented, the research follows the listed steps:
    - Analyse and evaluate the proposed concept with respects to the control capability and the rating of the DSTATCOM.
    - Find the mathematical model of the DSTATCOM.
    - According to the DSTATCOM model, design of the control schemes of the DSTATCOM.
    - Verify the control of DSTATCOM with in the simulation results.

1.6 Thesis Layout:

The thesis work is presented in the different chapters. A brief overview of the chapters is as follows:

Chapter I: This chapter gives an overview of problems of distribution system introduction of power flow controlling devices is given with their advantages. This is followed by a brief outline of the proposed work.

Chapter II: It gives an overview of literature survey. This chapter begins with research and development in Distributed Compensation technology. Various PFCDs are introduced, categorized and compared according to their operational characteristics.

Chapter III: A new concept, called Distributed Shunt Compensator (DSTATCOM), is presented in chapter III with its advantages over lumped compensation presented with STATCOM.

Chapter IV: Addresses the modeling and control of the DSTATCOM. The chapter deals with modelling of the DSTATCOM. Once the model of DSTATCOM is developed, it is simulated, its various centralized and decentralized control strategy which are proposed (New) for its application in voltage regulation of line and reactive power sharing of load.

Chapter V: This chapter covers the performance evaluation of the proposed system with proposed autonomous control of DSTATCOM for voltage regulation utilizing centralized and decentralized control for reactive power sharing.

Chapter VI: This chapter presents the main conclusions based on the proposed work and also enlists the suggestions for the further work based on the present investigation.

CHAPTER-2

LITERATURE REVIEW

2.1 General:

Incorporation of Distributed Power Flow Controlling Devices (DPFCDs) into the subtransmission and distribution system is becoming increasingly popular now a day because of its advantages over lumped compensators. PFCD are lumped in configuration and are accordingly placed at a specific location in transmission line, so failure of that point bring entire system to shut down, whereas Distributed PFCD can be placed at multiple location and failure of one device is compensated by joint effort of other units. Such devices provide high system reliability due to massive redundancy, have low cost due to small rating module, they have co-ordinated control to provide variety of compensation and provide smart solution to the radial distribution system problem, and they also augmented with the DGs to increase the system stability. This chapter cover a comprehensives different control strategy, connection configuration/topologies and operation control in grid connected mode of Distributed Power Flow Controlling Devices (DPFCDs).

2.2 Reviews of Literatures:

A large number of publications have appeared in the field of VSC operation as reactive power compensating unit, distributed generation, Active filter etc. in current and voltage controlled mode with centralized and decentralized control. When VSCs incorporated with renewable energy sources (mainly photovoltaic, micro cogeneration, variable speed wind power technologies), these act as distributed generator for sharing of power to cater the load in both grid connected and Islanding mode of operations. Whereas, when VSC designed with only DC link capacitor, it will act as compensating unit. A large number of control strategies have been introduced for parallel operation of VSCs in both centralized and decentralized manner. A detailed summary of literature is presented in subsequent sections of the chapter in the following sequence.

(1) Research and development in Distributed Compensation technology
(2) Synchronizing and estimation of reference signals
(3) Control Strategies for sharing between Distributed compensating unit

2.2.1 Research and development in Distributed Compensation technology:

Lumped type compensating devices are used to control power flow and voltage drop in the distribution system but maintenance cost and reliability are main hindrance in the development of this devices. Recently D. Diwan et.al [61] suggested a new concept of Distributed FACTs (D-FACTS) as an alternative solution which is cost effective power flow control.

D-FACTs devices are small and light in weight power flow controller devices, manufactured out of cheap parts. These devices are rated about 10KVA-15KVA are clamped on the distribution line and can be controlled so as to increase or decrease the impedance of the line provide requisite reactive power, which in turn help in controlling the active power flow[2]. The uniqueness of these devices lies in their placement in the network independent of constraints and can be at multiple positions suited accordingly. For series compensation, the line impedance is changed using these device, by producing a voltage drop across the line in quadrature with the line current, resulting in either purely reactive compensation. The commands for changing input impedance can be communicated to these devices remotely and under certain condition they can be configured to operate autonomously. Each D-FACTs device on different lines can be used to achieve a control objective by coordinating them to work together. Under this condition the flow of power on all lines can be controlled using just any one of the lines, but this is specific for a specific system. In a single loop system the flow cannot be controlled independently as it is completely coupled. The D-FACTs potential can be measured through the extent to which the line flow can be controlled independently. To achieve the desired control these devices are placed in the system at different location. A known overloaded element such as transformer or line can be relieved by the use of D-FACTs devices, which reduces the flow through an overloaded element, as these devices improve the operation of power grid. Generally there are three types of D-FACTs devices.

(1) Distributed static series controller or DSSC (Series compensation)
(2) Distributed static shunt controller or D-STATCOM (Shunt compensation)
(3) Distributed power flow controller or DPFC (Series-Shunt compensation)

2.2.1.1 Distributed static series controller or DSSC:

DSSC uses modules of small rated (10KVA to 15KVA) single phase inverter and a single turn transformer along with controller [2]. Each module is clinched on the line, floating electrically and mechanically on the transmission line. The transformer and mechanical parts of the module form a complete magnetic circuit only after the module is clinched around the conductor. The amplitude of the current through the structure during short-circuits is directly linked with DC bus capacitor. If we have lower the DC bus capacitor value then the short circuit current will be low. The impedance of the line can be increased or decreased by controlling each module. In series compensation the injection of impedance or voltage is in series with the line. The typical implementation of DSSC is shown in Fig.2.1

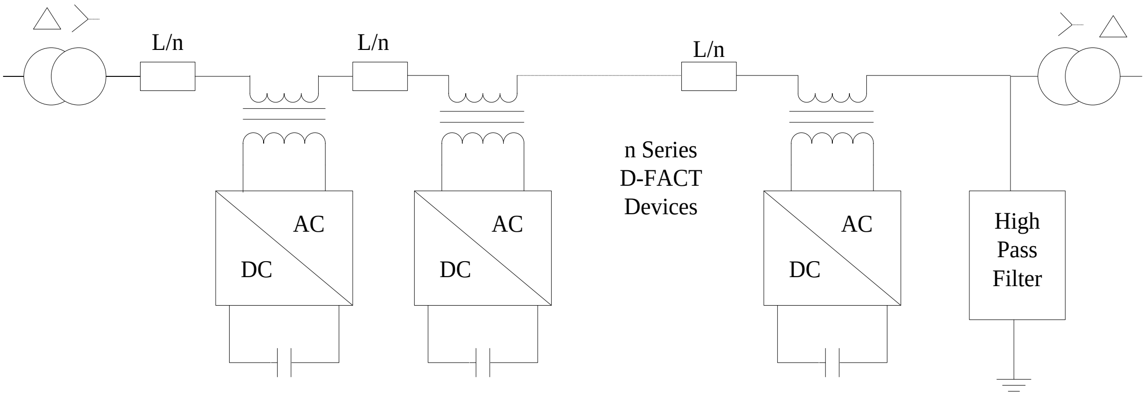

Fig.2.1- Distributed Static Series Compensator

Operational Characteristics

The real *(P)* and reactive power *(Q)* flow, along a transmission line connecting two buses, having bus voltages magnitude V_1 and V_2, and voltage phase angle difference δ are given by following equations[1].

$$P_{12} = \frac{V_1 V_2 \ Cos\delta}{X_L} \tag{2.1}$$

$$Q_{12} = \frac{V_1^2 - V_1 \ V_2 \, \mathrm{Cos}\, \delta}{X_L} \tag{2.2}$$

where X_L = The impedance of the transmission line.

The real power can be controlled by changing phase angle with the help of phase shifter transformer, but this method provides limited dynamic control. The real power is controlled by varying series impedance by inserting capacitor or inductor in series with line. Alternatively real power may be controlled in which a voltage source inverter can be used to realize a controllable active lossless element such as a capacitor or inductor by inserting synchronous fundamental voltage in the line that is orthogonal to the line current [2].

There are three modes of operation of DSSC.

(a) By-pass mode: In this mode of operation the effect of transformer can be altered.
(b) Capacitive mode: In this mode of operation the capacitive voltage can be inserted in series with the transmission line.
(c) Inductive mode: An inductive voltage can be injected in series with the transmission line in this mode.

So distributed injection of impedance or voltage of each module can be accomplished by using a single turn transformer and a switch.

A large number of publications have appeared in the field of DSSC operation. By using DSSC the power handling capacity which can be improved with reliable operation [1-23]. D. Diwan et.al [2] discussed the design considerations for implementing distributed static series controller for power control solutions on the power grid. In [2] a concept of distributed series impedance (DSI) is introduced which can realize variable line impedance, helping to control active power flow. The concept was further extended to realize a DSSC. In [5] a two machine power system is put under investigation in order to verify the DSSC capability for increasing the transient stability. The content of reference in [6] has presented a novel concept of DSSC which uses multiple low power single phase inverter that clip on the transmission conductor to dynamically control the impedance of the line. In [9] a new feedback based control strategy, based on the calculation of instantaneous power flow, is used to generate an orthogonal injected voltage with respect to the line current. Direct and indirect control for controlling both angular position and voltage magnitude with SPWM for gate pulse generation is reported in literature [5]. Two staged Tabu search for determining optimal location of DFACTs in radial distribution system with distributed generation is also presented in literature [24]. Stage 1 in the paper deals in optimizing the location and stage 2 is used for optimizing the output. NING et al proposed a novel DFACTS controller with active variable inductance (AVI) [28].

Recently L.Ming et al [23] has proposed a new idea of virtual inductor implementation method as Direct Reactance Synthesis (DRS). In reported literature a novel cluster control strategy is presented to improve the low compensation operation efficiency of DFACTs [25]. D. Divan et al [26] gave a new idea about the Smart Wire technology, which is used to convert an existing transmission line to a smart asset, able to monitor and regulate its power flow, thereby shifting excess power to underutilized lines in the network. The technology is a distributed solution, with a fleet of modules fixed directly to the conductor. Each module acts autonomously, resulting in high reliability without the costly hardwere required to make centralized FACTS devices reliable. As such, the modules can be incrementally deployed on existing subtransmission lines in a very specific and targeted manner, providing sensing of line status along the length of the line, as well as providing the mechanism to achieve actual control of line currents.

2.2.1.2 Distributed static shunt controller or DSTATCOM:

D-STATCOM is a three phase shunt connected voltage source inverter connected to the grid as current source. D-STATCOM mitigates the reactive power to regulate the line voltage. Fig 2.2 shows the structure of the D-STATCOM and how it is connected into the system for reactive power compensation.

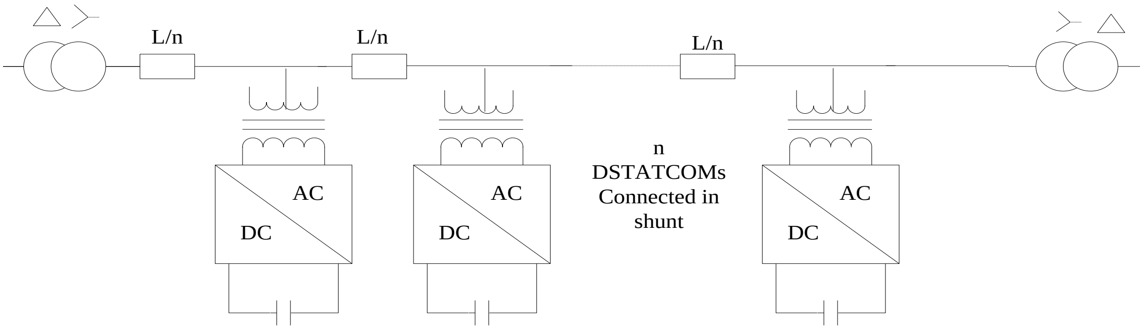

Fig.2.2 -D-STATCOM Constituents and its Connection to System

Operational Characteristics

The control of D-STATCOM can be seen either by voltage control, where phase angle and voltage is controlled to have desired output or, is current controlled to inject current in quadrature with voltage to quenched desired reactive power in the line is met. A scheme for IGBT based voltage source inverter serving as D-STATCOM is presented[35]. V_i represents the injected voltage, δ is power angle and V_s is system voltage. The reactive power output of device whether inductive or capacitive depends upon the mode of operation of D-STATCOM. It generates or absorbs the desired VAR at the point of connection when the phase angle between the inverter voltage and the line voltage is dynamically adjusted using the D-STATCOM controller.

There are three basic modes of operation of D-STATCOM.

(a) If V_i is equal to the V_s, the reactive power is zero and the D-STATCOM does not generate or absorb reactive power.

(b) If V_i is greater than V_s then device shows an inductive reactance connected parallel with load, the current I flows from D-STATCOM to AC system and it generates leading VARs for the system.

(c) If V_i is less than V_s, then the current I flows from AC system to device and it absorbs lagging VArs from the system

Various methods are reported to reduce or mitigate voltage sags, as against conventional methods which either utilizes capacitor banks, introduction of new parallel feeders and by installing uninterruptible power supplies (UPS). However, the power quality problems are not solved in completion due to uncontrollable reactive power compensation and high costs of new feeders and UPS in case they are employed. The D-STATCOM has emerged as a promising device to provide, not only voltage sag mitigations but also provide solution to a host for other power quality problems such as voltage stabilization, voltage swell mitigation, flicker suppression, power factor correction, and harmonic control.

Due to this versatile capability of compensation of D-STACOM, exponential growth in research is witnessed in the operation of this device. In [27], a space vector predictive current control technique was developed. It is accomplished by calculating the duration of time spent on the appropriate inverter states in order to derive D-STATCOM. The aim of the current control is for the phase current to exactly follow the desired current reference with a minimum current ripple and phase delay. In [28] three methods for mitigating the load voltage sags and swells caused by load variations and three-phase faults were presented. In the first method, the proportional gain of the PI controller is maintained constant and dc side configuration in D-STATCOM is modified for mitigating voltage distortions. In the second method, dc side topology of the D-STATCOM is unchanged and the proportional gain of the PI controller is modified for mitigating voltage distortions. The third method is a combination of advantages of two mentioned methods, i.e. both dc side topology of the D-STATCOM is modified and the proportional gain of the PI controller is selected intelligently. Conventional controllers for DSTATCOMs are mainly based on PI controllers. The tuning of PI controllers is a complex task for a nonlinear system with lot of switching devices. In order to overcome these problems, Computational intelligence (CI) techniques is reportedly used [28]. Application of CI techniques in designing adaptive controller for DSTATCOM is yet to be explored to the fullest by the researchers. As reported in [29] and [30] control techniques may be based on neural networks (NNs). In [29], the PI controllers are replaced by a NN trained with the back propagation algorithm. But, the training is carried out offline and hence the ANN based controller is not adaptive. In [30], a NN based reference current generator is used, which is a partially adaptive control strategy. Here, though the reference generator adapts its NN weights online, but the DC voltage regulation is handled by conventional PI controllers. Bhattacharya et al [31] gave a concept of integration and control of energy storage system such as supercapacitor into a Distribution system STATCOM with voltage controller to enhance power quality. The application of DSTATCOM to improve voltage profile of distribution system with wind generation is investigated in [18]. And, in [32] cascaded multilevel type DSTATCOM is used, where, phase shifted PWM technique is used to generate firing pulses. A Sinusoidal PWM based control strategy was used to develop 12 pulse D-STATCOM converter using IGBT as switch in [33]. A novel voltage control strategy based on active-disturbance rejection control under unbalance voltage condition was proposed in [34]. In many paper, SRF based direct current control strategy was also used for reactive power and harmonics compensation of load [35-36, 40-43, 66].

When VSCs incorporated with renewable energy sources (mainly photovoltaic, micro cogeneration, variable speed wind power technologies), these state to act as distributed generator for both grid connected and Islanding mode. A large number of publications available in the operation of distribution generation. In [37-42] VSC used as active power source for load sharing. Parallel operation of VSC based on centralized and decentralized control strategies have been presented in [37, 38, 42] for load sharing. There are many publication based on the following techniques master slave [46, 47], distributed logic control [48] and wireless control (droop control) [37-

42,48-65] have been used for power sharing between the inverters. The master slave and central mode control techniques present an effective current sharing but do not allow true redundancy because of vulnerability of the master or in the central unit, upon failure it would shut down the whole system. Whereas, in the droop control each inverter has its own control system for the parallel operation, improving the redundancy and modularity of the system in comparison to the previous techniques.

A Voltage Source Inverter can also be used as active power filter (APF) for harmonics compensation. B. singh and V. Verma et al [66] proposed a simple SRF-based control scheme to decompose load current into four parts; positive sequence fundamental frequency active current, positive sequence fundamental frequency reactive current, current at harmonic frequencies and negative sequence fundamental frequency current. With these current components, selective compensation of combinations of them can be made which respects the rating of the APF used. M. Basu et al [67] presented a technical overview for parallel operation of active power filters based on various control strategies like master slave control, central limit control, average current sharing, circular chain control and droop control with their pros and cons. In [68] a distributed active-filter system (DAFs) is proposed to reduce the voltage harmonic distortion of power systems. The proposed DAFS consists of several active-filter units (AFUs) that are installed on various locations, and each unit operates as a harmonic conductance to reduce the voltage harmonics. The AFUs of the DAFS can share the harmonic filtering workload without any communications among them.

This feature is accomplished by the droop relationship between the harmonic conductance and the voltampere (VA) of each active filter. The slope of the droop is determined by the voltampere rating of the active filter to ensure that the sharing of filtering workload which is in proportion with the capacity of the active filter.

2.2.1.3 Distributed static shunt-series controller or Distributed Power Flow Controller- (DPFC):

Distributed Power Flow Controller (DPFC), recently introduced, is a powerful device within the family of DFACTs devices, which provides higher reliability at much lower cost than conventional PFC devices. It is derived from the UPFC and has the same capability of simultaneously adjusting all the parameters of the power system: line impedance, transmission angle, and bus voltage magnitude. DPFC consist of several D-FACTs devices in series with the line. They can inject voltage of controllable magnitude and also phase angle can be controlled up to 360˚. There is a voltage source converter which is shunt connected between the line and ground to provide active power for each series D-FACTs device and also compensate reactive power. In normal unified power controller, there is an exchange of active power between series and shunt converter through a common dc link [7]. But in case of DPFC, the distributed converters are spread along the subtransmission line or distribution line. So in order to supply active power to all series D-FACTs device, the common dc link should have the same length as subtransmission line, which is too costly. For flexible and independent placement of series and shunt converter the common dc link between series and shunt converter is eliminated in DPFC. The scheme of DPFC in a two bus system is shown in Fig.2.3.

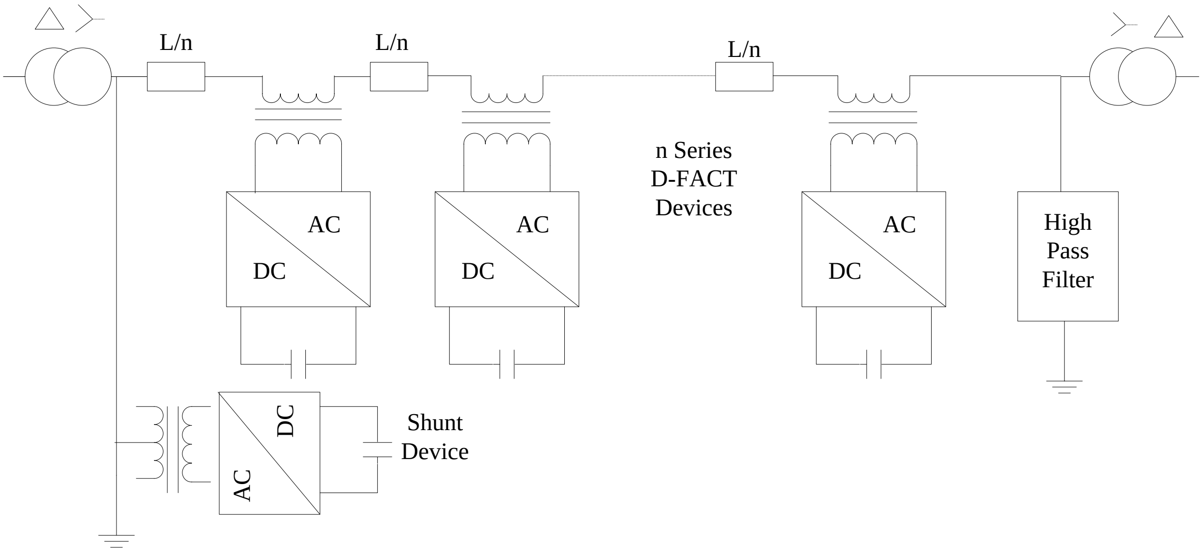

Fig. 2.3- DPFC Connected in a two Bus System.

Operational Characteristics

The DPFC uses the transmission line to exchange active power between converters at harmonic frequency. The principle is based on the definition of active power, which is the mean value of the product of voltage and current, where the voltage and current comprise fundamental and harmonics. The active power is given by [8]:

$$P = \sum_{n=1}^{\infty} Vn\ In\ Cos\emptyset n \qquad (2.3)$$

Where n= order of harmonics.

ϕ_n = phase angle between and current.

V_n = voltage at n^{th} harmonic

I_n = current at n^{th} harmonic frequency.

Equation (2.3) shows that active powers at different frequencies are separated from each other and voltage or current of one frequency have no effect on other frequency component. In DPFC 3rd harmonic is selected to exchange active power between converters and line, because it is a zero-sequence harmonic and can be easily filtered by Y-Δ transformers.

Growing demand and aging of network makes it desirable to fast and reliable control the power flow in distribution systems. The Distributed Power Flow Controller (DPFC) recently presented in [7], is a powerful device within the family of PFC devices. S. Bhattachaya et al [69] proposed the distributed power flow controller (DPFC) which is effective to control the active power flow through the lines. This modular DPFC has low cost, high reliability and makes it possible to have the transformer less connection to the existing network. In [69] the development and analysis of modeling techniques and feedback schemes based on per phase control of DPFC is described. In [8] design procedure of DPFC) is presented. In [79] a control scheme to improve the DPFC performance during the failure of a single series converter is proposed. The principle of the control is based on the facts that, the failure of single series converter will lead to unsymmetrical current at the fundamental frequency. By controlling the negative and zero sequence current to zero, the failure of the series converter is compensated. Ahmad Jamshidi et al [71] proposed a control scheme for power quality improvement and sag mitigation in distribution system using DPFC.

This thesis proposes a distributed compensation for radial distribution system for alleviating the problem of reactive power compensation in the system due to which voltage sag occurs at receiving end as well as for reactive power compensation of load.

In the thesis also explores the use of distributed STATCOM compensators to achieve stable steady state and dynamic compensation of the voltage profile along a radial distribution network under widely varying load conditions.

2.2.2 Synchronization and estimation of reference signals:

Correct estimation of reference signals for proper synchronization of DSTATCOM with grid is as prerequisite for effective control. Any deviation from exact reference may lead to circulation of hazardously high level of circulating currents which may put at risk the operation of DSTATCOM unit. The estimation has to be very fast so as to apply the control in real time, thus time domain techniques are more advisable as compared to frequency domain techniques. Various time domain techniques such as IRPT, SRF synchronous detection technique, symmetrical components technique, etc. are presented in the literatures for realizing a fast control. SRF based technique is seems to be most suitable technique for parallel operation of inverter and demands a fast PLL which should provide the sine and cosine signals for synchronization. The detailed survey of the literature is presented in the following sub sections:

2.2.2.1 Synchronous Reference Frame Control:

Synchronous reference frame control, also called *dq0* control, uses a Park's transformation module, e.g., $abc \rightarrow dq0$, to transform the grid current and voltage waveforms into a reference frame that rotates synchronously with the grid voltage. The application of the Park transform in power systems was demonstrated in principle when Ferrero and Superti-Furga derived power definitions based on the Park voltage and current vector. It achieved practical status when Akagi and Nabae developed a novel compensator design methodology using just that. There are many publications in which SRF theory based control strategy has been used for compensation. In [66] based on synchronous reference frame control selective compensation of load was presented. [71][67] also used it for harmonics compensation. By using SRF based control, the control variables become dc values; thus, filtering and controlling become easier. The control block for battery supported DSTATCOM in which the synchronous reference frame (SRF) theory is used for reference signal generation is shown in Figure 2.4.

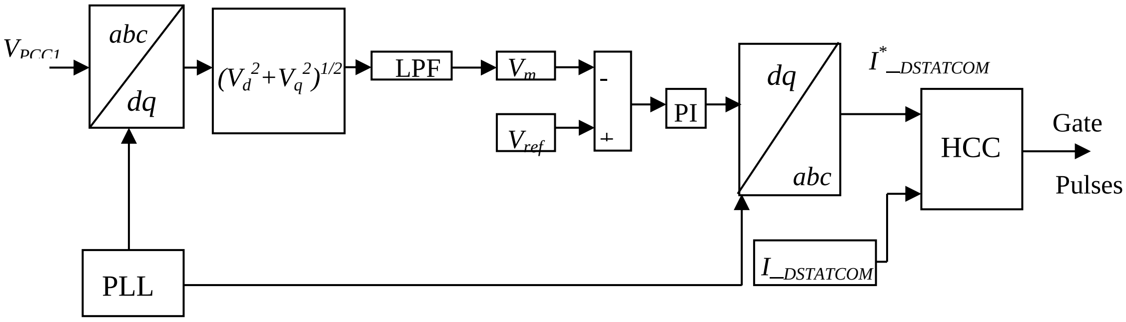

Fig.2.4: General structure for SRF control

In this diagram, load voltages (v_{La}, v_{Lb}, v_{Lc}) are transformed to the rotating reference frame using the *abc-dq0* conversion using the Park's transformation with unit vectors (*SinΘ* , *CosΘ*) derived using a PLL (phase locked loop) as,

$$\begin{pmatrix} V_{Ld} \\ V_{Lq} \\ V_{L0} \end{pmatrix} = 2/3 \begin{pmatrix} Cos\Theta & -Sin\Theta & 1/2 \\ Cos\,(\Theta-2\Pi/3) & -Sin\,(\Theta-2\Pi/3) & 1/2 \\ Cos\,(\Theta+2\Pi/3) & Sin\,(\Theta+2\Pi/3) & 1/2 \end{pmatrix} \begin{pmatrix} V_{La} \\ V_{Lb} \\ V_{Lc} \end{pmatrix} \tag{2.4}$$

The d-q components are then passed through low pass filters to extract the dc components of V_{Ld} and V_{Lq}. After that magnitude is calculated as,

$$V_L = (V_d^2+V_q^2)^{1/2} \tag{2.5}$$

And then it is compared with reference voltage of the load which is required and passed through the *PI* controller to get reference current signal for DSTATCOM to compensate reactive power of load. The *dq0* control structure is normally associated with proportional–integral *(PI)* controllers since they have a satisfactory behaviour when regulating dc variables. The matrix transfer function of the controller in *dq0* coordinates can be written as,

$$G_{PI}^{dq}(S) = \begin{pmatrix} K_P+K_I/S & 0 \\ 0 & K_P+K_I/S \end{pmatrix} \tag{2.6}$$

Where K_P and K_I are the Proportional and Integral gain. The output of PI is q-component of load current which is supplied by DSTATCOM to boost the load voltage. And to get the reference DSTATCOM current ($i_{Sa}*$, $i_{Sb}*$, $i_{Sc}*$) in a-b-c frame is obtained from the reverse Park's transformation as shown in below.

$$\begin{pmatrix} i_{Sa}^{*} \\ i_{Sb}^{*} \\ i_{Sc}^{*} \end{pmatrix} = \begin{pmatrix} Cos\Theta & Sin\Theta & 1 \\ Cos\,(\Theta\text{-}2\Pi/3) & Sin\,(\Theta\text{-}2\Pi/3) & 1 \\ Cos\,(\Theta+2\Pi/3) & Sin\,(\Theta+2\Pi/3) & 1 \end{pmatrix} \begin{pmatrix} i_{Sd}^{*} \\ i_{Sq}^{*} \\ i_{S0}^{*} \end{pmatrix} \tag{2.7}$$

The error between the sensed DSTATCOM current (i_{Sa}, i_{Sb}, i_{Sc}) and the reference DSTATCOM current (i_{Sa}^{*}, i_{Sb}^{*}, i_{Sc}^{*}) are used over a Hysteresis Current Controller (HCC) to generate gating pulses to the VSC of DSTATCOM.

2.2.2.2 Stationary Reference Frame Control:

In this case, the grid voltages are transformed into stationary reference frame using the $abc \rightarrow \alpha\beta 0$ module by using Clark's Transformation. The advantage of applying $\alpha\beta 0$ transformation is to separate zero-sequence component from abc-phase component. The α and β makes no contribution to zero-sequence component. So that no zero-sequence component present in three phase three wire system. Clark's Transformation matrix is given by

$$\begin{pmatrix} \boldsymbol{V_{S0}} \\ \boldsymbol{V_{S\alpha}} \\ \boldsymbol{I_{S\beta}} \end{pmatrix} = \left(\frac{2}{3}\right)^{1/2} \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{pmatrix} \begin{pmatrix} \boldsymbol{V_{Sa}} \\ \boldsymbol{V_{Sb}} \\ \boldsymbol{V_{Sc}} \end{pmatrix} \tag{2.8}$$

Since the control variables are sinusoidal in the nature, so employment of different type of controller is necessary because a PI controller is fail to remove the steady-state error when controlling sinusoidal waveforms. Proportional resonant (PR) controller gained a large popularity in the last decade in current regulation of grid-tied systems. In the PR case, the controller matrix in the stationary reference frame is given by

$$G_{PR}^{\alpha\beta}(S) = \begin{pmatrix} K_P + \frac{K_I S}{S^2+\omega^2} & 0 \\ 0 & K_P + \frac{K_I}{S^2+\omega^2} \end{pmatrix} \qquad (2.9)$$

Where, ω is the resonance frequency of the controller, K_P is the proportional gain, and K_I is the integral gain of the controller.

Characteristic to this controller is the fact that it achieves a very high gain around the resonance frequency, thus being capable to eliminate the steady-state error between the controlled signal and its reference [71]. The width of the frequency band around the resonance point depends on the integral time constant Ki. A low Ki leads to a very narrow band, whereas a high Ki leads to a wider band. Moreover, high dynamic characteristics of PR controller are reported in variety of applications [72].

2.2.3 Control Strategies for parallel operation of DSTATCOM (Inverter) unit:

In distribution systems, there may be more than one inverter acting in parallel for the compensation of load. Therefore, the parallel operation of voltage source inverters with the grid or with other inverters, are sensitive to disturbances from other sources or load and can easily be damaged by overcurrent. Hence, careful supervision should be given to the control of parallel operation of inverters and design of a system. Various control methods are proposed and are discussed in [35-48]. The following features as reported must be accomplished, when two or more inverters operate in parallel:

(1) Amplitude, frequency and phase synchronization among the output voltages of inverters,

(2) Proper current distribution according to the capacities,

(3) Flexibility and

(4) Hot-swap feature at any time

The conventional control strategies for the parallel-connected inverters can be classified into two types; active load sharing/current distribution and droop control. Some of the conclusions of recent research on parallel operation of inverters are given below.

Active load sharing/current distribution: The main objective of the active current distribution control is to generate a reference current for each parallel-connected inverter and this can be subdivided into; central limit control (CLC), master–slave control (MSC), average current sharing (ACS)/distributed logical control (DLC) and circular chain control (3C). In case of CLC all the units should have the same configuration and each module tracks the average current to achieve an equal current distribution. In [67] it is used for harmonics compensation with the parallel operation of Active Power Filters (APFs), where it is observed that APF module which deals with the higher order harmonics should have the higher switching frequency. Since the harmonic current magnitude is inversely proportional to the harmonic order, the power rating is low. Thus it also helps to reduce the switching losses. The main disadvantage is this control strategy is that if central unit fails the whole system will shut down. In the MSC method, one inverter is specified as the master, and all other inverters act as the slaves. The master inverter gives a reference current to the slave inverters. Thus the master module is responsible for the output voltage regulation. In [46, 47] for the parallel operation of DGs MSC control strategy has been used for load sharing. But in MSC system, if the master unit fails, the system will still shut down. This is a major disadvantage of this method. The output currents of all parallel-connected inverters, in the MSC and CLC methods, must be collected and the total number of inverters being used must be pre-known. If one of them fails, the parallel-connected system would shut down. This problem can be overcome by the DLC mode. V. Verma and et al [78] proposed Master Slave operation with decentralized control for parallel operation of DGs. In the ACS/DLC mode, an individual control circuit is used for each inverter. For controlling the output current and to trace the same average reference current, current control mode is used. There is no effect on the parallel connected inverter when a defect is found in any module [49-60]. It can also be used as a power-sharing technique where each inverter controls the active and reactive power flow in order to match the average active power of the system. In the 3C mode, the successive module tracks the current of the previous module to achieve an equal current distribution, and the first module tracks the last one to form a circular chain connection. But there is possibility of flow of circulating current between the inverter if any communication mismatch of reference signal occurs.

Droop Control**:** The droop control method for the parallel-connected inverters can avoid the communication mismatch of reference current. It is also defined as wireless control (WC) with no interconnection between the inverters. In this case, the inverters are controlled in such a way that the amplitude and frequency of the reference voltage signal will follow a droop as the load current increases and these droops are used to allow independent inverters to share the load in proportion to their capacities [44].

This concept is aquired from the power system theory, in which a generator connected to the utility mains drops its frequency when the power required increases [63].The droop characteristic control was first introduced in [39] for parallel connected inverters working in a standalone system. More recently, droop control has been extended to microgrid distributed control [37, 40-42]. Droop control with no interconnection of lines could be more useful for either active load sharing or for a distributed generation network connected to the grid or off-grid. Some improvement in control has also been achieved to overcome its limitations such as poor transient response etc. Hot-swap operation is another benefit of using the droop control method. Low sensitivity to line impedance unbalances and harmonic power sharing capability are the other advantages of a droop controller. A countable number of researches have been done considering droop control for load sharing [44-65]. To achieve good power sharing, the control loop makes tight adjustments over the output voltage frequency and amplitude of the inverter, in order to compensate the active and reactive power unbalances [62]. A detailed analysis of the behavior of droop control based generators was presented in [58]. There are many control schemes based on the droop method to share linear loads [59]. Nevertheless, nowadays the proliferation of nonlinear loads has become a problem, and therefore the units must both share harmonic current and balance active and reactive power. In [60], a controller is proposed which share nonlinear loads by adjusting the output voltage bandwidth with the delivered harmonic power. A novel control strategy that adjust the output impedance of the units by adding virtual resistors [74] or reactors [75] is reported to be imbedded in the droop method, with the purpose to share the harmonic current content properly. In another approach reported in literature [76], the droop method exhibits slow dynamic response, since it requires low-pass filters with a reduced bandwidth to calculate the average value of the active and reactive power [77]. The stability and the dynamics of the whole system are strongly influenced by the characteristics of these filters and by the value of the droop coefficients, which are bounded by the maximum allowed deviations of the output voltage amplitude and frequency. In [61], a novel control scheme that is able to improve the transient response of parallel-connected inverters without using communication signals is reported. A wireless controller was developed, by adding a supplemental transient droop characteristic to the conventional static droop approach; the presented technique improves the paralleled-system dynamics. In [63] a control scheme based on the droop method is proposed which automatically adjusts its parameters by using an estimation method of the grid impedance based on power variations caused by the VSI at the point of common coupling (PCC). S.D. Henry et al [53] explored the influence of distributed resources on voltage collapse and introduces a droop control scheme to aid in the estimation of voltage stability margins. An artificial voltage droop is used by the aforesaid researchers to permit the observance of impending voltage instability. In [53], droop control scheme relies on information obtained from offline voltage stability studies to determine when droop control should be activated and the voltage droop characteristic required to ensure that voltage problems are not masked. The concept of “Virtual Synchronous Generator” (VSG) which is to control inverters to behave like a real synchronous generator has been proposed in [49] for equal real and reactive power sharing. R. Majumder and A. Ghosh et al [46] proposed the co-ordination operation of inertial and inertia less DGs for load sharing. From [49] it is shown that a large inertial DG can provide a ride through during the power shortfall in the microgrid. Otherwise a DSTATCOM needs to be connected to provide the much needed ride through during power imbalance in the microgrid. Load sharing in an autonomous microgrid through angle droop control has investigated in [40] with special emphasis on highly resistive lines.

2.3 Conclusion:

From the above literature it is concluded that a distributive approach of static shunt compensator offer several advantages. It increases reliability, flexibility of the system with low cost, and provide smart solution for improving the transient stability of the system with multirole of the hardware. DSTATCOM devices are capable of providing a variety of compensation in distribution system like harmonics compensation, reactive power compensation and negative sequence compensation.

CHAPTER-3

SYSTEM CONFIGURATION AND OPERATION

3.1 General:

To enable the study of multiple DSTATCOM connections at various places in the radial distribution network for voltage regulation is the identified area of study. An appropriate system configuration of three wire radial system with multiple DSTATCOMs is considered and the same is discussed in this chapter with its operation characteristics. The advantages of distributive compensation also discussed at the last in this chapter.

3.2 System Configuration:

A simplified single line diagram for distributed shunt compensation is shown in Fig. 3.1. It consists of multiple D-STATCOM devices of small rating connected in multiple locations in the radial distribution line. A single D-STATCOM unit employs an inverter (VSC) to convert the DC link voltage (V_{dc} across the capacitor) to an ac voltage of adjustable magnitude and phase. Therefore the D-STATCOM can be treated as a voltage-controlled source. The D-STATCOM can also be seen as a current-controlled source by connecting a series inductor and working out the current rather than power control

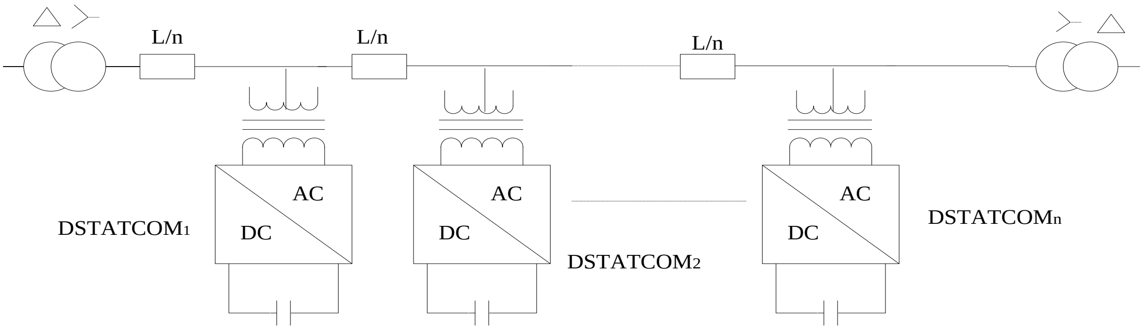

Fig.3.1: D-STATCOM Connection to the radial System

An L-C filter is connected at the output of Voltage Source Converter to smooth out the output voltage waveform. The basic function of each unit is given below.

Voltage Source Converter: A voltage-source converter is a power electronic device, which can generate a sinusoidal voltage with any required magnitude, frequency and phase angle. The VSC is used to inject the voltage in such a manner that it can compensate the difference between the nominal voltage and the actual. The converter normally works upon some energy storage element which supplies the energy and the converter is also able to establish a DC bus voltage. The solid-state electronics in the converter is then switched to get the desired output voltage. Normally the VSC is not only used for voltage dip mitigation, but also for mitigating other power quality issues, e.g. flicker and harmonic and voltage unbalance.

L-C filter: The voltage ripples are present in stator voltages due to the PWM switching of VSCs. In order to reduce the noise of high frequency, a low pass filter (Capacitive filter) is used at the PCC. The main criterion for capacitor selection is to achieve a resonant frequency of the filter approximately in the middle between operating frequency (50 Hz) and switching frequency. It is included in the circuit compulsorily otherwise; the system may be unstable, particularly during the no-load operation, when resonance is struck [1]. There are some limitations to the volume of capacitors.

Interfacing Inductor: An interfacing inductor is connected between VSC output and grid.

There are two main functions of this inductor;

(1) Interfacing inductor combined with L-C filter acts as 2nd order L-C-L filter. In case of L-C filter the resonance frequency dependent on the capacitor value of filter and inductance value of grid, this varies over time. It is difficult to reduce resonance, because resonance frequency changes with the grid inductance and, in addition, the harmonics distortion spectrum of grid changes with time. The resonance problem is solved to great extent by using L-C-L filter.

(2) It also creates a voltage angle difference between the VSC output voltage and PCC voltage, due to which an active power can be consumed by VSC to maintain DC link voltage constant and to compensate switching losses.

DC link Capacitor: The DC side of the voltage source converter is connected to a DC capacitor, which carries the input ripple current of the converter and is the main reactive energy storage element. This capacitor could be charged by a battery source, or could be recharged by the converter itself. The value of the capacitor is selected so that it can maintain DC link voltage approximate equal to twice the peak of phase value of PCC voltage. There are two different criteria by which the value of DC link capacitors can be calculated first is based on Energy Conservation Principle and second is based on DC ripple Current.

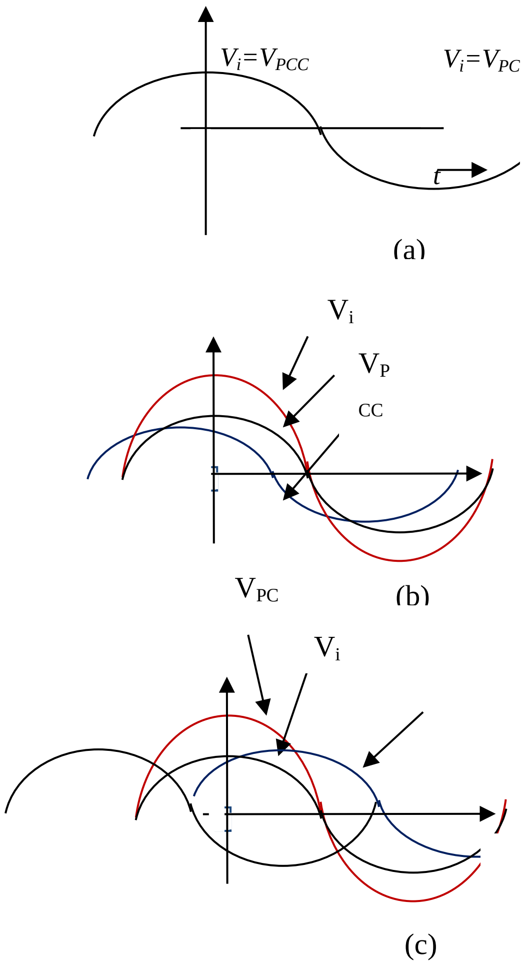

Fig.3.2: Operation of DSTATCOM (a) No load mode (*Vs*=*Vi*), (b) Capacitive mode, (c) Inductive mode

3.3 Operation of D-STATCOM:

The controller of the each D-STATCOM unit is used to operate the VSC in such a way that the phase angle between the inverter voltage and the line voltage is dynamically adjusted so that the D-STATCOM generates or absorbs the desired *VARs* at the point of connection. The phase of the output voltage of the inverter V_i, is controlled in the same way as the distribution system voltage, V_s. Figure 3.2 shows the three basic operation modes of the D-STATCOM output current *I*, which varies depending upon V_i.

If V_i is equal to V_{PCC}, the reactive power is zero and the D-STATCOM does not generate or absorb reactive power. When V_i is greater than V_{PCC}, the D-STATCOM 'sees' an inductive reactance connected at its terminal. Hence, the system 'sees' the D-STATCOM as a capacitive reactance. The current, I, flows through the coupling inductor from the D-STATCOM to the ac system, and the device generates capacitive reactive power. If V_{PCC} is greater than V_i, the system 'sees' an inductive reactance connected at its terminal and the D-STATCOM 'sees' the system as a capacitive reactance. Then the current flows from the ac system to the D-STATCOM, resulting in the device absorbing inductive reactive power.

3.4 Advantages of distributed shunt compensation:

The concept of distributive approach for realizing STATCOM devices is needed due to various reasons which are as follows.

A. *Distributed nature-*

Due to the lumped nature of Power Controlling devises these are placed at specific point (not in wide area) of transmission line, so failure of that point bring entire system to shut down, whereas, DSTATCOMs can be placed at multiple positions and failure of one place is compensated by joint efforts of other devices. These devices provide high system reliability due to massive redundancy; single unit failure has negligible impact on system performance [6].

B. *Cost-*

It has technically proven that high system ratings require high power rating devices with significant engineering effort and high cost. High fault currents and insulation requirement stress the power electronics system. While DSTATCOM devices are modular small in size and light in weight and rated about 10 KVA to 15 KVA which results in decrease in device cost. DSTATCOM devices improve flexibility of locating new generation and allow power flow along the contract path-enables bulk energy trading and reduce overall energy costs [6].

C. *Coordinated control-*

DSTATCOM devices on different lines can be used to achieve a control objective by coordinating them to work together. A known overloaded line can be relieved by the use of this devices. So by reducing the flow through an overloaded line, these devices improve the operation of power grid. These devices have the ability to increase or decrease steady state line current under system controller command, or autonomously [5].

D. *Smart Solution-*

In case in a power system containing many DSTATCOM modules, if any one module fails to compensate real and reactive power then this failure does not affect the system operation as other module compensate on behalf of the failed one.

DSTATCOM devices exhibit variety of operation characteristics with exemplary merits in term of:

E. *Range of compensation-*

The DSTATCOM module can inject 10 KVAR to 20 KVAR of effective positive or negative inductance, or quadrature voltage. It seems inconceivable that a small rated DSTATCOM module could appreciably affect power flow on a transmission line [3]. For a typical 138 kV transmission line with a thermal current limit of 770 Amperes gives a line capacity of 184 MVA. The reactive voltage drop across the line inductance is 608 volts/mile. This suggests that an injection of 60 volts (5 modules) per mile per phase can change the impedance of the line, and potentially its power flow by 10%. For the 138 kV transmission line under consideration, this represents as much as 18 MW of additional power flow capability [3].

F. *Variety of compensation-*

Distributed nature devices offer basically three types of compensation namely series, shunt and series-shunt compensation. Distributed series compensation provides an effective control of active and reactive power. Improvement of voltage profile and compensation of harmonics are done by the use of distributed shunt compensation and by the use of series and shunt compensation it is easy to control the transmission parameters like transmission angle, line impedance and bus voltage.

G. *Multirole in the circuit-*

DSTATCOM devices provide multirole operation in power system. They operate in a way so as to increase the power handling capacity of line, improve the transient stability with improved power quality. They have ability to increase or decrease steady state line current under system command, or autonomously [6]. DSTATCOM have an ability to monitor actual conductor temperature and manually or automatically limit currents as a function of conductor temperature [6].Their operation minimize loop flows and wheeling losses—improved asset utilization and lower operating cost. The devices may also be controller to operate in multiple roles. For instance, if any section of line witness unbalance in the current, that particular DSTATCOM device may switch the role from reactive power compensation to current balancing, whereas, other DSTATCOM devices in the network share the responsibility of reactive power compensation.

H. Augmentation with DG-

With the advent of power electronics grid quality power conversion from renewable energy sources has become a reality, and such distributed generation may easily be augmented into grid through the DC bus of shunt devices with just a modification in control and protection system. Such incorporation of DGs increases the system stability. Since they are connected as current sources they can have easy exit and entry to implement peak shaving without the need for additional generation or increase in conductor capacity. When transmission line operated at leading power factor these devices may extract the power from line and store on the DC bus in storage device. This may provide better line regulation.

3.5Conclusion:

Various advantages and scopes of the devices in terms of distributed nature, cost, coordinated control, smart solution, range of compensation, variety of compensation, and multirole in circuit are emphasized in this chapter. for numerous merit points, it is concluded that distributive shunt compensation shoud used for voltage regulation in the line and reactive power sharing of load.

CHAPTER-4

MODELLING AND CONTROL THEORY

4.1General:

To get insight knowledge of the system, an accurate and simple modeling of an electrical system is a prerequisite. The system behaviour and dynamics can be observed beforehand experimental ways by mathematical equation through simulations. This chapter deals with a mathematical modelling of DSTATCOM in grid connected system which is developed using VSCs with a dc link capacitor. This mathematical model forms simple equation which can be solved to implement a virtual active and reactive power source to the real system because we do not know the behaviour and dynamics of system. Without the modeling of the system unpredictable, unexpected operation may occur.

4.2 System Modeling:

DSTATCOM unit is modelled with DC link capacitor, a three-phase PWM inverter having six IGBT switches, interfacing inductor and, an *L–C* output filter, connected to the grid for compensation of voltage drop of line and reactive demand of load.

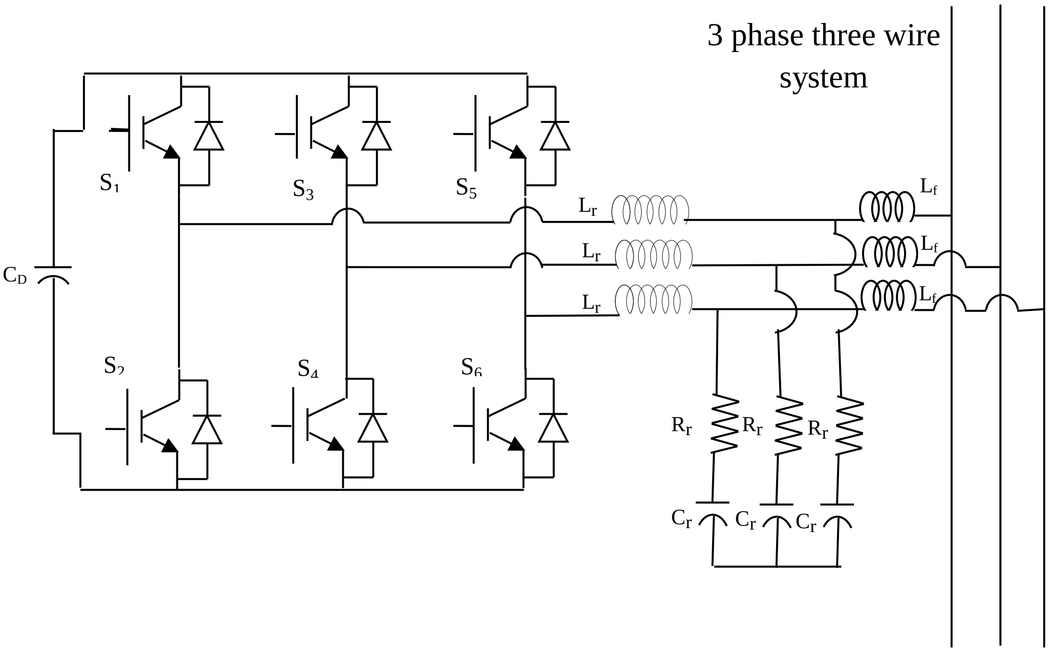

Fig.4.1 Each DSTATCOM Circuit Model.

In figure 4.1, the selection of components like IGBTs, inductor, DC link capacitor and the ripple filter are made according to design requirement.

Selection of DC Capacitor Voltage

The minimum dc bus voltage of VSC should be greater than and equal to twice the peak of the phase voltage of the system as [84], which is calculated by equation 4.1.

$$V_{DC} \geq \frac{2\sqrt{2}\, V_{LL}}{\sqrt{3}m} \tag{4.1}$$

Where m is the modulation index and is considered as 0.9 and V_{LL} is the ac line output voltage of VSC.

Design and Selection of components used with VSC:

To maintain required DC link voltage a capacitor of suitable value is necessary. There are two different criteria by which the value of DC link capacitors has been calculated.

(1) *DC link Capacitor based on Energy Conservation Principle*

The design of DC link capacitor (C_D) of VSC depends on the instantaneous energy available to the VSC at the time of transients. Considering the energy stored in the capacitor is for meeting the energy demand of the load for a fraction of power cycle, the relation can be expressed as, [84],

$$\frac{1}{2} C_D [V_{dc}^2 - V_{dc1}^2] = 3V_P \alpha I t \tag{4.2}$$

Where V_{dc} is the reference DC voltage and V_{dc1} is the minimum voltage level of DC bus, α is the overloading factor, V_P is the phase voltage, I is the phase current, and t is the time by which the DC bus voltage is to be recovered.

(2) *DC Link Capacitor Based on DC ripple Current*

The value of DC link capacitor is given for load balancing of the consumer loads by VSC as [84],

$$C_D = \frac{I_d}{2*\omega*V_{dc\ ripple}} \tag{4.3}$$

Where I_d is the DC link current (P_{dc}/V_{dc}), ω is angular frequency and $V_{dc\ ripple}$ is 5% of V_{dc}.

(3) *Design of Interfacing Inductor for VSC of DSTATCOM*

The selection of the interfacing inductance (L_f) of VSC depends on the current

$$L_f = \frac{\sqrt{3}mV_{dc}}{12hf_s\Delta i} \tag{4.4}$$

ripple Δi, switching frequency f_s , dc bus voltage (V_{dc}), and L_f is given as,

Where,

m = modulation index,

h = overload factor,

Δi = ripple current,

f_s = switching frequency of VSC, and

V_{dc} = DC link Voltage.

(4) *Design of ripple filter*

The ripple filter is designed based on the switching frequency (f_s). Usually cutoff frequency (f_c) is below *70%* of switching frequency; here half of f_s is taken as f_c. The reactance given by the capacitor and inductor at cutoff frequency is

$$X_{Cr} = \frac{1}{(2*\pi* f_c *C_r)} \tag{4.5}$$

$$X_{Lr} = (2*\pi* f_c *L_r) \tag{4.6}$$

By considering suitable values of X_{Cr} and X_{Lr} according to load the values of ripple filter elements can be calculated with the help of above formulas.

4.3 Synchronization:

Voltage source inverters connected to the grid in applications such as DSTATCOM require synchronization with the grid voltage. Since in practice the grid voltage can be unbalanced and distorted, but extraction of a correct reference signal as well as the operation of the whole control system of the DSTATCOM is strongly dependant on a precise estimation of the phase of the fundamental positive sequence phasor of the grid voltage at the point of common coupling (PCC). The harmonic distortion, if present in the grid voltage, affects the whole control loop, because the synchronization phase signal used for the reference frame transformations is distorted. A common technique used for determining of the phase of a sinusoidal signal (or a phasor) is called phase-locked loop (PLL). Generally, a PLL is a circuit synchronizing it output signal with a reference or input signal in frequency as well as in phase. In the synchronized state, the phase error between the system output signal and the reference signal is zero, or it remains constant [3].

4.3.1 PLL synchronization techniques:

The most widely accepted synchronization solution to a time-varying signal can be described by the basic structure shown as block diagram in Figure 4.2, where the difference between phase angle of the input and that of the output signal is measured by the phase detection (PD) and passed through the loop filter (LF). The LF output signal drives the voltage-controlled oscillator (VCO) to generate the output signal, which could follow the input signal [80].

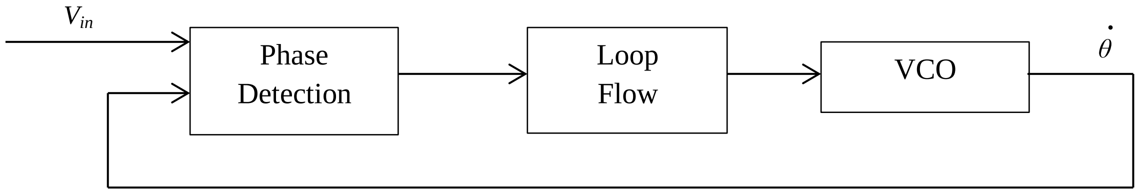

Fig.4.2: Closed-loop synchronization structure

4.3.1.1 Synchronous Reference Frame –PLL:

Synchronous Reference Frame PLL (SRF-PLL) is widely used in three-phase systems. The block diagram of SRF-PLL is illustrated in Fig 4.2, where the instantaneous phase angle θ is detected by synchronizing the PLL rotating reference frame to the utility voltage vector. The PI controller sets the direct or quadrature axis reference voltage v_d or v_q to zero, which results in the reference being locked to the utility voltage vector phase angle. In addition, the voltage frequency f and amplitude v_m can be obtained as the by-products. Under ideal utility conditions without any harmonic distortions or unbalance, SRF-PLL with a high bandwidth can yield a fast and precise detection of the phase and amplitude of the utility voltage vector. In case the utility voltage is distorted with high-order harmonics, the SRF-PLL can still operate if its bandwidth is reduced at the cost of the PLL response speed reduction in order to reject and cancel out the effect of these harmonics on the output. However, the PLL bandwidth reduction is not an acceptable solution in the presence of the unbalanced utility voltage [81-82]. Note that, the amplitude, phase and frequency values provided by SRF-PLL are not correspondingly to individual-phase but average information, and SRF-PLL may not be applied to single phase systems in a straightforward manner. However, it provides a useful structure for single-phase PLLs as long as the 90-degree-shifted orthogonal component of the single phase input signal is created [83].

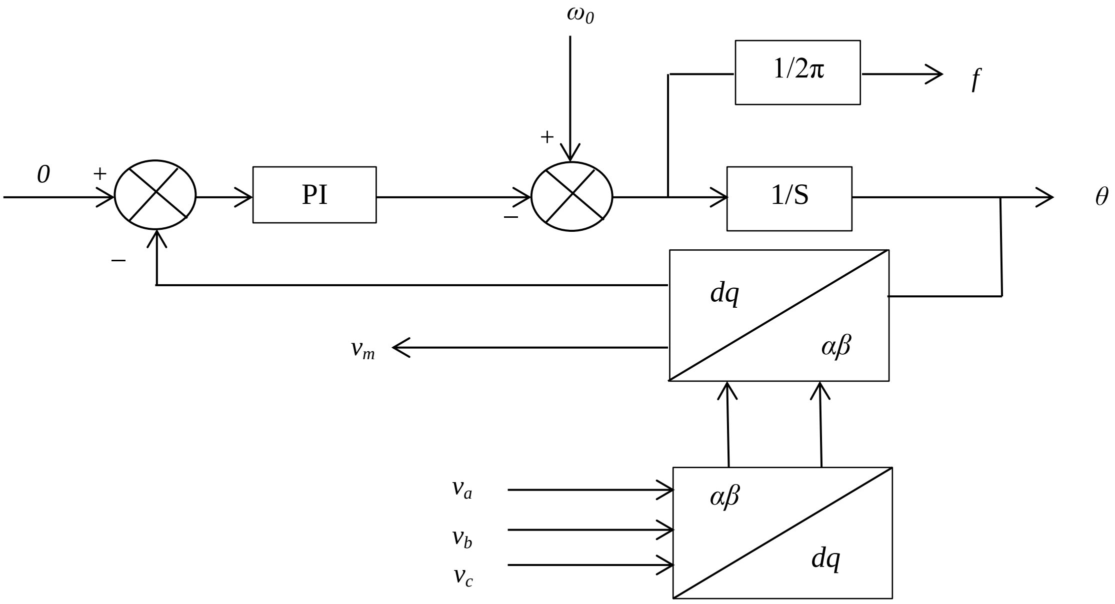

Fig.4.3: Block diagram of SRF-PLL

4.3.1.2 PQ–PLL:

Rolim et al. [14] point out that PLL may fail in tracking the system voltage during starting, under some adverse conditions, and oscillations caused by the presence of sub harmonics can pull the stable point of operation synchronized to the sub harmonic frequency. In order to settle these problems, a robust digital synchronizing PLL based on the instantaneous real and imaginary power theory (PQ-PLL) is presented to maintain synchronization in presence of sub harmonics, harmonics, and unbalances conditions. The block diagram of PQ-PLL is shown in Fig.4.4.

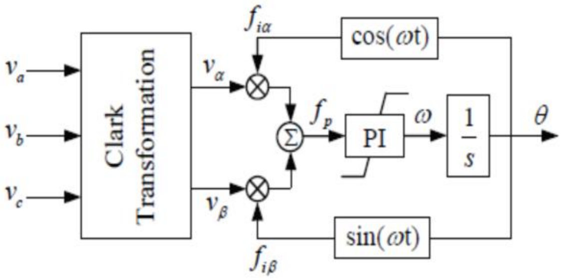

Fig.4.4: Block diagram of PQ-PLL

It has the similar structure to the conventional SRF-PLL, but it can be easily understood from the viewpoint of the instantaneous power theory. Besides, the fundamental positive-sequence components can be obtained as a byproduct.

4.3.1.3 Double Synchronous Reference Frame –PLL:

Double Synchronous Frame PLL (DSF-PLL) [80] is based on transforming both the positive and negative sequence components of the utility voltage into the double synchronous frame, which can completely eliminate the detection errors of the conventional SRF-PLL. The block diagram of DSF-PLL is shown in Figure 4.5.

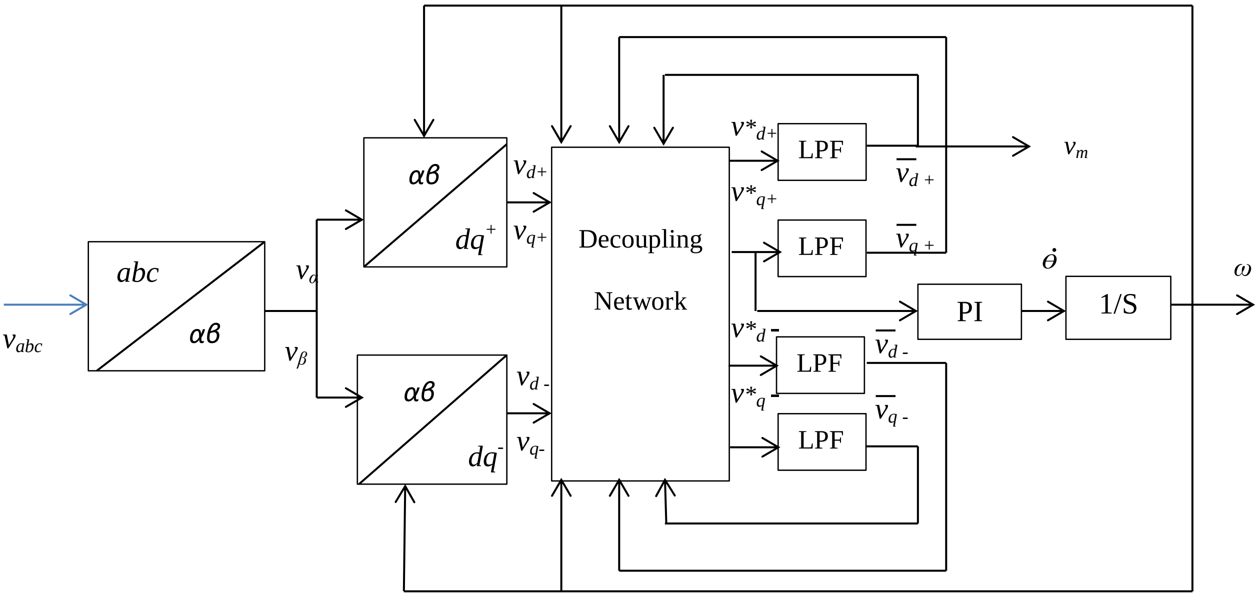

Fig.4.5: Block diagram of DSRF-PLL

Its unique decoupling network can cancel out the double frequency oscillations at 2ω in v_{q+}^*, therefore, there is no need to reduce the PLL bandwidth for the accurate positive sequence component estimation compared with the conventional SRF-PLL. It is very suitable to the control of grid-interfaced converters operating in the severe frequency derivation and unbalanced conditions.

$$\begin{bmatrix} v_{d^+} \\ v_{q^+} \end{bmatrix} = \begin{bmatrix} v^{*}_{d^+} \\ v^{*}_{q^+} \end{bmatrix} + \begin{bmatrix} v^{\sim}_{d^+} \\ v^{\sim}_{q^+} \end{bmatrix} \tag{4.7}$$

$$\begin{bmatrix} v^{\sim}_{d^+} \\ v^{\sim}_{q^+} \end{bmatrix} = \begin{bmatrix} \cos 2\theta & \sin 2\theta \\ -\sin 2\theta & \cos 2\theta \end{bmatrix} \begin{bmatrix} v^{-}_{d^-} \\ v^{-}_{q^-} \end{bmatrix}$$

$$\begin{bmatrix} v^{*}_{d^+} \\ v^{*}_{q^+} \end{bmatrix} = \begin{bmatrix} v_{d^+} \\ v_{q^+} \end{bmatrix} - \begin{bmatrix} \cos 2\theta & \sin 2\theta \\ -\sin 2\theta & \cos 2\theta \end{bmatrix} \begin{bmatrix} v^{-}_{d^-} \\ v^{-}_{q^-} \end{bmatrix}$$

$$\begin{bmatrix} v_{d^-} \\ v_{q^-} \end{bmatrix} = \begin{bmatrix} v^{*}_{d^-} \\ v^{*}_{q^-} \end{bmatrix} + \begin{bmatrix} v^{\sim}_{d^-} \\ v^{\sim}_{q^-} \end{bmatrix} \tag{4.8}$$

$$\begin{bmatrix} v^{\sim}_{d^-} \\ v^{\sim}_{q^-} \end{bmatrix} = \begin{bmatrix} \cos(-2\theta) & \sin(-2\theta) \\ -\sin(-2\theta) & \cos(-2\theta) \end{bmatrix} \begin{bmatrix} v^{-}_{d^+} \\ v^{-}_{q^+} \end{bmatrix}$$

$$\begin{bmatrix} v^{*}_{d^-} \\ v^{*}_{q^-} \end{bmatrix} = \begin{bmatrix} v_{d^-} \\ v_{q^-} \end{bmatrix} - \begin{bmatrix} \cos(-2\theta) & \sin(-2\theta) \\ -\sin(-2\theta) & \cos(-2\theta) \end{bmatrix} \begin{bmatrix} v^{-}_{d^+} \\ v^{-}_{q^+} \end{bmatrix}$$

4.3.1.4 Enhanced phase-locked loop (EPLL):

Enhanced phase-locked loop (EPLL) is a frequency-adaptive nonlinear synchronization approach. The block diagram of EPLL is shown in Figure 4.6 and Figure 4.7. Its major improvement over the conventional PLL lies in the PD mechanism which allows more flexibility and provides more information such as amplitude and phase angle. There are three independent internal parameters K, K_p K_V and K_i K_v. Parameter K dominantly controls the speed of the amplitude convergence. K_pK_v and K_i K_v control the rates of phase and frequency convergence.

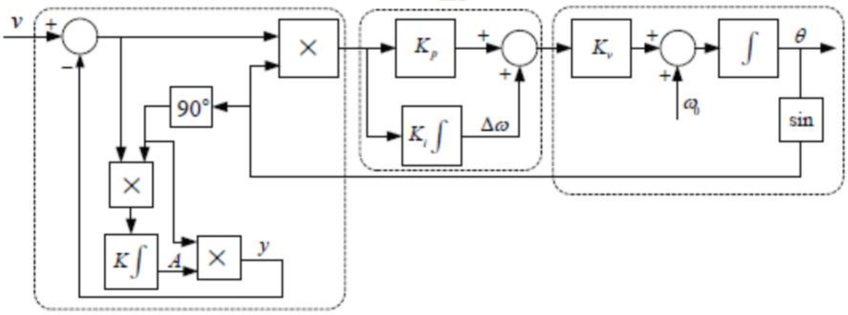

Fig.4.6: Block diagram of single-phase EPLL

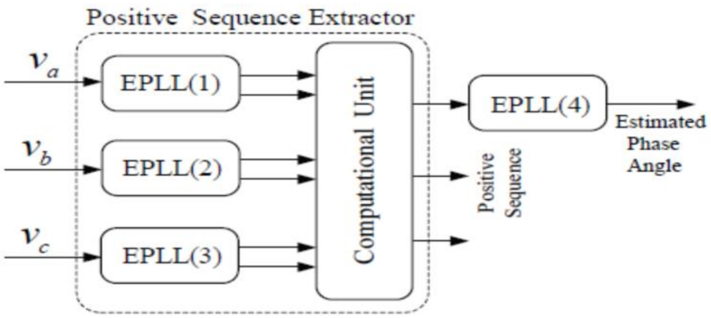

Fig.4.7: Block diagram of three-phase EPLL

EPLL can provide higher degree of immunity and insensitivity to noise, harmonics and unbalance of the input signal. It is an effective method for synchronization of the grid-interfaced converters in polluted and variable frequency environments. In addition, EPLL can provide the 90 degrees shift of the input signal. Therefore, it is an attractive solution in some single phase system applications. It is recommended for the accurate detection of the parameters and generation of reference signal for each compensating unit SRF based PLL has been used.

4.4 Control Strategies:

This section is subdivided in two parts. First deals with reported control strategies for the parallel-connected DSTATCOMs and in the later part proposed new autonomous current control technique for voltage regulation is dealt in details.

4.4.1 Reported Control Strategies:

The reported control strategies for the parallel-connected DSTATCOMs can be classified into two types;

(1) Centralized Control
(2) Decentralized Control

4.4.1.1: Centralized Control:

The main objective of this control is to generate a reference current based on the information received from each unit placed distantly for each parallel-connected inverter and this can be subdivided into;

(a) Central Limit Control
(b) Distributed Control
(c) Master Slave Control

(a) Central Limit Control:

In Central limit control, a central control unit is used to measure the total amount of reactive component of load and then each DSTATCOM unit is assigned to compensate a specific amount of component. Therefore it requires the minimum number of sensors for detection, as shown in Figure 4.8(a). It can also be referred as concentrated control. Generally SRF based control strategy has been used for extraction of q component from the load phase current. The technique extracts reference current for providing compensation.

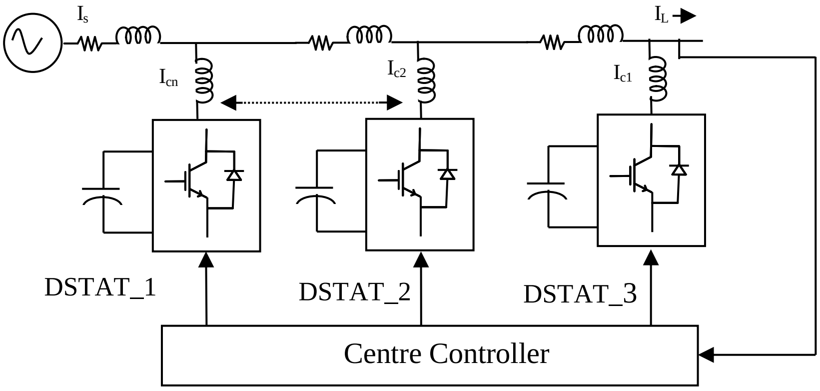

Fig.4.8 (a): Single line diagram for Central Limit Control

If there are 3 DSTATCOMs unit working in parallel and one is responsible for giving the reference signal for other for reactive power compensation. In [67] it is used for harmonics compensation with the parallel operation of Active Power Filters (APFs), where it is observed that APF module which deals with the higher order harmonics should have the higher switching frequency. Since the harmonic current magnitude is inversely proportional to the harmonic order, the power rating is low. Thus it also helps to reduce the switching losses. The main disadvantage is this control strategy is that if central unit fails the whole system will shut down.

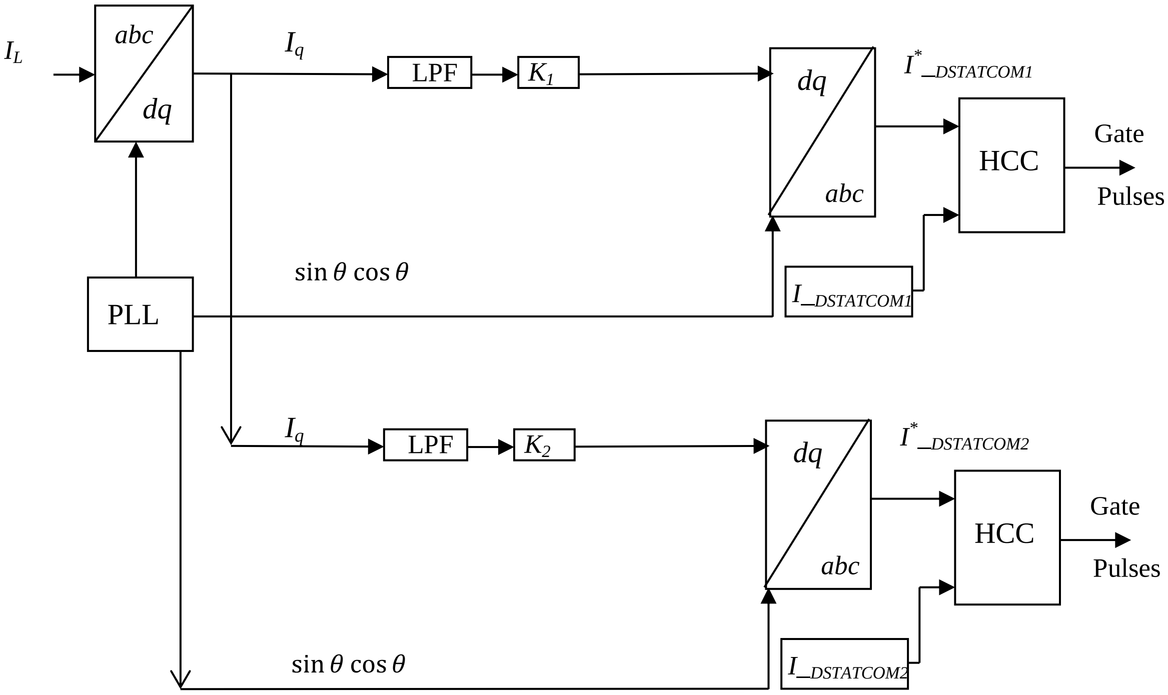

Fig.4.8 (b): Reference current generation for central limit control

(b) Distributed Control:

In this case, compensating reactive current is equally distributed to the each DSTATCOM unit and therefore identical modules are required. If there are N modules operating then the current reference of each module will be,

$$I_{lqN} = I_{lq} / N$$

Since it maintains interconnection between the inverters, number of sensors are also higher than the central limit control, shown in Figure 4.9 (a). The reference current generation technique has been depicted in –Figure 4.9 (b).

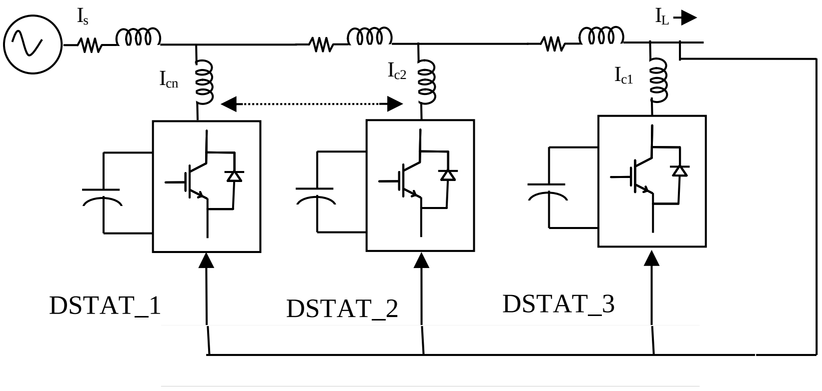

Fig.4.9 (a): Single line diagram for Distributed Control

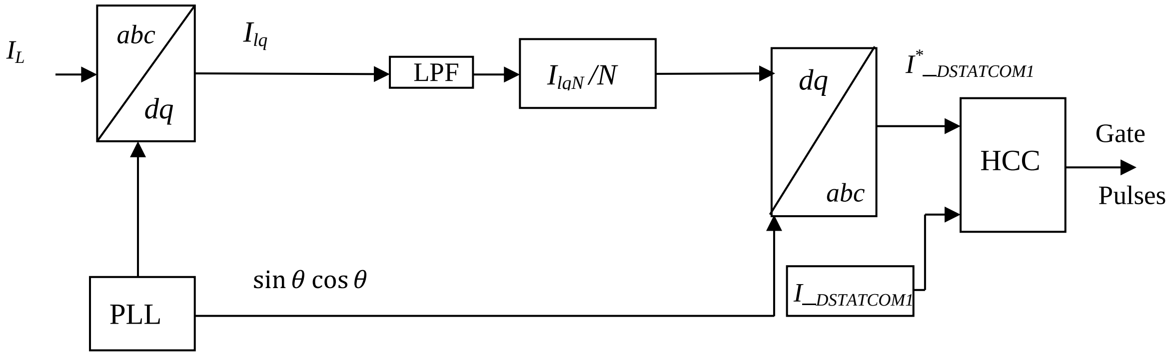

Fig.4.9 (b): Reference current generation for Distributed Control

The main advantage of this technique is its easy maintenance and installation. It is clear that in both central and distributed control system, the reference current of each DSTATCOMs are resulting from the same control algorithm and therefore all the DSATCOMs maintain interconnected control. Hence a fault in any communication or malfunctioning of any unit can cause the system halt.

(c) Master Slave Control / Capacity Limit Control:

In Master Slave technique one DSTATCOM unit acts as "Master" and sets the voltage and frequency of the grid in islanded mode, while other units adopts the voltage and frequency from Master, and in grid connected mode all DSTATCOMS operate in current control mode as shown in Figure 4.10(a) schematic diagram for Master Slave Scheme.

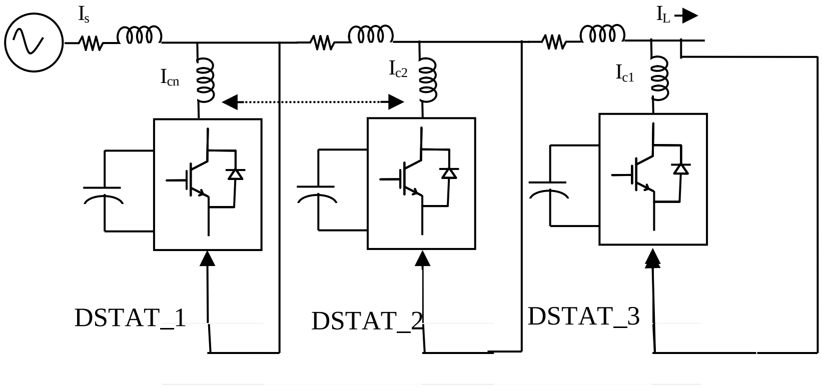

Fig.4.10 (a): Single line diagram for Master Slave Control

The DSTATCOM unit with highest rating is often favourable to act as "Master". The output current of each unit is optimized in such a way that the unit with large capacity compensates more current and the one with small capacity compensates less current. In this way, the feasibility and security of modular DSTATCOMs can be guaranteed.

Figure 4.10 (b) generates the current commands in dq frame for all DSTATCOM's for reactive power sharing according to their ratings.

Q_1, Q_2, Q_3, Q_4, --------Q_n are the reactive power rating of DSTATCOM$_1$, DSTACOM$_2$, DSTATCOM$_3$, DSTATCOM$_4$, ---------- DSTATCOM$_n$. And M_1, M_2, M_3, M_4, --------M_n are the weights of DSTATCOMs. Whenever DSTATCOM is in active condition then its weight is one otherwise zero.

Total rated reactive power capacity of DSTACOM units is given by

$$Q_L = M_1Q_1 + M_2Q_2 + M_3Q_3 + M_4Q_4 + \text{--------} + M_nQ_n \tag{4.9}$$

Reference current signal for K$^{\text{th}}$ DSTATCOM unit is given by

$$i_{CK} = i_{Lq} * M_K * Q_K / Q_L \text{ ; (where K=1,2,3,-------,n)} \tag{4.10}$$

Where Q_K is the reactive power rating of K^{th} DSTATCOM unit and i_{Lq} is the total reactive component of load current.

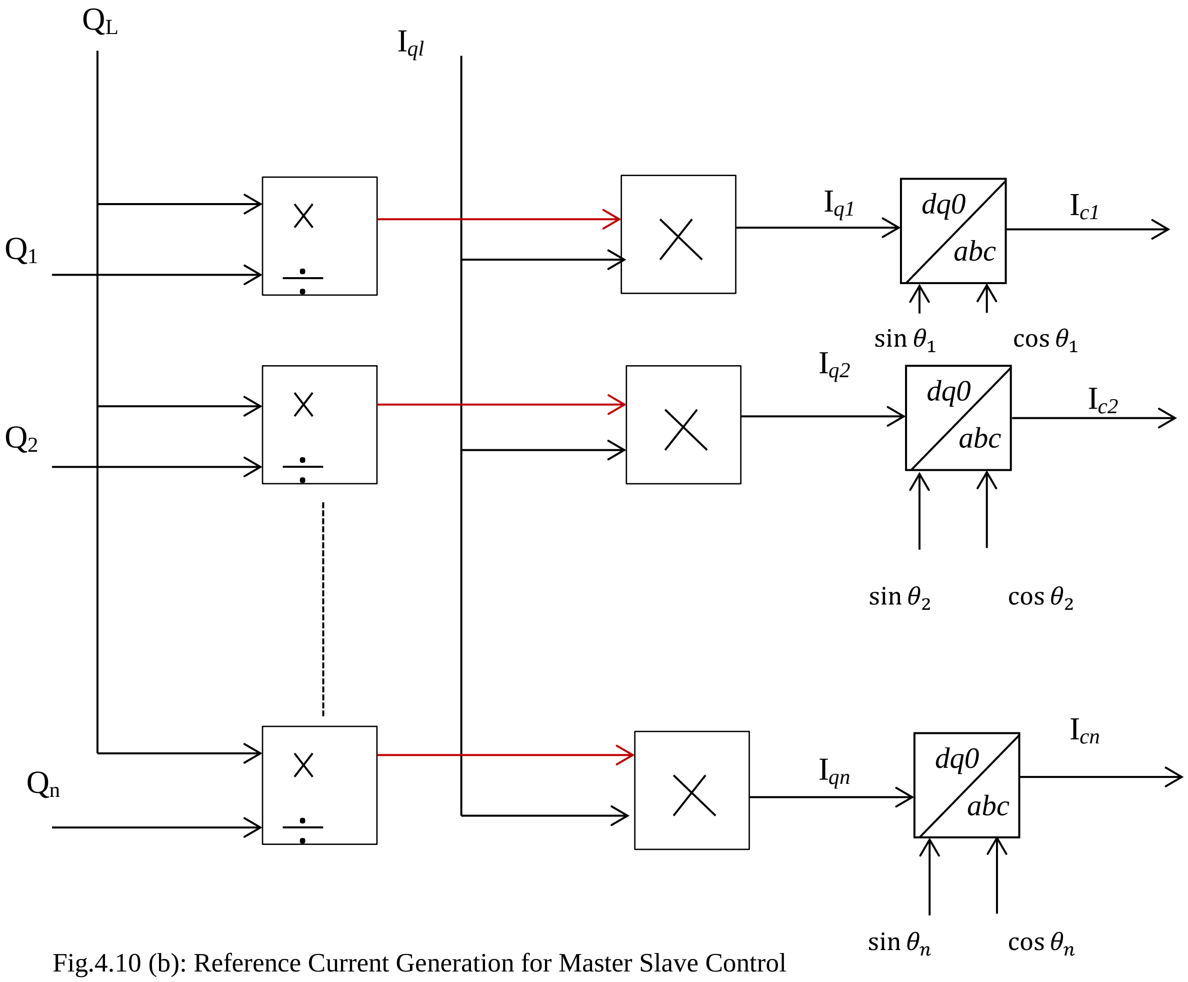

Fig.4.10 (b): Reference Current Generation for Master Slave Control

4.2.1.2 Droop Control:

To understand the concept of Droop Control, first of all it is necessary to have a basic knowledge about power flow transfer through the line under steady state condition. The circuit showed in Figure 4.11(a) represents a power line between two sections of a power system, with power transfer from one section to the other. The power transfer through the power line in the sinusoidal steady state is derived, using the short-line model and complex phasor. The analysis below is valid for both single phase and balanced three phase systems. Referring to Figure 4.11(a), the complex power flowing into the power line at point A is:

$$\overline{S}_A = \overline{P}_A + j\overline{Q}_A = \overline{V}_A \overline{I}^* = \overline{V}_A \left(\frac{\overline{V}_A - \overline{V}_B}{Z} \right)^* \tag{4.11}$$

$$= \overline{V}_A \left(\frac{\overline{V}_A - \overline{V}_B e^{j\delta}}{Z e^{-j\theta}} \right) \tag{4.12}$$

Where δ is denoted the transmission power or load angle, φ in Figure 4.11(b) is the power factor angle at point A. Thus, the active and reactive power flowing into the line at A are:

$$\overline{P}_A = \frac{V_A^2 \cos\theta}{Z} - \frac{V_A V_B \cos(\theta + \delta)}{Z} \tag{4.13}$$

$$\overline{Q}_A = \frac{V_A^2 \sin\theta}{Z} - \frac{V_A V_B \sin(\theta + \delta)}{Z} \tag{4.14}$$

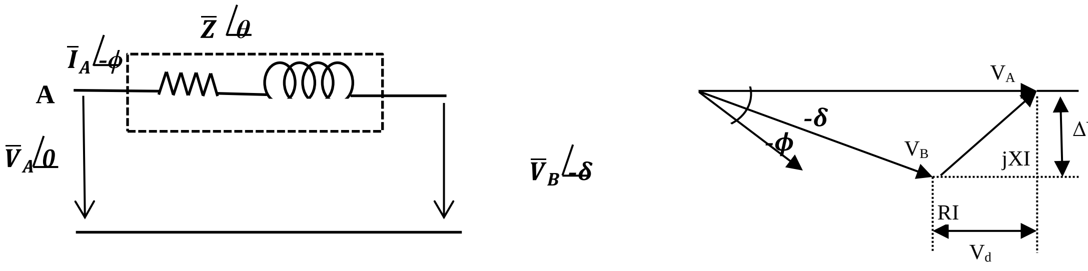

Fig.4.11: (a) Power flow through a line, (b) phasor diagram.

As Z cosθ = R and Z sinθ = X, Equations (4.13) and (4.14) are rewritten as:

$$\overline{P}_A = \frac{V_A^2}{R^2 + X^2}[XV_B \sin\delta + R(V_A - V_B\cos\delta)] \tag{4.15}$$

$$\overline{Q}_A = \frac{V_A^2}{R^2 + X^2}[-RV_B \sin\delta + X(V_A - V_B\cos\delta)] \tag{4.16}$$

Hence,

$$\Delta V_d = (V_A - V_B\cos\delta) = \frac{RP_A + XQ_A}{V_A} \tag{4.17}$$

$$\Delta V_q = (V_B\sin\delta) = \frac{XP_A - RQ_A}{V_A} \tag{4.18}$$

For overhead lines *X* >> *R*, which means that *R* may be neglected. If also the power angle δ is small, then sin δ ≅ δ and cos δ ≅ 1. Equations (4.17) and (4.18) then

$$(V_A - V_B) \cong \frac{XQ_A}{V_A} \tag{4.19}$$

$$\delta \cong \frac{XP_A}{V_A V_B} \tag{4.20}$$

become:

For *X* >> *R*, a small power angle δ and small voltage difference V_A - V_B, equations (4.19) and (4.20) show that the power angle depends predominantly on the active power *P*, whereas the voltage difference depends predominantly on the reactive power *Q*. In other words, the angle δ can be controlled by regulating the active power *P*, whereas the inverter voltage V_A is controllable through the reactive power *Q*. Control

$$f - f_0 = -k_p(P - P_0) \tag{4.21}$$

$$v - v_0 = -k_q(Q - Q_0) \tag{4.22}$$

of the frequency dynamically controls the power angle and, thus, the real power flow. Thus, by adjusting *P* and *Q* independently, frequency and amplitude of the grid voltage are determined. These conclusions are drawn form the basis for the well-known frequency and voltage droop control through respectively active and reactive power:

f_0 and V_0 are rated frequency and grid voltage respectively, while P_0 and Q_0 are the (momentary) set points for active and reactive inverter power. The frequency and voltage droop control characteristics as a function of active and reactive power are shown graphically in Figure 4.11. On the other hand, low voltage cable grids generally have a mainly resistive nature, and the resistance R cannot longer be neglected. On the contrary, often X may be neglected instead of R. In that case, from equations (4.17) and (4.18) it can be seen that adjusting the active power P influences the voltage amplitude, while adjusting the reactive power Q influences the frequency. The relationships have changed in such a radical way that the droop regulation described by (4.21) and (4.22) is no longer effective.

In the general case, both X and R has to be considered. Then, using of an orthogonal linear rotational transformation matrix T from active and reactive power P and Q to the modified active and reactive power P' and Q' is reported [37-42, 48-65].

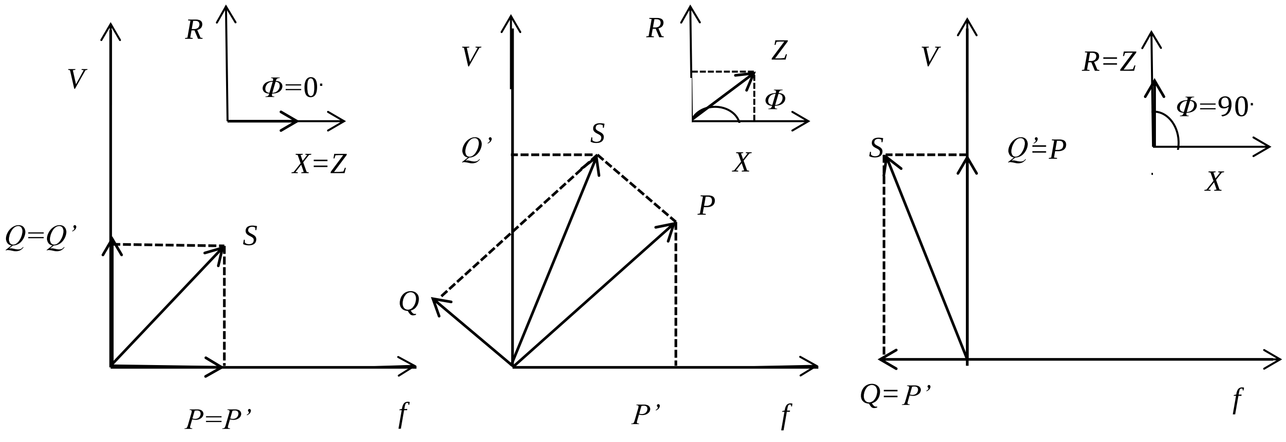

Fig. 4.12: Influence of active and reactive power on voltage and frequency for different line impedance ratios: (a) R/X=0, (b) R/X=1, (c) R/X=∞.

$$\begin{bmatrix} P' \\ Q' \end{bmatrix} = T \begin{bmatrix} \cos\emptyset & -\sin\emptyset \\ \sin\emptyset & \cos\emptyset \end{bmatrix} \begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} \frac{X}{Z} & \frac{-R}{Z} \\ \frac{R}{Z} & \frac{X}{Z} \end{bmatrix} \begin{bmatrix} P \\ Q \end{bmatrix} \tag{4.23}$$

$$\sin\delta \cong \frac{ZP'_A}{V_A V_B} \tag{4.24}$$

$$V_A - V_B\cos\delta \cong \frac{ZQ_A}{V_A} \tag{4.25}$$

With ϕ = π /2 - θ = atan(R/X). Applying this transformation to (4.24) and (4.25) results in:

For a small power angle δ and voltage difference V_A-V_B, (4.24) and (4.25) show that the power angle depends only on *P'*, whereas the voltage difference depends only on *Q'*. In other words, the angle δ can be controlled by *P*', whereas the inverter voltage V_1 is controllable through *Q*'. As the grid frequency is influenced through the angle δ, the definition of *P'* and *Q'* permits to independently influence grid frequency and amplitude. This is illustrated graphically in Figure 4.13. The effect of *P'*, *Q'*, *P* and *Q* on voltage and frequency is illustrated for different ratios of *R/X*. To derive *P*' and *Q*', it suffices to know the ratio *R*/*X*. Knowledge of the absolute values of the line impedance is not needed.

From Fig. 4.12, it can be seen that for mainly inductive lines *P*' ≅ *P* and *Q*' ≅ *Q*, whereas for mainly resistive lines *P*' ≅ -*Q* and *Q*' ≅ *P*. Hence, the optimal frequency and voltage droop regulation becomes:

$$f - f_0 = -k_p(P' - P'_0) = -k_p\frac{X}{Z}(P - P_0) + k_p\frac{R}{Z}(Q' - Q'_0) \tag{4.26}$$

$$v - v_0 = -k_q(Q' - Q'_0) = -k_q\frac{R}{Z}(P - P_0) - k_q\frac{X}{Z}(Q' - Q'_0) \tag{4.27}$$

4.4.2 Autonomous control for voltage regulation:

Voltage regulation of long weak distribution lines is a challenging problem, particularly when it is not cost-effective to upgrade the entire feeder system. Power electronic converter systems offer an attractive alternative, with their potential to provide both steady state and transient voltage compensation for a limited capital investment. However, operation of these systems with weak networks and/or with multiple distributed installations needs careful attention to avoid unexpected interactions and to achieve optimum regulation performance. DSTATCOM are controlled to achieve stable steady state by providing requisite compensation dynamically to improve the voltage profile along a radial distribution network under widely varying load conditions. The autonomous control, in of each unit cooperates to compensate voltage drop of the line occurring due to ahead line impedance, by supplying reactive power. In this scheme each unit injects reactive component of current of the point of common coupling in such manner that it compensate the voltage drop of the preceding section of line and a leading current flows throughout the line. The reference signal is generated by comparing the rated voltage with sensed voltage at point of common coupling (PCC). Figure 4.13 shows the control scheme for generation of reference signal. In this scheme for each unit only the information of PCC is provided and then exist no communication between the units. The control is automatic and the voltage of PCC under widely varying load conditions. This method avoids the communication mismatch of reference current so there is no possibility of flow of circulating current between the DSTATCOM units. This scheme provides high system reliability due to massive redundancy; single unit failure has negligible impact on system performance. Due to autonomous character it is suited for long distribution lines.

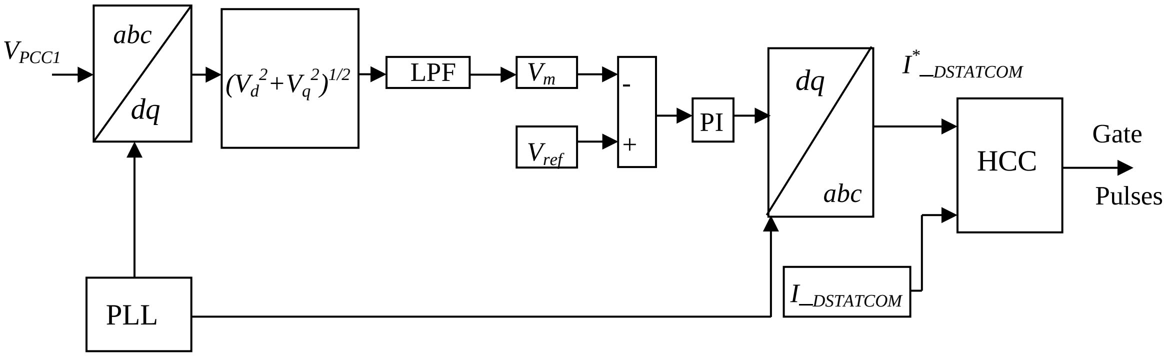

Fig.4.13: Autonomous control for voltage regulation

This control strategy has fast response under widely varying loading condition as compare to conventional control strategy for voltage regulation of radial distribution system.

4.5 Conclusion:

From the above discussion it is concluded that proposed current controlled autonomous control voltage regulation of line may offer better alternating and faster response than distributed and Droop control strategies for voltage regulation, whereas, Droop control is preferable over centralized control for reactive and active power compensation of load, because of avoidable of the communication mismatching and less requirement of sensors. It only requires local information of point of common coupling.

CHAPTER-5

MATLAB SIMULATION MODEL AND PERFOMANCE EVALUATION

5.1 General:

Previous Chapter IV has dealt with the VSC modelling, equations and control strategies for its operation. This chapter is divided in two sections. The first section deals with the performance and evaluation of proposed autonomous voltage regulation with and without distributed compensation technique for reactive power sharing of load. In the second section decentralised control of DSTATCOM for reactive power sharing is described. The simulated results in MATLAB environment are presented to validate the effectiveness of the proposed control scheme.

5.2Performance evaluation of proposed System with autonomous control of DSTATCOMs for voltage regulation:

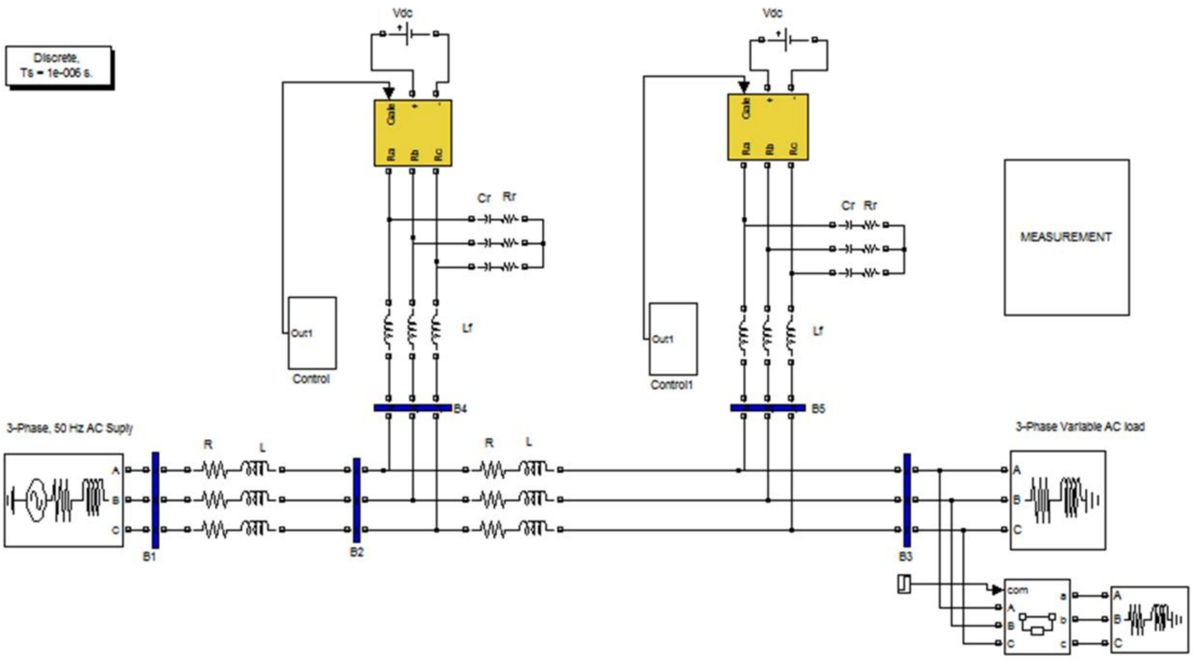

Fig. 5.1: Simulink model of the considered system

The Grid, DSTATCOMs with input side LC filter, control unit, distributed line impedance respected as RL line impedance and three phase RL load are modelled in MATLAB using Power System Block set. Figure 5.1 depicts the setup used to study the performance of the distributed compensation of radial system for voltage regulation in grid connected mode with proposed autonomous current control scheme through simulation. The grid block depicting grid consists of three-phase voltage source acting as “infinite bus” supplying the power to the load with proposed scheme under specified conditions is assumed. The considered load to evaluate the effectiveness of the proposed scheme is evaluated with widely variable star connected 215 KVA RL load at 0.8 pf lagging depicted in Fig.5.1. Out of this load 107.5 KVA load is considered critical, which is required to be supported all the times. The simulated results are studied to evaluate the performance of DSTATCOMs under grid connected modes for voltage regulation. Table 5.1 depicts parameters of the considered system.

TABLE 5.1. PARAMETERS OF THE CONSIDERED SYSTEM FOR AUTONOMOUS CURRENT CONTROL OF DSTATCOMs

Source Impedance	$R_S = 0.1\Omega$, $L_s = 0.5$ mH
Load Rating	107.5KVA to 215 KVA at 0.8 lag pf
Line Impedance	$R_L = 0.0632\Omega$, $L_L = 0.6038$ mH
LC Filter Parameters	C = 1 μF, R = 10 Ω& L= 0.8 mH
Switching Frequency	10 KHz
Cut off Frequency	5.626 KHz
Mains Voltage Per Phase (rms)	239.6 Volt
$DSTATCOM_1$ rating	17.97 KVAr to 45 KVAr
$DSTATCOM_2$ rating	60 KVAr
DC Voltage at Each DSTATCOM	700 Volt

The results in Fig. 5.2(a) clearly describes that the proposed scheme is able to boost up the voltage profile of line. Initially a load of 107.819 KVA is in under operation from $t = 0.0$ *sec* to $t = 0.16$ *sec* , representing a balanced loading condition. Voltage magnitude at PCC_1 and PCC_2 during $t = 0.0$ *sec* to $t = 0.16$ *sec* is lesser than the source voltage due to line impedance. At $t = 0.16$ *sec* when $DSTATCOM_1$ and $DSTATCOM_2$ are switched in the scheme, increase in voltage of PCC_1 and PCC_2 has been observed. At $t = 0.16$ *sec* each *DSTATCOM* is injecting reactive component of current to overcome the voltage drop of preceding section of line. From Fig. 5.2(a) it is observed that injected current is exact in quadrature with the voltage of point of common coupling. Leading current flows through the line to avoid zero regulation.

From t = 0.16 *sec* to t = 0.3 *sec* $DSTATCOM_1$ injects 25*A* to compensate the voltage drop of its preceding section and 85*A* is supplied by $DSTATCOM_2$,for which the saturated limit is kept equivalent to compensating the voltage drop of its preceding section and a part of reactive demand of load. From Fig. 5.2(a) it may be observed that, the transients due to disturbances like load perturbations is taken care by the $DSTATCOM_1$. At $t = 0.3$ *sec* , a load of same rating is suddenly switched in the circuit, To maintain the status quo for voltage profile throughout the line $DSTATCOM_1$ increases the amount of compensation from 25 *A* to 63.63 *A*.

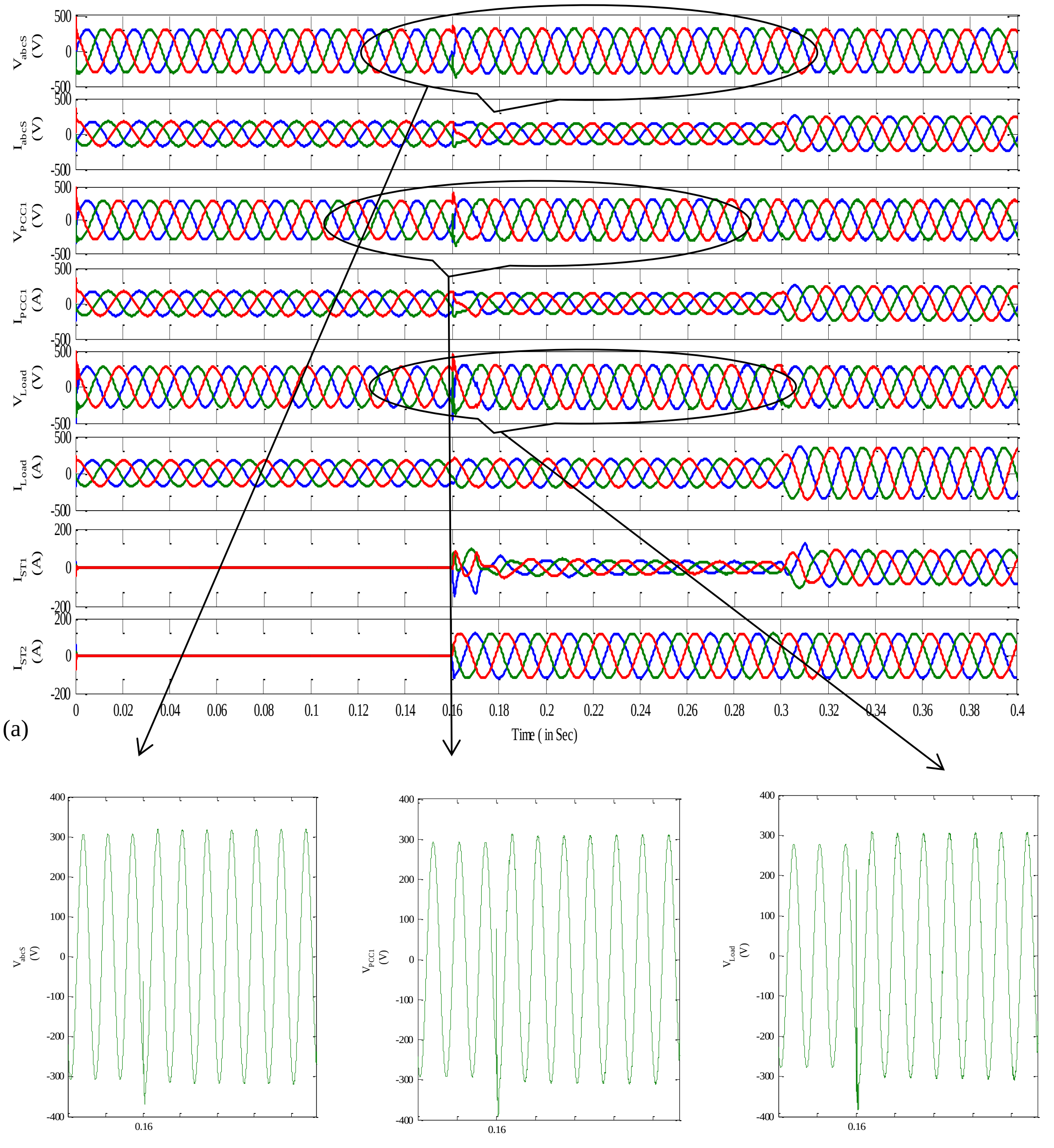

Fig. 5.2: (a) Current and Voltage waveforms of Distributed Compensation under Grid connected mode in Autonomous Current Control of DSTATCOMs. (b) Zoomed of voltage waveforms.

5.3 Performance evaluation of proposed system using autonomous control with distributed compensation for voltage regulation and reactive power sharing of load:

The simulated results are studied to evaluate the performance of *DSTATCOMs* under grid connected modes for voltage regulation and reactive power sharing of load. The control unit for reference current generation combined the features of both autonomous voltage control and distributed control, which is shown in figure 5.3.

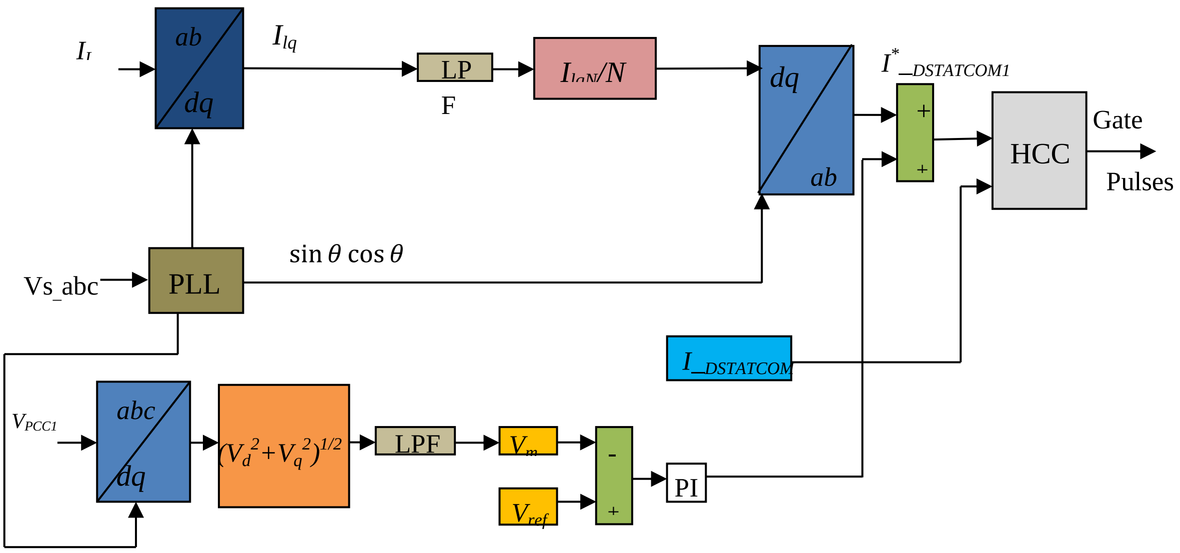

Fig. 5.3: Reference current generation in combined structure of Autonomous control and Distributed control.

Table 5.2 depicting parameters of the considered system.

TABLE 5.2: PARAMETERS OF THE CONSIDERED SYSTEM FOR AUTONOMOUS CURRENT CONTROLWITH DISTRIBUTED CONTROL OF DSTATCOMs

Source Impedance	$R_S = 0.1\Omega$, $L_s = 0.5$ mH
Load Rating	107.5KVA to 215 KVA at 0.8 lag pf
Line Impedance	$R_L = 0.0632\Omega$, $L_L = 0.6038$ mH
LC Filter Parameters	C = 1 µF, R = 10 Ω& L= 0.8 mH
Switching Frequency	10 KHz
Cut off Frequency	5.626 KHz
Mains Voltage Per Phase (rms)	239.6 Volt
$DSTATCOM_1$ rating	33 KVAr to 73.7 KVAr
$DSTATCOM_2$ rating	40KVA rto 90 KVAr
DC Voltage at Each DSTATCOM	700 Volt

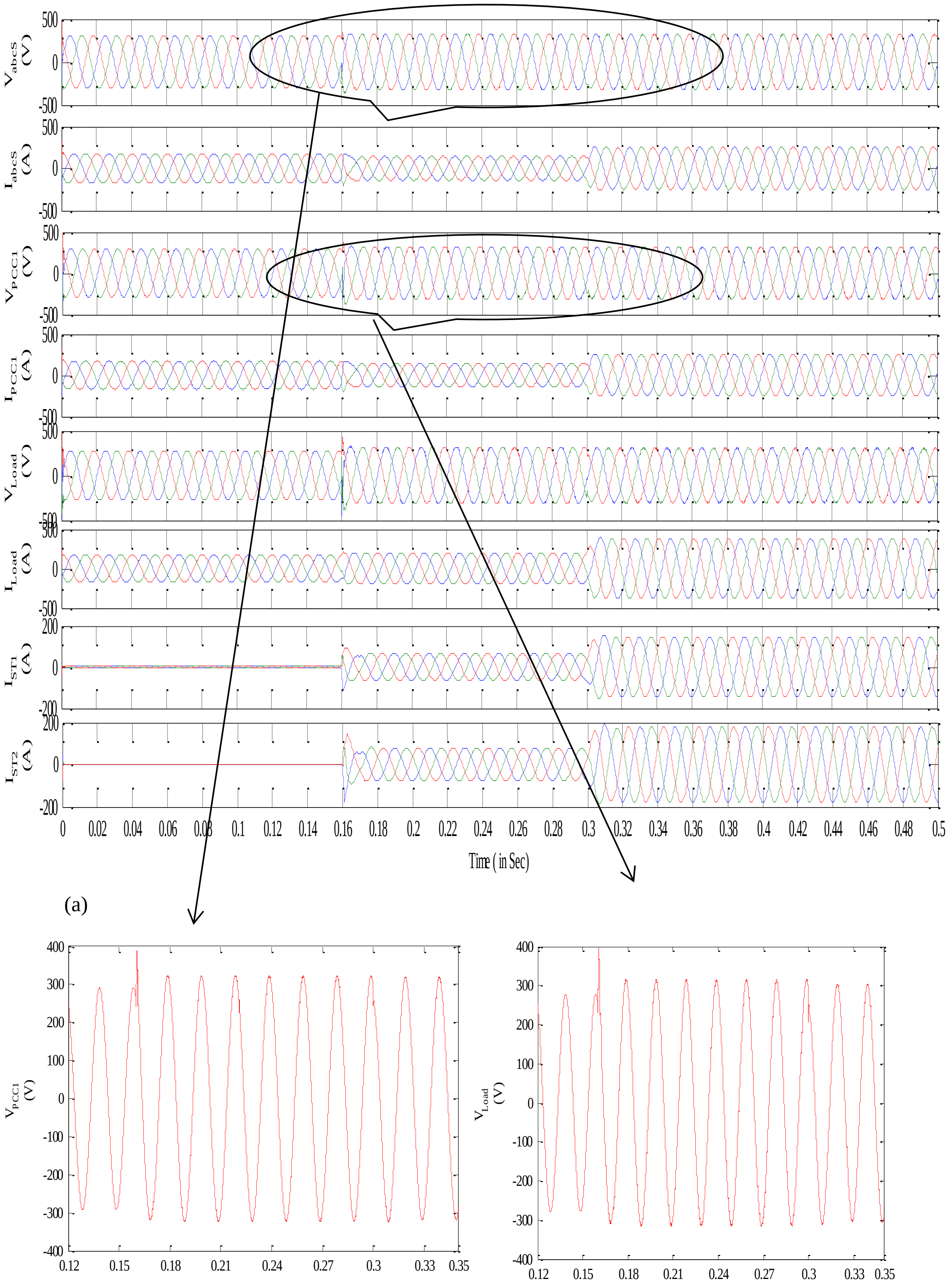

Fig. 5.4 (a) Current and Voltage waveforms of distributed compensation under grid connected mode of DSTATCOMs using Autonomous current control with distributed technique (b) Zoomed of voltage waveforms.

Initially a load of 107.819 KVA is in under operation from t = 0.0 *sec* to t = 0.16 *sec*, representing a balanced loading condition. At t = 0.16 *sec* when $DSTATCOM_1$ and $DSTATCOM_2$ are switched in the scheme, increase in voltage of PCC_1 and PCC_2 has been observed. At t = *0.16 sec* each *DSTATCOM* is injecting reactive component of current to overcome the voltage drop of preceding section of line with a half amount of reactive component of load. From Fig. 5.4(a) it is observed that injected current is exact in quadrature with the voltage of point of common coupling. It is also observed that an amount of source current is decreases and it flows in the same phase of the source.

From Fig. 5.5 it may be observed that, the transients due to disturbances like load perturbations is taken care by the $DSTATCOM_1$and $DSTATCOM_2$. At t = *0.3 sec* , a load of same rating is suddenly switched in the circuit, and to maintain same voltage profile at unity power factor both units increase the amount of compensation from 33 KVAr to 73.7 KVAr and 40 KVAr to 90 KVAr respectively.

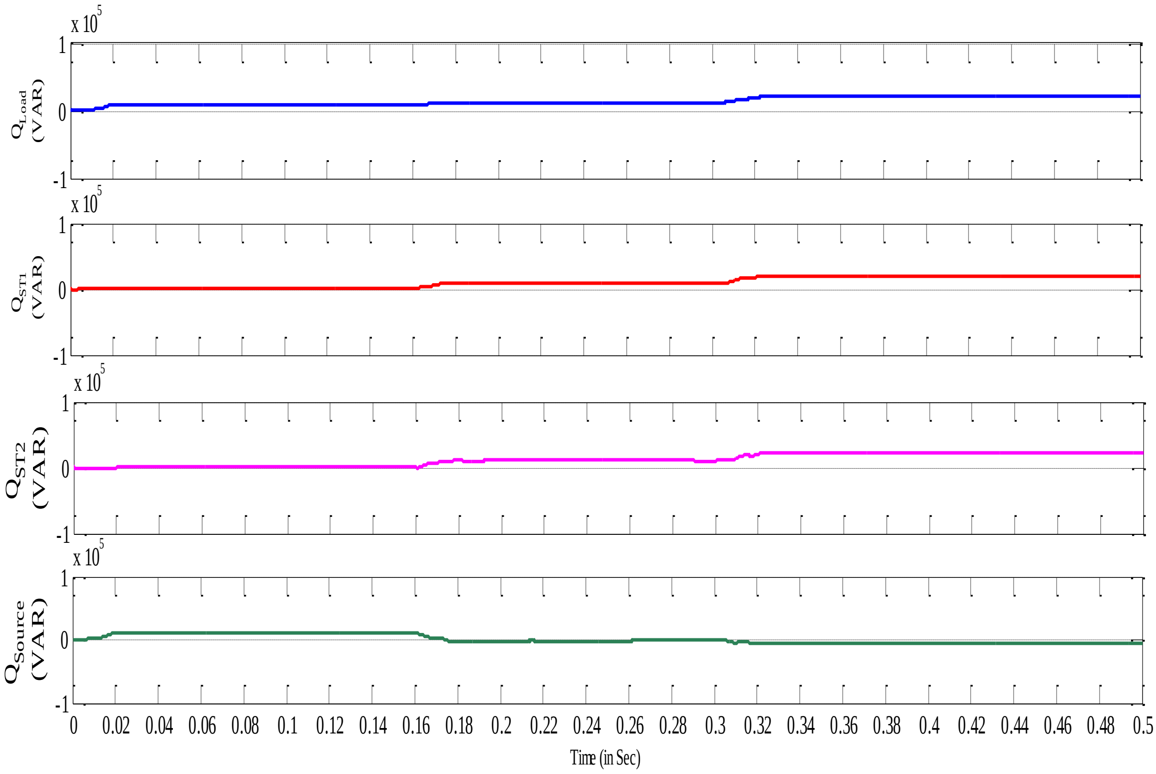

Fig. 5.5: Reactive Power waveforms of proposed scheme using Autonomous current control with Distributed control techniques.

5.4 Performance evaluation of proposed system using Decentralized control for reactive power sharing of load:

Figure 5.7 evaluate the performance of DSTATCOMs using Droop control under grid connected modes for reactive power sharing of load. The control unit for reference current generation is shown in fig.5.6.

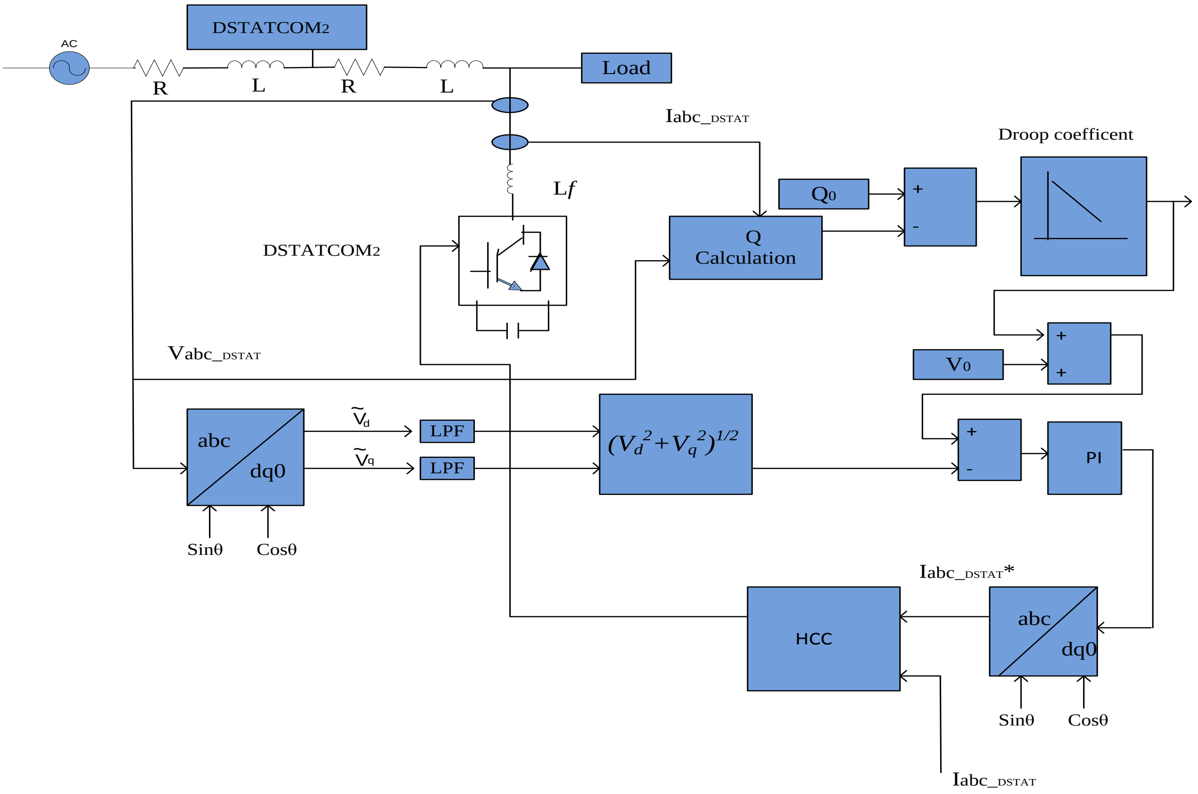

Fig. 5.6: Reference current generation for Droop control.

Table5.3 depicts the parameters of the considered system.

TABLE 5.3: PARAMETERS OF THE CONSIDERED SYSTEM FOR DROOP CONTROL OF DSTATCOMs

Source Impedance	$R_S = 0.1\Omega$, $L_s = 0.5$ mH
Load Rating	107.5KVA to 215 KVA at 0.8 lag pf
Line Impedance	$R_L = 0.0632\Omega$, $L_L = 0.6038$ mH
LC Filter Parameters	C = 1 μF, R = 10 Ω& L= 0.8 mH
Switching Frequency	10 KHz
Cut off Frequency	5.626 KHz
Mains Voltage Per Phase (rms)	239.6 Volt
$DSTATCOM_1$ rating	25.68 KVAr to 45.83KVAr
$DSTATCOM_2$ rating	30.49 KVAr to 51.56 KVAr
DC Voltage at Each DSTATCOM	700 Volt

The results in Fig.5.7 clearly describes that the proposed scheme is able to boost up the voltage profile of line by sharing the reactive power with the load. Initially a load of 41.56 KW and 55.42 KVAr is in under operation from t = 0.0 *sec* to t = 0.08 *sec*, representing a balanced loading condition. Voltage magnitude at *PCC1&PCC2* during t = 0.0 *sec* to t = 0.08 *sec* is lesser than the source voltage due to line impedance and total power of load is supplied by source only. At t = 0.08 *sec* when $DSTATCOM_1$ and $DSTATCOM_2$ are switched in the scheme, increase in voltage of PCC_1 and PCC_2 has been observed. From the Fig. 5.8 it is seen that as load terminal voltage increases; an amount of reactive power is also increased because it is directly proportional to the square of voltage. Figure 5.9 shows that source only supplies the total demand of active power of load and thus unity power factor is maintained on the line. As at t = *0.08 sec* each *DSTATCOM*s are injecting reactive component of current to compensate reactive power demand (55.42KVAr) of load; a decrease in source current is observed. From Figure 5.7 it is also observed that during this time interval injected current is in exact in quadrature with the voltage of point of common coupling and source current is in same phase of source voltage. At this stage the currents injected byDSTATCOM$_1$ and DSTATCOM$_2$ is 37.13 *A* and 40.56 *A* respectively. From Fig 5.7 it may be observed that, the transients due to disturbances like load variations is taken care by the DSTATCOM$_1$and DSTATCOM$_2$. At t = *0.3 sec*, a load of 107.5 KVA is suddenly switched in the circuit, and to compensate reactive demand of it both units increase the amount of compensation from 25.68 KVAr to 45.83 KVAr and 30.49 KVAr to 51.16 KVAr respectively.

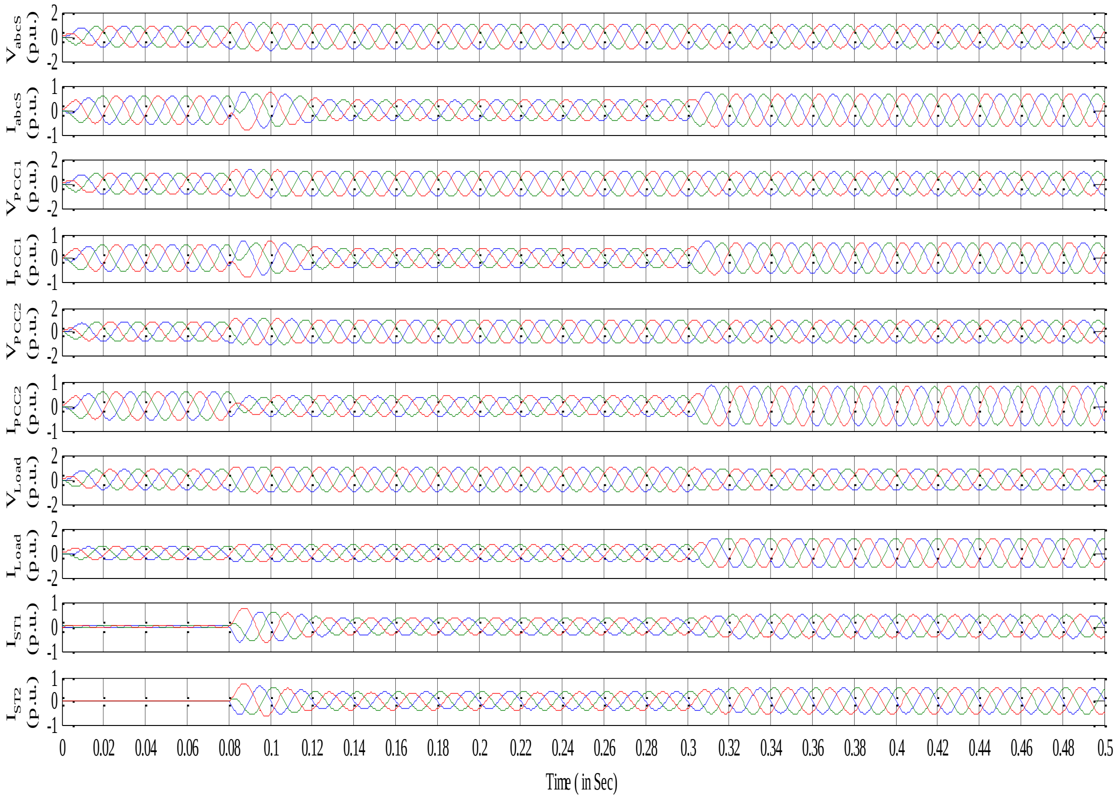

Fig. 5.7: Voltage and current waveforms for proposed scheme using Droop Control

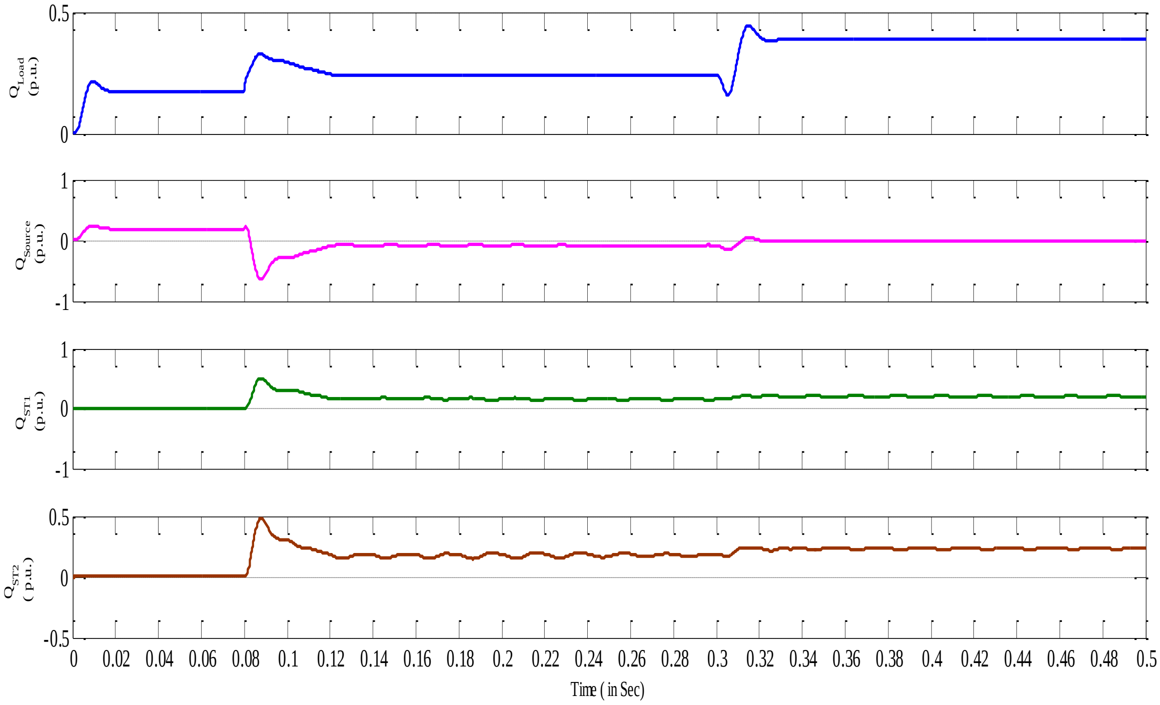

Fig. 5.8: Reactive Power waveforms of proposed scheme using Droop control.

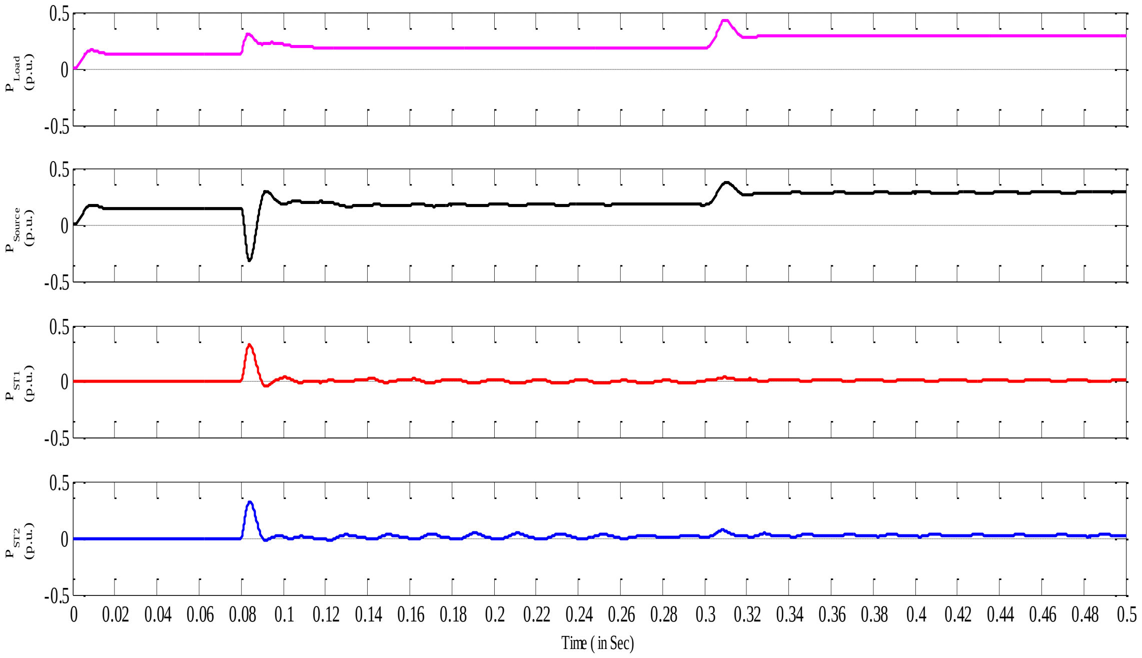

Fig. 5.9: Active Power waveforms of proposed scheme using Droop control.

5.5 Conclusion:

The result clearly demonstrate in this chapter the effectiveness of proposed control technique to be fast, flexible and efficient for control of DSTATCOMs for voltage regulation and compensation of reactive power. This is concluded that autonomous current control is best suited for voltage regulation in radial system, because it has fast response with system dynamics. It is more advantageous when it is combined with the distributed control for reactive power compensation of load. It is evident from results that the control is effective even under varying load condition.

CHAPTER-6

MAIN CONCLUSION AND FUTURE SCOPE OF THE WORK

6.1 General:

Inclusion of parallel operation of VSC in the grid for compensation is a popular research area and is the requirement of future need. A current controlled technique is more efficient and faster than voltage control for case of interfacing with ac grid. The flexibility provided by the said control include fast response with system dynamics, fast absorption of transients, auto protection of DSTATCOMs due to current limiting feature. The present chapter summaries the investigations carried out and accordingly main conclusion are derived and suggestions for further work are also presented.

6.2 Main Conclusion:

The MATLAB / Simulink environment using SimPower systems block set has been used to develop the model and carrying out simulation work. A distributive approach has been presented for compensation in grid connected mode and all DSTATCOMs acting as current controlled sources. The current controlled DSTATCOMs for compensation offer several advantages over voltage controlled DSTATCOMs. The study conducted and reported in the thesis clearly demonstrate the advantages of fast, flexible and efficient control of DSTATCOMs for voltage regulation and load compensation over the reported control of parallel operated voltage source converter. Three control strategies have been proposed in this thesis for distributed compensation. One of them is based on autonomous current control, which only requires the information of point of common coupling for control parameters, and the same is used for the voltage regulation. In the second control strategy autonomous current control is combined with distributed control strategy for voltage regulation and load sharing. Decentralized control of DSTATCOMs is demonstrated for reactive power compensation of load using the described in third developed control technique. The effectiveness of proposed schemes have been discussed, and validated through simulation results. These schemes enables the DSTATCOMs to share the loads based on their capacity and handles the transients effectively so that the same is not reflected in the mains.

The presented results reveal that autonomous control is best suited for voltage regulation in radial system, because it has fast response with system dynamics and this is more advantageous along with the distributed control for reactive power sharing of load. The scheme utilizes less number of sensors and hence system cost decreases drastically.

It is also observed that low rating VSCs are used to maintain constant voltage profile at unity power factor and reactive power sharing in distributed compensation and thus overall system cost reduces. The proposed scheme provides smart solution with coordinated control with a variable range of compensation, it also enhance system reliability with variety of compensation. The results demonstrate that all proposed schemes have shown fast response in handling load sharing and transients, besides regulating the voltage of line.

6.3 Future Scope of Work:

The presented control schemes pave the way for variety of additional scope to the presented work. For instance the scheme can be modified to provide distributive compensation of harmonics, negative sequence and unbalancing of load. The inherent quality of the scheme may be utilized in a cost effective way for enhancing the power handling capacity of system.

The concept of distributive compensation with some modification can be augmented with parallel operated DGs to increase system stability. The proposed scheme with some modification can be incorporated with distributed series and distributed series-shunt compensation. Above all hardware implementation on small scale incorporating the storage element and VSCs in proposed configuration with all control schemes may be done.

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