**Arab Academy for Science, Technology and Maritime Transport**

**College of Engineering and Technology**

**Electrical &Control Engineering**

# Dynamic Performance of Dstatcom used for Voltage Regulation in Distribution System

**A thesis submitted to partial fulfilment for the degree of Master of Science**


Presented By:

*Mai Sroor Ibrahim Mohamed*

**Prof. Rania Metwally El-Sharkawy**

Arab Academy for Science and Technology

**Prof. Rizk Mohamed Hamouda**

Faculty of Engineering- Ain Shams University


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**Prof. Rania Metwally El-Sharkawy**

Supervisor

**Prof. Rizk Mohamed Hamouda**

Supervisor

**Prof.Yasser Galal**

Examiner

**Prof.Ibrahim Helal**

Examiner

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# ABSTRACT

The impact of Distributed Static Compensator size and location on the voltage regulation of a distribution system is investigated in this research work. Possibility of coordination between Distributed Static Compensator units at different locations in the system is critical to maximize the benefit from the device and to enhance the system voltage. Distributed Static Compensator model available in Matlab Simulink is adopted for the study. This research work focuses on the applications of Distributed Static Compensator on the distribution facility feeding a combination of dynamic and static loads.. For the purpose of current analysis, the detailed model of the Distributed Static Compensator module is utilized with its different control systems tuned to provide the best dynamic performance of the Distributed Static Compensator, The dynamic behavior of the Distributed Static Compensator due to switching on a large industrial load, line outage and voltage sag are presented.

Possible coordination between different compensators for the purpose of achieving the best system average voltage with minimum reactive compensation is studied. Effect of Distributed Static Compensator size on the system voltage in case of voltage sag will be demonstrated. This study is conducted on the IEEE 14 bus system (69 KV/13.8kv) without any compensation. The results show the effectiveness of using the Distributed Static Compensator on the system voltage regulation during normal operating conditions as well as in cases when the system is subjected to abnormal conditions. System improved performance is depicted.

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# LIST OF ACRONYMS/ABBREVIATIONS

| | |
|---|---|
| FACTS | Flexible AC Transmission System |
| TCSC | Thyristor – Controlled Series Capacitor |
| SSSC | Static Synchronous Series Compensator |
| SVC | Static Var Compensator |
| STATCOM | Static Synchronous Compensator |
| TCR | Thyristor Controlled Reactor |
| TSC | Thyristor Switched Capacitor |
| FIS | Fuzzy Inference System |
| FVSI | Fast Voltage Sensitivity Index |
| TSC | Thyristor Switched Capacitor |
| DSTATCOM | Distributed Static Synchronous Compensator |

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*Chapter One*

# 1 INTRODUCTION

## 1.1 PREFACE

Power systems are often interconnected, forming very large power pools. Operation of such power systems becomes increasingly complicated due to rapid growth of loads without a corresponding increase in transmission capability. The active and reactive power control generally plays a major role in power system.In recent years power systems, worldwide have grown in size and complexity. The interconnections between individual utilities have increased, and many power elements have been required to operate at their maximum limits for long periods of time. Development in the power industry forced electric utilities to make better use of the available transmission facilities of their power systems. This resulted increased power transfer, reduced transmission margins, and diminished voltage stability margin.Recently power system voltage instability has become one of the power utility problems gaining a great attention due to its direct or indirect impact on recent blackout incidents. Power system planning and operation has to deal with a significant degree of uncertainty about time and location [1]. With the increased loading of existing power transmission systems, the problem of voltage stability has become a major concern in power system operation, and also reactive power optimization has gained more importance. Reactive power compensation in power systems has to be comprehensive to maintain all voltages within acceptable limits during both light and heavy load conditions. During light load the system may need a decrease in the voltage by adding a reactor, on the other hand, during heavy load conditions, the system might need capacitive reactive power support. The main objective of an electric power system and its operation is to maintain the system security while respecting certain constraints imposed on the system [2].

## 1.2 UTILIZED POWER SYSTEM TERMINOLGY

### 1.2.1 Power System Adequacy

It is the ability of a power system to supply consumers’ electric power and energy requirements at all times.

### 1.2.2 Power System Reliability

It is the degree to which the performance of an electrical system results in power being delivered to consumers within accepted standards and desired amounts.
A reliable supply of power is maintained for vital electrical loads. This is done by supplying two (or more) sources of power to these loads, providing load shedding of non-vital loads to avoid overloading the remaining generating capacity, and supplying redundant equipment from separate power sources and distribution circuits. The supporting auxiliaries for a piece of equipment shall be supplied from the same source of power as the main piece of equipment.

### 1.2.3 Power System Security

It is the ability of a power system to withstand sudden disturbances [3].

### 1.2.4 Reactive Power Management

Reactive power is used to provide the voltage levels necessary for active power to do useful work and it is essential to move active power through the transmission and distribution system to the customer. Voltages are controlled by predicting and correcting reactive power demand from loads, as shown in “(Figure 1-1)”, balance between reactive power sources and sinks must be maintained to provide adequate voltage level.

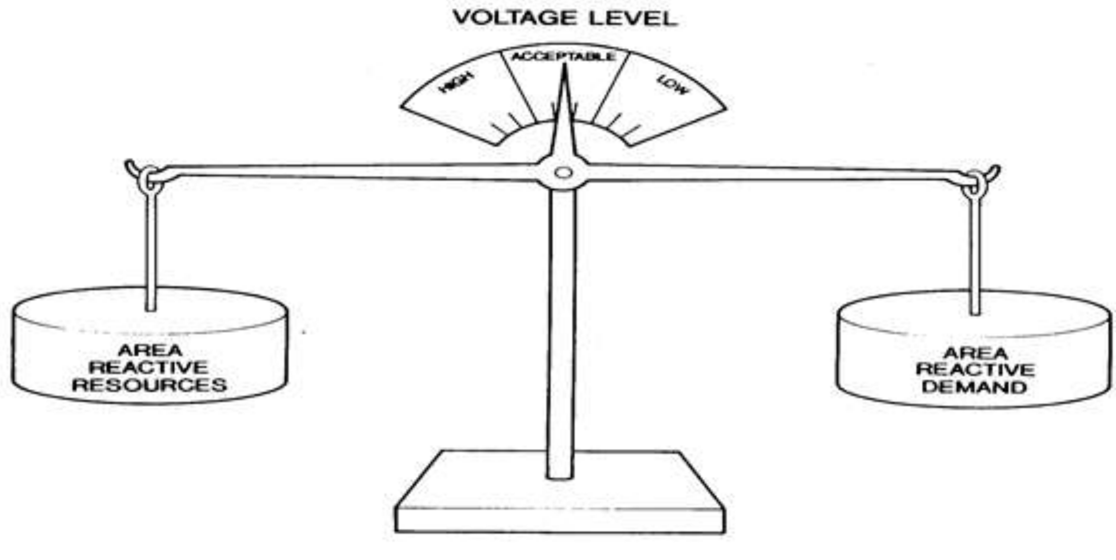



**Figure 1-1:Reactive power management**

### 1.2.5 Power System Stability

It is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with system variables bounded so that system integrity is preserved

## 1.3 THESIS MOTIVATION

Due to the extensive use of highly sensitive electronic equipment, improved power quality is of great importance for many segments of modern industry. Consumer expectations regarding environment and the availability of reliable electric power supply has increased tremendously in the recent years. This has given a thrust to the development of new equipment that can help in mitigating the power quality problems. Custom power devices are increasingly being adopted for the purpose of improving power quality and reliability [4-5]. Thyristor based systems were initially proposed for reactive power compensation and used for reduction of voltage flicker due to arc furnace loads [6]. However, due to several disadvantages of passive devices such as large size, fixed compensation value and possibility of resonance etc., special attention has been given to the equipment based on the voltage-source converter (VSC) technology.

The use of compensators with improved qualifications such as distribution static synchronous compensator, Dstatcom, has garbed researcher's attention for solving power quality problems. Dstatcom is a compensation device used in a shunt configuration across the mains of the primary distribution system. Dstatcom makes use of a voltage source converter and internally generates capacitive (i.e. leading) as well as inductive (i.e. lagging) reactive power. The use of Dstatcom for solving problems of voltage sags, flickers and swell…etc have been reported in [7]. Instantaneous reactive power compensator using switching devices have been reported [8]. References [9-10] listed multifunctional capabilities of Statcom and presented indirect current control scheme for a Dstatcom [11]. The control system of the Dstatcom is very fast and has the capability to provide adequate reactive power compensation to the distribution system [12-13]. Due to this capability, Dstatcom can be effectively used to regulate voltage drop that occurs during the starting of large loads and/or large induction motors where the required starting current is very high [14].

None of the previous researches has focused on the possibility of coordination between compensator devices to achieve the best adjustment of the system voltage. In the meantime the dynamic behavior of the Dstatcom under different system disturbances has not been fully explored. This research work focuses on the applications of Dstatcom on the distribution facility feeding a combination of dynamic and static loads.. For the purpose of current analysis, the detailed model of the Dstatcom module is utilized with its different control systems tuned to provide the best dynamic performance of the Dstatcom.

Determining the location of Dstatcom in the power system is critical to maximize the benefit from the device. Possible coordination between different compensators for the purpose of achieving the best system average voltage with minimum reactive compensation is studied. Effect of Dstatcom size on the system voltage in case of voltage sag will be demonstrated. Three different techniques are used to determine the weakest bus and the amount of reactive compensation required to enhance the system voltage. Moreover, the dynamic performance of the Dstatcom under different system disturbance is studied and illustrated.

## 1.4 THESIS OUTLINE

In this research work, the use of Dstatcom in a 14-bus IEEE power system was modeled, studied and improved performance based on its utilization demonstrated. The thesis is divided into five chapters:

- Chapter one: It starts with a brief introduction, research motivation and thesis objective.

- Chapter two: is an overview of power system stability including the power stability types and comparing between them, stability study conditions (steady state, transient and dynamic conditions) and also make comparison between them. Also this chapter overviews different types of FACTS devices and explain three methods which are used to identify the best location for any FACTS device .One of those methods is through trial and error, the second one is by using sensitivity analysis; while the third method is by utilizing fuzzy rules. This chapter demonstrates that the weakest line in any power system can be identified by using (Fast Voltage Stability Index).

- Chapter three: This chapter shows system modeling and identification of the weakest bus of IEEE 14 bus system.

- Chapter four: This chapter demonstrated simulation results of adopted system with Dstatcom and the response of this fact device during (fault, line outage and increasing loads ) .

- Chapter five: This chapter demonstrated total consumed reactive power during normal and abnormal conditions when IEEE 14 bus system supported by Dstacom and the possible benefits that can be obtained from co-ordination between more than one compensator in the system also this chapter indicates that one compensator unit located at the weakest bus has the power to regulate the system voltage with minimum amount of reactive power comparing to other buses. More than one unit will not reduce the amount of reactive power required to enhance the average voltage

- Chapter six: Concludes the thesis

*Chapter Two*

# 2 LITERATURE SURVEY AND BACKGROUND.

## 2.1 AN OVERVIEW OF POWER SYSTEM STABILITY

Power system stability may be defined as "Ability of the electrical power system to respond to a disturbance frome normal operating condition so as to returning to a condition where the operation is again normal"[15-16]. Stability is a condition of equilibrium between opposing forces, therefore the instability may occurs when a disturbance cause imbalance between the opposing forces. The power system is a highly nonlinear system that operates in a constantly changing environment; loads, generator outputs, topology, and key operating parameters change continually. During the transient disturbance the stability of system depends on the nature of the disturbance and the initial operating condition. The disturbance may be small or large. Following a transient disturbance, the power system is stable when it will reach a new equilibrium state and the system remain intact. The system will keep at normal state by the actions of automatic controls and possibly human operators. On the other hand, the system is unstable, when will result in a run-away or run-down situation for example, a progressive increase in angular separation of generator rotors, or a progressive decrease in bus voltages. The unstable system condition may be led to cascading outages and a shut-down of a main portion of the power system. Instability of the power system can take different forms and is influenced by a wide range of factors. The power system stability can be classified in to various categories and subcategories as follow show in"(Figure 2-1)" **[**17**]**

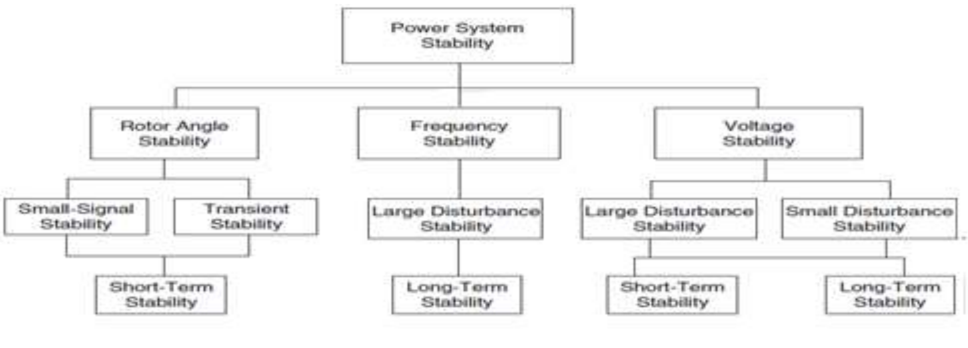



**Figure 2-1: Classification of power system stability.**

### 2.1.1 Voltage Stability

Voltage stability is defined as the "ability of a power system to remain steady voltages at all buses in the system at normal operating conditions, and after being subjected to a disturbance". In other word the power system is voltage stable if the voltages at all buses after disturbance are close to voltages at normal condition before disturbance. While , it may became unstable if outage of equipments such as (generator ,line, transformer, bus bar, etc), overload and/or generation decrement causing weakening of voltage control. Voltage stability is also called load stability.The main factor causing voltage instability is the inability of the power system to meet the demands reactive power in the heavily loaded systems to keep desired voltages [18-19-20]. The voltage stability is classified into two categories:

- Small disturbance voltage stability: It is concerned with a system's ability to control voltages after small disturbances such as incremental changes in load. Its analysis is done in steady state condition.

- Large disturbance voltage stability: It is ability of the system to control voltages following large disturbance such as system faults, loss of generation, or circuit contingencies [17-19].

.

## 2.2 STABILITY STUDY CONDITIONS

The studies of stability usually classified in to three types depend on the nature and order of magnitude of the disturbance [15-16]; such as:

### 2.2.1 Steady State Stability

It is defined as ability of the power system to maintain synchronsim between the machines of the system and external tie lines following a small slow disturbance such as (normal load fluctuations , the action of automatic voltage regulators and turbine governors). Steady state limit is the maximum flow of power through transmission lines without loss the stability during normal power increasing ( gradually power increasing). Steady state stability and steady state stability limit are used interchangeably. The power transferred between the alternator and the motor is expressed as follow, when neglected the losses:

$$PG = PM = \frac{V_G * V_m}{X} \sin(\delta) \tag{2.1}$$

The maximum power will be transferred when δ = 90°.

$$P\max = \frac{V_G * V_m}{X} \tag{2.2}$$

Where:

VG is the generator voltage terminal.

VM is the motor voltage terminal.

x is the reactance connected between the generator and motor.

δ is load angle.

### 2.2.1.1 Steady State Stability Improvement

From equation (2.2) above the maximum power transfer which flow from generator to the load (motor) is proportional directly with product of internal voltage of two machines and proportional inversely to the line reactance (x). Therefore to improve the stability limit by increasing the maximum power transfer via :

- Increasing the excitation of a generator or motor or both to increase the internal emfs and load angle δ will decrease.
- Reducing the transfer reactance by connected more lines in parallel.

## 2.2.2 Transient Stability

It is defined the ability of the power system to remain stable during the period following major diturbance such as (transmission system fault, sudden load change , loss of generating or line switching). The transient stability studies usually carried out during short time period may be equal to one swing. Transient stability limit referred to the ability of the alternator to meet the demand of the loads in power system. In order to know the system is stable or not, at the power systems have rotating synchronous machines, usually swing equation is used.

Let anguler displacement = $\Theta$ radians

Angular velocity (w) = $\frac{d\Theta}{dt}$ radians / second.

Angulare acceleration ($\alpha$) = $\frac{dw}{dt} = \frac{d^2\Theta}{dt^2}$ radians / second$^2$.

Accelerating Power (Pa) = $T_a$.w watts.

Angular momentum (M) = J w J-s$^2$ / radian.

Where:

T is Torque in Nm.

J is moment of inertia in kg-m$^2$ or J-s$^2$ / radian$^2$.

$$P_a = P_m - P_e \tag{2.3}$$

$$P_a = W\ T_a = J\alpha W = M\alpha \tag{2.4}$$

$$\theta = W_m T + \delta_m \tag{2.5}$$

Where:

$w_m$ is the synchronous speed of the machine radian/second.

$\delta_m$ is the angular displacement of rotor in degree.

Differentiating with respect to time (t) to result :

$$\frac{d\theta}{dt} = W_m + \frac{d\delta m}{dt} \tag{2.6}$$

$$\frac{d^2\theta}{dt^2} = \alpha = \frac{d^2\delta m}{dt^2} \tag{2.7}$$

substituting equation (2.7) into equation (2.4)

$$M\frac{d^2\delta_m}{dt^2} = P_a = P_m - P_e \tag{2.8}$$

substituting equation (2.1) into equation (2.8) to give swing equation below.

$$M\frac{d^2\delta_m}{dt^2} = P_a = P_m - P_{\max}\sin(\delta) \tag{2.9}$$

Where:

Pa: accelerating power.

Pe: electrical power .

Pm: input mechanical power supplied by prim mover.

$$Jw = M \tag{2.10}$$

From equation (2.10) above M is not constant due to the swing make variation in (w). In practice assum w = wn where wn is the normal angular velocity of the machine. Therefore M will consider constant value and call ineritia constant.

#### 2.2.2.1 Transient Stability Improvement

From swing equation there are two factors effected to the transient stability: The first is the angular swing of the machine during and following the fault conditions. The second is the critical clearing time.

The methods which utilized  to improve the system stability are:

- Increasing system voltage: Transient stability is improved by raising the voltage at generation and load terminals. When the voltage is increased that mean the higher value of maximum power will transfer through lines of system.

- Reduction in transfer reactance: When reducing the transfer reactance will also increasing the maximum power transfer, therefore the stability also improve. The line reactance can be reduced via connected more lines in parallel.

- High speed circuit breaker and automatic reclosing: To improve the transient stability and reducing the effect of the fault must be using high speed circuit breaker to remove the fault at shortest time.

- Turbine fast valving.

- Application of braking resistors.

- Single pole switching.

- Quick acting automatic voltage regulators.

### 2.2.3 Dynamic Stability:

It is the ability of the power system to remain in synchronism after the initial swing (transient stability period) until the system has stable to the new steady state equilibrium condition. The distinction made between the steady state and dynamic stability is not clearly because of the stability problems in both the cases are similar, therefore the two are generally covered under one study. The difference between them only in the degree of details for modeling of the machines. In dynamic stability analysis, the excitation systems and the turbine control systems are represented along with the models of the synchronous machines, but the steady state problems use very simple generator model which treats the generator as a constant voltage source. The probability of dynamic instability is much higher than steady state instability because of the small disturbances are continually occurring on the power system like small variations, change in turbine speeds ....etc are not big enough to make the system out of the synchronism [17-21].

## 2.3 COMPARISON BETWEEN THE STABILITY STUDY CONDITIONS.

"Table2-1" below demonstrate the important differences between the steady state and dynamic stability and transient stability [21]:

**Table 2-1: Diffrenences between steady state and dynamic stability.**

| Transient stability. | Steady state stability and Dynamic stability. |
|---|---|
| • It is resulting from large sudden disturbances such as (transmission system fault, sudden load change , loss of generation, etc). | • It is resulting from small slow disturbances such as small changes in load . |
| • Take very short time period that will be equal to time of one swing ( one second or less). | • Lager than period time of transient stability. |
| • Do not allow the linear analysis to be used but using nonlinear algebric or differential equation (such as swing equation) | • Linear mode can be used for analysis. |
| • Transient stability studies is very important in power system to ensure the stability of the system during the contingency conditions. | • Dynamic and steady state stability studies are less extensive because of these cases are the normal conditions of the system . |
| • Improve by several factors such as increase the system voltage, increas the maximum power transfer capability, reduction in transfer reactance,high speed clearing fault (by using high speed circuit breaker) ….etc | • Improving In steady state by increasing the excitation of generator or motor to increase the maximum power transfer but in Dynamic stability can be improve by using proper rating power system stabilisers. |

## 2.4 FLEXIBLE A.C TRANSMISSION SYSTEM

From ancient time the voltage stability is one of the very important factors in the power system network. Recently with high development and the significant growth of the world the study of voltage stability is more and more important. This growth in the world accompanied by expansion in the electricity networks and increasing demand of electric energy. According to this conditions, the probability of transient, oscillatory and voltage instability will be increased, which are now brought into concerns of many utilities especially in planning and operation. Voltage instability is one of the major reasons which cause voltage collapse in the system. Voltage collapse may lead to a partial or full power interruption in the system. Power system network can be modified to alleviate voltage instability or collapse by adding reactive power sources.

Voltage instability was one of the important reasons for the recent and worst North American power interruption on August 14th, 2003. The voltage collapse may be caused by the voltage instability, and voltage collapse may lead to a partial or full power interruption in the system. The only way to save system from voltage collapse is to reduce reactive power load or add additional reactive power prior to reach to collapse point. Therefore reactive power source equipment inserted in the power system at appropriate location to compensate the reactive power and improve voltage stability of the system such as (shunt capacitors compensation). Recently with the evolution in power electronic devices along with developments in control theory have allowed the design and implementation of structural controllers known as Flexible a.c transmission system (FACTS). These controller devices used in power transmission system have led to many applications of them not only to improve the voltage stability but also to provide operating flexibility to the power system. Although, (FACTS) devices are quite expensive, they are far better than the traditional reactive power compensation, as they provide smooth and fast response to secure power system stability during steady state and transient conditions.

## 2.5 FACT DEVICES

Flexible AC Transmission Systems, called FACTS, got in the recent years a well-known term for higher controllability in power systems by means of power electronic devices. FACTS is defined by the IEEE as" a power electronic based system and other static equipment that provide control of one or more AC transmission system parameters to enhance controllability and increase power transfer capability"[3]. Several FACTS-devices have been introduced for various applications worldwide. The basic applications of FACTS-devices are:

- Power flow control.
- Increase of transmission capability.
- Voltage control.
- Reactive power compensation.
- Improving voltage stability.
- Improving power quality.
- Damping of power oscillations.
- Improving HVDC link performance.

## 2.6 TYPES OF FACT DEVICES

### 2.6.1 Series Compensation:

In series compensation the FACTS are connected in series with the power system. It works as a controllable voltage source. Therefore the basic principle of all series FACTS controllers are that they inject voltage in series with the line. In switched impedance controller, the variable impedance when multiplied with the current flow through the line represents an injected voltage in the line. It can be used to control active power flow (P). Series inductance occurs in long transmission lines and when a large current flow causes a large voltage drop. To compensate, series capacitors are connected [22-23]. The examples of series compensation are:

- Thyristor – Controlled Series Capacitor (TCSC): It is a series capacitor bank is shunted by a thyristor- controlled reactor shown in “(Figure 2-2)”.

- Static Synchronous Series Compensator (SSSC): It is a solid-state synchronous voltage source employing an appropriate dc to ac inverter with Gate Turn-Off thyristor. It can inject sinusoidal voltage through a transformer connected in series with the system show in“(Figure 2-3)” below.The amplitude and phase angle of this voltage is variable and controllable [24].

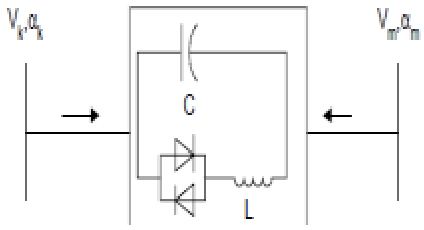



**Figure 2-2:TCSC**

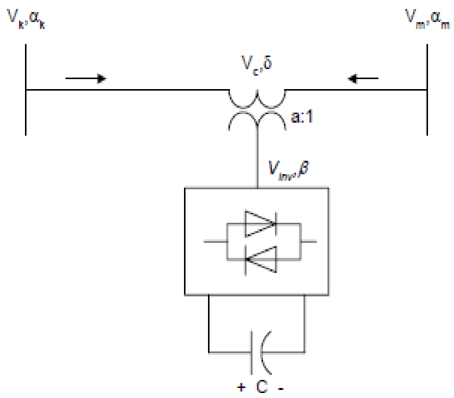



**Figure 2-3:SSSC**

### 2.6.2 Shunt Compensation:

In shunt compensation, FACTS is connected in shunt (parallel) with the power system. It works as a controllable current source. Therefore the basic principle of all shunt FACTS controllers is injecting current into the system at the point of connection. It is used to generate or absorb reactive power (reactive power control ). The most commonly example of shunt compensation are :

- Static Var Compensator (SVC).
- Static Synchronous Compensator (STATCOM). Shows in“(Figure 2-4)” below.

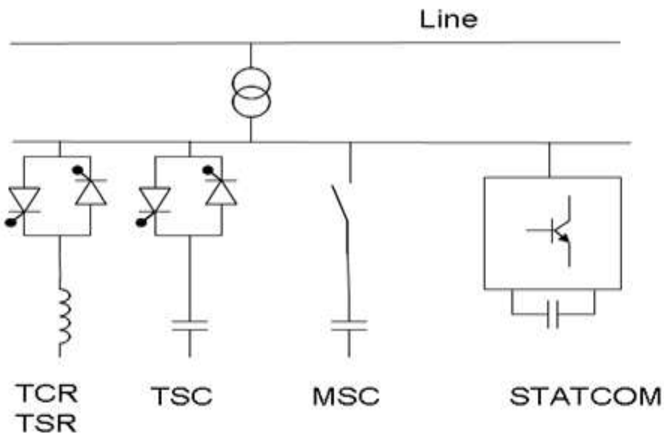


**Figure 2-4: Basic structure of SVC and STATCOM.**

### 2.6.2.1 Static Var Compensator (SVC):

A static Var compensation scheme with any desired control range can be formed by using combinations of the elements described above. "(Figure 2-5)" shows a typical SVC scheme consisting of a TCR, a three-unit TSC, and harmonic filters (for filtering TCR-generated harmonics).At power frequency, the filters are capacitive and produce reactive power of about 10 to 30% of TCR Mvar rating.

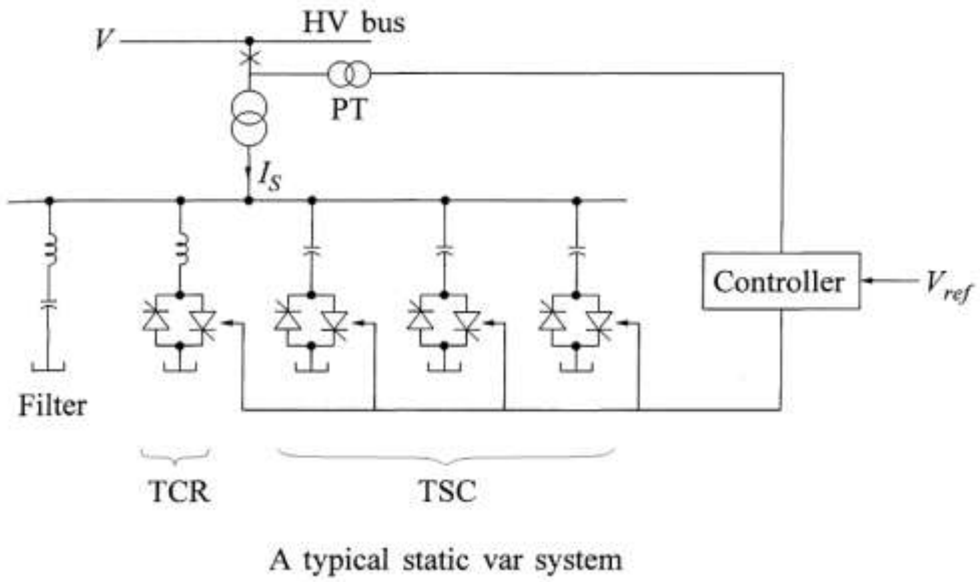


**Figure 2-5:SVC**

In order to ensure a smooth control characteristic, the TCR current rating should be slightly larger than that of one TSC unit. "(Figure 2-6)" shows The steady-state V/I characteristic of the SVC and the corresponding V/Q characteristic respectively. The linear control range lies within the limits determined by the maximum susceptance of the reactor ($B_{LMX}$), the total capacitive susceptance ($B_C$) as determined by the capacitor banks in service and the filter capacitance.If the voltage drops below a certain level (typically 0.3 Pu) for an extended period, control Power and thyristor gating energy can be lost, requiring a shutdown of the SVC.

The SVC can restart as soon as the voltage recovers. However, the voltage may drop to low values for short periods, such as during transient faults, without causing the SVC to trip. The slope reactance $X_{SL}$ has a significant effect on the performance of the SVC.A large value of $X_{SL}$ makes the SVS less responsive, i.e., changes in system conditions cause large voltage variations at the SVC high voltage bus. The value of $X_{SL}$ is determined by the steady-state gain of the controller (Voltage regulator).

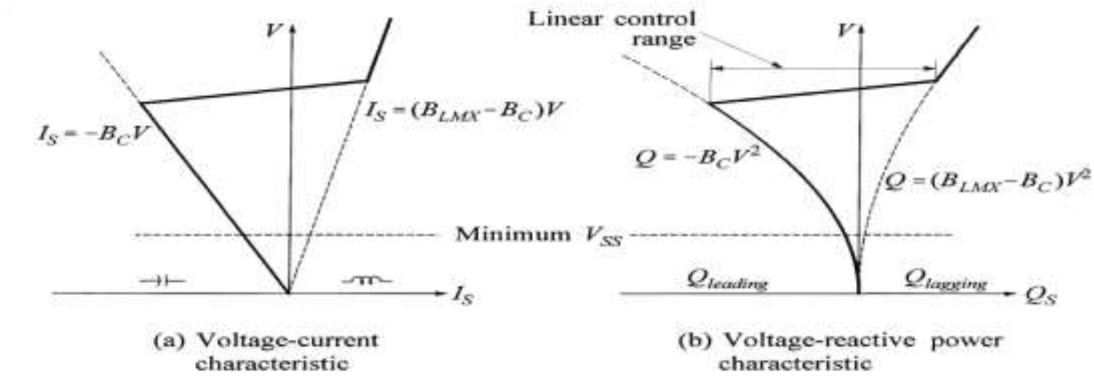



**Figure 2-6:steady-state V/I and V/Q characteristic of the SVS**

### 2.6.2.2 Statcom:

The STATCOM is a shunt-connected device with the ability to either generate or absorb reactive power at a faster rate because no moving parts are involved. It does not employ capacitor or reactors banks to produce reactive power as the static var compensator (SVC); the capacitor bank in the STATCOM is used to maintain constant DC voltage for the voltage-source converter operation .

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

A STATCOM can improve power-system performance in such areas are the following:

- The dynamic voltage control in transmission & distribution system.
- The power oscillation damping in power-transmission system.
- The voltage flicker control.
- The control of not only reactive power but also ( if needed ) active power in the connected line; requiring a dc energy source .
- Supply reactive power even at low bus voltage

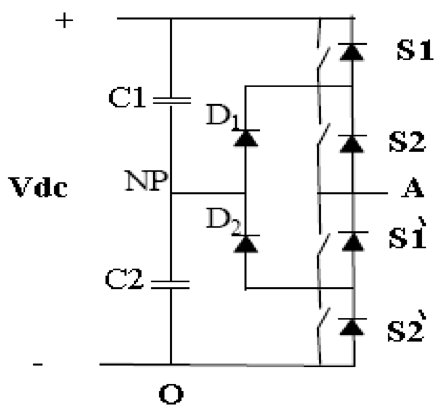
Actually a STATCOM can be classified into two different types voltage source inverter ( VSI ) and current source inverter ( CSI ). The main different between the VSI and The CSI, that in VSI the inverter is fed from voltage source and the load current is forced to fluctuate from positive to negative, and vice versa. To cope with inductive loads, the power switches with freewheeling diodes are required. Where as in a CSI, the input behaves as a current source, and the load current is maintained constant irrespective of load on the inverter and the output voltage is forced to change There are varieties of STATCOM configureurations, but their composition are basically the same. Any STATCOM is composed of:

**a) inverters with a capacitor or dc source in its dc side:**

The function of an inverter is to change a dc input voltage to a symmetrical ac output voltage of desired magnitude and frequency. A variable output voltage can be obtained by varying the input dc voltage and maintaining the gain of the inverter constant. On the other hand, if the dc input voltage is fixed and it is not controllable, a variable output voltage can be obtained by varying the gain of the inverter, which is normally accomplished by Pulse-Width-Modulation (PWM) control. The output voltage waveforms of ideal inverters should be sinusoidal, For low and medium-power applications, square-wave or quasi-square-wave voltage may be acceptable; and for high-power application, low distorted sinusoidal waveforms are required. With the availability of high-speed power semiconductor devices, the harmonic contents of output voltage can be minimized or reduced significantly by switching techniques. The multilevel voltage source inverter is recently applied in many industrial applications such as ac power supplies, drive systems, etc. One of the significant advantages of multilevel configureuration is the harmonic reduction in the output waveform without increasing switching frequency or decreasing the inverter power output. The output voltage waveform of a multilevel inverter is composed of the number of levels of voltages, typically obtained from capacitor voltage sources.

The so-called multilevel starts from three levels. The multilevel inverters can be classified into three types :

- **Diode-Clamped Multilevel Inverter (DCMI):**The diode-clamped multilevel inverter uses capacitors in series to divide up the dc bus voltage into a set of voltage levels. To produce m levels of the phase voltage, an m level diode-clamp inverter needs m-1 capacitors on the dc bus. The dc bus consists of two capacitors, i.e., C1, and C2 . For a dc bus voltage Vdc, the voltage across each capacitor is Vdc/2, and each device voltage stress will be limited to one capacitor voltage level, Vdc/2,through clamping diodes. DCMI output voltage synthesis is relatively straightforward. “(Figure 2-7)” explains how the staircase voltage is synthesized, point O is considered as the output phase voltage reference point. there are three switch combinations to generate three level voltages across A and O.




| Output VAO | Switch State | | | |
|---|---|---|---|---|
| | S1 | S2 | S1\ | S2\ |
| V3=Vdc | 1 | 1 | 0 | 0 |
| V2=Vdc/2 | 0 | 1 | 1 | 0 |
| V1=0 | 0 | 0 | 1 | 1 |

**Figure 2-7:The three-level neutral-point-clamped phase leg**

- **Flying-capacitor Multilevel Inverter (FCMI):** "(Figure 2-8)" shown below uses a ladder structure of dc side capacitors where the voltage on each capacitor differs from that of the next capacitor. To generate m-level staircase output voltage, m-1 capacitors in the dc bus are needed. Each phase-leg has an identical structure. The size of the voltage increment between two capacitors determines the size of the voltage levels in the output waveform .

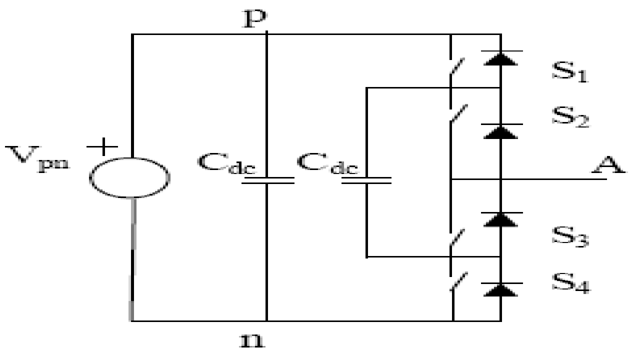



**Figure 2-8:Three-level flying capacitor phase leg.**

- **Multilevel Inverter Using Cascaded-Inverters with Separated DC Sources :** The general function of this multilevel inverter is the same as that of the other two previous inverters. The multilevel inverter using cascaded-inverter with SDCSs synthesizes a desired voltage from several independent sources of dc voltages as shown in "(Figure 2-9)" , which may be obtained from either batteries, fuel cells, or solar cells. This new inverter can avoid extra clamping diodes or voltage balancing capacitors.

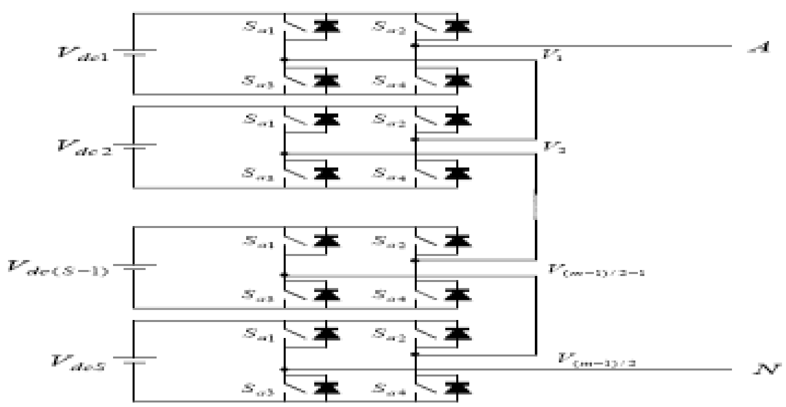



**Figure 2-9:Three-level flying capacitor phase leg.**

### b) Coupling transformers:

It is used to couple the inverter to the AC power system. The transformer primary windings must be isolated from each other, while the secondary windings may be connected in wye or delta.The transformer secondary is normally connected in wye to eliminate triplen harmonics (n=3, 6, 9, ……).

### c) DC source:

The DC interface provides the interface between the DC side of STATCOM and other energy sources, Which could be any kind of energy storage device or DC source, such as wind turbines, DC generator, photovoltaic systems, or other electronics devices. The traditional STATCOM doesn't have a DC source, it only has a DC capacitor to maintain its DC side voltage.In theory, the DC capacitor is not required to be very large. Therefore, the STATCOM is not like a Static Var Compensator (SVC), whose capacity is mainly determined by the size of capacitor.

The capacitor serves only as a DC source and is necessary for unbalanced system operation and harmonic absorption. For a STATCOM with energy storage, this DC capacitor is still required, but its main function is no longer as a DC voltage source, but as a lower pass filter (harmonic absorption) to reduce the DC current ripple from/into the DC source.

### d) Controller:

Mainly the controller of the STATCOM is the controller of a VSI. There are many topologies to control the VSI voltage. If the switch is capable of operating at higher frequencies, which is typically the case with fully controlled semiconductors, PWM concept can be applied.

### 2.6.2.2.1 Theory Of Operation:

It provides the desired reactive-power generation and absorption entirely by means of electronic processing of the voltage and current waveforms in a voltage-source converter (VSC). Where a VSC is connected to a utility bus through magnetic coupling. A single-line STATCOM power circuit is shown in“(Figure 2-10)”.

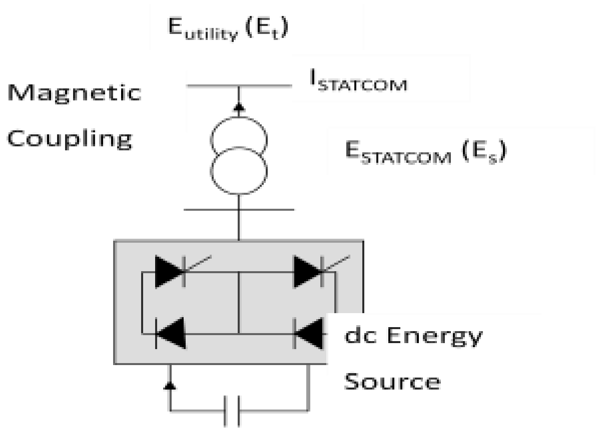



**Figure 2-10: Three-level flying capacitor phase leg.**

A STATCOM is seen as an adjustable voltage source behind a reactance, this meaning that capacitor banks and shunt reactors are not needed for reactive-power generation and absorption, thereby giving the STATCOM a compact design, or small footprint, as well as low noise and low magnetic impact. The exchange of reactive power between the converter and the ac system can be controlled by varying the amplitude of the 3-phase output voltage, Es of the converter,  if the fundamental of the inverter output voltage (Es) is in phase with the utility bus voltage (Et ). When the amplitude of the output voltage is increased above that of the utility bus voltage, Et, then current flows through the reactance from the converter to the ac system and the converter generates capacitive-reactive power for the ac system.If the amplitude of the output voltage is decreased below the utility bus voltage, then the current flows from the ac system to the converter and the converter absorbs inductive-reactive power from the ac system.If the output voltage equals the ac system voltage, the reactive-power exchange becomes zero, in which case the STATCOM is said to be in a floating state as shown in“(Figure 2-11)”.

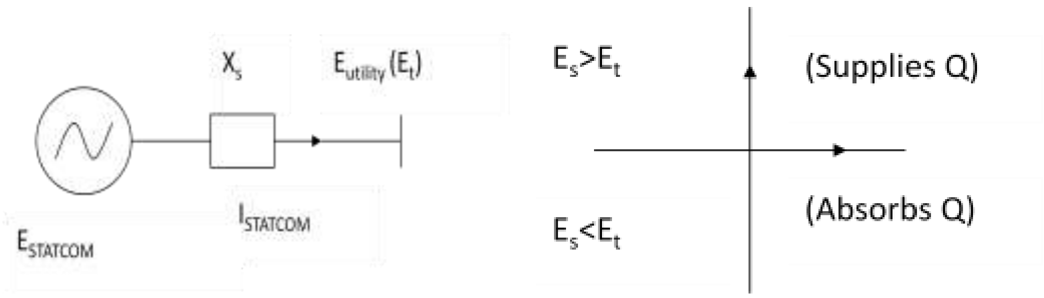



**Figure 2-11:Three-level flying capacitor phase leg.**

## 2.7 METHOS OF IDENTIFICATION OF THE WEAKEST BUSBAR

### 2.7.1 Trial and Error Method:

In this method, several trials with different size of fixed reactive compensator at different location have been considered. In every trial, the average value of the system voltage and the voltage standard deviation are calculated.The best location (weakest busbar) is identified as that at which the average voltage is the best with minimum standard deviation.

### 2.7.2 Sensitivity Analysis:

The basic equation(2.11) used in Newton-Raphson method is

$$\begin{bmatrix} \delta P \\ \delta Q \end{bmatrix} = \begin{bmatrix} J1 & J2 \\ J3 & J4 \end{bmatrix} \begin{bmatrix} Aa \\ A|V| \end{bmatrix} \tag{2.11}$$

Where J is the Jacobian Matrix. The reactive power is less sensitive to changes in phase angles and is mainly dependent on changes in voltage magnitudes [25]. Similarly, real power change is less sensitive to the change in the voltage magnitude and is most sensitive to the change in phase angle. So, it is quite accurate to set J2 and J3 of the Jacobian matrix to zero. The diagonal elements of J4 indicate the reactive power sensitivity of i-th bus. $\partial Qi/\partial|Vi|$ also indicates the degree of weakness for the ith bus.

### 2.7.3 Fuzzy Set Theory:

The traditional set theory (classical set) deal with only one value membership 0 or 1. The object wholly includes or wholly excludes without partial membership. Crisp sets handle black-and-white concepts, for example, the classical set of days of the week unquestionably includes Monday, Thursday, and Saturday. It just as unquestionably excludes butter, liberty, and dorsal fins, and so on show “(Figure 2-12)” below.

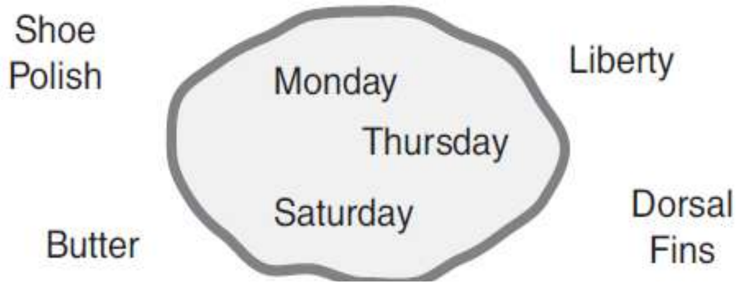



**Figure 2-12:Classical set description**

During the development of the world all the systems which surroud us are complex. This complexity arises from uncertainty in the form of ambiguity. Therefore the classical set theory are not sufficient to realistically describe vague concepts[25,26] . In 1965 Fuzzy set theory was proposed by Professor L. A. Zadeh which deal with uncertainty problems [27]. A classical set is defined by crisp boundaries, i.e., there is no uncertainty in the prescription or location of the boundaries of the set. But fuzzy set defined as a fuzzy set consists of a universe of discourse and a membership function that maps every element in the universe of discourse to a membership value between 0 and 1. Where the input space somtimes is referred to as the universe of discourse. A fuzzy set is in contrast with classical, or crisp sets because members of a crisp set would not be members unless their membership was full, or complete, in that set (i.e., their membership is assigned a value of 1). In other hand, the membership elements in a fuzzy set not necessary to be complet. Elements of a fuzzy set are mapped to a universe of membership values on the interval 0 to 1. If an element of universe, say x, is a member of fuzzy set A, then the membership is given by $\mu A(x) \in [0, 1]$ . One of the most commonly used examples for explain the crisp set and fuzzy set memberships is the concept of the "young". The age of any specific person is accurate. However, classifying the age is "young" or not is involves fuzziness and is sometimes confusing and difficult. Therefore crisp set with sudden change membership value from 1 to 0 at age 35 is unreasonable, Show “(Figure 2-13)”. In Fuzzy set, an age to "young" relates with a membership value ranging from 0 to 1. For instance, one might think that age 10 is "young" with membership value 1, age 30 with membership value 0.75, age 50 with membership value 0.1, and so on. Show “(Figure 2-14)” below .

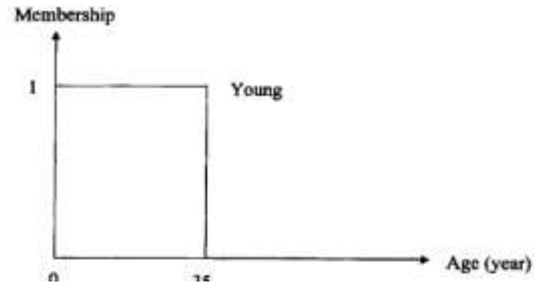



**Figure 2-13:A possible description of the vague concept "young" by a crisp set.**

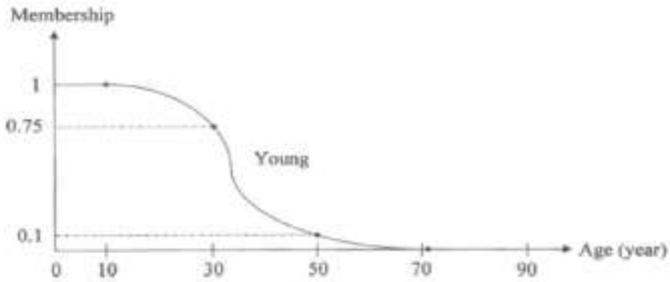



**Figure 2-14:A possible description of the vague concept " young" by a fuzzy set.**

There are several types of fuzzy membership function, the most famous types of membership functions which are needed in most circumstances: trapezoidal, triangular (a special case of trapezoidal),Gaussian, and bell-shaped. All these fuzzy sets are continuous, normal, and convex show "(Figure 2-15)" below. Among the four, the first two are more widely used. In this thesis trapezoidal memberships are used.

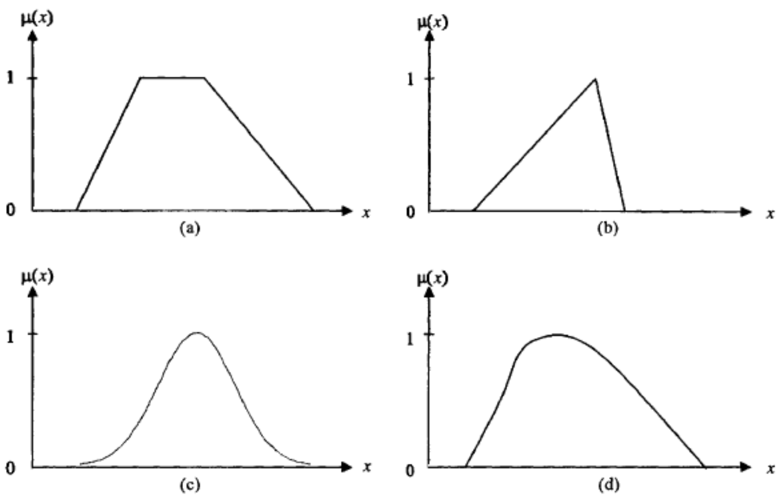



**Figure 2-15:Four commonly used input fuzzy sets in fuzzy control and modeling.**

### 2.7.3.1 Fuzzy Set Operations:

Let three fuzzy sets A,B and C on the universe X. For a given element x of the universe, the following function theoretic operations for the set theoretic operations unions, intersection and complement are defined for A,B and C on X:

- Union (fuzzy logic OR operator) :

$$\mu A \cup B\ (x) = \max(\ \mu A(x) V\ \mu B(x)) \quad (2.12)$$

- Intersection (fuzzy logic AND operator) :

$$\mu A \cap B(x) = \min(\mu A(x) \Lambda \mu B(x)\ ) \quad (2.13)$$

- Complement (fuzzy logic NOT operator) :

$$\mu \bar{A}(x) = 1 - \mu A(x) \quad (2.14)$$

These operations at equations (2-12, 2-13 and 2.-14) also known as the standard fuzzy operations. They represented by Venn diagrams show “(Figure 2-16)”, “(Figure 2-17)”and “(Figure 2-18)” below. The membership value of any element x in the null set ∅ is 0 [28].

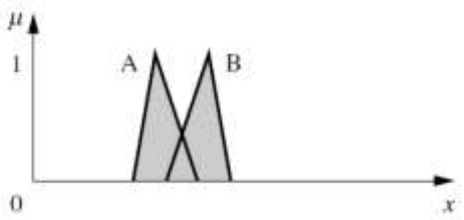



**Figure 2-16:Union of fuzzy sets A and B.**

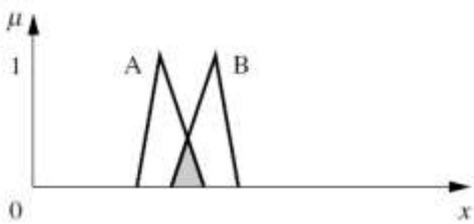



**Figure 2-17:intersection of fuzzy sets A and B**

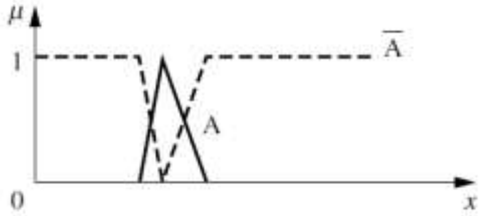



**Figure 2-18:Complement of fuzzy set A**

- Fuzzy Cartesian Product

Let A be a fuzzy set on universe X and B be a fuzzy set on universe Y , then the Cartesian product between fuzzy sets A and B will result in a fuzzy relation R which is contained with the full Cartesian product space

$$A \times B = R \subset X \times Y$$

where the fuzzy relation Rhas membership function.

$$\mu R(x,y)) = \mu_{AxB}(X,Y) = \min(\mu A\ (X),\ \mu B\ (Y))$$

Each fuzzy set could be thought of as a vector of membership values; each value is associated with a particular element in each set. For example, for fuzzy set A that has four elements, hence column vector size 4 × 1 and for fuzzy set (vector) B that has five elements, hence a row vector of 1 × 5. The resulting fuzzy relation R will be represented by a matrix of size 4 × 5 (i.e.,) R will have four rows and five columns.

- Fuzzy Cartesian Composition

Let R be a fuzzy relation on the Cartesian space X ×Y , S be a fuzzy relation

on Y × Z, and T be a fuzzy relation on X × Z, then the fuzzy set max–min

composition is defined as: T= RoS

$$=\{\ (x, z)\ ,\ \max_{y}\{\ \min\_(\mu R\ (x, y)\ ,\ \mu S\ (y, z)\}\ /x \in X, y \in Y\ z \in Z\}$$

## 2.8 IDENTIFICATION OF THE WEAKEST LINE.

Voltage stability index proposed by I.Musirin et al. [29] can be conducted on a system by evaluating the voltage stability referred to a line. The voltage stability index referred to a line is formulated from the 2-bus representation of a system. The voltage stability index developed is derived by first obtaining the current equation through a line in a 2-bus system. Representation of the system illustrated in "(Figure 2-19)"

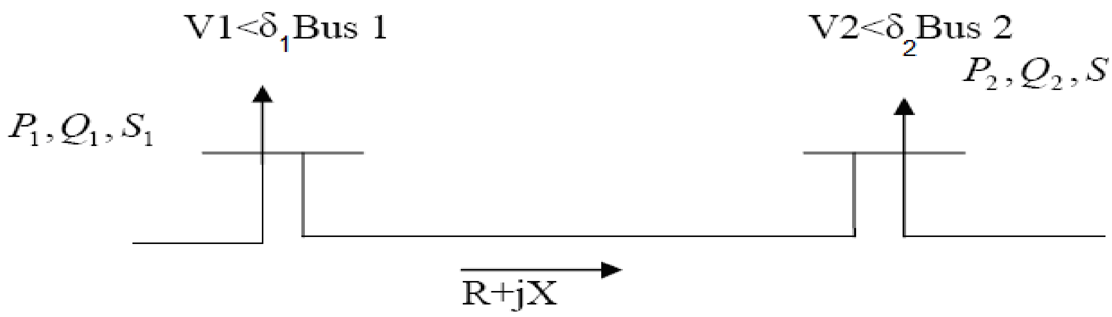



**Figure 2-19:Bus system model**

V1, V2 = voltage at the sending and receiving buses.

P1, Q1 = active and reactive powers at the sending bus.

P2, Q2 = active and reactive powers at the receiving bus.

S1, S2 = apparent powers on the sending and receiving buses.

δ = angle difference between the sending and receiving buses (δ1 – δ2).

By taking the sending end bus, bus 1, as the reference (i.e. δ1 = 0 and δ2 = δ), then the general current relationship can be written as;

$$I = \frac{V_1\angle 0 - V_2\angle\delta}{R + JX} \tag{2.15}$$

Where R is the line resistance and X is the line reactance.The apparent power at bus2 ( the receiving end power) can be written as:

$$S_2 = V_2 I^* \tag{2.16}$$

$$I = \frac{S_2^*}{V_2^*} = \frac{P_2 - jQ_2}{V_2\angle\delta} \tag{2.17}$$

Equating (2.15) and (2.17) we obtained,

$$\frac{V_1\angle 0 - V_2\angle\delta}{R + JX} = \frac{P_2 - jQ_2}{V_2\angle\delta} \tag{2.18}$$

$$V_1 V_2 \angle -\delta - V_2{}^2 \angle\delta = (P_2 - jQ_2)(R + jX) \tag{2.19}$$

Separating the real part and imaginary parts yields

$$V_1 V_2 Cos\delta - V_2{}^2 \angle\delta = (P_2 R + X Q_2) \tag{2.20}$$

And

$$-V_1 V_2 Sin\delta - V_2{}^2 \angle\delta = (X P_2 - RQ_2) \tag{2.21}$$

Rearrange equation(2.21) and substitute at (2.20) yields ), the voltage quadratic equation at the receiving end bus is written as;

$$V_2^2 - (\frac{R}{X}\sin\delta + \cos\delta)V_1 V_2 + (X + \frac{R}{X}^2)Q_2 = 0 \tag{2.22}$$

$$V_2 = \frac{(\frac{R\sin\delta}{X} + \cos\delta)V_1 \pm \sqrt{[(\frac{R\sin\delta}{X} + \cos\delta)V_1]^2 - 4(X + \frac{R^2}{X})Q_2}}{2} \tag{2.23}$$

To obtain real roots for V2, the discriminator is set greater than or equal to ‘0’; i.e.:

$$\frac{4.Z^2.Q_2.X}{(V_1^2).(R\sin\delta + X\cos\delta)^2} \le 1 \tag{2.24}$$

The angle difference δ is normally very small then,

$\delta \approx 0$ , $R \sin \delta \approx 0$ , $X \cos \delta \approx X$

Taking the symbols "i" as the sending bus and"j" at the receiving bus ,the fast voltage stability index,FVSI can be identify

$$FVSI_{12} = \frac{4.Z^2.Q_2}{V_1^2.X} \tag{2.25}$$

Where:

Z=line impudence

X=line reactance

$Q_2$=reactive power at the receiving end

$V_1$=Sending end voltage

The line that exhibits FVSI closed to 1.0 implies that it is approaching its instability point. If FVSI goes beyond 1.0, one of the buses connected to the line will experience a sudden voltage drop leading to system collapse.Critical line is defined as that line which when removed from the system might lead to a voltage collapse. The scenario of system blackout due to voltage collapse can be illustrated as shown in "(Figure 2-20)". The occurrence of voltage collapse is initiated by voltage drop at certain bus due to load increase not supported by local power reactive or other elements support to improve the voltage performance.

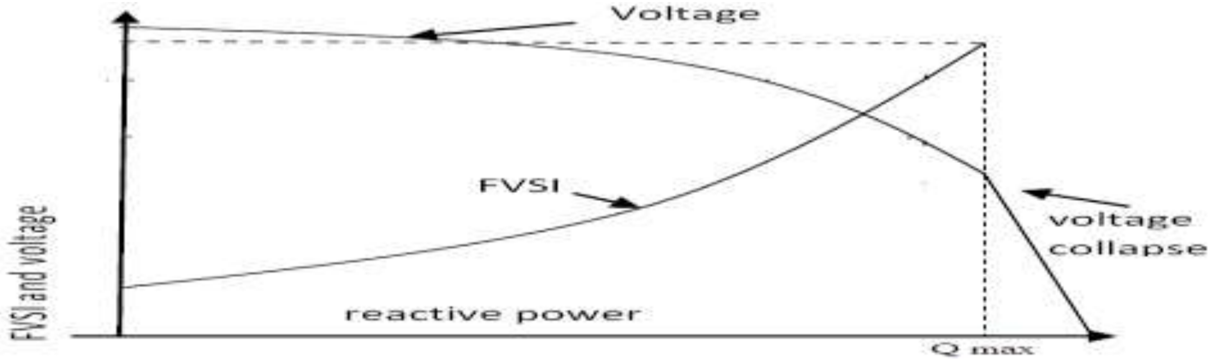



**Figure 2-20:FVSI and voltage versus Qload curve to determine voltage collapse**

From the graph, it is shown that as the reactive power loading at a particular load bus is increased; the FVSI value of the highest sensitive corresponding connecting line was also increased accordingly. The increase of reactive power loading will also cause to the voltage profile to decrease until reaching the collapse point. At this point, the reactive power increase is called as the maximum allowable load or also termed as maximum loadability. Any attention to continue increasing the reactive power loading after maximum loadability, voltage will drop accordingly which would lead to the whole system.

*C h a p t e r   T h r e e*

# 3 SYSTEM MODELING AND IDENTIFICATION OF THE WEAKEST BUSBAR

## 3.1 INTRODUCTION

MATLAB simulink program is used for IEEE 14 Bus system (69 kv /13.8kv) without any compensation. The test system shown in “(Figure 3-1)” has 14 buses. These buses are inter connected via transmission lines, each represented in the form of a (pi) model. Bus1 is a slack bus, bus 2& bus 3 are a PV bus and other buses are load buses. The detailed system data is shown in Appendix (A). By logic generators not allowed to connect directly to any bus bar so the three generators are far a way from the system by 100km which represented by (Pi section) as shown in “(Figure 3-2)” that grantees that the system will be supported by generators if there is any problem in one of these lines. The value of R,Land C of others pi sections that connected between buses is calculated as shown in Appendix (A). There are two main steps to model this system ;the first one is tuning three generators to give the required voltage, reactive power and active power in bus 1, 2 and 3 as shown in the load flow ,see Appendix (B);the other step is tuning transformers that represented by (Star Grounded –Delta) to give 13.8kv.

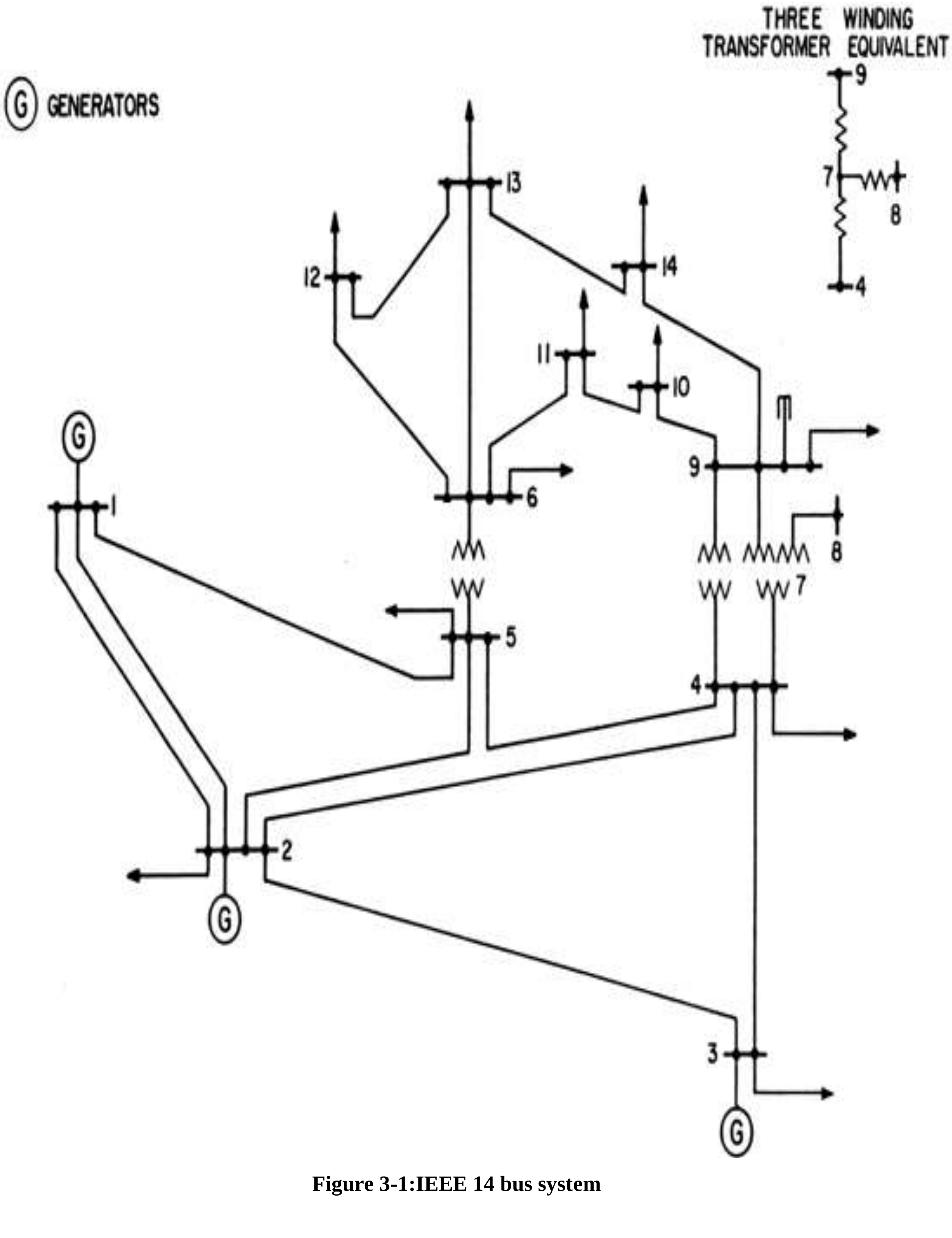



**Figure 3-1:IEEE 14 bus system**

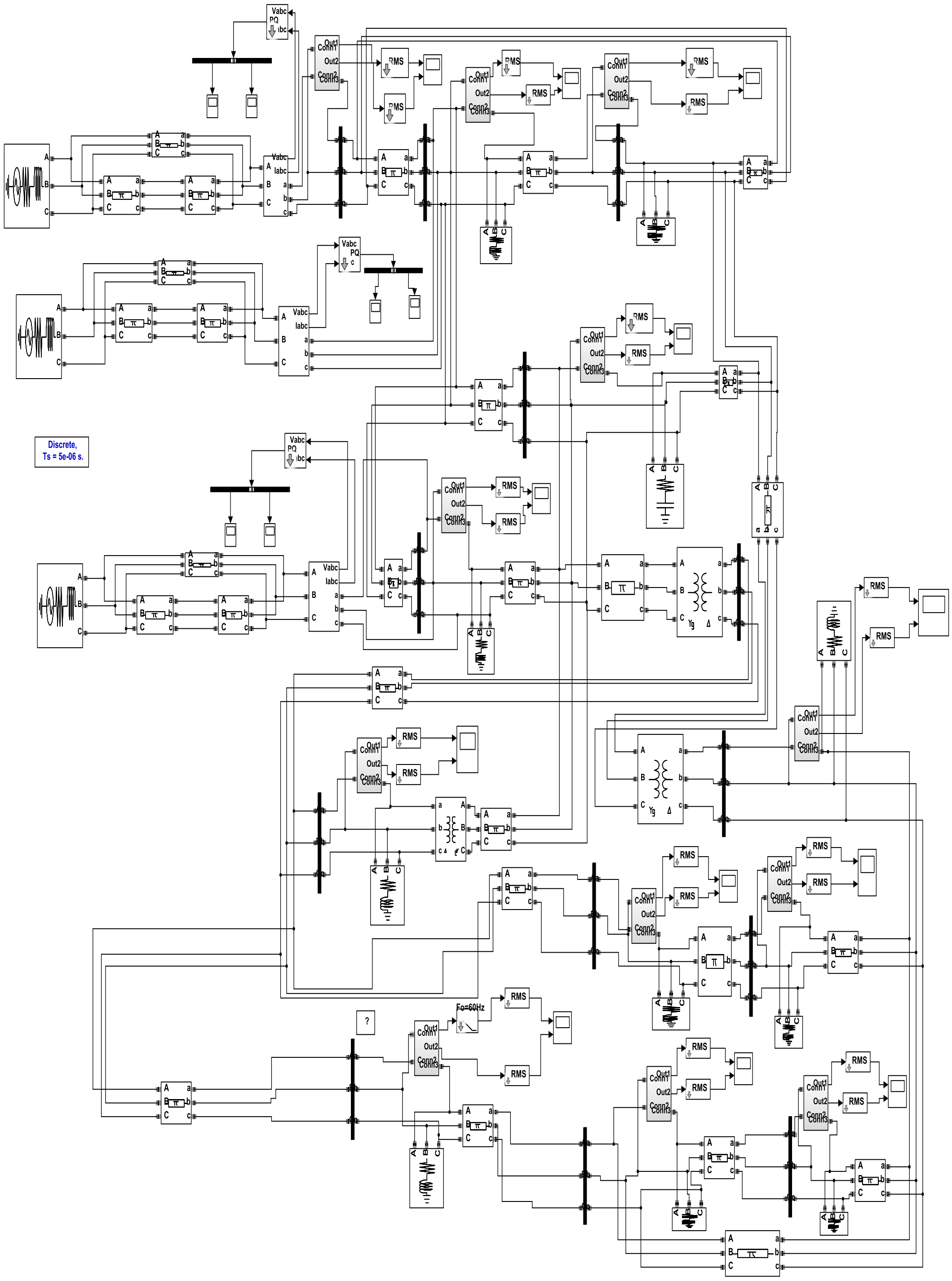


**Figure 3-2:IEEE 14 bus system model**

### 3.1.1 Identification of Weakest Busbar

The increase in power demand and limited sources for electric power has resulted in an increasingly complex interconnected system, forced to operate closer to the limits of stability. Voltage instability is mainly associated with reactive power imbalance. the weakest bus in the system and the critical line referred to a bus where the weakest bus is the best location for Fact devices where they are used to enhance the power system stability and support the voltage by compensation of reactive power.

This thesis investigates the voltage system stability enhancement by using FACT device such as DSTATCOM. Practically the location of any FACT device in the power system is very important factor to give the best results so we use three methods to know the best location for Dstatcom such as trial and error, Sensitivity analysis and fuzzy logic control. the weakest bus is the best location for Dstatcom.

#### 3.1.1.1 Trial and Error Method

In this method, several trials with different size of fixed reactive compensator at different location have been considered. In every trial, the average value of the system voltage and the voltage standard deviation are calculated. The best location (weakest busbar) is identified as that at which the average voltage is the best with minimum standard deviation. Using trial and error method, bus 14 has been found to have the best average voltage and the minimum standard deviation. This means it is the weakest bus and the best location for any FACT device.

"Table 3-1", "Table 3-2", "Table 3-3"and "Table 3-4" show the system average voltage and the corresponding standard deviation when load buses are injected by different values of reactive power (10 MVAR-20MVAR-30MVAR). It is observed that 20MVAR reactive compensator unit has been chosen for the rest of the analysis unless otherwise stated.

**Table 3-1:Average voltage and standard deviation at 10 MVAR**

| 10 MVA at bus | Bus voltage p.u | System average voltage | System standard deviation |
|---|---|---|---|
| 4 | 0.980 | 0.9797857143 | 0.02935783802 |
| 5 | 0.986 | 0.9797857143 | 0.02948408426 |
| 6 | 1.004 | 0.9876428571 | 0.02625590313 |
| 7 | 0.987 | 0.9860714286 | 0.02639389617 |
| 8 | 1.004 | 0.987 | 0.02695763873 |
| 9 | 0.975 | 0.9876428571 | 0.02509868279 |
| 10 | 0.976 | 0.9882571429 | 0.02482972626 |
| 11 | 0.991 | 0.9887142857 | 0.02533046887 |
| 12 | 1 | 0.9890714286 | 0.02600676913 |
| 13 | 0.988 | 0.989 | 0.02549229575 |
| **14** | **0.971** | **0.9835714** | **0.02385553887** |

**Table 3-2:Average voltage and standard deviation at 20 MVAR**

| 20 MVA at bus | Bus voltage p.u | System average voltage | System standard deviation |
|---|---|---|---|
| 4 | 1.022 | 0.9927857143 | 0.02578531856 |
| 5 | 1.024 | 0.9928571429 | 0.02592807949 |
| 6 | 1.036 | 1.007857143 | 0.02162953385 |
| 7 | 1.015 | 1.004571429 | 0.02101942736 |
| 8 | 1.048 | 1.006357143 | 0.02399883075 |
| 9 | 1.016 | 1.007785714 | 0.01852865954 |
| 10 | 1.018 | 1.009285714 | 0.01837866998 |
| 11 | 1.029 | 1.009785714 | 0.0201961049 |
| 12 | 1.044 | 1.010285714 | 0.02305716056 |
| 13 | 1.026 | 1.010285714 | 0.02117757767 |
| **14** | **1.014** | **1.011** | **0.01744788157** |

**Table 3-3: Average voltage and standard deviation without Compensation**

| 30 MVA at bus | Bus voltage pu | System average voltage | System standard deviation |
|---|---|---|---|
| 4 | 0.974 | 0.9754285714 | 0.0313271089 |
| 5 | 0.980 | | |
| 6 | 0.980 | | |
| 7 | 0.966 | | |
| 8 | 0.966 | | |
| 9 | 0.952 | | |
| 10 | 0.95 | | |
| 11 | 0.960 | | |
| 12 | 0.963 | | |
| 13 | 0.957 | | |
| **14** | **0.934** | | |

**Table 3-4:Average voltage and standard deviation at 30 MVAR**

| 30 MVA at bus | Bus voltage pu | System average voltage | System standard deviation |
|---|---|---|---|
| 4 | 1.052 | 1.000071429 | 0.0231469352 |
| 5 | 1.055 | 0.9968571429 | 0.0242423983 |
| 6 | 1.061 | 1.021642857 | 0.0208724591 |
| 7 | 1.057 | 1.017214286 | 0.0180877960 |
| 8 | 1.083 | 1.019571429 | 0.0248156468 |
| 9 | 1.053 | 1.021857143 | 0.0148172541 |
| 10 | 1.057 | 1.024 | 0.0156889406 |
| 11 | 1.059 | 1.0245 | 0.0190815917 |
| 12 | 1.079 | 1.025071429 | 0.0247370869 |
| 13 | 1.056 | 1.025214286 | 0.0212339975 |
| **14** | **1.049** | **1.026** | **0.01744788157** |

**Table 3-5: Average voltage and standard deviation at bus 14**

| MVAR at bus 14 | System average voltage | System standard deviation |
|---|---|---|
| **Without compensation** | 0.9754 | 0.03132 |
| **10 MVAR** | 0.98357 | 0.02385 |
| **20 MVAR** | **1.011** | **0.01744** |
| **30 MVAR** | 1.026 | 0.01600 |

It is observed from and "Table 3-5" that 20MVAR reactive compensator unit has been chosen for the rest of the analysis unless otherwise stated.

### 3.1.1.2 Sensitivity Analysis:

The diagonal elements of J4 in equation indicate the reactive power sensitivity of i-th bus. $\partial Qi/\partial|Vi|$ also indicates the degree of weakness for the ith bus [30],as $\partial Qi/\partial|Vi|$ is high and $\partial|Vi| /\partial Qi$ becomes low, indicating a minimum change in voltage for variation Q (reactive power) of the bus ;thus The bus corresponding to the maximum value of $\partial Qi/\partial|Vi|$ is the strongest bus and the bus corresponding to the minimum value of $\partial Qi/\partial|Vi|$ is the weakest bus. In this method weakest load bus of any multi bus system can be defined [31]. The ith diagonal element of the matrix [J]-1 also indicates the Q-V sensitivity of load bus i.

According to Appendix (A) and Appendix(B) equation (3.1) is calculated and The results of the sensitivity analysis on the system under study without any compensation are shown in "Table 3-6".

$$\frac{\partial \mathrm{Q_i}}{\partial |V_i|} = -2|V_i|\,|Y_{ii}|\,\mathrm{Sin}\,\theta_{\mathrm{ii}} - \Sigma_{j\neq i}|V_j|\,|Y_{ij}|\,Sin\left(\theta_{ij} - \delta_i + \delta_j\right) \tag{3.1}$$

**Table 3-6: Sensitivty analysis**

| Bus | $\partial Qi/\partial\|Vi\|$ |
|---|---|
| 1 | 20.95823 |
| 2 | 31.224425 |
| 3 | 9.91839 |
| 4 | 37.1510577 |
| 5 | 33.9268 |
| 6 | 17.1937344 |
| 7 | 18.9865 |
| 8 | 5.483982 |
| 9 | 23.0004856 |
| 10 | 13.959 |
| 11 | 8.13439585 |
| **12** | **5.210665963** |
| 13 | 10.15545 |
| **14** | **4.936575** |

From the obtained results, it is obvious that $\partial Qi/\partial|Vi|$ at bus no.14 is very small and $\partial|Vi|/\partial Qi$ becomes high, indicating a maximum change in voltage for variation Q (reactive power) at this bus ;so bus no.14 is the most sensitive bus in the system and bus no.12 is the second one ;so bus no.14 is the weakest bus and followed by bus no.12.

### 3.1.1.3 Fuzzy membership :

An approach based on fuzzy set theory and heuristic rules to determine the weak buses in a system is the following: Two membership functions are chosen, the first one is for reactive power loss, while the second one is for voltage sensitivity. The voltage membership function is assumed to be in the form of “(Figure 3-3)”, which is described by:

$$u_i(V) = \begin{cases} \dfrac{V}{V_{\min}}; & 0 \le V \le V_{\min} \\ 1; & V_{\min} \le V \le V_{\max} \\ 0; & V \ge V_{\max} \end{cases} \tag{3.2}$$


**Figure 3-3: Voltage membership function**

where Vmin and Vmax is the minimum and maximum voltage assigned for each bus respectively; V is the bus voltage,while the membership function for the reactive power losses has the same form of “(Figure 3-3)”, and is described by the following equations:

$$u_i(Q_{loss}) = \begin{cases} 0; & Q_{loss} \le Q_{base} \\ 1; & Q_{base} \le Q_{loss} \le QV_{\min} \\ \dfrac{a - Q}{a - QV_{\min}}; & QV_{\min} \le Qloss \le a \\ 0; & Q \ge a \end{cases} \tag{3.3}$$

Qbase is the total bus reactive power losses at the base load, the nominal operating load. QVmin is the reactive power loss corresponding to the minimum bus voltage, and is calculated using the relation between Q and V given by Equation (3.5), and a is the reactive power losses at V = 0.

A fuzzy decision S is chosen for each bus i given by the fuzzy multiplication of Equations (3.2) and Equations (3.3) as:

$$S(i) = u_v(i) \otimes u_q(i) = \min(u_v(i), u_q(i)) \qquad (3.4)$$

Buses having the lowest values of S are specified as weak buses. In the following section, the steps of identification of weak buses are explained.

Here we will discuss the algorithm solution. Assume that data necessary for system steady state load flow are available in Appendix (B)., in this case. The following steps are used for identifying the weak buses.

- **Step 1**. Calculate the load flow for the system base case, that is, the load flow at normal loading condition. Determine the system active and reactive losses from the solution of load flow, by using the voltage and angle at each bus as shown in "Table 3-7".

**Table 3-7: Base solution**

| Bus(i) | Bus Voltage | | Load | | Genera tion | |
|---|---|---|---|---|---|---|
| | Magnitude (p.u) | Angle Degree | MW | Mvar | MW | Mvar |
| 1 | 1.060 | 0.00 | 0.00 | 0.00 | 233.913 | 36.693 |
| 2 | 1.025 | -4.795 | 21.700 | 12.70 | 40.000 | 33.038 |
| 3 | 0.990 | -13.026 | 94.200 | 19.100 | 0.00 | 38.860 |
| 4 | 0.974 | -10.060 | 47.800 | -3.900 | 0.00 | 0.00 |
| 5 | 0.980 | -8.494 | 7.600 | 1.600 | 0.00 | 0.00 |
| 6 | 0.980 | -14.808 | 11.200 | 7.500 | 0.00 | 0.00 |
| 7 | 0.966 | -13.511 | 0.00 | 0.00 | 0.00 | 0.00 |
| 8 | 0.966 | -13.511 | 0.00 | 0.00 | 0.00 | 0.00 |
| 9 | 0.952 | -15.410 | 29.500 | 16.600 | 0.00 | 0.00 |
| 10 | 0.95 | -15.645 | 9.000 | 5.800 | 0.00 | 0.00 |
| 11 | 0.960 | -15.374 | 3.500 | 1.800 | 0.00 | 0.00 |
| 12 | 0.963 | -15.833 | 6.100 | 1.600 | 0.00 | 0.00 |
| 13 | 0.957 | -15.907 | 13.800 | 5.800 | 0.00 | 0.00 |
| 14 | 0.934 | -16.849 | 14.900 | 5.000 | 0.00 | 0.00 |
| **Total** | | | **259.300** | **73.600** | **273.91** | **108.590** |

- Ste**p 2.** For each bus, find the relation between the reactive power loss and the voltage of that bus. A quadratic function is assumed in the following equation (3.5), where ai , bi , and ci are constants obtained from curve fitting; Vi is the amplitude of the voltage of buses i; i =1, 2,.., N.

$$Q_{loss}(i) = a_i + b_i V_i + c_i V_i^2 \; ; \quad i = 1,2,...N \tag{3.5}$$

ai , bi , and ci are constants can be calculated by solving the following three equations for load buses.

$$
\begin{aligned}
Q_{loss}(i) &= a_i + b_i V_i + c_i V_i^2 \; ; \quad i = 1,2,...N \qquad && \textit{Base case} \\
Q_{loss}(i) &= a_i + b_i V_i + c_i V_i^2 \; ; \quad i = 1,2,...N \qquad && \text{Increasing load by 50\%} \\
Q_{loss}(i) &= a_i + b_i V_i + c_i V_i^2 \; ; \quad i = 1,2,...N \qquad && \text{Increasing load by 70\%}
\end{aligned}
\tag{3.6}
$$

**Table 3-8:Voltage in different cases**

| | Voltage at | | |
|---|---|---|---|
| **Bus(i)** | **Base case** | **Increasing load By 50%** | **Increasing load By 70%** |
| 4 | 0.974 | 0.901 | 0.873 |
| 5 | 0.980 | 0.910 | 0.882 |
| 6 | 0.980 | 0.854 | 0.790 |
| 9 | 0.952 | 0.822 | 0.758 |
| 10 | 0.95 | 0.813 | 0.746 |
| 11 | 0.960 | 0.826 | 0.759 |
| 12 | 0.963 | 0.824 | 0.754 |
| 13 | 0.957 | 0.814 | 0.742 |
| 14 | 0.934 | 0.782 | 0.705 |

**Table 3-9:Qlosses from load flow in different cases**

| Bus(i) | $Q_{losees}$ from load low | | |
|---|---|---|---|
| | **Base case** | **Increasing load By 50%** | **Increasing load By 70%** |
| 4 | 3.293 | 29.926 | 49.358 |
| 5 | 14.972 | 58.121 | 85.608 |
| 6 | 7.905 | 22.284 | 33.149 |
| 9 | 3.418 | 11.409 | 18.045 |
| 10 | 0.095 | 0.237 | 0.354 |
| 11 | 0.267 | 0.555 | 0.735 |
| 12 | 0.2 | 0.593 | 0.902 |
| 13 | 0.734 | 2.07 | 3.105 |
| 14 | 0.442 | 1.41 | 2.253 |

**Table 3-10:Values of A,B and C.**

| Bus(i) | A | B | C |
|---|---|---|---|
| 4 | 3259.053 | -6475.5605 | 3259.0533 |
| 5 | 3942.963 | -7660.7969 | 3727.186589 |
| 6 | 364.8560 | -651.254957 | 292.876723 |
| 9 | 232.23388 | -447.5270 | 217.6199445 |
| 10 | 3.754515 | -7.13865 | 3.458871 |
| 11 | 4.450025 | -6.923591 | 2.673201 |
| 12 | 8.9479034 | -16.39611 | 7.593050 |
| 13 | 27.908341 | -50.795117 | 23.40624 |
| 14 | 20.99 | -40.6856 | 19.998 |

**3-11:Qlosses at base case and minimum voltage**

| Bus(i) | $Q_{losses}$ at voltage of base case | $Q_{losses}$ at Vmin=0.95v |
|---|---|---|
| 4 | 3.29299 | 8.21640 |
| 5 | 14.97199 | 28.9918 |
| 6 | 7.9050 | 10.485086 |
| 9 | 3.4179596 | 3.485224 |
| 10 | 0.09500 | 0.094429 |
| 11 | 0.26700 | 0.2851777 |
| 12 | 0.200 | 0.224317 |
| 13 | 0.73400 | 0.777115 |
| 14 | 0.4420 | 0.393860 |

- St**ep 3.** Derive the membership function of the reactive power losses from the assumed membership function of the bus voltage using the above equation. Here, we use a trapezoidal membership function for the bus voltage and the reactive power losses. The formulation of these memberships is shown in “Figure 3-3”.

- S**tep 4.** At a specific loading condition, determine, for each bus, the value of the voltage membership and the value of reactive power loss membership as shown in “Table 3-12”.

- **Step 5.** According to equation (3.4) ;multiply the two fuzzy sets to obtain the decision S(i) for each bus. Arrange in an ascending order, for each loading condition these decisions, from the smallest to the largest one. Buses having the smallest S are specified as weak buses and we may need to install capacitor at these buses . “Table 3-13” shows that bus 14 is the weakest bus.

**Table 3-12: Voltage and reactive power losses membership**

| **Bus(i)** | $u_v(i)$ | $u_q(i)$ |
|---|---|---|
| 4 | 1 | 1 |
| 5 | 1 | 1 |
| 6 | 1 | 1 |
| 9 | 1 | 1 |
| 10 | 1 | 1 |
| 11 | 1 | 1 |
| 12 | 1 | 1 |
| 13 | 1 | 1 |
| 14 | 0.9831 | 0.9976 |

**Table 3-13: Decision S(i) for each bus.**

| **Bus(i)** | **Voltage(p.u)** | $u_v(i)$ | $u_q(i)$ | $S(i) = u_v(i) \otimes u_q(i)$ |
|---|---|---|---|---|
| 4 | 0.974 | 1 | 1 | 1 |
| 5 | 0.980 | 1 | 1 | 1 |
| 6 | 0.980 | 1 | 1 | 1 |
| 9 | 0.952 | 1 | 1 | 1 |
| 10 | 0.949 | 1 | 1 | 1 |
| 11 | 0.960 | 1 | 1 | 1 |
| 12 | 0.963 | 1 | 1 | 1 |
| 13 | 0.957 | 1 | 1 | 1 |
| 14 | 0.934 | 0.9831 | 0.9976 | 0.98074 |

*C h a p t e r   F o u r*

# 4 SIMULATION OF ADOPTED SYSTEM.

## 4.1 CONTROL SYSTEM OF DSTATCOM

The use of compensators with improved qualifications such as distribution static synchronous compensator (DSTATCOM) has garbed researcher's attention for solving power quality problems. The (DSTATCOM) is a compensation device used in a shunt configuration across the mains of the primary distribution system. DSTATCOM makes use of a voltage source converter and internally generates capacitive (i.e. leading) as well as inductive (i.e. lagging) reactive power. The control system of the DSTATCOM is very fast and has the capability to provide adequate reactive power compensation to the distribution system. Due to this capability, DSTATCOM can be effectively used to regulate voltage drop that occurs during the starting of large loads and/or large induction motors where the required starting current is very high .Dstatcom is palced at bus 14 ;while the size“ Mvar” of Dstatcom can be determined by using Bstatcom as shown in “(Figure 4-1)”. Bstatcom is an ideal three phase voltage and current measurement, the size of Dstatcom can change by changing the value of base power.

During switching Dstatcom to the system the current will be huge as well as transient voltage as shown in “(Figure 4-2)”; low pass filter is used to reduce this transient value so the transient voltage can be controlled as not exceed 1.05pu.To calculate the consumed active and reactive power, single phase voltage and single phase current are measured and these signals are connected to low pass filter to reduce the transient. The filtered voltage and current signals are connected to fourier analysis to give magnitude and angle. The product block takes three signals (magnitude voltage, magnitude current and sin angle) to give the total consumed reactive power.

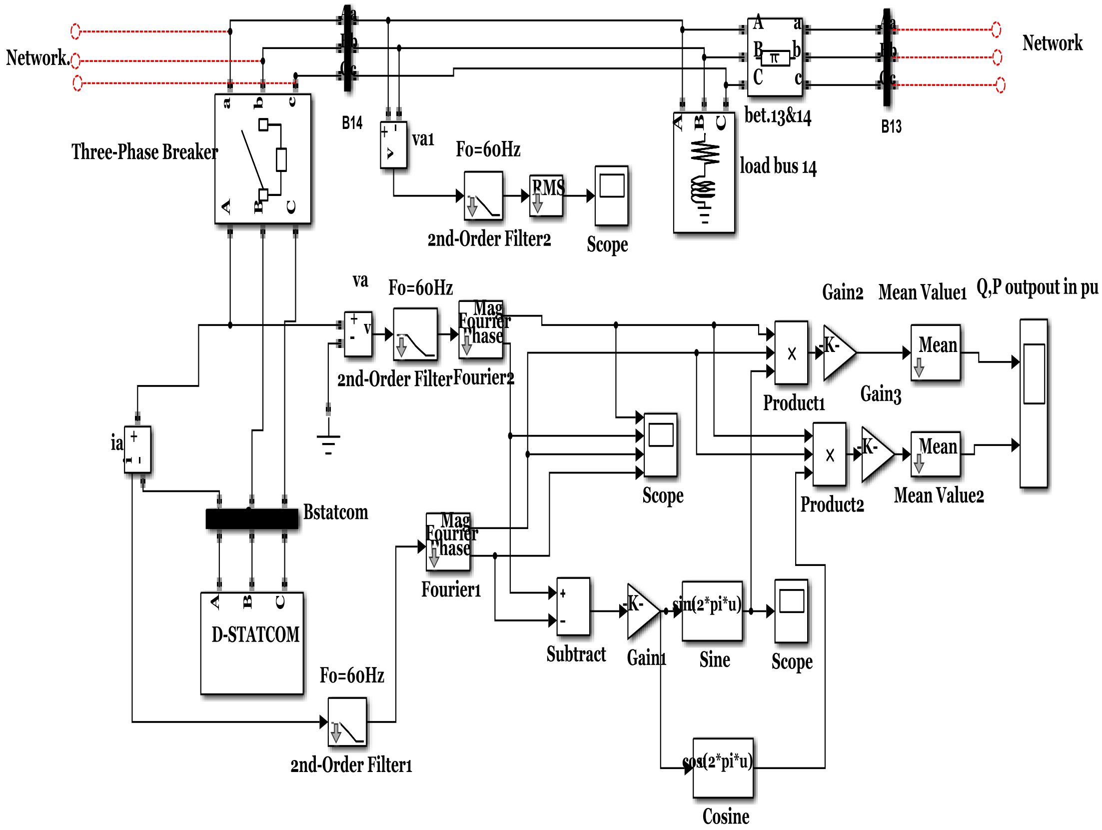



**Figure 4-1:Dstatcom at bus 14**

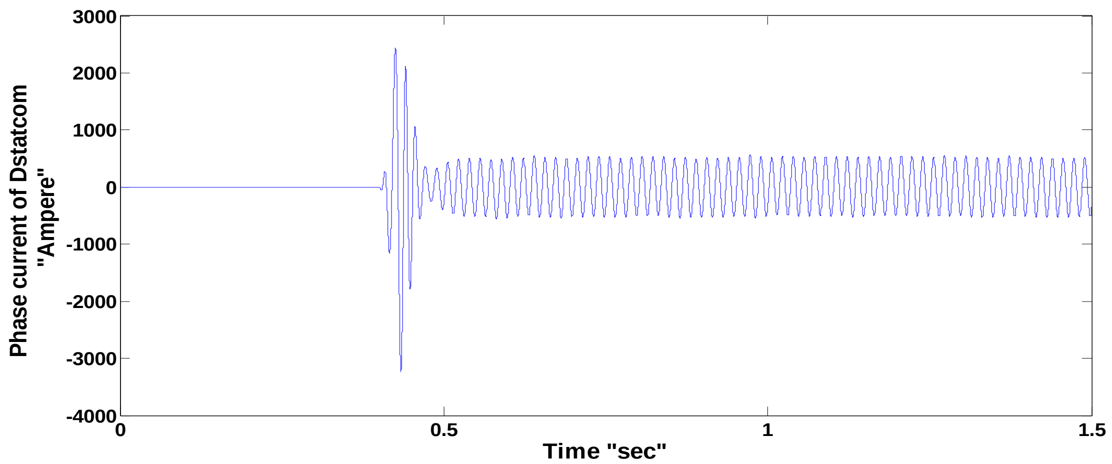



**Figure 4-2: Transient current**

"(Figure 4-3)" shows the controller of Dstatcom [32]which consists of the following:

- **Measurement unit:** It gives Idq and magnitude AC voltage

- **AC voltage regulator**: Compares between reference AC voltage and the magnitude AC voltage to give ($I_{q\ ref}$).

- **DC voltage regulator:** Compares between reference DC voltage and the magnitude DC voltage to give ($I_{d\ ref}$).

- **Mux**: Has two inputs ($I_{q\ ref}$) and ($I_{d\ ref}$) to give one output "$I_{dq\ ref}$".

- **Current regulator:** Compares between ($I_{dq\ ref}$) and the given ($I_{dq}$) from the measurement unit to give ($V_{dq}$) .

according to comparison between magnitude AC voltage and AC reference voltage ;angle (phi) can be calculated from (Vdq) which used as a modulation index for PWM

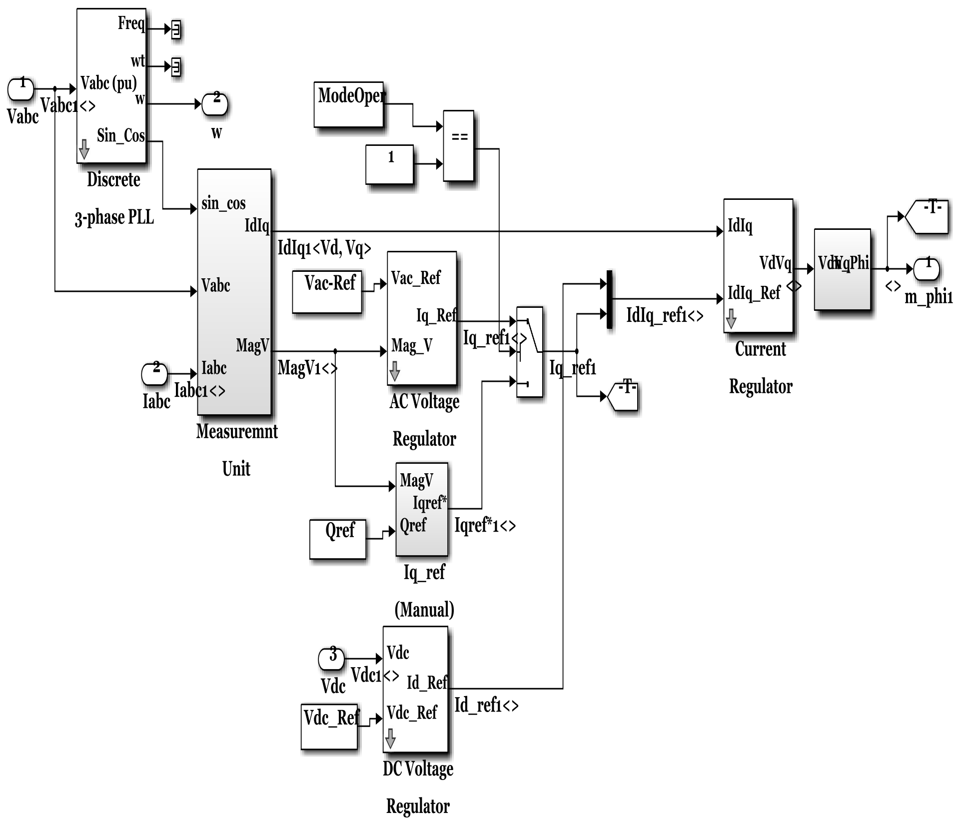



**Figure 4-3: Controller of Dstatcom**

“(Figure 4-4)” shows The voltage control system in ac voltage regulator of the Dstatcom is adjusted to reference voltage and according to this value the reactive power will conduct.

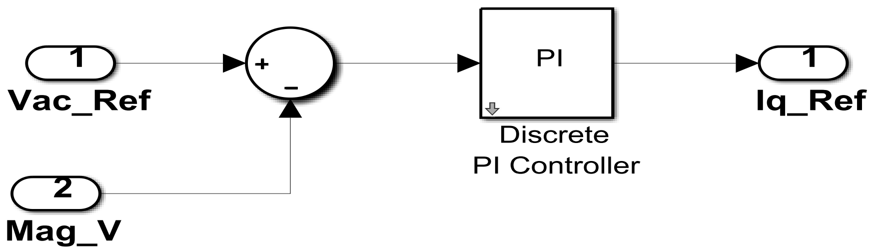



**Figure 4-4: AC voltage regulator**

## 4.2 SYSTEM VOLTAGE CONTROL USING DSTATCOM UNIT

To achieve the best results power quality and power reliability[33] are taken to consideration by sizing Dstatcom according to network requirement and by placing Dstatcom in more than one place according to the sensitivity of each bus respectively .In this section, the effect of using Dstatcom unit to regulate the system voltage is studied. The effect of changing the location as well as the size of the compensator unit on the system voltage is conducted.

According to the sensitivity analysis method $\partial Qi/\partial|Vi$ of bus no 12 comes next to that of bus no 14. For this reason, bus no.12 and bus no.14 have been chosen to be the most suitable locations for the compensator unit. “Table 3-5” has shown that 20MVAR reactive compensator unit has been chosen for the rest of the analysis unless otherwise stated, so the optimum size for Dsatacom will be 20MVAR for the following analysis.

### 4.2.1 Compensator located at bus 14

A 20MVAR compensator unit size is located at bus 14. The overall system dynamic performance under different scenarios is studied. The voltage control system of the Dstatcom shown in Figure 3-4 is adjusted such that to set the voltage at bus 14 to 1p.u. or 0.98 pu.. “(Figure 4-5)” shows the effect of switching on the compensator unit on the voltage at bus no.14. The compensator is switched on at t=0.4 sec. It is clear that the Dstatcom unit injects the required capacitive reactive power to regulate the voltage at the bus to the set values. “(Figure 4-6)” shows the instantaneous reactive power injected by the voltage control unit under different values of the voltage reference set values.

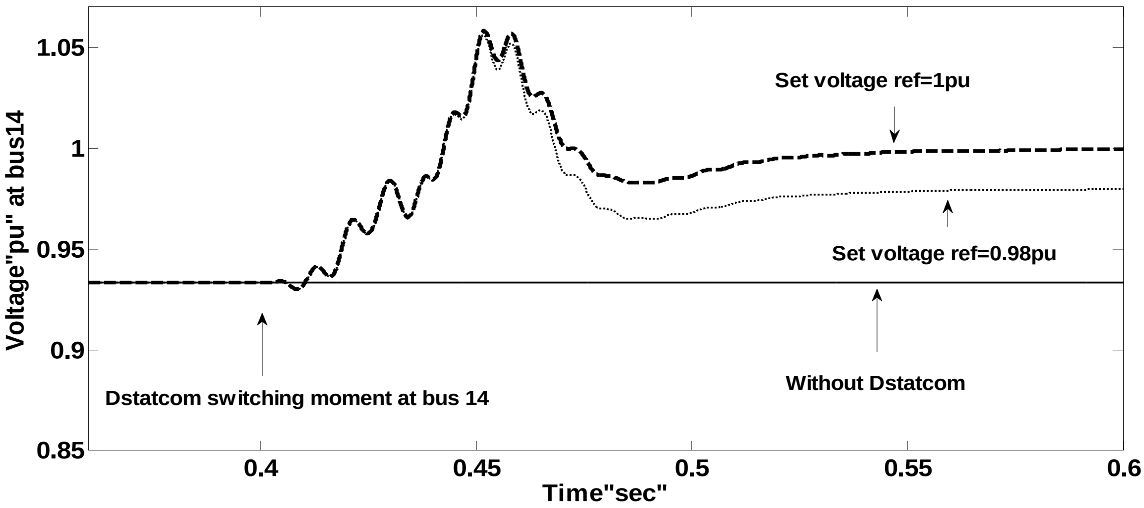



**Figure 4-5:Voltage at bus 14 when a 20MVAR Dstatcom unit is located at bus no.14**

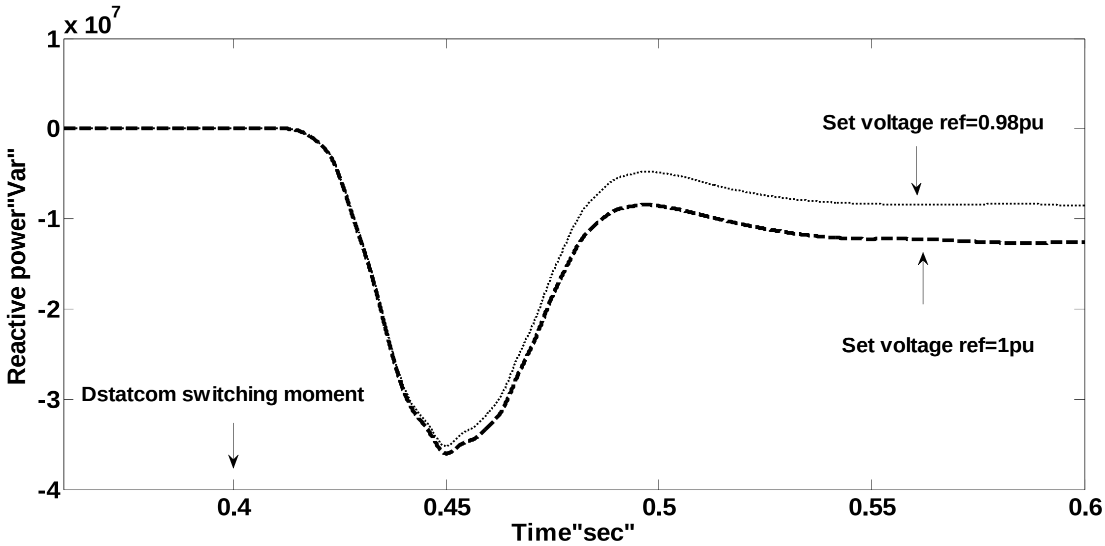



**Figure 4-6:Injected reactive power at bus 14 when a 20MVAR Dstatcom unit is located at bus no.14**

### 4.2.2 Compensator located at bus 12

The previous scenario is repeated when a 20MVAR compensator unit size is located at bus 12 and the overall system performance is investigated. “(Figure 4-7)” and “(Figure 4-8)” show the effect of voltage control at bus no. 12 on the weakest bus voltage (bus no.14) and on bus 12. The effect is clear in raising the bus voltage. The instantaneous reactive power injected in this case at bus no 12 is shown in “(Figure 4-9)”.

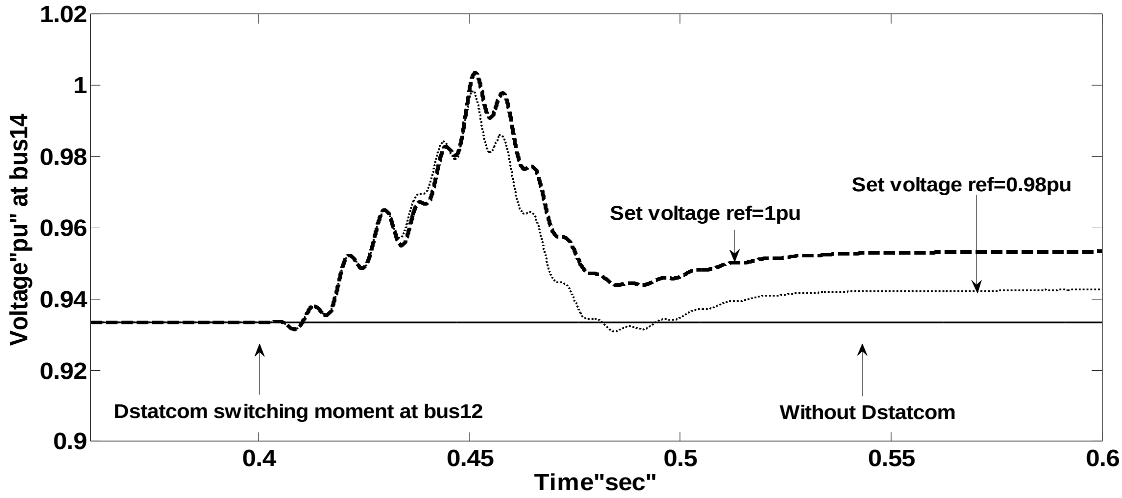



**Figure 4-7:Voltage at bus 14 when a 20MVAR Dstatcom unit is located at bus no.12**

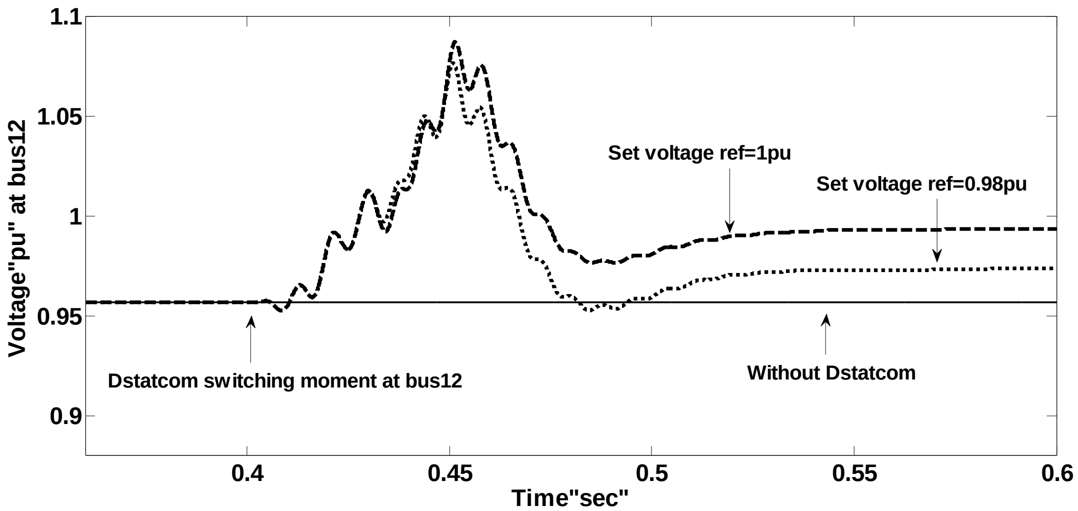



**Figure 4-8:Voltage at bus 12 when a 20MVAR Dstatcom unit is located at bus no.12**

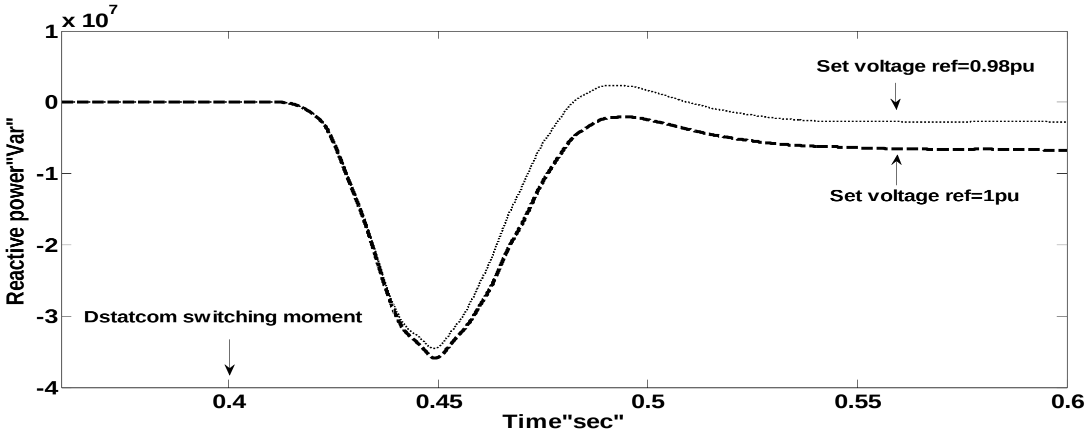



**Figure 4-9:Injected reactive power at bus 12 when a 20MVAR Dstatcom unit is located at bus no.12**

### 4.2.3 Two Compensators at Bus 12 and Bus 14.

The effect of using two Dstatcom units with 10MVAR size each at bus 12 and bus 14 on the system voltage is studied. The voltage control system of the compensator located at bus 14 is set to 0.98 pu and that at bus 12 is set to 1.0. The compensators are switched on at t=0.4 sec. “(Figure 4-10)” shows the variation of the voltage at bus no.14 while “(Figure 4-11)” shows the voltage at bus no 12. It is clear the two compensators forces the voltages at the two bus bars to the set values. The injected reactive power of the two units is shown in “(Figure 4-12)”.The reactive power changes by changing the voltage as shown in “(Figure 4-13)”;so any small change in reference voltage will affect on the consumed reactive power.

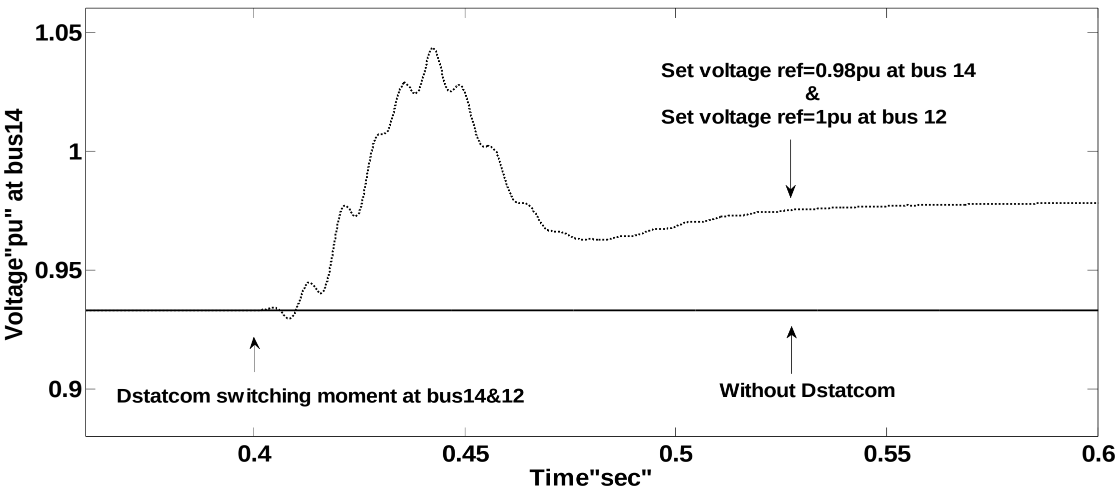



**Figure 4-10:Voltage at bus 14 when two compensators units are used at bus 12 and bus 14 with 10MVAR size each**

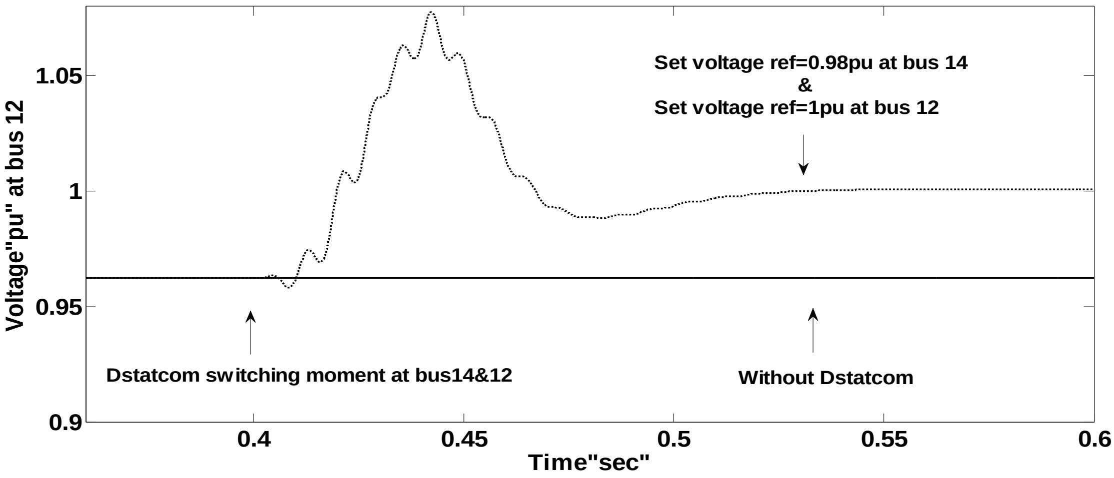



**Figure 4-11:Voltage at bus 12 when two compensators units are used at bus 12 and bus 14 with 10MVAR size each**

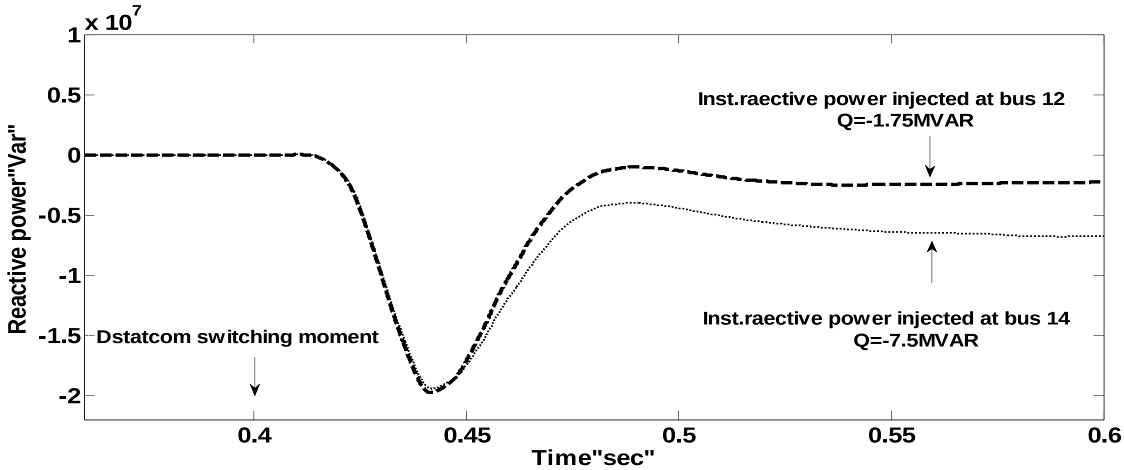



**Figure 4-12:Injected reactive power at bus 12 and 14 when two compensators units are used at bus 12 and bus 14 with 10MVAR size each**

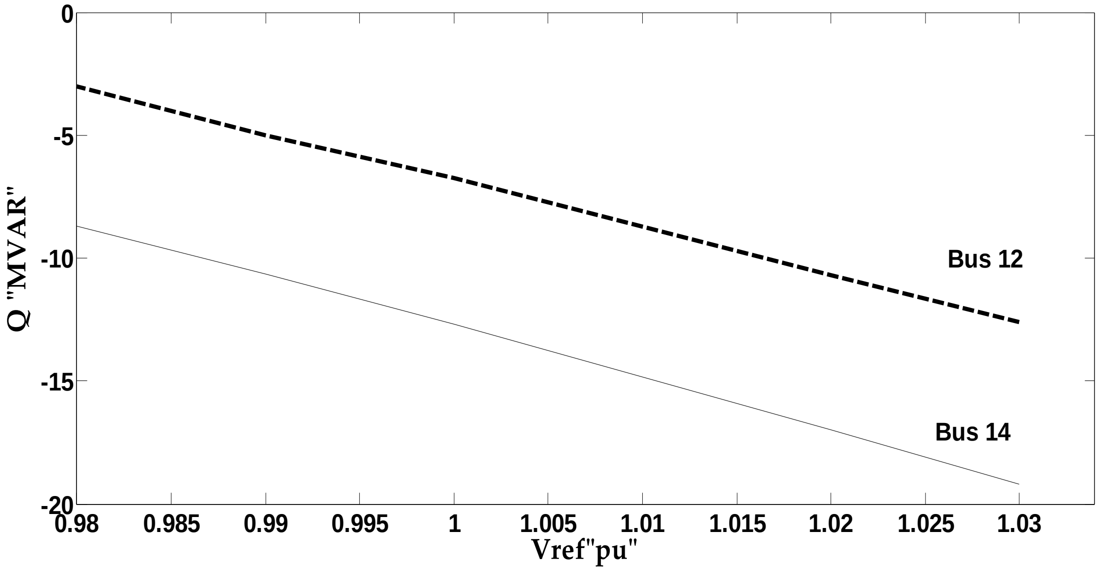



**Figure 4-13:Injected reactive power at bus 12 and 14 at different Vref**

## 4.3 RESPONSE OF DSTATCOM

This thesis shows how Dstacom supports the system during fault condition and when reactive power loads increased where there is line outage that makes voltage-collapse, this weakest line can be identify by using Fast Voltage Stability Index (FVSI).

### 4.3.1 Voltage Sag.

External short circuit can be represented by three phase fault on the transmission system level as shown in “(Figure 4-14)” which effect on distributed system “14 bus system” by voltage sag.

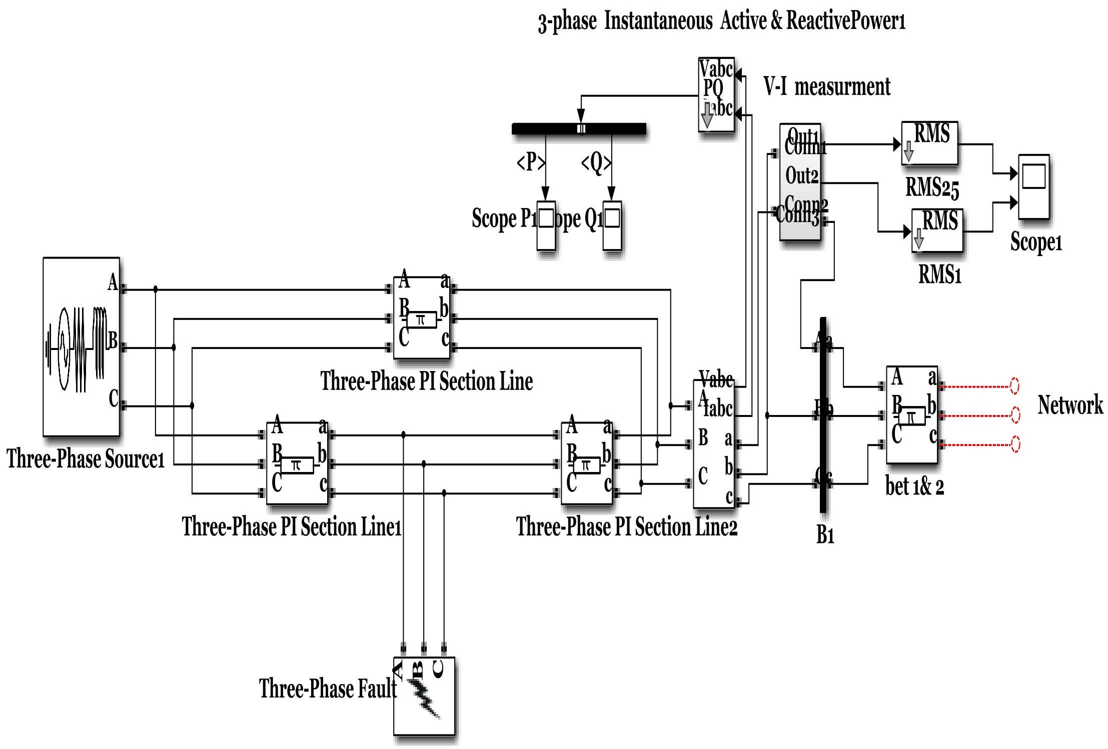



**Figure 4-14:Three phase fault on the transmission system level**

The effect of the compensator size on the system in case of voltage sag is investigated. A comparison between 20 MVAR and 100MVAR units(100MVAR is unrealistic unit ;it used only for demonstrating the fault condition by using Dstatcom) are undertaken. A voltage sag due to a three phase fault on the transmission system level occurs at t=0.6 sec to t=0.9sec. “(Figure 4-15)” shows that 20 MVAR compensator units lightly improves the voltage at bus no 14 while the sag remains because of the limited compensator size. Using a larger size compensator (100MVAR in this case), the voltage at bus 14 is totally recovered. Yet, practically, using such large size compensator is not economical. “(Figure 4-16)”shows the required reactive compensation during the period of the voltage sag in the two cases.

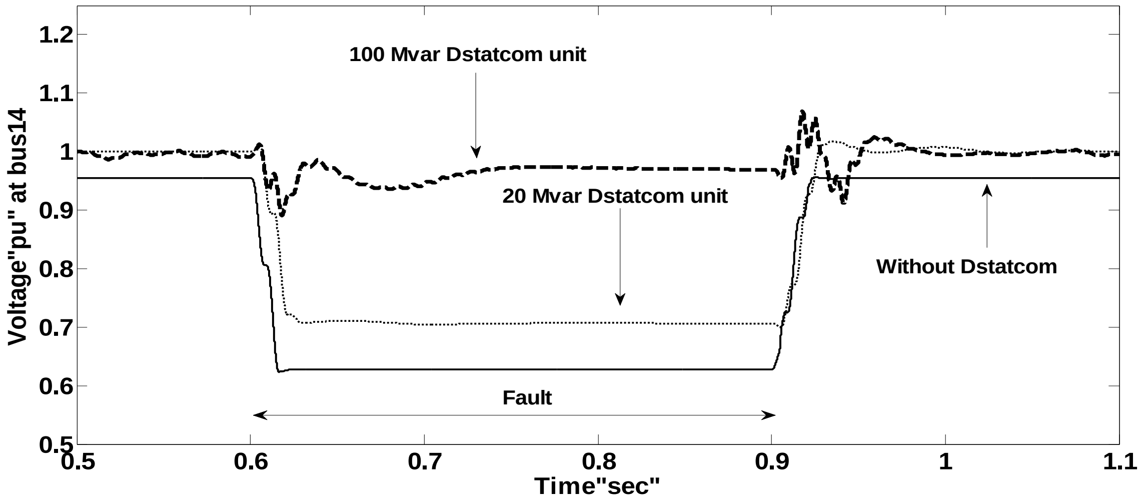



**Figure 4-15:Voltage at bus 14 during fault**

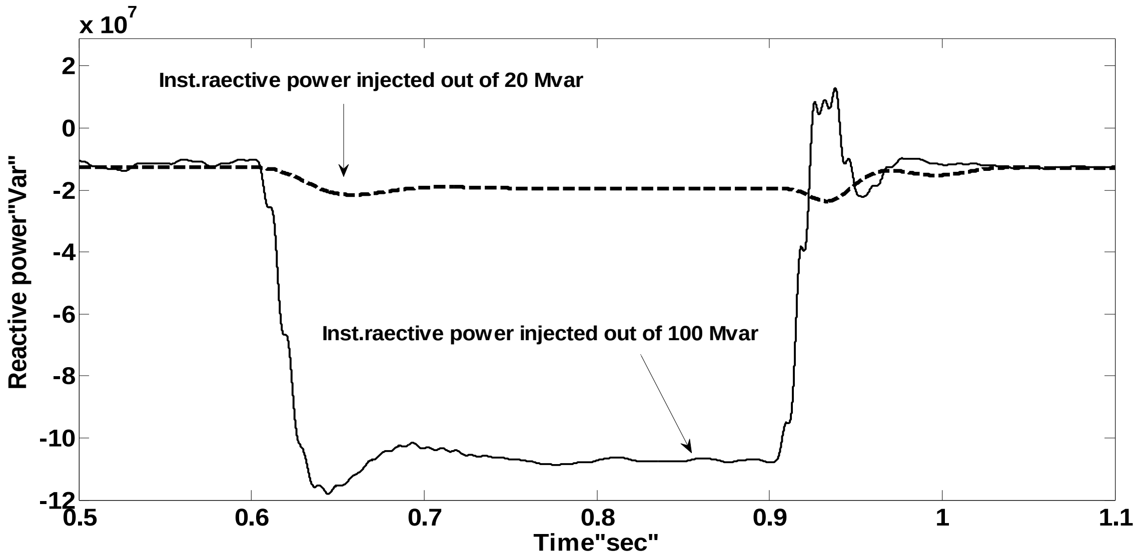



**Figure 4-16: Consumed reactive power at bus 14 during fault**

## 4.3.2 Line Outage

In case of IEEE 14 Bus system, line which connects bus 9 to bus 14 is considered to be the critical line according to the fast voltage stability index (FVSI), by Taking the symbols ‘i’ as the sending bus and ‘j’ as the receiving bus ,FVSI is calculated as shown in “Table 4-1”;where Qi ,Vi,X and Z are given in Appendix( A) and Appendix (B).In this section line(14-9) is removed by switch as shown in“(Figure 4-17)” to simulate contingency in the system and the dynamic response of the compensator unit located at bus 14 is demonstrated. “(Figure 4-18)” shows the variation of the voltage at bus 14 with and without Dstatcom during line outage.. The compensator of 20 MVAR is switched on at t=0.6 sec. As a result the compensator forces the voltage to recover to the set reference value. The amount of reactive power needed corresponding to this case is illustrated in “(Figure 4-19)”. At t=0.9 sec the line is reconnected to the system and the compensator keeps the voltage at the set value.

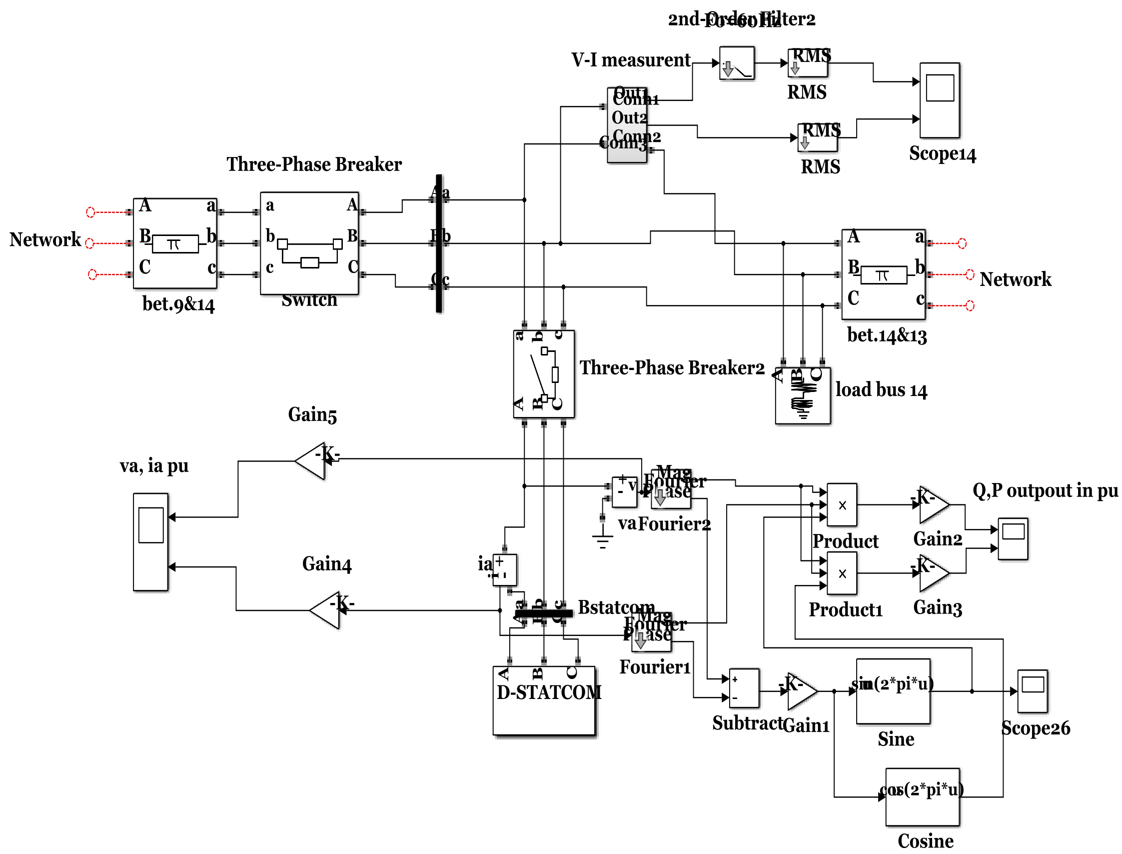



**Figure 4-17:System during line outage**

**Table 4-1:Fast voltage stability index**

| Bus | line | FVSI |
|---|---|---|
| 4 | 2-4 | -0.0290 |
| | 3-4 | -0.031401 |
| | 5-4 | $-7.52*10^{-3}$ |
| 5 | 1-5 | 0.01344 |
| | 2-5 | 0.011728 |
| | 4-5 | 0.003 |
| 6 | 11-6 | 0.0763 |
| | 12-6 | 0.10185 |
| | 13-6 | 0.053674 |
| 9 | 10-9 | 0.071123 |
| | **14-9** | **0.25128** |
| | 4-9 | Out |
| | 7-9 | Out |
| 10 | 9-10 | 0.0247 |
| | 11-10 | 0.05717 |
| 11 | 6-11 | 0.018311 |
| | 10-11 | 0.0181575 |
| 12 | 6-12 | 0.0209822 |
| | 13-12 | 0.031030 |
| 13 | 6-13 | 0.0395 |
| | 12-13 | 0.111 |
| | 14-13 | 0.11488 |
| 14 | 13-14 | 0.094310 |
| | 9-14 | 0.0728 |

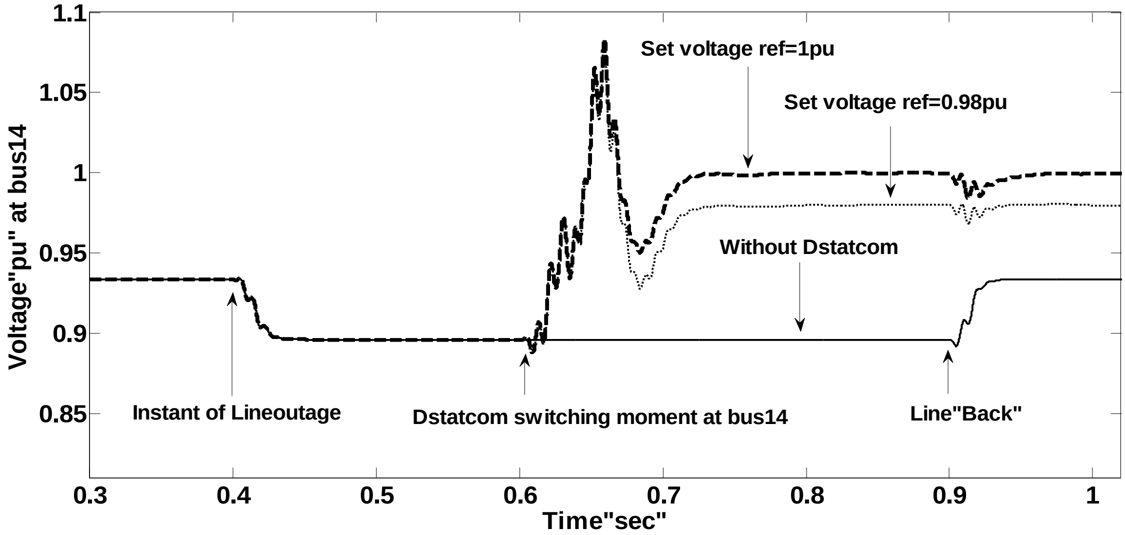



**Figure 4-18: Voltage at bus 14 during line outage**

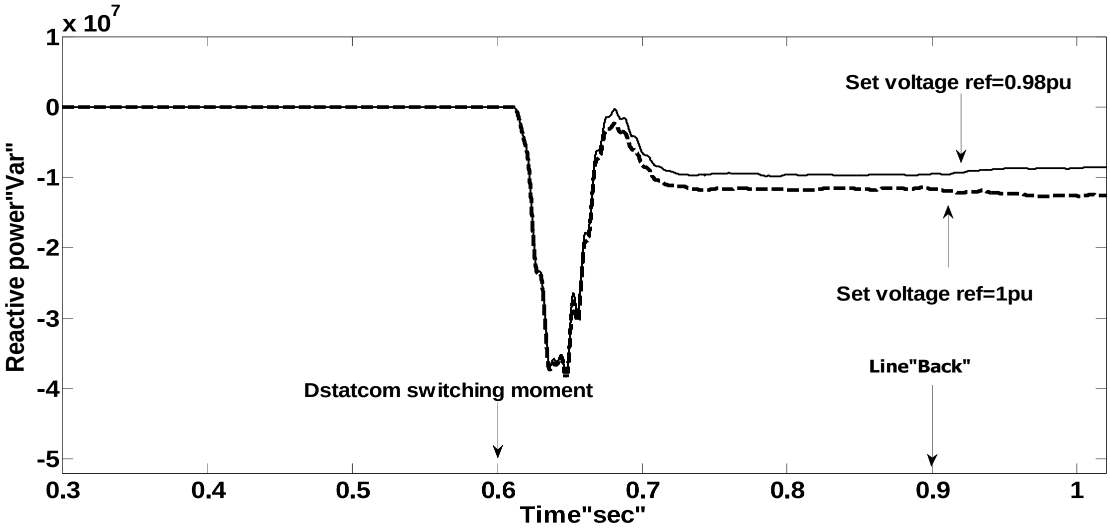



**Figure 4-19: Consumed reactive power at bus 14 during line outage**

### 4.3.3 Increasing Load

#### 4.3.3.1 Increasing loads by 20% in addition to start up two large induction motors:

20% increase in system load [see Appendix( D) ] ;where in addition to start up two large induction motors each of 200hp at bus 14 occurs at t=0.55 through a switch and two motors are connected to the bus 14 through (pi section) to prevent linearity during simulation as shown in “(Figure 4-20)” .“(Figure 4-21)” shows that when loads increased, the voltage sag occurs at bus no 14. At t=0.8 sec the Dstatcom (20MVAR) is switched on with set reference voltage equal to 1 pu. After a short transient period, the compensator succeeded to raise the bus voltage but not to the set value because of the limited compensator size. In case of using larger size compensator (40MVAR), the voltage at bus no. 14 recovered to the set value. Reactive power injected at bus no. 14 in both cases is shown in“(Figure 4-22)”.

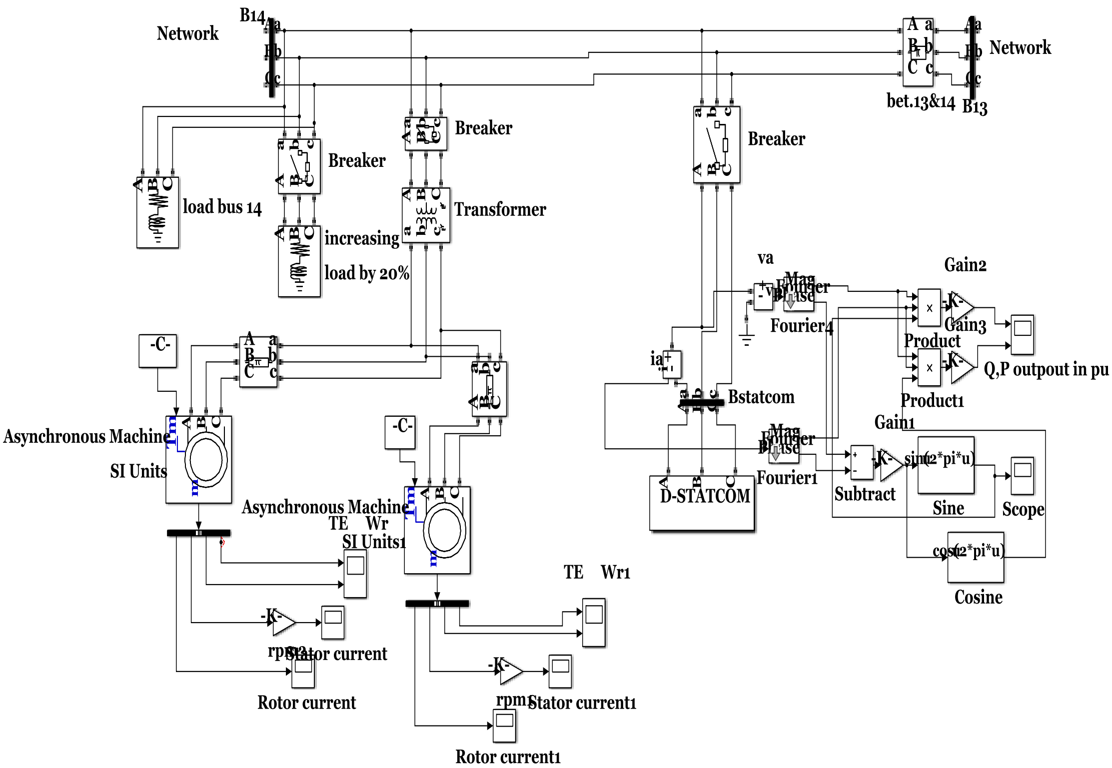



**Figure 4-20: System during increasing loads by 20% in addition to two motors**

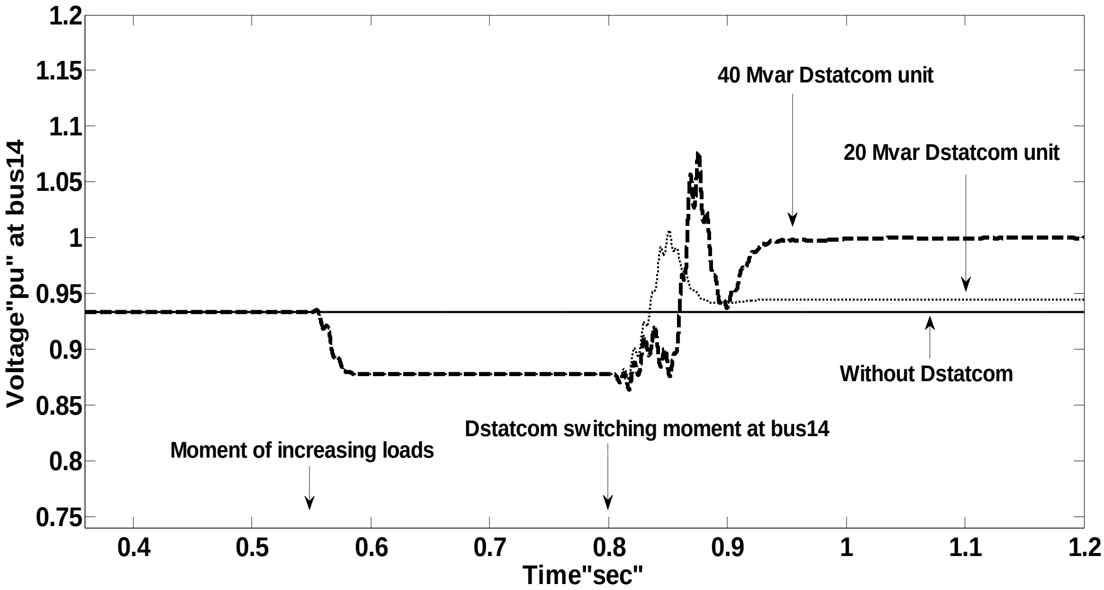



**Figure 4-21:Voltage at bus 14 in case of increasing the load**

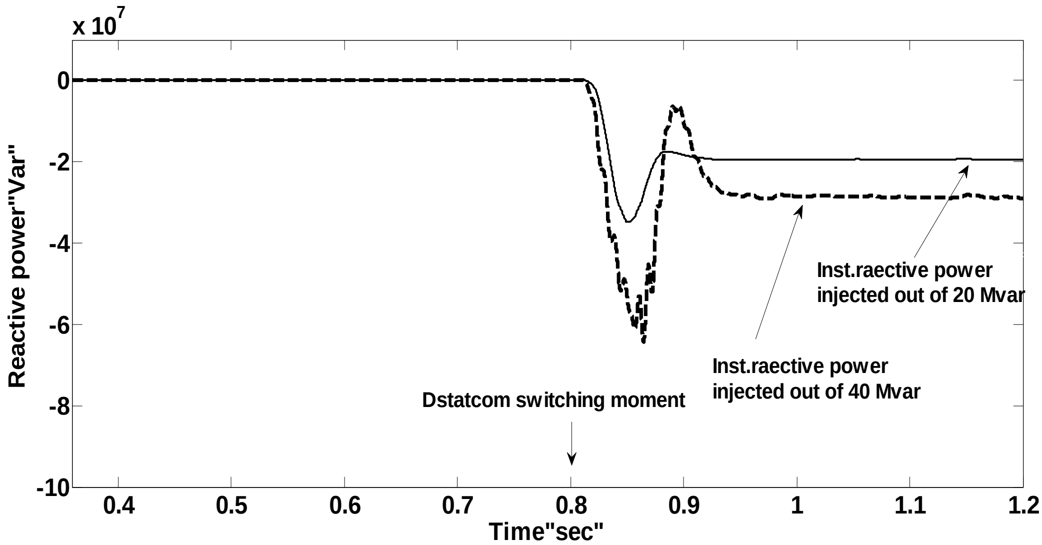



**Figure 4-22:Injected reactive power at bus 14 in case of increasing the load**

## 4.3.3.2 Increasing and decreasing loads by 20%:

"(Figure 4-23)" and"(Figure 4-24)" show simulation block diagrams of 20% increase and decrease in system load [Appendix( D)] ,The voltage and the consumed reactive power in case of increasing loads by20% and decreasing loads by 20% at t=0.55sec are shown in "(Figure 4-25)" and "(Figure 4-26)" .Dstatcom (20MVAR"limited") with reference voltage 0.98pu is switched at t=0.8sec where the voltage at bus 14 recovered to this set value .The reactive power in case of increasing load will consumed 22MVAR as a capacitive reactive power more than the limited value because it is overloaded and in case of decreasing loads the reactive power will be inductive.

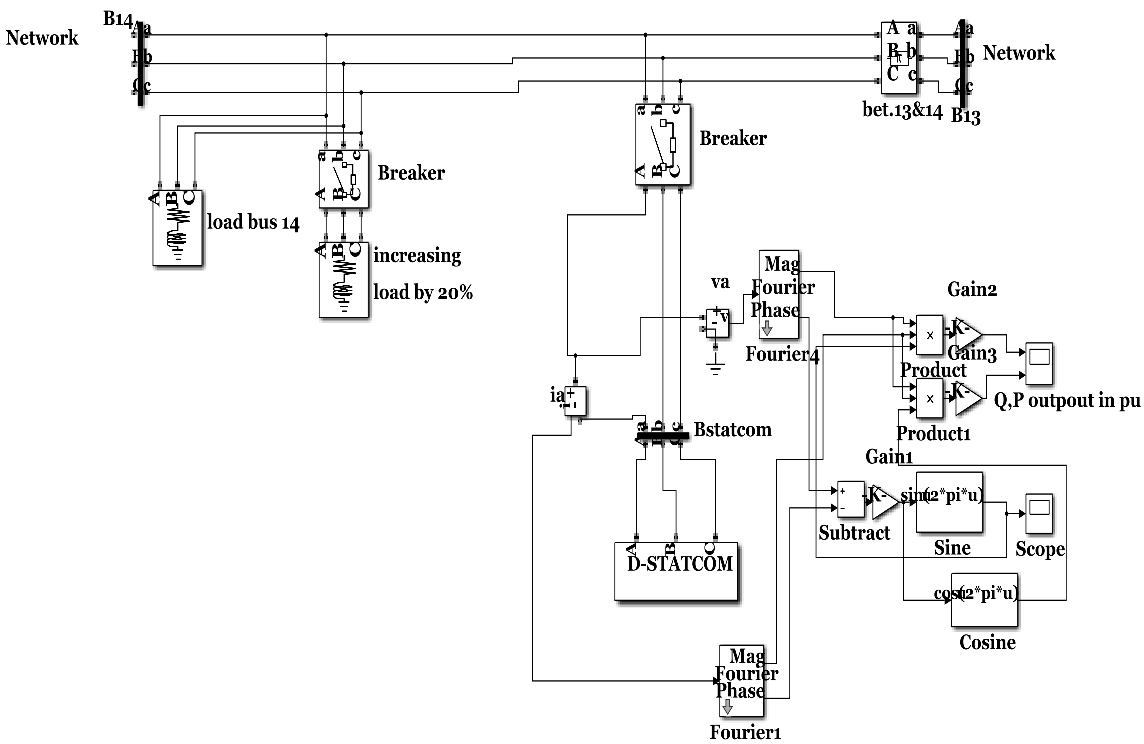



Figure 4-23:Simulation block diagram during increasing loads by 20%

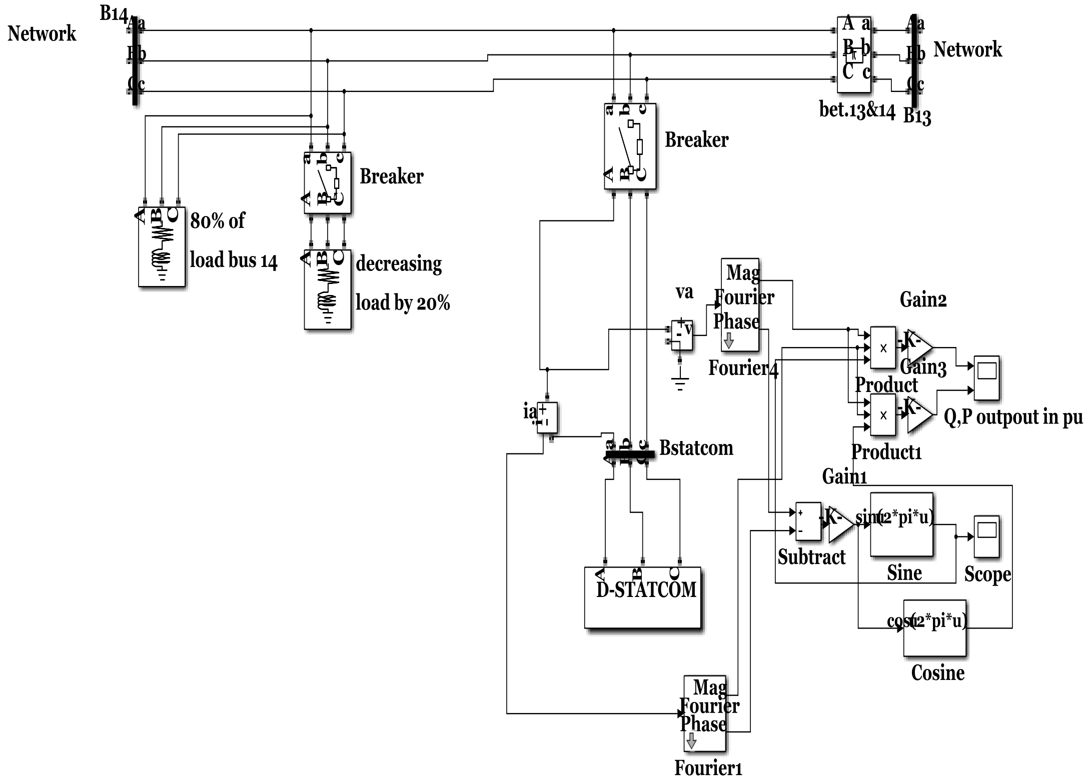



**Figure 4-24: Simulation block diagram during decreasing loads by 20%**

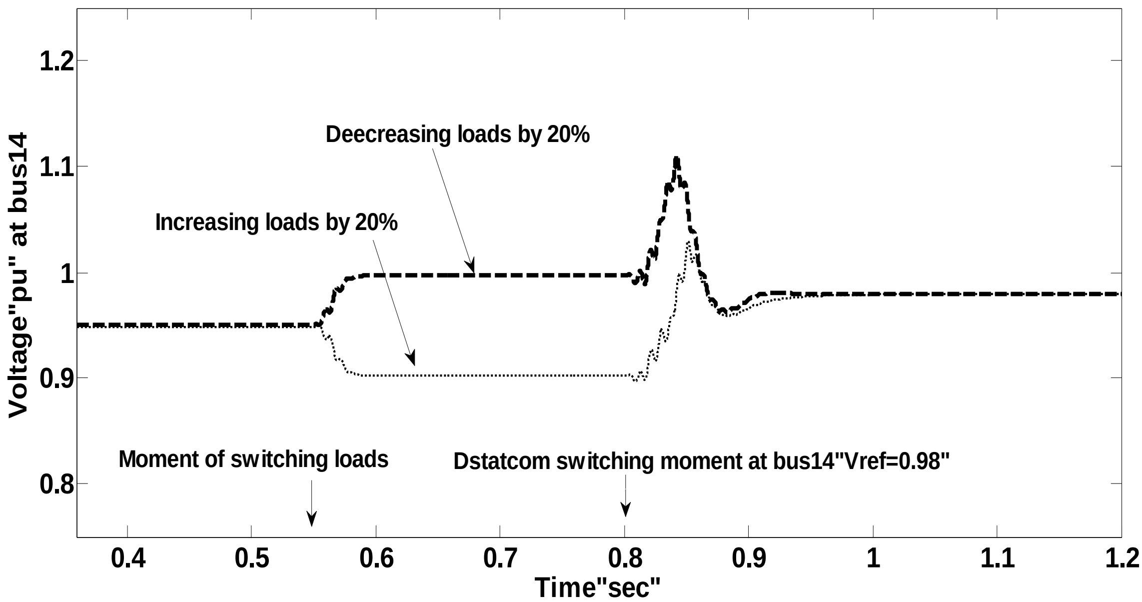



**Figure 4-25:Voltage at bus 14 in case of increasing and decreasing loads by 20%**

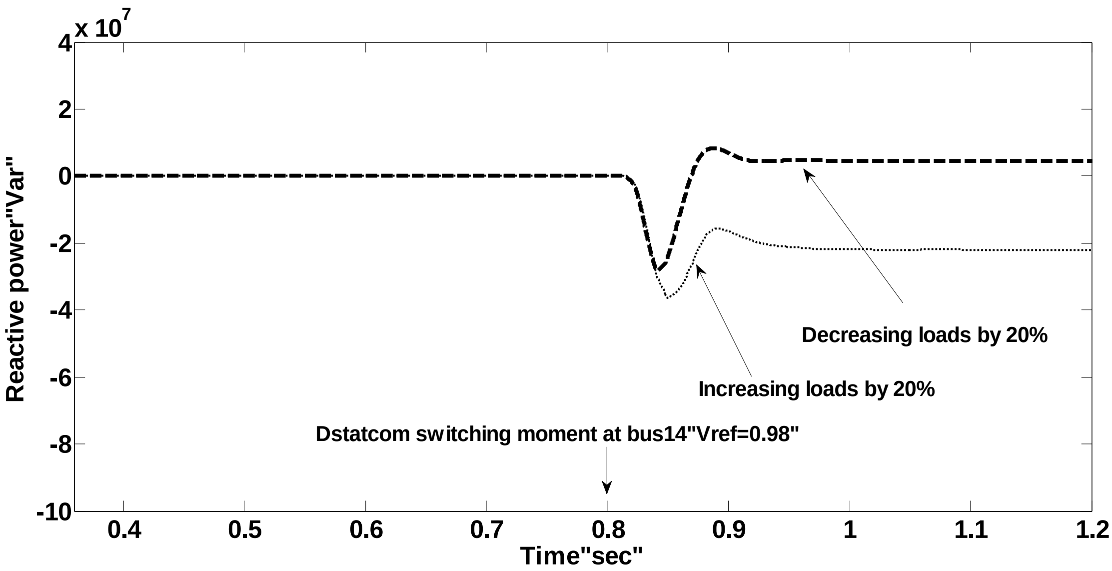



**Figure 4-26:Reactive power at bus 14 in case of increasing and decreasing loads by 20%**

#### 4.3.3.3 Increasing loads by 20% in addition to start up four large induction motors:

If 20% increase in system load in addition to start up four large induction motors each of 200hp at bus 14 occurs at t=0.55sec.the torque, voltage, stator current and speed are measured.

"(Figure 4-27)" , "(Figure 4-28)" and"(Figure 4-29)" show supporting the system by Dstatcom ,constant capacitor and capacitive load respectively at bus 14 during increasing the loads of the system by 20% in addition to start up four large induction motors at bus 14 occurs at t=0.55sec .Dstatcom has the best response which support the system earlier than the others;"(Figure 4-30)" , "(Figure 4-31)", "(Figure 4-32)" and "(Figure 4-33)" show the comparison between torque, voltage, stator current and speed if the system in the following cases :

- **Without compensation:** system is not supported by any reactive power
- **With constant capacitive load:** the capacitive value is equal to the consumed reactive power when the system is supported by Dstatcom "Vref=1pu" where Qc equal 18.3 Mvar during increasing loads.
- **With Dstatcom:** system is supported by Dstatcom with $v_{ref}$ "1 pu"

- **With constant capacitor: :** by trial the capacitive value to give 1 pu at bus 14 where the capacitance value is equal to **(**$3*10^{-4}$).

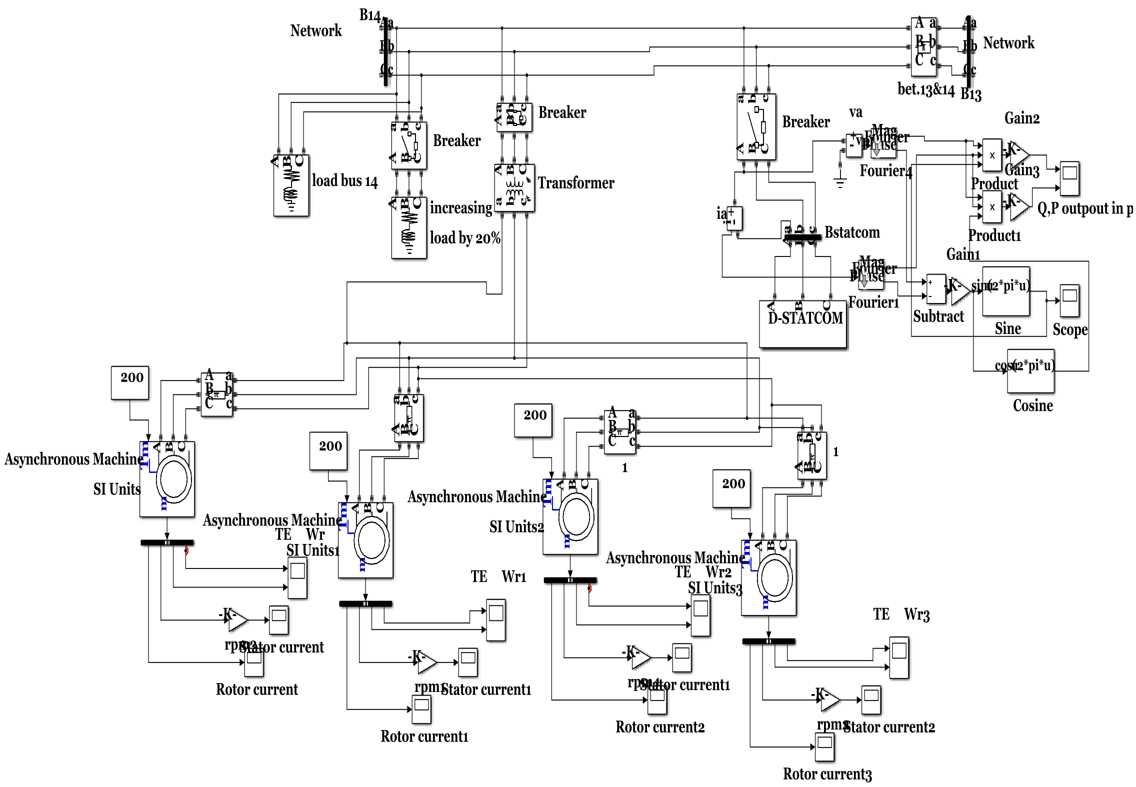



**Figure 4-27: IEEE 14 bus system supported by Dstatcom during increasing loads by 20% in addition to four motors**

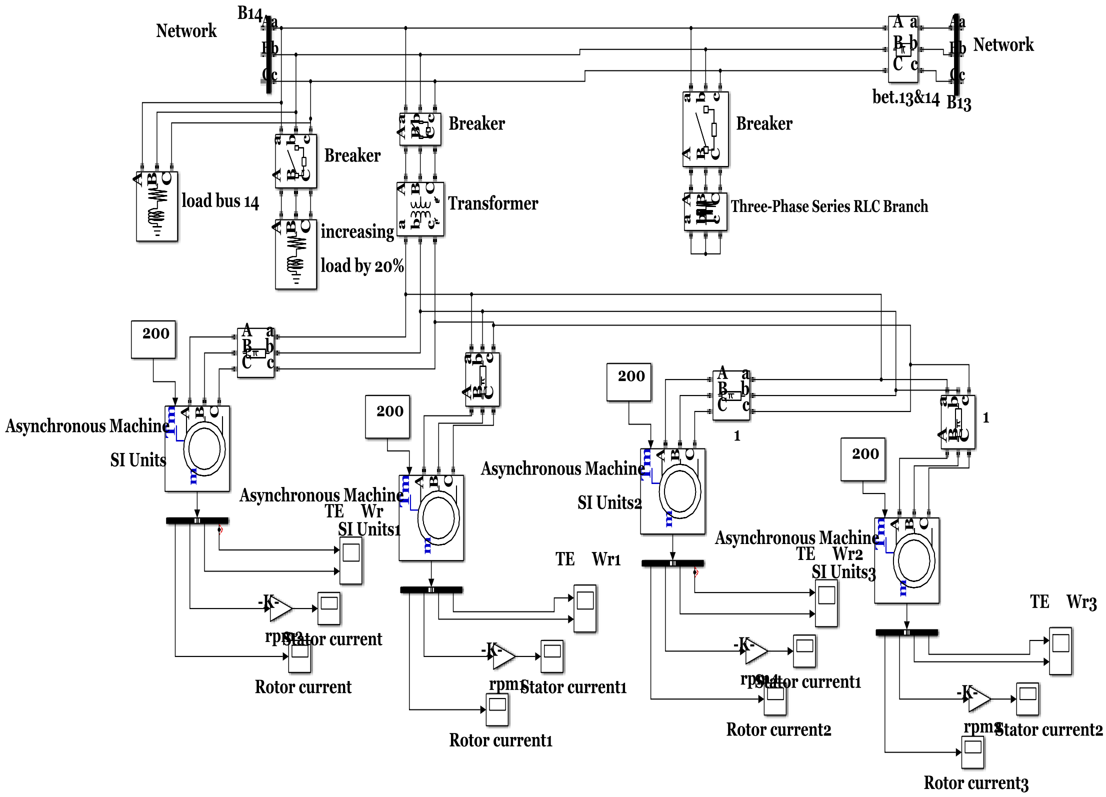



**Figure 4-28:IEEE 14 bus system supported by constant capacitor during increasing loads by 20% in addition to four motors**

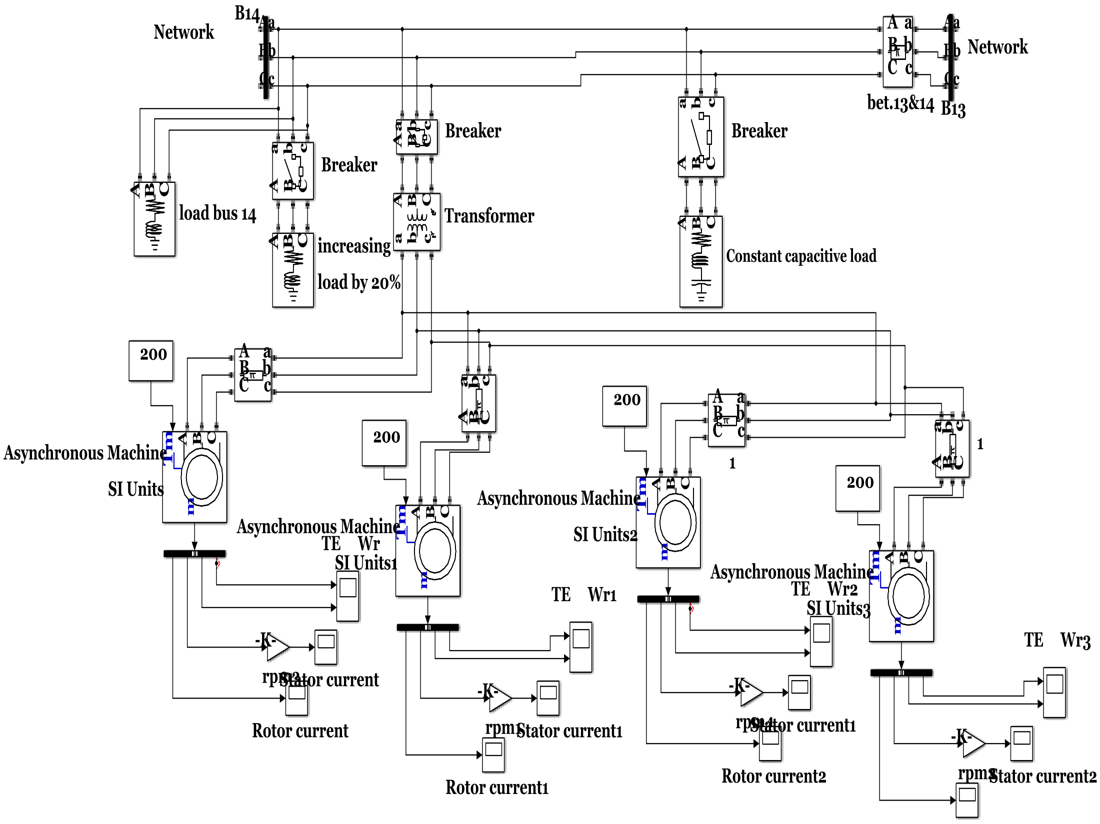



**Figure 4-29: IEEE 14 bus system supported by capacitive load during increasing loads by 20% in addition to four motors**

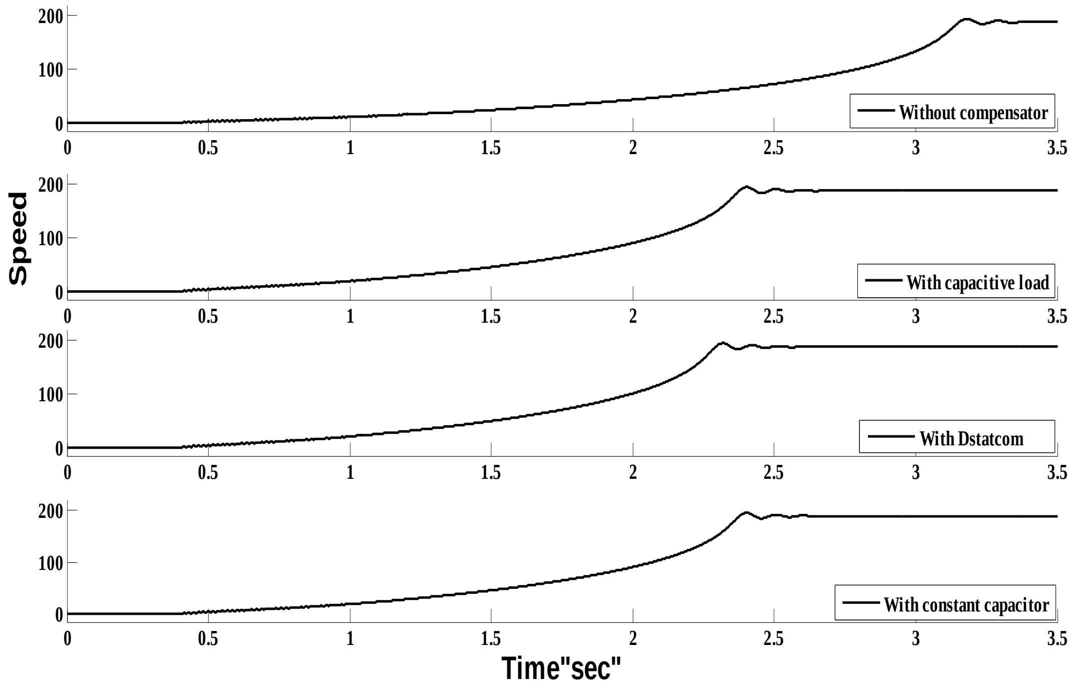



**Figure 4-30: Speed of induction motors when system is supported by different types of compensation**

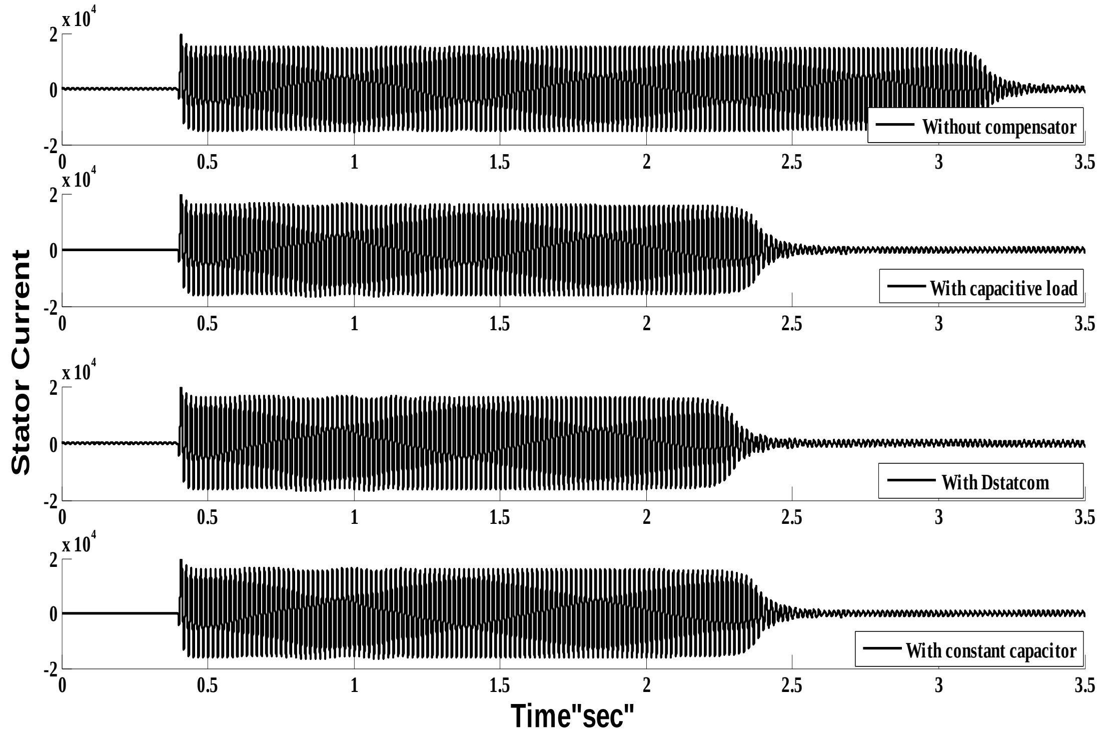



**Figure 4-31:Stator current of induction motors when system is supported by different types of compensation**

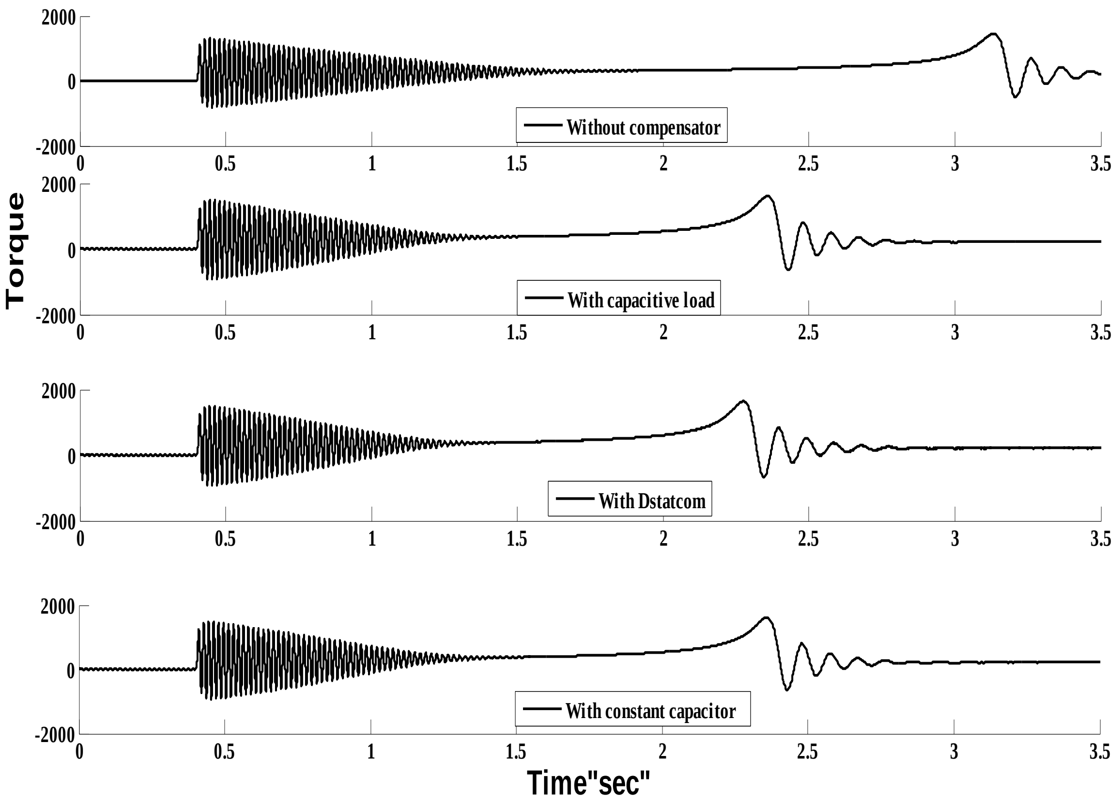



**Figure 4-32:Torque of induction motors when system is supported by different types of compensation**

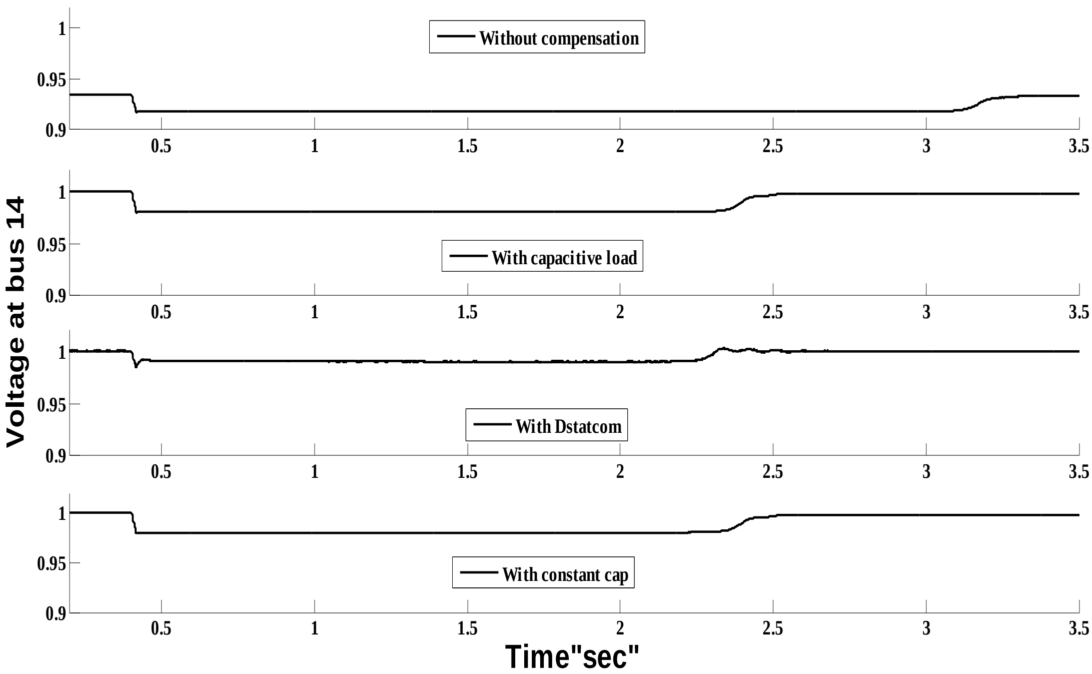



**Figure 4-33:Voltage at bus 14 when system is supported by different types of compensation**

## 4.4 Nose Curve

Evaluation of power system security is necessary in order to develop ways to maintain system operation when one or more elements fail. A power system is secure when it can withstand the loss of one or more elements and still continue operation without major problems it is important to analyze the power system to identify the overloads and predict problems that can occur.

The power system may suffer from one of the following problems:

- Severe: when several elements such as lines and transformers become overloaded and at risk of damage.

- Critical: when the power system becomes unstable and will go to collapse.

In static voltage stability analysis, slowly developing changes in the power system occur that eventually lead to a shortage of reactive power and declining voltage. This phenomenon can be seen from the plot of power transferred versus the voltage at receiving end. The plots are popularly referred to as P-V curve or “Nose” curve. Now, identification of voltage collapse point is obtained using this conventional P-V curve. There is a critical point beyond which there is no load flow solution and the load flow method will not converge. Such a load point represents the “knee” point of the P-V curve. This is the point at which the voltage collapse occurs .Equation (4.1) derived from thevenin circuit “(Figure 4-34)” which shows that voltage at load buses with compensation and without compensation can be calculated with respect to the load active power PL and load reactive power QL.

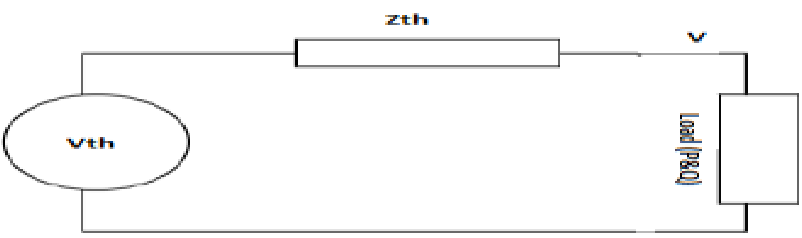



**Figure 4-34:thevenin circuit**

$$S = V \; I^{*} \tag{4.1}$$

$$I = \frac{S^*}{V^*} = \frac{P - jQ}{V \angle 0} \tag{4.2}$$

$$V_{th} \angle \theta_{th} = V + I \; Z_{th} \tag{4.3}$$

$$V_{th} \angle \theta_{th} = V + \left(\frac{P - jQ}{V \angle 0}\right)(R_{th} + X_{th}) \tag{4.4}$$

$$V_{th} = \sqrt{\left(V + \frac{PR_{th}}{V} + \frac{QX_{th}}{V}\right)^2 + \left(\frac{PX_{th}}{V} - \frac{QR_{th}}{V}\right)^2} \tag{4.5}$$

$$V^2 V_{th}^2 = (V^4 + 2V^2 PR_{th} + 2V^2 QX_{th} + \frac{P^2 R_{th}^{\;2}}{V^2} + \frac{Q^2 X^2{}_{th}}{V^2} + \frac{P^2 X_{th}^2}{V^2} + \frac{Q^2 R^2{}_{th}}{V^2}$$

(4.6)

$$0 = (V^4 + V^2 (2PR_{th} + 2QX_{th} - V^2{}_{th}) + Z_{th}^2 \, (p^2 + Q^2)$$

(4.7)

$$V = V_L = \sqrt{\frac{E_{Th}{}^2}{2} - K_1 \pm \sqrt{R_{Th}^2 P^2 + K_2 + Q_L^2 X_{Th}^2 - X_{Th} E_{Th}^2 Q_L + \frac{E_{Th}{}^4}{4} - K_3}}$$

$$K_1 = Q_L X_{th} R_{th} P$$

$$K_2 = 2 \; Q_L X_{th} R_{th} P - R_{Th} P E_{Th}^2$$

$$K_3 = Z_{Th}^2 P^2 + Z_{Th}^2 Q_L^2$$

(4.8)

**Where:**

Eth: thevenin voltage.

Zth: Total thevenin impedance.

Xth: thevenin line reactance .

Rth: thevenin resistance.

V : load voltage.P:Active power.

$Q_L$:load reactive power.

“(Figure 4-35)”and “(Figure 4-36)” show how Open circuit voltage “Eth” and short circuit current at bus 12 and bus 14.Eth and Isc can be calculated by putting three phase fault and by removing the load at the required bus and replaced by a constant value of a capacitive load as shown in “Table 4-2” ,so the required Zth can be calculated in “Table 4-3” and “Table 4-4” . “(Figure 4-37)” and “(Figure 3-38)” show the total nose curve in different cases by coding equation(4.1) in matlab as shown in Appendix (C).

Figure 4-37)” and “(Figure 3-38)” indicate that load active power bus 14 reach zero faster than bus 12 which indicates that bus 14 is the weakest bus.

**Table 4-2:Average voltage and standard deviation**

| **Dstatcom location (MVAR)** | | **Vref (p.u.)** | | **Injected Qc (MVAR)** | |
|---|---|---|---|---|---|
| **Bus 14** | **Bus 12** | **Bus 14** | **Bus 12** | **Bus 14** | **Bus12** |
| 20 | - | 0.99 | - | 10.65 | 0 |
| - | 20 | - | 0.99 | 0 | 5 |
| 10 | 10 | 0.98 | 1 | 7.5 | 1.75 |

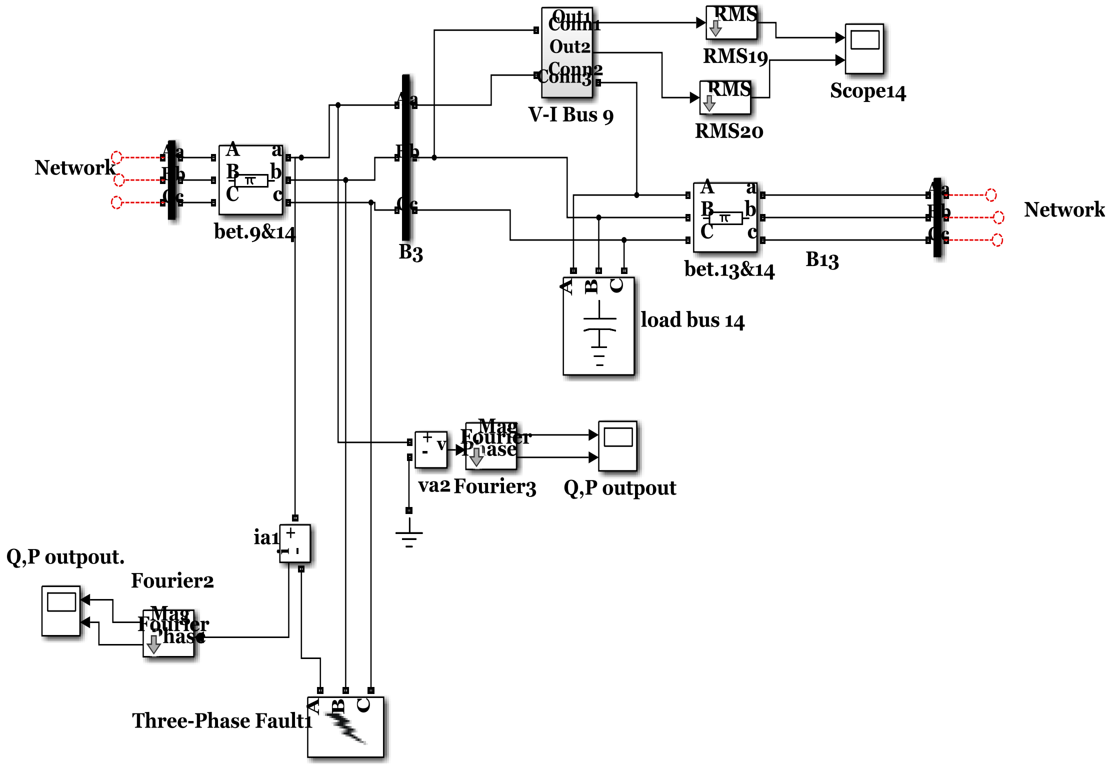



**Figure 4-35 : Short circuit current and open circuit voltage at bus 14**

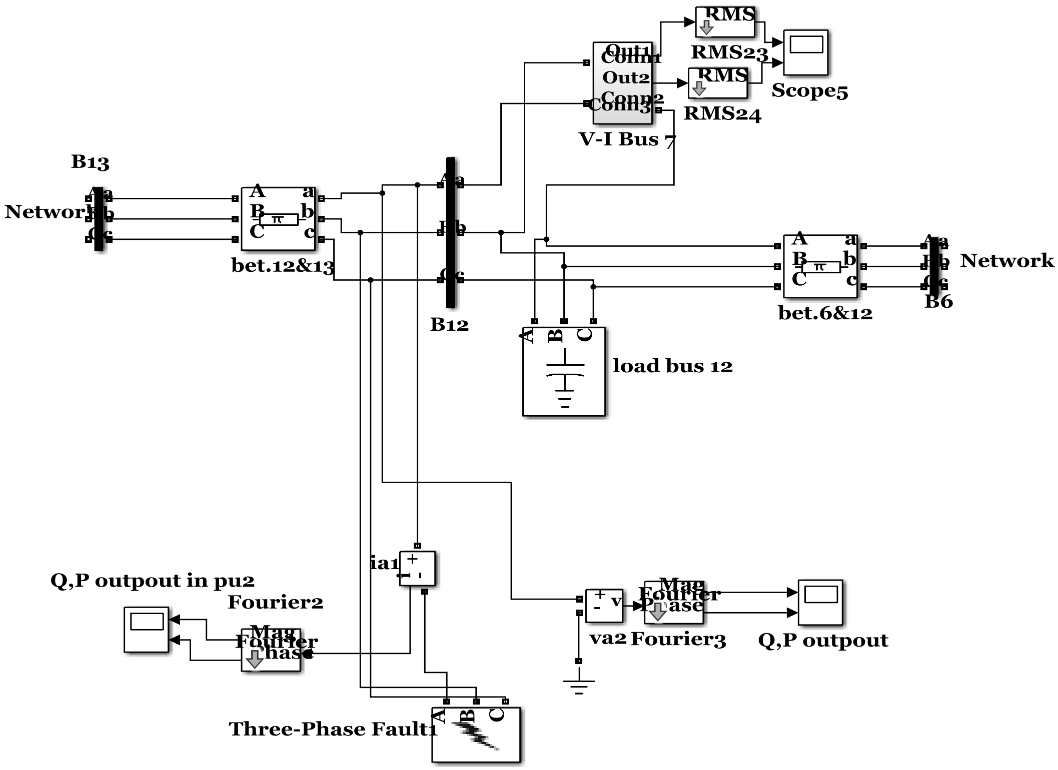



**Figure 4-36: Short circuit current and open circuit voltage at bus 12**

**Table 4-3: Eth, Rth, Xth and Isc calculations at bus 14**

| Dsatacom location(MVAR) | Vref of Dstatcom) | Eth (pu) | Isc (pu) | Rth (pu) | Xth (pu) |
|---|---|---|---|---|---|
| **Without compensation** | - | 0.99293 | 2.366 | 0.165725 | 0.38855 |
| **10MVAR at bus14 & 10MVAR at bus12** | 0.98pu at bus14 & 1pu at bus 12 | 1.034554 | 2.41454 | 0.163276 | 0.396138 |
| **20MVAR at bus 14** | 0.99pu at bus14 | 1.043340 | 2.412346 | 0.165510 | 0.39957 |

**Table 4-4:Eth, Rth, Xth and Isc calculations at bus 12**

| Dsatacom location(MVAR) | Vref of Dstatcom | Eth (pu) | Isc (pu) | Rth (pu) | Xth (pu) |
|---|---|---|---|---|---|
| **Without compensation** | - | 0.9864 | 2.2 | 0.177 | 0.412 |
| **10MVAR at bus14 & 10MVAR at bus12** | 0.98pu at bus14 & 1pu at bus 12 | 1.004645 | 2.239 | 0.17712 | 0.41226 |
| **20MVAR at bus 12** | 0.99pu at bus12 | 1.013432 | 2.2069 | 0.182885 | 0.42120 |

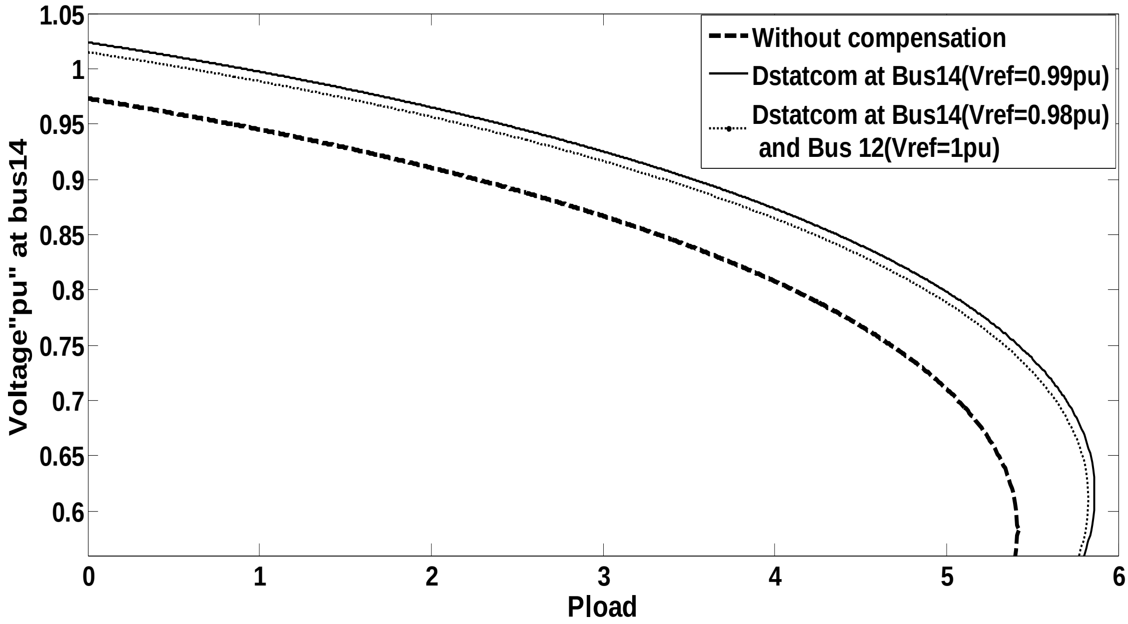



**Figure 4-37:Nose cure at bus 14**

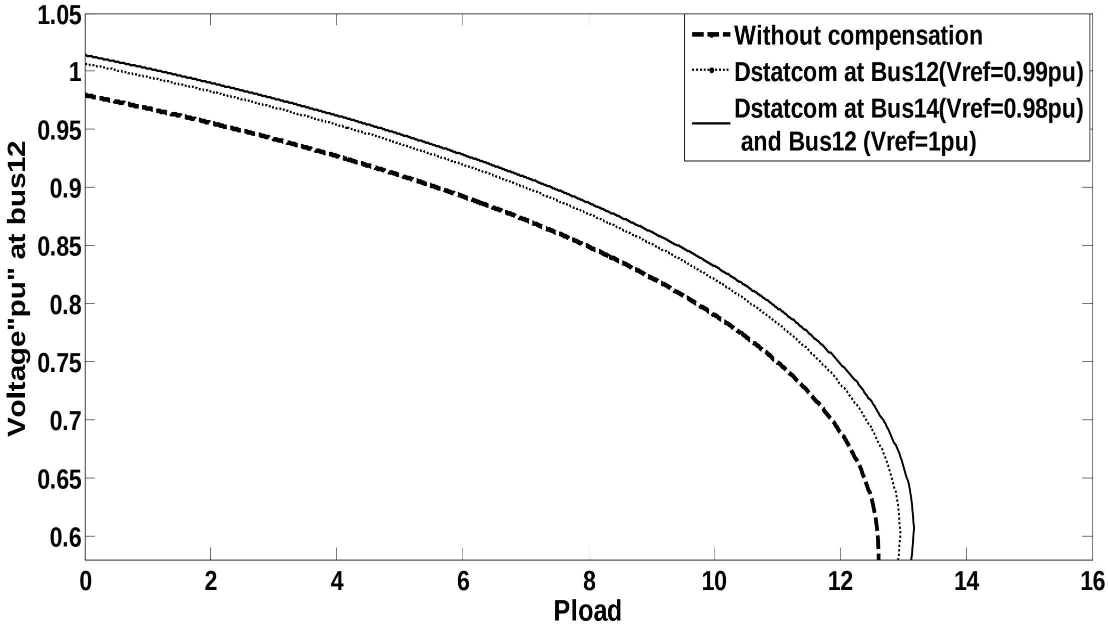



**Figure 4-38: Nose cure at bus 12**

*C h a p t e r  F i v e*

# 5 RESULTS.

## 5.1 SYSTEM VOLTAGE CONTROL USING DSTATCOM UNIT

### 5.1.1 Compensator located at bus 14:

A 20MVAR compensator unit size is located at bus 14. The overall system dynamic performance under different scenarios is studied. “Table 5-1” shows that by changing the voltage reference value from 0.98 to 1 pu change the required reactive power from -8.7 MVAR to -12.7MVAR ; the reference voltage affects on the total system average voltage and standard deviation; this table demonstrates that the average voltage during each case are semi equal , but the reference voltage affects on the consumed reactive power and standard deviation

Chapter 4 demonstrates bus 14 is the best location for Dstatcom. If Dstatcom is placed in load buses such as bus 6,9,10,11,12,13 and 14 to enforce the voltage at bus 14 to be 1 pu “13800 volt” by regulating the reference voltage in AC voltage regulator for each bus; the consumed reactive power will be calculated in each case as shown in “Table 5-2” which demonstrates that bus 14 consumes the minimum reactive power.

**Table 5-1:Average voltage and standard deviation when Dstatcom is located at bus 14**

| Bus | Vref (pu) | Vavg (pu) | S.D (σ) | Q(Mvar) |
|---|---|---|---|---|
| 14 | 1 | 1.011232 | 0.02138 | -12.7 |
| | 0.98 | 1.0008585 | 0.02420 | -8.7 |

**Table 5-2:Injected Qc to approach 1pu at bus 14**

| Bus / Vref | 6 | 9 | 10 | 11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|
| 1.06 | 20 VAR | | | | 18.8Mvar | | |
| 1.021 | | 23.5MVAR | | | | | |
| 1.028 | | | 19.5Mvar | | | | |
| 1.05 | | | | 20Mvar | | | |
| 1.04 | | | | | | 18.2Mvar | |
| 1 | | | | | | | 12.7Mvar |

### 5.1.2 Compensator located at bus 12:

The previous scenario is repeated when a 20MVAR compensator unit size is located at bus 12 and the overall system performance is investigated. “Table 5-3” shows that by changing the voltage reference value from 0.98 to 1 pu change the required reactive power from -3 MVAR to -6.75MVAR. The reference voltage affects on the total system average voltage and standard deviation, this table demonstrates that the bus 14 is the best location for Dsatacom by comparing average voltage and standard deviation when Dsatacom is placed at bus 14 and bus 12.

**Table 5-3:Average voltage and standard deviation when Dstatcom is located at bus 12**

| Bus | Vref (pu) | Vavg (pu) | S.D (σ) | Q(Mvar) |
|---|---|---|---|---|
| 12 | 1 | 0.99438 | 0.02561 | -6.75 |
| | 0.98 | 0.981936 | 0.02405 | -3 |

### 5.1.3 Two Compensators at Bus 12 and Bus 14.

A20MVAR compensator unit size is located at bus 12 & bus14.“Table 5-4” shows the sizing of Dstatcom which depends on reference voltage where The best one is 0.98 pu at bus 14 and 1 pu at bus 12 which consume a capacitive MVAR as well as MVAR will be inductive if the reference voltage is 1 pu at bus 14 and 0.98 pu at bus 12.Bus 14 required at least 8 Mvar,for example by using two Dstatcom with 5MVAR at bus 14 and 15 Mvar at bus 12 as shown in. “Table 5-4”,bus 14 will consume a capacitive MVAR more than 5MVAR

The effect of using two Dstatcom units with 10MVAR size each at bus 12 and bus 14 on the system voltage is studied where the voltage control system of the compensator located at bus 14 is set to 0.98 pu and that at bus 12 is set to 1.0. “Table 5-5” shows different scenarios for different size of the two compensator units with overall size equal to 20 MVAR,The voltage reference of the voltage controllers of the compensators is changed and the required reactive power is measured in each case. The system average voltage and its standard deviation are calculated as shown in “Table 5-6”. One of the study objectives was to see the possible benefits that could be obtained from coordination between more than one compensator in the system also this study indicate that one compensator unit located at the weakest bus has the power to regulate the system voltage with the minimum amount of reactive power. More than one unit will not reduce the amount of reactive power required to enhance the average voltage.

**Table 5-4:Consumed reactive power when Dstatcom is located at bus 12 and bus 14**

| Dstatcom location (MVAR) | | Vref (p.u.) | | Injected (MVAR) | |
|---|---|---|---|---|---|
| Bus 14 | Bus 12 | Bus 14 | Bus 12 | Bus 14 | Bus 12 |
| 10 | 10 | 0.98 | 1 | -7.5 | -1.75 |
| 12 | 8 | 0.98 | 1 | -7.5 | -1.75 |
| 8 | 12 | 0.98 | 1 | -7.5 | -1.75 |
| 5 | 15 | 0.98 | 1 | -6.6 | -2.35 |
| 10 | 10 | 1 | 1 | -13.4 | 1.35 |
| 10 | 10 | 1 | 0.98 | -13.5 | 2.1 |

**Table 5-5:Total consumed reactive power**

| Dstatcom location (MVAR) | | Vref (p.u.) | | InjectedQc MVAR | | Voltage in pu | |
|---|---|---|---|---|---|---|---|
| **Bus 14** | **Bus 12** | **Bus 14** | **Bus 12** | **Bus 14** | **Bus 12** | **Bus 14** | **Bus 12** |
| 20 | - | 0.98 | - | 8.7 | 0 | 0.98 | 0.995 |
| - | 20 | - | 0.995 | 0 | 6 | 0.955 | 0.995 |
| - | 20 | - | 1.01 | 0 | 8.8 | 0.964 | 1.01 |
| - | 20 | - | 1.02 | 0 | 10.7 | 0.978 | 1.02 |
| - | 20 | - | 1.033 | 0 | 13.2 | 0.98 | 1.033 |
| 10 | 10 | 0.98 | 0.995 | 8.75 | 0 | 0.98 | 0.995 |
| 10 | 10 | 0.98 | 1.01 | 5.2 | 5.2 | 0.98 | 1.01 |
| 10 | 10 | 0.98 | 1.02 | 3 | 8.6 | 0.98 | 1.02 |
| 10 | 10 | 0.98 | 1.033 | 0 | 13.4 | 0.98 | 1.033 |

**Table 5-6: Total Average voltage and standard deviation**

| Dstatcom location (MVAR) | | Vref(p.u.) | | Vavrg in pu | ST.D in pu |
|---|---|---|---|---|---|
| **Bus 14** | **Bus 12** | **Bus 14** | **Bus 12** | | |
| 20 | - | 0.98 | - | 1.0008 | 0.0242 |
| - | 20 | - | 0.995 | 0.9918 | 0.0278 |
| - | 20 | - | 1.01 | 0.9996 | 0.0265 |
| - | 20 | - | 1.02 | 1.0050 | 0.0255 |
| - | 20 | - | 1.033 | 1.0122 | 0.0251 |
| 10 | 10 | 0.98 | 0.995 | 1.0008 | 0.0244 |
| 10 | 10 | 0.98 | 1.01 | 1.0052 | 0.0238 |
| 10 | 10 | 0.98 | 1.02 | 1.0080 | 0.0242 |
| 10 | 10 | 0.98 | 1.033 | 1.0113 | 0.0243 |

## 5.2 RESPONSE OF DSTATCOM

### 5.2.1 Voltage sag

20 MVAR and 100 MVAR compensator are used at bus no 14 during sag while, 20 MVAR compensator units lightly improves the voltage at bus no 14 while the sag remains because of the limited compensator size.Using a larger size compensator (100MVAR in this case), the voltage at bus 14 is totally recovered ;using such large size compensator is not economical but it used to demonstrate that during fault the system consumed a large amount of reactive power to recover the system voltage as shown in “Table 5-7”.

**Table 5-7: Consumed reactive power and voltage without compensation at bus 14 during fault**

| Bus | Size of Dstatcom (MVAR) | Voltage at bus 14 (pu) | Q(Mvar) |
|---|---|---|---|
| 14 | 100 | 0.97 | -100 |
| | 20 | 0.7 | -20 |

### 5.2.2 Line outage

The compensator of 20 MVAR is used during line outage. the reference voltage affects on the total system average voltage and standard deviation as well as the consumed reactive power as shown in “Table 5-8” and “Table 5-9”.

;

**Table 5-8:Total consumed reactive power during line outage**

| Dstatcom location (MVAR) | | Vref (p.u.) | | Injected (MVAR) | |
|---|---|---|---|---|---|
| Bus 14 | Bus 12 | Bus 14 | Bus 12 | Bus 14 | Bus 12 |
| 10 | 10 | 0.98 | 1 | -9.3 | $-8*10^{-5}$ |
| 10 | 10 | 1 | 0.98 | -13.2 | 5.3 |
| 20 | - | 0.98 | - | -10 | - |
| 20 | - | 1 | - | -12 | - |
| - | 20 | - | 0.98 | - | -5.7 |
| - | 20 | - | 1 | - | -7.6 |

**Table 5-9:Average voltage and standard deviation during line outage**

| Dstatcom location (MVAR) | | Vref(p.u.) | | Vavrg in pu | ST.D in pu |
|---|---|---|---|---|---|
| Bus 14 | Bus 12 | Bus 14 | Bus 12 | | |
| 10 | 10 | 0.98 | 1 | 0.998190 | 0.02449 |
| 10 | 10 | 1 | 0.98 | 0.99024635 | 0.026142 |
| 20 | - | 0.98 | - | 0.996068 | 0.02500 |
| 20 | - | 1 | - | 1.002350 | 0.024532 |
| - | 20 | - | 0.98 | 0.98220 | 0.0326 |
| - | 20 | - | 1 | 0.98652 | 0.031634 |
| - | - | - | - | 0.9682 | 0.040055 |

### 5.2.3 Increasing load

When system loads increased by 20% in addition to two motors ;Dstatcom (20MVAR) is switched to the system with set reference voltage equal to 1 pu the compensator succeeded to raise the bus voltage but not to the set value because of the limited compensator size. In case of using larger size compensator (40MVAR), the voltage at bus no. 14 recovered to the set value. According to the reference voltage of the compensator the consumed reactive power will be injected .“Table 5-10” shows the total consumed reactive power in both cases and the voltage at bus 14 before and after compensation. This table indicates that during increasing static and dynamic loads the system needs more reactive power ;so the system should be supported by (31MVAR) capacitive reactive power as well as the limited reactive power (20MVAR) is not suitable for this case

**Table 5-10:Total consumed reactive power during increasing loads by 20% in addition to two motors**

| **Bus** | **$V_{ref}$ pu** | **Size of Dstatcom MVAR** | **Voltage at bus 14 (pu) before compensation** | **Voltage at bus 14 (pu) after compensation** | **$Q_{consumed}$ (Mvar)** |
|---|---|---|---|---|---|
| 14 | 1 | 40 | 0.87 | 1 | -31 |
| | | 20 | 0.87 | 0.944 | -20 |
| | | Without Dstatcom | 0.934 | - | - |

If system loads (static loads only) increased by 20% and decreased by 20% ;Dstatcom (20MVAR) is switched to the system with set reference voltage equal to 0.98 pu the compensator succeeded to raise the bus voltage to this set value. The total consumed reactive power in case of increasing loads will be 22MVAR as a capacitive reactive power more than the set value because the system is overloaded and the voltage will change from 0.9 pu to 0.98 pu ( set vaue “0.98pu”) ; but in case of decreasing loads the consumed reactive power will be inductive as the system is enforced to be in the set value “0.98 pu”.“Table 5-11” shows The total consumed reactive power the voltage at bus 14 in each case and the voltage at bus 14 before and after compensation

**Table 5-11:Total consumed reactive power during increasing and decreasing loads by 20%**

| Bus | Vref 0.98 pu | Size of Dstatcom MVAR | Voltage at bus 14 (pu) before compensation | Voltage at bus 14 (pu) after compensation | $Q_{consumed}$ (Mvar) |
|---|---|---|---|---|---|
| 14 | Dec. | 20 | 0.997 | 0.98 | $0.5*10^{-7}$ |
| | Inc. | 20 | 0.9 | 0.98 | -22 |

*Chapter Six*

# 6 CONCLUSION.

In this work, several methods have been utilized to identify the weakest busbar in an IEEE 14 bus system. The potential benefits that can be derived by applications of Dstatcom to industrial facility have been investigated. A study specifying the location as well as the suitable size of the Dstatcom unit that enhances the system voltage profile has been undertaken.. The study revealed that a small change in the reference voltage leads to a large change in the required reactive compensation. Locating the voltage compensator unit at the weakest bus will enhance the system average voltage.

One of the study objectives was to see the possible benefits that could be obtained from coordination between more than one compensator in the system indicated that one compensator unit located at the weakest bus has the power to regulate the system voltage with the minimum amount of reactive power. A trial has been made to see if using more than one compensator can help enhancing voltage regulation and decreasing the required reactive power, More than one unit will not reduce the amount of reactive power required to enhance the average voltage.The study indicated that the best results are obtained by locating one compensator with proper size at the weakest bus. The results indicated also the capability of the Dstatcom with proper size to counteract voltage sag ,increasing loads and/or line outage.

Dstatcom has a good response which reduce time to interact with any power system, and it can be  used with static and dynamic loads; so it can be used in industrial work .this thesis shows economical results by using Dstatcom in different cases and the reference voltage can control the amount of the consumed reactive power

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# APPENDIX A

The following figure represents the single line diagram for IEEE 14 bus test system. In addition, the are tables present the data used in the  analysis for the same system

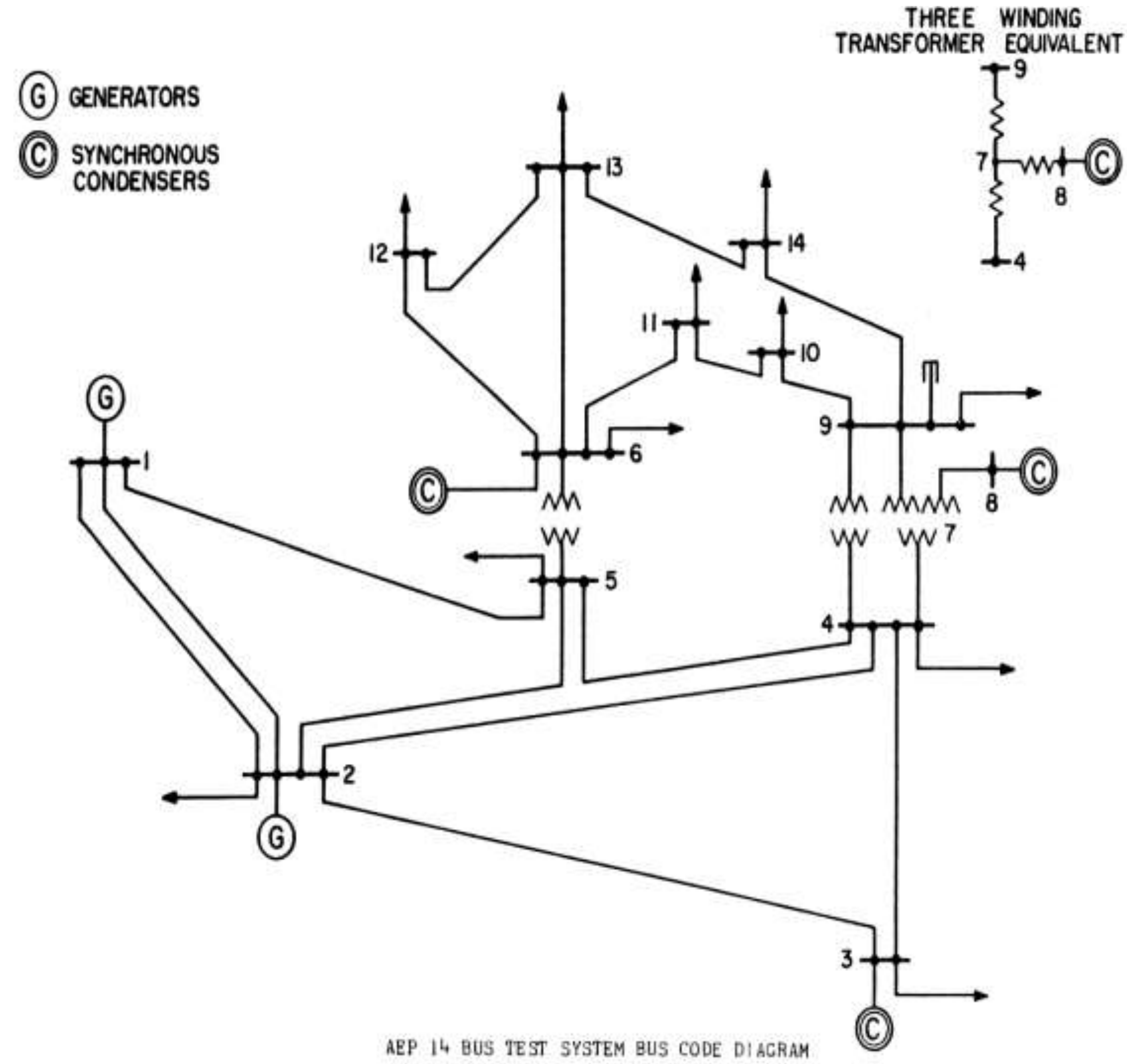


**Figure A-1:Single line diagram for IEEE 14 bus test system**

**Table A-1:Line data-IEEE 14 bus system**

| Line number | From bus | To bus | Line impedance ($p.u.$) | | Half line charging susceptance ($p.u.$) | MVA rating |
|---|---|---|---|---|---|---|
| | | | Resistance | Reactance | | |
| 1 | 1 | 2 | 0.01938 | 0.05917 | 0.02640 | 120 |
| 2 | 1 | 5 | 0.05403 | 0.22304 | 0.02190 | 65 |
| 3 | 2 | 3 | 0.04699 | 0.19797 | 0.01870 | 36 |
| 4 | 2 | 4 | 0.05811 | 0.17632 | 0.02460 | 65 |
| 5 | 2 | 5 | 0.05695 | 0.17388 | 0.01700 | 50 |
| 6 | 3 | 4 | 0.06701 | 0.17103 | 0.01730 | 65 |
| 7 | 4 | 5 | 0.01335 | 0.04211 | 0.00640 | 45 |
| 8 | 4 | 7 | 0 | 0.20912 | 0 | 55 |
| 9 | 4 | 9 | 0 | 0.55618 | 0 | 32 |
| 10 | 5 | 6 | 0 | 0.25202 | 0 | 45 |
| 11 | 6 | 11 | 0.09498 | 0.1989 | 0 | 18 |
| 12 | 6 | 12 | 0.12291 | 0.25581 | 0 | 32 |
| 13 | 6 | 13 | 0.06615 | 0.13027 | 0 | 32 |
| 14 | 7 | 8 | 0 | 0.17615 | 0 | 32 |
| 15 | 7 | 9 | 0 | 0.11001 | 0 | 32 |
| 16 | 9 | 10 | 0.03181 | 0.0845 | 0 | 32 |
| 17 | 9 | 14 | 0.12711 | 0.27038 | 0 | 32 |
| 18 | 10 | 11 | 0.08205 | 0.19207 | 0 | 12 |
| 19 | 12 | 13 | 0.22092 | 0.19988 | 0 | 12 |
| 20 | 13 | 14 | 0.17093 | 0.34802 | 0 | 12 |

**Table A-2:Values of R,L and C in simulation block(PI section line)**

| Line | R(ohm/Km) | $X_L$ | L(H/Km) | $B/_2$ | $C/_2$(F/Km) | $V_{base}$ |
|---|---|---|---|---|---|---|
| 1-2 | 0.9227 | 2.8171 | $7.472*10^{-3}$ | $5.545*10^{-4}$ | $1.471*10^{-6}$ | 69KV |
| 1-5 | 2.5724 | 10.6189 | 0.02828 | $4.599*10^{-4}$ | $1.220*10^{-6}$ | 69KV |
| 2-3 | 2.2372 | 9.4254 | 0.025 | $3.93*10^{-4}$ | $1.042*10^{-6}$ | 69KV |
| 2-4 | 2.7666 | 8.39145 | 0.0223 | $5.166*10^{-4}$ | $1.37*10^{-6}$ | 69KV |
| 2-5 | 2.71139 | 8.2784 | 0.022 | $3.75*10^{-4}$ | $9.47*10^{-7}$ | 69KV |
| 3-4 | 3.19035 | 8.1427 | 0.0216 | $3.64*10^{-4}$ | $9.638*10^{-7}$ | 69KV |
| 4-5 | 0.6356 | 2.0049 | $5.318*10^{-3}$ | $1.344*10^{-4}$ | $3.566*10^{-7}$ | 69KV |
| 4-7 | - | - | $1.056*10^{-3}$ | - | - | 13.8 KV |
| 4-9 | - | - | $2.809 *10^{-3}$ | - | - | 13.8 KV |
| 5-6 | - | - | $1.273*10^{-3}$ | - | - | 13.8 KV |
| 6-11 | 0.18088 | 0.78785 | $2.09*10^{-3}$ | - | - | 13.8 KV |
| 6-12 | 0.2341 | 0.48716 | $1.292*10^{-3}$ | - | - | 13.8 KV |
| 6-13 | 0.12597 | 0.248086 | $6.581*10^{-4}$ | - | - | 13.8 KV |
| 7-8 | - | 0.033546 | $8.898*10^{-4}$ | - | - | 13.8 KV |
| 7-9 | - | 0.20950 | $5.557*10^{-4}$ | - | - | 13.8 KV |
| 9-10 | 0.06058 | 0.16092 | $4.268*10^{-4}$ | - | - | 13.8 KV |
| 9-14 | 0.242682 | 0.514911 | 1.3658 | - | - | 13.8 KV |
| 10-11 | 0.156256 | 0.36577 | $9.702*10^{-4}$ | - | - | 13.8 KV |
| 12-13 | 0.42072 | 0.38065 | $1.01*10^{-3}$ | - | - | 13.8 KV |
| 13-14 | 0.325519 | 0.66276 | $1.758*10^{-3}$ | - | - | 13.8 KV |

**Table A-3: Transformer tap setting data-IEEE14 bus system**

| From bus | To bus | Tap setting value $(p.u.)$ |
|---|---|---|
| 4 | 7 | 0.978 |
| 4 | 9 | 0.969 |
| 5 | 6 | 0.932 |

**Table A-4:Shunt capacitor data-IEEE 14 bus system**

| Bus number | Susceptance $(p.u.)$ |
|---|---|
| 9 | 0.19 |

**Table A-5:Bus data-IEEE 14 bus system**

| Bus number | Bus voltage Magnitude $(p.u.)$ | Bus voltage Phase angle (degree) | Generation Real power $(MW)$ | Generation Reactive power $(MVAR)$ | Load Real power $(MW)$ | Load Reactive power $(MVAR)$ | Reactive power limits $Q_{\min}$ $(MVAR)$ | Reactive power limits $Q_{\max}$ $(MVAR.)$ |
|---|---|---|---|---|---|---|---|---|
| 1 | 1.060 | 0 | 114.17 | -16.9 | 0 | 0 | 0 | 10 |
| 2 | 1.045 | 0 | 40.00 | 0 | 21.7 | 12.7 | -42.0 | 50.0 |
| 3 | 1.010 | 0 | 0 | 0 | 94.2 | 19.1 | 23.4 | 40.0 |
| 4 | 1 | 0 | 0 | 0 | 47.8 | -3.9 | – | – |
| 5 | 1 | 0 | 0 | 0 | 7.6 | 1.6 | – | – |
| 6 | 1 | 0 | 0 | 0 | 11.2 | 7.5 | – | – |
| 7 | 1 | 0 | 0 | 0 | 0 | 0 | – | – |
| 8 | 1 | 0 | 0 | 0 | 0 | 0 | – | – |
| 9 | 1 | 0 | 0 | 0 | 29.5 | 16.6 | – | – |
| 10 | 1 | 0 | 0 | 0 | 9.0 | 5.8 | – | – |
| 11 | 1 | 0 | 0 | 0 | 3.5 | 1.8 | – | – |
| 12 | 1 | 0 | 0 | 0 | 6.1 | 1.6 | – | – |
| 13 | 1 | 0 | 0 | 0 | 13.8 | 5.8 | – | – |
| 14 | 1 | 0 | 0 | 0 | 14.9 | 5.0 | – | – |

# APPENDIX B

**Table B-1:Load flow-14 Bus System**

Power Flow Solution by Newton-Raphson Method

Maximum Power Mismatch = 0.000126875

No. of Iterations = 6

| Bus | Voltage | Angle | ------Load------ | | ---Generation--- | | Injected |
|---|---|---|---|---|---|---|---|
| No. | Mag. | Degree | MW | Mvar | MW | Mvar | Mvar |
| 1 | 1.060 | 0.000 | 0.000 | 0.000 | 233.913 | 36.693 | 0.000 |
| 2 | 1.025 | -4.795 | 21.700 | 12.700 | 40.000 | 33.038 | 0.000 |
| 3 | 0.990 | -13.026 | 94.200 | 19.100 | 0.000 | 38.860 | 0.000 |
| 4 | 0.974 | -10.060 | 47.800 | -3.900 | 0.000 | 0.000 | 0.000 |
| 5 | 0.980 | -8.494 | 7.600 | 1.600 | 0.000 | 0.000 | 0.000 |
| 6 | 0.980 | -14.808 | 11.200 | 7.500 | 0.000 | 0.000 | 0.000 |
| 7 | 0.966 | -13.511 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 8 | 0.966 | -13.511 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 9 | 0.952 | -15.410 | 29.500 | 16.600 | 0.000 | 0.000 | 0.000 |
| 10 | 0.949 | -15.645 | 9.000 | 5.800 | 0.000 | 0.000 | 0.000 |
| 11 | 0.960 | -15.374 | 3.500 | 1.800 | 0.000 | 0.000 | 0.000 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 12 | 0.963 | -15.833 | 6.100 | 1.600 | 0.000 | 0.000 | 0.000 |
| 13 | 0.957 | -15.907 | 13.800 | 5.800 | 0.000 | 0.000 | 0.000 |
| 14 | 0.934 | -16.849 | 14.900 | 5.000 | 0.000 | 0.000 | 0.000 |
| Total | | | 259.300 | 73.600 | 273.913 | 108.590 | 0.000 |

Line Flow and Losses

| --Line-- | | Power at bus & line flow | | | --Line loss-- | | Transformer |
|---|---|---|---|---|---|---|---|
| from | to | MW | Mvar | MVA | MW | Mvar | tap |
| 1 | | 233.913 | 36.693 | 236.773 | | | |
| | 2 | 159.071 | 14.060 | 159.691 | 4.414 | 7.738 | |
| | 5 | 74.860 | 22.631 | 78.206 | 2.998 | 7.811 | |
| 2 | | 18.300 | 20.338 | 27.359 | | | |
| | 1 | -154.657 | -6.323 | 154.786 | 4.414 | 7.738 | |
| | 3 | 74.727 | 3.700 | 74.818 | 2.512 | 6.785 | |
| | 4 | 56.337 | 10.627 | 57.330 | 1.852 | 0.699 | |
| | 5 | 41.893 | 12.345 | 43.674 | 1.060 | -0.183 | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 3 | | -94.200 | 19.760 | 96.250 | | | |
| | 2 | -72.215 | 3.085 | 72.281 | 2.512 | 6.785 | |
| | 4 | -21.985 | 16.677 | 27.595 | 0.561 | -1.906 | |
| 4 | | -47.800 | 3.900 | 47.959 | | | |
| | 2 | -54.485 | -9.928 | 55.382 | 1.852 | 0.699 | |
| | 3 | 22.546 | -18.583 | 29.218 | 0.561 | -1.906 | |
| | 5 | -59.620 | 6.764 | 60.003 | 0.507 | 0.378 | |
| | 7 | 27.711 | 15.181 | 31.597 | 0.000 | 2.103 | 0.978 |
| | 9 | 16.048 | 10.465 | 19.159 | 0.000 | 2.019 | 0.969 |
| 5 | | -7.600 | -1.600 | 7.767 | | | |
| | 1 | -71.862 | -14.820 | 73.375 | 2.998 | 7.811 | |
| | 2 | -40.834 | -12.528 | 42.712 | 1.060 | -0.183 | |
| | 4 | 60.128 | -6.386 | 60.466 | 0.507 | 0.378 | |
| | 6 | 44.968 | 32.133 | 55.269 | 0.000 | 6.966 | 0.932 |
| 6 | | -11.200 | -7.500 | 13.479 | | | |
| | 5 | -44.968 | -25.168 | 51.532 | 0.000 | 6.966 | |
| | 11 | 7.609 | 6.150 | 9.783 | 0.095 | 0.198 | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | 12 | 7.969 | 2.861 | 8.467 | 0.092 | 0.191 |
| | 13 | 18.190 | 8.657 | 20.145 | 0.279 | 0.550 |
| 7 | | 0.000 | 0.000 | 0.000 | | |
| | 4 | -27.711 | -13.078 | 30.642 | 0.000 | 2.103 |
| | 8 | 0.000 | -0.000 | 0.000 | 0.000 | 0.000 |
| | 9 | 27.711 | 13.078 | 30.642 | 0.000 | 1.106 |
| 8 | | 0.000 | 0.000 | 0.000 | | |
| | 7 | -0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 9 | | -29.500 | -16.600 | 33.850 | | |
| | 4 | -16.048 | -8.446 | 18.135 | 0.000 | 2.019 |
| | 7 | -27.711 | -11.972 | 30.186 | 0.000 | 1.106 |
| | 10 | 5.026 | 1.744 | 5.320 | 0.010 | 0.026 |
| | 14 | 9.233 | 2.074 | 9.463 | 0.126 | 0.267 |
| 10 | | -9.000 | -5.800 | 10.707 | | |
| | 9 | -5.016 | -1.718 | 5.302 | 0.010 | 0.026 |
| | 11 | -3.984 | -4.082 | 5.704 | 0.030 | 0.069 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 11 | | -3.500 | -1.800 | 3.936 | | |
| | 6 | -7.514 | -5.952 | 9.586 | 0.095 | 0.198 |
| | 10 | 4.014 | 4.152 | 5.775 | 0.030 | 0.069 |
| 12 | | -6.100 | -1.600 | 6.306 | | |
| | 6 | -7.878 | -2.670 | 8.318 | 0.092 | 0.191 |
| | 13 | 1.778 | 1.070 | 2.075 | 0.010 | 0.009 |
| 13 | | -13.800 | -5.800 | 14.969 | | |
| | 6 | -17.911 | -8.107 | 19.660 | 0.279 | 0.550 |
| | 12 | -1.767 | -1.061 | 2.061 | 0.010 | 0.009 |
| | 14 | 5.878 | 3.367 | 6.775 | 0.086 | 0.175 |
| 14 | | -14.900 | -5.000 | 15.717 | | |
| | 9 | -9.107 | -1.807 | 9.285 | 0.126 | 0.267 |
| | 13 | -5.793 | -3.193 | 6.614 | 0.086 | 0.175 |
| Total loss | | | | | 14.631 | 35.002 |

**Table B-2:Y Bus**

Y bus :Columns 1 through 5:

| | | | | |
|---|---|---|---|---|
| 6.0250 -19.4981i | -4.9991 +15.2631i | 0 | 0 | -1.0259 + 4.2350i |
| -4.9991 +15.2631i | 9.5213 -30.3547i | -1.1350 + 4.7819i | -1.6860 + 5.1158i | -1.7011 + 5.1939i |
| 0 | -1.1350 + 4.7819i | 3.1210 - 9.8507i | -1.9860 + 5.0688i | 0 |
| 0 | -1.6860 + 5.1158i | -1.9860 + 5.0688i | 10.5130 -38.3431i | -6.8410 +21.5786i |
| -1.0259 + 4.2350i | -1.7011 + 5.1939i | 0 | -6.8410 +21.5786i | 9.5680 -34.9754i |
| 0 | 0 | 0 | 0 | 0 + 3.9679i |
| 0 | 0 | 0 | 0 + 4.7819i | 0 |
| 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 + 1.7980i | 0 |
| 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 |

Y bus :Columns 6 through 10 :

| | | | | |
|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 |
| 0 | 0 + 4.7819i | 0 | 0 + 1.7980i | 0 |
| 0 + 3.9679i | 0 | 0 | 0 | 0 |
| 6.5799 -17.3407i | 0 | 0 | 0 | 0 |
| 0 | 0 -19.5490i | 0 + 5.6770i | 0 + 9.0901i | 0 |
| 0 | 0 + 5.6770i | 0 - 5.6770i | 0 | 0 |
| 0 | 0 + 9.0901i | 0 | 5.3261 -24.2825i | -3.9020 +10.3654i |
| 0 | 0 | 0 | -3.9020 +10.3654i | 5.7829 -14.7683i |
| -1.9550 + 4.0941i | 0 | 0 | 0 | -1.8809 + 4.4029i |
| -1.5260 + 3.1760i | 0 | 0 | 0 | 0 |
| -3.0989 + 6.1028i | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | -1.4240 + 3.0291i | 0 |

Y bus :Columns 11 through 14

| | | | |
|---|---|---|---|
| 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 |
| -1.9550 + 4.0941i | -1.5260 + 3.1760i | -3.0989 + 6.1028i | 0 |
| 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | -1.4240 + 3.0291i |
| -1.8809 + 4.4029i | 0 | 0 | 0 |
| 3.8359 - 8.4970i | 0 | 0 | 0 |
| 0 | 4.0150 - 5.4279i | -2.4890 + 2.2520i | 0 |
| 0 | -2.4890 + 2.2520i | 6.7249 -10.6697i | -1.1370 + 2.3150i |
| 0 | 0 | -1.1370 + 2.3150i | 2.5610 - 5.3440i |

# APPENDIX C

**Table C-1: Without compensation-Nose curve for bus 12**

```
A=0.486492;
Q=0.016;
x=0.412;
R=0.177;
RD=0.03133;
vD=0.973;
QD=0.000256;
xD=0.1697;
B=0.23667;
zD=0.2;
PLp=[0:0.001:0.769];
vp=sqrt((A-Q.*x-R.*PLp + sqrt(RD.*PLp.^2+2.*PLp.*R.*x.*Q-
R.*vD.*PLp+QD.*xD-Q.*x.*vD+B-zD.*PLp.^2-zD.*QD)));
PLn=[0.769:-0.001:0];
vn=sqrt((A-Q.*x-R.*PLn - sqrt(RD.*PLn.^2+2.*PLn.*R.*x.*Q-
R.*vD.*PLn+QD.*xD-Q.*x.*vD+B-zD.*PLn.^2-zD.*QD)));
PL=[PLp PLn];
v2=[vp vn];
plot(PL*16.4,v2)
```

**Table C-2:Vref"0.99pu" at bus 12-Nose curve for bus 12**

```
A=0.513522;
Q=0.016;
x=0.42120;
R=0.182885;
RD=0.0334469;
vD=1.0270444;
QD=0.000256;
xD=0.177409;
B=0.2637050;
zD=0.2108646;
PLp=[0:0.001:0.79];
vp=sqrt((A-Q.*x-R.*PLp + sqrt(RD.*PLp.^2+2.*PLp.*R.*x.*Q-
R.*vD.*PLp+QD.*xD-Q.*x.*vD+B-zD.*PLp.^2-zD.*QD)));
PLn=[0.79:-0.001:0];
vn=sqrt((A-Q.*x-R.*PLn - sqrt(RD.*PLn.^2+2.*PLn.*R.*x.*Q-
R.*vD.*PLn+QD.*xD-Q.*x.*vD+B-zD.*PLn.^2-zD.*QD)));
PL=[PLp PLn];
v2=[vp vn];
plot(PL*16.4,v2)
```

**Table C-3:Vref"0.98 pu at bus 14 and 1pu at bus12"- Nose curve for bus 12**

```
A=0.5208325;
Q=0.016;
x=0.42;
R=0.182415;
RD=0.033275;
vD=1.041665;
QD=0.000256;
xD=0.1764;
B=0.2712665;
zD=0.21;
PLp=[0:0.001:0.803];
vp=sqrt((A-Q.*x-R.*PLp + sqrt(RD.*PLp.^2+2.*PLp.*R.*x.*Q-
R.*vD.*PLp+QD.*xD-Q.*x.*vD+B-zD.*PLp.^2-zD.*QD)));
PLn=[0.803:-0.001:0];
vn=sqrt((A-Q.*x-R.*PLn - sqrt(RD.*PLn.^2+2.*PLn.*R.*x.*Q-
R.*vD.*PLn+QD.*xD-Q.*x.*vD+B-zD.*PLn.^2-zD.*QD)));
PL=[PLp PLn];
v2=[vp vn];
plot(PL*16.4,v2)
```

**Table C-4:Without compensation-Nose curve for bus 14**

```
A=0.49295499;
Q=0.05;
x=0.3855;
R=0.165725;
RD=0.02746477;
vD=0.9859099;
QD=0.0025;
xD=0.14861025;
B=0.24300462;
zD=0.1761145;
PLp=[0:0.001:0.81];
vp=sqrt((A-Q.*x-R.*PLp + sqrt(RD.*PLp.^2+2.*PLp.*R.*x.*Q-
R.*vD.*PLp+QD.*xD-Q.*x.*vD+B-zD.*PLp.^2-zD.*QD)));
PLn=[0.81:-0.001:0];
vn=sqrt((A-Q.*x-R.*PLn - sqrt(RD.*PLn.^2+2.*PLn.*R.*x.*Q-
R.*vD.*PLn+QD.*xD-Q.*x.*vD+B-zD.*PLn.^2-zD.*QD)));
PL=[PLp PLn];
v2=[vp vn];
plot(PL*6.7,v2)
```

**Table C-5:Vref"0.99pu” at bus 12-Nose curve for bus 14**

```
A=0.544279177;
Q=0.05;
x=0.39957;
R=0.165510;
RD=0.0273935;
vD=1.08855;
QD=0.0025;
xD=0.159656;
B=0.296239;
zD=0.187056;
PLp=[0:0.001:0.875];
vp=sqrt((A-Q.*x-R.*PLp + sqrt(RD.*PLp.^2+2.*PLp.*R.*x.*Q-
R.*vD.*PLp+QD.*xD-Q.*x.*vD+B-zD.*PLp.^2-zD.*QD)));
PLn=[0.875:-0.001:0];
vn=sqrt((A-Q.*x-R.*PLn - sqrt(RD.*PLn.^2+2.*PLn.*R.*x.*Q-
R.*vD.*PLn+QD.*xD-Q.*x.*vD+B-zD.*PLn.^2-zD.*QD)));
PL=[PLp PLn];
v2=[vp vn];
plot(PL*6.7,v2)
```

**Table C-6:Vref"0.98 pu at bus 14 and 1pu at bus12"- Nose curve for bus 14**

```
A=0.5351514033;
Q=0.05;
x=0.396138;
R=0.163276;
RD=0.0266590;
vD=1.0703028;
QD=0.0025;
xD=0.1569253;
B=0.2863870244;
zD=0.1835848;
PLp=[0:0.001:0.87];
vp=sqrt((A-Q.*x-R.*PLp + sqrt(RD.*PLp.^2+2.*PLp.*R.*x.*Q-
R.*vD.*PLp+QD.*xD-Q.*x.*vD+B-zD.*PLp.^2-zD.*QD)));
PLn=[0.87:-0.001:0];
vn=sqrt((A-Q.*x-R.*PLn - sqrt(RD.*PLn.^2+2.*PLn.*R.*x.*Q-
R.*vD.*PLn+QD.*xD-Q.*x.*vD+B-zD.*PLn.^2-zD.*QD)));
PL=[PLp PLn];
v2=[vp vn];
plot(PL*6.7,v2)
```

# APPENDIX D

**Table D-1:20% increasing loads**

| Bus | MW | MVAR | Increasing 20%(MW) | Increasing 20%( MVAR) |
|---|---|---|---|---|
| 2 | 21.7 | 12.7 | 4.34 | 2.54 |
| 3 | 94.2 | 19.1 | 18.84 | 3.82 |
| 4 | 47.8 | -3.9 | 9.56 | 0.78 |
| 5 | 7.6 | 1.6 | 1.52 | 0.32 |
| 6 | 11.2 | 7.5 | 2.24 | 1.5 |
| 9 | 29.5 | 16.6 | 5.9 | 3.32 |
| 10 | 9 | 5.8 | 1.8 | 1.16 |
| 11 | 3.5 | 1.8 | 0.7 | 0.36 |
| 12 | 6.1 | 1.6 | 1.22 | 0.32 |
| 13 | 13.8 | 5.8 | 2.76 | 1.16 |
| 14 | 14.9 | 5 | 2.98 | 1 |

**Table D-2:80%decreasing loads**

| Bus | 80%(MW) | 80%( MVAR) |
|---|---|---|
| 2 | 17.36 | 10.16 |
| 3 | 75.36 | 15.28 |
| 4 | 38.24 | -3.58 |
| 5 | 6.08 | 1.28 |
| 6 | 8.96 | 6 |
| 9 | 23.6 | 13.28 |
| 10 | 7.2 | 4.64 |
| 11 | 2.8 | 1.44 |
| 12 | 4.88 | 1.28 |
| 13 | 11.04 | 4.64 |
| 14 | 11.92 | 4 |

# ملخص الرسالة

تم بحث التأثير الخاص بإضافة الموازن الاستاتيكي ( DSTATCOM) على تغير الجهد في شبكة توزيع كهرباء تحتوي على اربعة عشر قضيب توصيل.حيث تم دراسة إختيار السعة المناسبة للموازن الاستاتيكي (DSTATCOM)و كذلك إستخدامه في مختلف المواقع على الشبكة لتحسين الجهد بشبكة التوزيع الكهربية .

هذا البحث يركز على تطبيقات الموازن الاستاتيكي ( DSTATCOM) في مجال شبكات التوزيع اثناء تغيير الاحمال سواءاً الديناميكية او الثابتة .تم تعديل النموذج التفصيلي الخاص بالموازن الاستاتيكي (DSTATCOM) من أجل الوصول لأفضل أداء ديناميكي له لإصلاح و تثبيت الجهد بجميع قضبان التوصيل بالشبكة .حيث تم دراسة الجهد أثناء عمليات الغلق و الفتح للأحمال الصناعية الكبيرة و خروج احد خطوط التوزيع و حالات هبوط الجهد .

إستعرض البحث إستخدام سعات مختلفة للموازن الاستاتيكي (DSTATCOM) بأماكن مختلفة مع الأخذ في الاعتبار الحفاظ على أقل إستهلاك للطاقة الغير فعالة .

هذه الدراسة تم تحقيقها و إثباتها على نظام توزيع قياسي مكون من 14 قطيب توصيل (69 ك.ف /13.8 ك. ف) بدون إضافة اي محسنات للجهد .

النتائج تشير إلى التأثير الواضح لأستخدام الموازن الاستاتيكي (DSTATCOM) على تغيير جهد النظام أثناء حالات التشغيل الطبيعية كما هي في الحالات الاخرى الغير طبيعية .تم عرض تحسن أداء الشبكة نتيجة للتعديلات و التحسينات التي تمت إضافتها .

**الأكاديمية العربية للعلوم والتكنولوجيا والنقل البحري**
**كلية الهندسة والتكنولوجيا**
**قسم هندسة الكهرباء والتحكم**

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رسالة ماجستير
في
هندسة الكهرباء والتحكم

مقدمة من

**المهندسة/ مي سرور إبراهيم**
بكالوريوس هندسة الكهرباء والتحكم

**أ.د. / رانيا متولي الشرقاوي**
**مشرف**

**أ.د. / رزق حمودة**
**مشرف**

-

**أ.د. / ياسر جلال**
**ممتحن**

**أ.د. / ابراهيم هلال**
**ممتحن**

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بكالوريوس هندسة الكهرباء والتحكم

تحت إشراف

**أ.د. / رانيا متولي الشرقاوي**
رئيس قسم هندسة الكهرباء والتحكم

الأكاديمية العربية للعلوم والتكنولوجيا
والنقل البحري

**أ.د. / رزق حمودة**
رئيس قسم هندسة الكهرباء والتحكم

هندسة عين شمس

**2016**