Chapter-1

<u>INTRODUCTION</u>

1.1 OVERVIEW

The increasing Industrialization, urbanization of life style has lead to increasing dependency on the electrical energy. This has resulted into rapid growth of power systems. This rapid growth has resulted into few uncertainties. Power disruptions and individual power outages are one of the major problems and affect the economy of any country. In contrast to the rapid changes in technologies and the power required by these technologies, transmission systems are being pushed to operate closer to their stability limits and at the same time reaching their thermal limits due to the fact that the delivery of power have been increasing. The major problems faced by power industries in establishing the match between supply and demand are:

• Transmission & Distribution; supply the electric demand without exceeding the thermal limit.

• In large power system, stability problems causing power disruptions and blackouts leading to huge losses.

These constraints affect the quality of power delivered. However, these constraints can be suppressed by enhancing the power system control. One of the best method for reducing these constraints are FACTS devices.

With the rapid development of power electronics, Flexible AC Transmission Systems (FACTS) devices have been proposed and implemented in power systems. FACTS devices can be utilized to control power flow and enhance system stability. Particularly with the deregulation of the electricity market, there is an increasing interest in using FACTS devices in the operation and control of power systems. A better utilization of the existing power systems to increase their capacities and controllability by installing FACTS devices becomes imperative. FACTS devices are cost effective alternatives to new transmission line construction [1].

Reactive power compensation is provided to minimize power transmission losses, to maintain power transmission capability and to maintain the supply voltage. Series compensation is

control of line impedance of a transmission line; with the change of impedance of a line either inductive or capacitive compensation can be obtained thus facilitating active power transfer or control. Thyristor Controlled Series Capacitor (TCSC) is a variable impedance type series compensator and is connected in series with the transmission line to increase the power transfer capability, improve transient stability, reduce transmission losses and dampen power system oscillations. Shunt compensation is used to increase the steady-state transmittable power and to control the voltage profile along the line. Static compensator (STATCOM) is a shunt compensator and one of the important members of FACTS family that are increasingly being applied to long transmission lines by the utility in modern power systems. They can have various applications concerned with operation and control of power system, such as scheduling power flow; decreasing unsymmetrical components damping the power oscillations and enhancing transient stability.

1.2 FLEXIBLE AC TRANSMISSION SYSTEM

The concept of Flexible AC Transmission Systems (FACTS) was first defined by N.G. Hingorani, in 1988 [2]. A Flexible Alternating Current Transmission System (FACTS) is a system comprised of static equipment used for the AC transmission of the electrical energy. It is meant to enhance controllability and increase power transfer capability of the network. It is generally a power electronic-based device. 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]. The primary advantage of FACTS devices, over its conventional counterpart is the rapid control of current, voltage and/or impedance. The conventional solutions such as capacitor, reactor and phase shifting transformers are normally less expensive than FACTS devices, but limited in their dynamic behaviour and are less optimal. The review of various FACTS devices is summarized in Chapter 3.

1.3 LOAD FLOW SOLUTIONS

Load flow studies are the backbone of power system analysis and design. Load flow studies are necessary for planning, economic scheduling and exchange of power between utilities. In addition, power flow analysis is required for many analyses such as transient stability and contingency studies. The load flow solution gives the nodal voltages and phase angles and hence the power injection at all the buses and power flows through interconnecting

transmission lines. Load flow equations are nonlinear and can be solved by an iterative method. In this thesis Newton Raphson method is used, as the number of iterations is independent of the size of the system, and convergence characteristic is independent of selection of slack bus. Details of Newton Raphson method, load flow solution with STATCOM are discussed in chapter 4.

1.4 LITERATURE REVIEW

The brief review on the placement of FACTS devices is presented here. The concept of FACTS and FACTS controllers was first defined by Hingorani, 1988 in [2-3]. FACTS usually refer to the application of high-power semiconductor devices to control different parameters and electrical variables such as voltage, impedance, phase angles, currents, reactive and active power [11-12]. FACTS can provide versatile benefits to transmission utilities such as control of power flow, increasing capabilities of lines to their thermal limits, reducing loop flows, providing greater flexibility [9-10].The value of FACTS application lies mainly in the ability of the transmission system to efficiently transmit power or to transfer power under contingency conditions [6]. FACTS technology is a collection of controllers that can be applied to control electrical variables and parameters. In general FACTS controllers can be divided into four categories: 1) Series controllers mainly TCSC and SSSC 2) Shunt controllers mainly STATCOM and SVC 3) Series-series controllers such as IPFC and 4) Combined series-shunt controllers such as UPFC [1]. Reactive power compensation is an important issue in powers system. The purpose of reactive power compensation is mainly to improve the voltage profile in the system and to minimize the power loss. The reactive power compensation of AC system can be done using fixed series or shunt capacitor however the slow nature of control and limits on frequency are the drawback and can be overcome by using FACTS controllers [6-8]. Thyristor controlled series compensator is a variable impedance series compensator, which controls the effective line reactance by connecting a variable reactance in series with the line. STATCOM is a second generation FACTS devices used for shunt reactive compensation. It is applied to improve voltage security, provide interface with the real power source, higher response to system changes and mitigation of harmonics [13-14]. Hassan, Cheng and Zakaria presented steady state modelling of STATCOM and TCSC for power flow control studies. STATCOM is modelled as a controllable voltage source in series with impedance. Newton-Raphson method algorithm was implemented to solve power flow equation in the presence of STATCOM. The algorithm

developed shows excellent convergence characteristics [14]. As FACTS devices are costly so type, number and location of the FACTS devices is very important, to decide the optimal location and parameters of FACTS devices the following objective functions are used in FACTS related researches: Transmission pricing issues by maximizing social welfare with or without consideration of FACTS' costs; Better utilization of FACT by maximizing FACTS devices total transferred power Reactive power or voltage control by minimizing Transmission losses, or voltage fluctuation. Increase system's security under emergency by minimizing transmission lines load ability. Thyristor-based FACTS are modelled as power injection, or controllable impedance (TCSC and SVC) or an ideal phase shifter (TCPST/TCPAR).

FACTS devices can be embedded into power flow equations with modification of the network admittance matrix and the Jacobian matrix. Radman and Raje discussed power flow calculation of power system with multiple flexible AC transmission system (FACTS controller) by modifying and adding new entries in Jacobian equation with no FACTS controller and considered three major FACTS controllers STATCOM, SSSC and UPFC [15]. Esquiuel and Acha considered the issue of controllable branch model suitable for assessing the steady state response of FACTS devices and presented nodal admittance model for series compensators, phase shifter and unified power flow controller.

1.5 OBJECTIVE OF THESIS

The work reported in this thesis has been carried out with the objective of studying the effect of FACTS controller namely STATCOM on load flow solution and also to develop the algorithm to solve load flow with STATCOM. STATCOM is used to compensate reactive power and thus to maintain voltage magnitude at 1 p.u. Reactive power compensation is an important issue in powers system. The purpose of reactive power compensation is mainly to improve the voltage profile in the system and to minimize the power loss.

1.6 ORGANIZATION OF THESIS

The thesis is organized into six chapters. The organization of thesis is as follows: The Chapter-1 highlights the brief overview, summary of work carried out by various researchers, the objective of the thesis and the outline of the thesis.

The Chapter-2 presents Study of load flow analysis using Gauss-Seidel Method and Newton-Raphson Method.

The Chapter-3 presents review on FACTS Controllers, opportunities and applications for FACTS.

The Chapter-4 presents the mathematical model of STATCOM and algorithm to solve load flow with STATCOM.

The Chapter-5 presents case study and results of load flow including STATCOM on 5-bus IEEE-14 bus and IEEE-30 bus systems.

The chapter-6 summarizes the conclusions drawn and scope for the future work.

Chapter-2

<u>LOAD FLOW</u>

2.1 STUDY OF LOAD FLOW ANALYSIS

Load-flow studies are very common in power system analysis. Load flow allows us to know the present state of a system, given previous known parameters and values. The power that is flowing through the transmission line, the power that is being generated by the generators, the power that is being consumed by the loads, the losses occurring during the transfer of power from source to load, and so on, are iteratively decided by the load flow solution, or also known as power flow solution. In any system, the most important quantity which is known or which is to be determined is the voltage at different points throughout the system. Knowing these, we can easily find out the currents flowing through each point or branch. This in turn gives us the quantities through which we can find out the power that is being handled at all these points.

In earlier days, small working models were used to find out the power flow solution for any network. Because computing these quantities was a hard task, the working models were not very useful in simulating the actual one. It's difficult to analyze a system where we need to find out the quantities at a point very far away from the point at which these quantities are known. Thus we need to make use of iterative mathematical solutions to do this task, due to the fact that there are no finite solutions to load flow. The values more often converge to a particular value, yet do not have a definite one. Mathematical algorithms are used to compute the unknown quantities from the known ones through a process of successive trial and error methods and consequently produce a result. The initial values of the system are assumed and with this as input, the program computes the successive quantities. Thus, we study the load flow to determine the overloading of particular elements in the system. It is also used to make sure that the generators run at the ideal operating point, which ensures that the demand will be met without overloading the facilities and maintain them without compromising the security of the system nor the demand.

The objective of any load-flow analysis is to produce the following information:

• Voltage magnitude and phase angle at each bus.

• Real and reactive power flowing in each element.

• Reactive power loading on each generator.

2.2 TYPES OF BUSES

Generally in an AC system, we have the variables like voltage, current, power and impedance. Whereas in a dc system, we have just the magnitude component of all these variables due to the static nature of the system, this is not the case in ac systems. AC systems bring one more component to the forefront, that of time. Thus any quantity in an AC system is described by two components: the magnitude component and the time component. For the magnitude we have the RMS value of the quantity, whereas for the time we take the phase angle component. Thus voltage will have a magnitude and a phase angle. Hence when we solve for the currents, we will get a magnitude and a phase angle. These two when combined, will give the power for the system, which will contain a real and a reactive term. The actual variables that are given as inputs to the buses and the operating constraints that govern the working of each bus decide the types of buses. Thus we have the two main types of buses: the load bus and the generator bus. At the load bus, the variables that are already specified are the real power (P) and the reactive power (Q) consumed by the load. The variables which are to be found out are voltage magnitude (V) and the phase angle of this voltage (δ). Hence load bus is also called PQ bus in power systems.

At the generator bus, the variables which are specified are the real power being generated (V) and the voltage at which this generation is taking place (V). The variables which are to be found out are the generator reactive power (Q) and the voltage phase angle (δ). This is done so for convenience as the power needs of the system need to be balanced as well as the operational control of the generator needs to be optimized.

Apart from these two we have the slack bus which is responsible for providing the losses in the whole system and the transmission lines and thus is specified by the variables voltage magnitude (V) and angle (δ).

If we are given any of the two inputs of the system, along with the fixed parameters like impedance of the transmission lines as well as that of the system, and system frequency, then using mathematical iterations we can easily find out the unknown variables. Thus the operating state of the system can be determined easily knowing the two variables. The variables to be specified and the variables to be computed are given below.

Type of bus	Specified quantities	Calculated quantities
Generator bus	Real power (P)	Reactive power (Q)
(PV Bus)	Voltage magnitude (V)	Voltage angle (δ)
Load bus	Real power (P)	Voltage magnitude (V)
(PQ Bus)	Reactive power (Q)	Voltage angle (δ)
Slack bus	Voltage magnitude (V)	Real power (P)
	Voltage angle (δ)	Reactive power (Q)

2.3 LOAD FLOW EQUATIONS AND THEIR SOLUTIONS

2.3.1 Development of Load Flow Equations

The real and reactive power components for any bus p can be used as:

$$P_p - jQ_p = V_p^* I_p$$

$$\Rightarrow \quad I_p = (P_p - jQ_p)/ V_p^*$$

Now the nodal current equations for a n-bus system can be written as

$$I_p = \sum_{q=1}^{n} Y_{pq} V_q, \qquad p=1,2,3........n;$$

$$I_p = Y_{pp} V_p + \sum_{\substack{q=1 \\ q \neq p}}^{q=n} Y_{pq} V_q$$

$$\Rightarrow \quad V_p = \frac{I_p}{Y_{pp}} - \frac{1}{Y_{pp}} \sum_{\substack{q=1 \\ q \neq p}}^{q=n} Y_{pq} V_q$$

Now,

$$V_p^* I_p = P_p - jQ_p$$

$$\Rightarrow \quad I_p = (P_p - jQ_p)/V_p^*$$

Substituting for Ip in the above equation,

$$V_p = \frac{1}{Y_{pp}}\left[\frac{P_p - jQ_p}{V_p^*} - \sum_{\substack{q=1 \\ q \neq p}}^{q=n} Y_{pq}\, V_q\right], p=1,2,3,\ldots,n;$$

We substitute Ip by active and reactive power, because the quantities are usually specified in a power system.

2.3.2 Load Flow Equation Solution Methods

To start with by solving the load flow equations, we first assume values for the unknown variables in the bus system. For instance, let us suppose that the unknown variables are the magnitude of the voltages and their angles at every bus except the Slack bus, which makes them the load bus or the PQ bus. In this case, we assume the initial values of all voltage angels as zero and the magnitude as 1p.u. Meaning, we choose a flat voltage profile. We then put these assumed values in our power flow equations, knowing that these values don't represent the actual system, even though it should have been describing its state. So, now we iterate this process of putting in the values of voltage magnitudes and angles and replacing them with a better set. So, as the flat voltage profile keeps converging to the actual values of the magnitudes and angles, the mismatch between the P and Q will reduce. Depending on the number of iterations we use and our requirements we can end the process with values close to the actual value. This process is called as the iterative solution method.

The final equations derived in the previous section are the load flow equations where bus voltages are the variables. It can be seen that these equations are nonlinear and they can be solved using iterative methods like:

1) Gauss-Seidel method

2) Newton-Raphson method

2.3.2.1 Gauss-Seidel method

The Gauss-Seidel method is based on substituting nodal equations into each other. It's convergence is said to be Monotonic. The iteration process can be visualized for two equations:
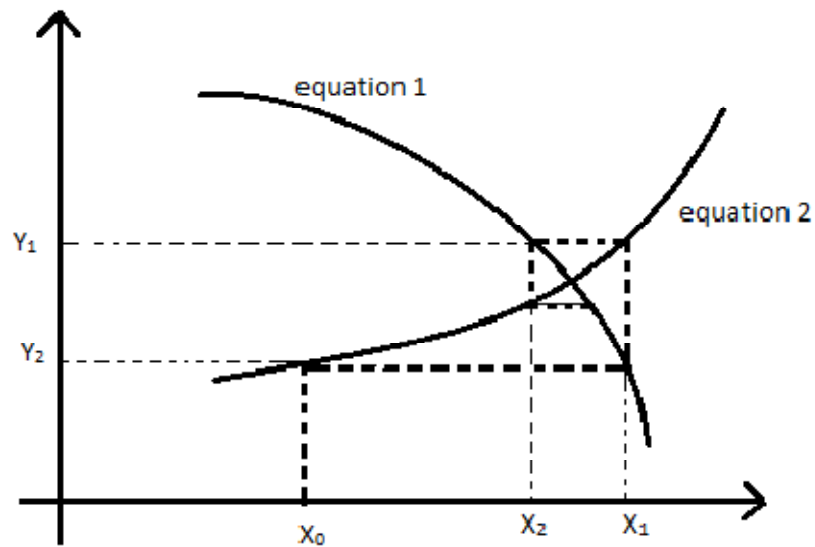

Fig 2.1

Although not the best load-flow method, Gauss-Seidel is the easiest to understand and was the most widely used technique until the early 1970s. Here, we use the Newton-Raphson method which is the most efficient load-flow algorithm.

2.3.2.2 Newton-Raphson (N-R) Method [26]

Newton-Raphson algorithm is based on the formal application of a well-known algorithm for the solution of a set of simultaneous non-linear equations of the form:

$$[F(x)] = [0]$$

Where: $[F(x)]$ is a vector of functions: f_1 --- f_n in the variables x_1 --- x_n.

The expression described above will not become equal zero until the N-R process has converged and the iterations been performed, assuming the initial set of values x_1, x_2, --- x_n. In the load-flow problem, where the x's are voltage magnitude and phase angle at all load buses and voltage phase angles at all generator buses i.e., angles at all buses except slack and $|V|$ for all PQ buses.

The equations for load flow problem which can be solved by using N-R method can be derived as:

$$P_p\text{-}jQ_p = V_p^*I_p = V_p^*\sum_{q=1}^{n} Y_{pq}V_q$$

Let,

$$V_p = e_p + jf_p \quad \text{and} \quad Y_{pq} = G_{pq}\text{-}jB_{pq}$$

$$P_p\text{-}jQ_p = (e_p + jf_p)^* \sum_{q=1}^{n} (G_{pq}\text{-}jB_{pq})(e_q + jf_q)$$

$$= (e_p\text{-}jf_p) \sum_{q=1}^{n} (G_{pq}\text{-}jB_{pq})(e_q + jf_q)$$

Separating the real and imaginary parts, we have:

$$P_p = \sum_{q=1}^{n} [e_p(e_qG_{pq}+f_qB_{pq}) + f_p(e_qG_{pq}\text{-}f_qB_{pq})]$$

And,

$$Q_p = \sum_{q=1}^{n} [f_p(e_qG_{pq}+f_qB_{pq}) - e_p(e_qG_{pq}\text{-}f_qB_{pq})]$$

Also,

$$|V_p|^2 = e_p^2 + f_p^2$$

The three sets of equations above are the load flow equations for the N-R method and we can see that they are non-linear in terms of real and imaginary components of nodal voltages. The left hand quantities i.e. P_p,Q_p for a load bus and P_p and $|V_p|$ for a generator bus are specified and e_p and f_p are unknown quantities are unknown quantities. For an n-bus system, the number of unknowns are (2n-1) because the voltage at the slack bus is known and is kept

fixed both in magnitude and phase. Thus, if bus 1 is taken as the slack bys, the unknowns are $e_2, e_3,.., e_{n-1}, e_n$ and $f_2, f_3,.., f_{n-1}, f_n$.

Thus to solve all these variables, we need to solve all the $2(n-1)$ equations.

The Newton-Raphson method helps us to replace a set of nonlinear power-flow equations with a linear set, using Taylor's series expansion. The mathematical background for this method is as follows:

Let the unknown variables be $(x_1, x_2,...., x_n)$ and the quantities specified be $y_1, y_2,..., y_n$

These are related by the set of non-linear equations

$$Y_1 = f_1(x_1, x_2, x_3 .....x_n)$$

$$Y_2 = f_2(x_1, x_2, x_3 .....x_n)$$

.

.

.

.

$$Y_n = f_n(x_1, x_2, x_3 .....x_n)$$

To be able to solve the above equations, we start with an approximate solution $(x_1^0, x_2^0,......x_n^0)$. Here, the 0 in the superscript implies the zero[th] iteration in the process of solving the above equations. We need to note that the initial solution for the equations should be close to the actual solution. In other respects, the chances exist for the solution to diverge rather than converge, which reduces our chances of achieving a solution for the equations. We assume a flat voltage profile i.e $V_p = 1.0 + j0.0$ for $p = 1,2,3...,n$; except the slack bus, which is satisfactory for almost all practical systems.

The equations are linearized about the initially assumed values. We then expand the first equation $y_1 = f_1$ and the results for the following equations.

Assuming $\Delta x_1^0, \Delta x_2^0,...... \Delta x_n^0$ as the corrections required for $x_1^0, x_2^0,...... x_n^0$ respectively for the next better solution. The equation $y_1 = f_1$ will be

$$y_1 = f_1(x_1{}^0 + \Delta x_1{}^0,\ x_2{}^0 + \Delta x_2{}^0 \ldots\ldots x_n{}^0 + \Delta x_n{}^0)$$

$$= f_1(x_1{}^0, x_2{}^0, \ldots x_n{}^0) + \Delta x_1{}^0 \frac{\partial f_1}{\partial x_1}\Big|x^0 + \Delta x_2{}^0 \frac{\partial f_1}{\partial x_2}\Big|x^0 + \ldots + \Delta x_n{}^0 \frac{\partial f_1}{\partial x_n}\Big|x^0 + \Phi_1$$

Where Φ_1 is function of higher order of Δx^8 and higher derivatives which are neglected according to N-R method. In fact this is the assumption which needs the initial solution close to the final solution. After all the equations are linearized and arranged in a matrix form, we get:

$$
\begin{bmatrix}
y_1 - f_1(x_1^0 + \Delta x_1^0, x_2^0 + \Delta x_2^0, \ldots x_n^0 + \Delta x_n^0) \\
y_2 - f_2(x_1^0 + \Delta x_1^0, x_2^0 + \Delta x_2^0, \ldots x_n^0 + \Delta x_n^0) \\
. \\
. \\
. \\
y_n - f_n(x_1^0 + \Delta x_1^0, x_2^0 + \Delta x_2^0, \ldots x_n^0 + \Delta x_n^0)
\end{bmatrix}
=
\begin{bmatrix}
\frac{\partial f_1}{\partial x_1} & \frac{\partial f_1}{\partial x_2} & \ldots & \frac{\partial f_1}{\partial x_n} \\
\frac{\partial f_2}{\partial x_1} & \frac{\partial f_2}{\partial x_2} & \ldots & \frac{\partial f_2}{\partial x_n} \\
. & . & .. & . \\
. & . & .. & . \\
\frac{\partial f_n}{\partial x_1} & \frac{\partial f_n}{\partial x_2} & .. & \frac{\partial f_n}{\partial x_n}
\end{bmatrix}
\begin{bmatrix}
\Delta x_1^0 \\
\Delta x_2^0 \\
. \\
. \\
. \\
\Delta x_n^0
\end{bmatrix}
$$

$$B = J.C$$

Here the matrix J is called the Jacobian matrix. The solution of the equations requires calculation of the vector B on the left hand side, which is the difference of the specified quantities and calculated quantities at $(x_1{}^0, x_2{}^0, \ldots\ldots x_n{}^0)$. Similarly the Jacobian is calculated at this assumption. Solution of the matrix equation gives $(\Delta x_1{}^0, \Delta x_2{}^0, \ldots\ldots \Delta x_n{}^0)$ and the next better solution is obtained as follows :

$$x_1{}^1 = x_1{}^0 + \Delta x_1{}^0$$

$$x_2{}^1 = x_2{}^0 + \Delta x_2{}^0$$

.

.

.

$$x_n{}^1 = x_n{}^0 + \Delta x_n{}^0$$

The better solution is now available and it is

$$(x_1{}^1, x_2{}^1.....x_n{}^1)$$

With these values the iteration process is repeated till:

(1) The largest element in the left column of the equations is less than the assumed value, or

(2) The largest element in the column vector $(\Delta x_1, \Delta x_2.....\Delta x_n)$ is less than assumed value.

Temporarily assuming that all buses except bus 1, are PQ buses. Thus, the unknown parameters consist of the $(n - 1)$ voltage phasors, $V_2, \ldots , V_n$. In terms of real variables, these are:

Angles $\theta_2, \theta_3, \ldots , \theta_n$ $(n - 1)$ variables

Magnitudes $|V_2|, |V_3|, \ldots , |V_n|$ $(n - 1)$ variables

The linearized equations thus becomes,

$$
\begin{bmatrix} \Delta P_2 \\ \Delta P_3 \\ . \\ . \\ \Delta P_n \\ \Delta Q_2 \\ \Delta Q_3 \\ . \\ . \\ \Delta Q_n \end{bmatrix} =
\begin{bmatrix}
\frac{\partial P_2}{\partial e_2} & \frac{\partial P_2}{\partial e_3} & \cdots & \frac{\partial P_2}{\partial e_n} & \frac{\partial P_2}{\partial f_2} & \frac{\partial P_2}{\partial f_3} & \cdots & \frac{\partial P_2}{\partial f_n} \\
\frac{\partial P_3}{\partial e_2} & \frac{\partial P_3}{\partial e_3} & \cdots & \frac{\partial P_3}{\partial e_n} & \frac{\partial P_3}{\partial f_2} & \frac{\partial P_3}{\partial f_3} & \cdots & \frac{\partial P_3}{\partial f_n} \\
. & . & \cdots & . & . & . & \cdots & . \\
. & . & \cdots & . & . & . & \cdots & . \\
\frac{\partial P_n}{\partial e_2} & \frac{\partial P_n}{\partial e_3} & \cdots & \frac{\partial P_n}{\partial e_n} & \frac{\partial P_n}{\partial f_2} & \frac{\partial P_n}{\partial f_3} & \cdots & \frac{\partial P_n}{\partial f_n} \\
\frac{\partial Q_2}{\partial e_2} & \frac{\partial Q_2}{\partial e_3} & \cdots & \frac{\partial Q_2}{\partial e_n} & \frac{\partial Q_2}{\partial f_2} & \frac{\partial Q_2}{\partial f_3} & \cdots & \frac{\partial Q_2}{\partial f_n} \\
\frac{\partial Q_3}{\partial e_2} & \frac{\partial Q_3}{\partial e_3} & \cdots & \frac{\partial Q_3}{\partial e_n} & \frac{\partial Q_3}{\partial f_2} & \frac{\partial Q_3}{\partial f_3} & \cdots & \frac{\partial Q_3}{\partial f_n} \\
. & . & \cdots & . & . & . & \cdots & . \\
. & . & \cdots & . & . & . & \cdots & . \\
\frac{\partial Q_n}{\partial e_2} & \frac{\partial Q_n}{\partial e_3} & \cdots & \frac{\partial Q_n}{\partial e_n} & \frac{\partial Q_n}{\partial f_2} & \frac{\partial Q_n}{\partial f_3} & \cdots & \frac{\partial Q_n}{\partial f_n}
\end{bmatrix}
\begin{bmatrix} \Delta e_2 \\ \Delta e_3 \\ . \\ . \\ \Delta e_n \\ \Delta f_2 \\ \Delta f_3 \\ . \\ . \\ \Delta f_n \end{bmatrix}
$$

In short form it can be written as,

$$
\begin{bmatrix} \Delta P \\ .... \\ \Delta Q \end{bmatrix} =
\begin{bmatrix} J_1 & . & J_2 \\ . & . & . \\ J_3 & . & J_4 \end{bmatrix}
\begin{bmatrix} \Delta e \\ ... \\ \Delta f \end{bmatrix}
$$

If the system consists of all kinds of buses, the above set of equations becomes,

$$
\begin{bmatrix} \Delta P \\ \dots \\ \Delta Q \\ \dots \\ |\Delta V_p|^2 \end{bmatrix} = \begin{bmatrix} J_1 & \cdot & J_2 \\ \cdot & \cdot & \cdot \\ J_3 & \cdot & J_4 \\ \cdot & \cdot & \cdot \\ J_5 & \cdot & J_6 \end{bmatrix} \begin{bmatrix} \Delta e \\ \dots \\ \Delta f \end{bmatrix}
$$

The elements of the Jacobian matrix can be derived from the three load flow equations used for N-R method.

The off-diagonal elements of J_1 are,

$$
\frac{\partial P_p}{\partial e_q} = e_p G_{pq} - f_p B_{pq} , q \neq p
$$

and the diagonal elements of J_1 are

$$
\frac{\partial P_p}{\partial e_p} = 2e_p G_{pp} + f_p B_{pp} - f_p B_{pp} + \sum_{\substack{q=1 \\ q \neq p}}^{n} (e_p G_{pq} + f_p B_{pq})
$$

$$
= 2e_p G_{pp} + \sum_{\substack{q=1 \\ q \neq p}}^{n} (e_p G_{pq} + f_p B_{pq})
$$

The off-diagonal elements of J_2 are,

$$
\frac{\partial P_p}{\partial f_q} = e_p B_{pq} - f_p G_{pq} , q \neq p
$$

and the diagonal elements are,

$$
\frac{\partial P_p}{\partial f_p} = 2f_p G_{pp} + \sum_{\substack{q=1 \\ q \neq p}}^{n} (f_p G_{pq} + e_p B_{pq})
$$

The off-diagonal elements of J_3 are,

$$\frac{\partial Q_p}{\partial e_q} = e_p B_{pq} + f_p G_{pq} \, , q \neq p$$

and the diagonal elements are,

$$\frac{\partial Q_p}{\partial e_p} = 2 e_p B_{pp} + \sum_{\substack{q=1 \\ q \neq p}}^{n} (f_p G_{pq} - e_q B_{pq})$$

The off-diagonal and diagonal elements for J4 respectively are,

$$\frac{\partial Q_p}{\partial f_q} = -e_p G_{pq} + f_p B_{pq} \, , q \neq p$$

$$\frac{\partial Q_p}{\partial f_p} = 2 f_p B_{pp} + \sum_{\substack{q=1 \\ q \neq p}}^{n} (e_q G_{pq} + f_p B_{pq})$$

The off-diagonal and diagonal elements of J_5 are,

$$\frac{\partial |V_p|^2}{\partial e_q} = 0 \, , q \neq p$$

$$\frac{\partial |V_p|^2}{\partial e_p} = 2 e_p$$

The off-diagonal and diagonal elements of J_6 are,

$$\frac{\partial |V_p|^2}{\partial f_q} = 0 \, , q \neq p$$

$$\frac{\partial |V_p|^2}{\partial f_p} = 2 e_p$$

The next step is that we calculate the residual column vector containing the ΔP ,ΔQ and the $|\,V\,|^2$. Let P_{sp} , Q_{sp} and $|V_{sp}|$ be the specified quantities at the bus p. Now, assuming a flat voltage profile, the value of P,Q and |V| at various buses are calculated. Then,

$$\Delta P_p = P_{sp} - P_p{}^0$$

$$\Delta Q_p = Q_{sp} - Q_p{}^0$$

$$| \Delta V_p |^2 = | V_{sp} |^2 - | V_p{}^0 |^2$$

where the superscript zero implies that the value calculated corresponding to initial assumption i.e zero[th] iteration.

After calculating the Jacobian matrix and the residual column vector corresponding to the initial solution, the desired increment vector $\begin{bmatrix} \Delta e \\ \Delta f \end{bmatrix}$ can be calculated by using any standard technique.

The next desired solution would be:

$$e_p{}^1 = e_p{}^0 + \Delta \, e_p{}^0$$

$$f_p{}^1 = f_p{}^0 + \Delta \, f_p{}^0$$

We use these voltage values in the next iteration. This process keeps repeating and the better estimates for the voltages of the buses will be:

$$e_p{}^{k+1} = e_p{}^k + \Delta \, e_p{}^k$$

$$f_p{}^{k+1} = f_p{}^k + \Delta \, f_p{}^k$$

We repeat this process until the magnitude of the largest element in the residual column vector is lesser than the assumed value.

2.3.3 Newton-Raphson Algorithm

1. We assume a suitable solution for all the buses except the slack bus. We assume a flat voltage profile i.e. Vp=1.0+j0.0 for p=1,2,…,n, p≠s, Vs=a+j0.0.

2. We then set a convergence criterion = ε i.e. if the largest of absolute of the residues exceeds ε, the process is repeated, or else its terminated.

3. Set the iteration count K=0.

4. Set the bus count p=1.

5. Check if a bus is a slack bus. If that is the case, skip to step 10.

6. Calculate the real and reactive powers P_p and Q_p respectively, using the equations derived for the same earlier.

7. Evaluate $\Delta P_p^k = P_{sp} - P_p^k$

8. Check if the bus p is a generator bus. If that is the case, compare Q_p^k with the limits. If it exceeds the limits, fix the reactive power generation to the corresponding limit and treat the bus as a load bus for that iteration and go to the next step. If lower limit is violated, set $Q_{sp} = Q_p^{min}$. If the limit is not violated evaluate the voltage residue.

$$| \Delta V_p |^2 = | V_p |_{sp}^2 - | V_p^k |^2$$

9. Evaluate . $\Delta Q_p^k = Q_{sp} - Q_p^k$.

10. Increment the bus count by 1, i.e. p = p+1 and finally check if all the buses have been taken into consideration. Or else, go back to step 5.

11. Determine the largest value among the absolute value of residue.

12. If the largest of the absolute value of the residue is less than ε, go to step 17.

13. Evaluate the Jacobian matrix elements.

14. Calculate the voltage increments Δe_p^k and Δf_p^k .

15. Calculate the new bus voltag $e_p^{k+1} = e_p^k + \Delta e_p^k$ and $f_p^{k+1} = f_p^k + \Delta f_p^k$. Evaluate and of all voltages.

16. Advance iteration count $K = K+1$ and go back to step 4.

17. Evaluate bus and line powers and output the results.

2.4 Comparison of Solution methods[26]

The other load flow solution method we did not discuss is the Gauss method, since Gauss-Seidel method is clearly superior, because its convergence is much better. So we compare only between Newton-Raphson and Gauss-Seidel solution methods. Taking the computer memory requirement into consideration, polar coordinates are preferred for solution based on Newton-Raphson method whereas rectangular coordinates for Gauss-Seidel method. The time taken to execute an iteration of computation is much smaller using Gauss-Seidel method in comparison to Newton-Raphson method, but if we consider the number of iterations required, Gauss-Seidel method has higher number of iterations than N-R method for a particular system, and the number of iterations increase with the increase in the size of the system. The convergence characteristics of N-R method are not affected by the selection of slack bus whereas the convergence characteristics of G-S method maybe seriously affected with the selection of the bus.

Nevertheless, the main advantage of G-S method over N-R method is the ease of programming and the efficient use of the computer memory. However, N-R method is found to be superior and more efficient than G-S method for large power systems, from the practical aspects of computational time and convergence characteristics. Even though N-R method can provide solutions to most of the practical power systems, it sometimes might fail in respect to some ill-conditioned problems.

Chapter-3

FACTS IN POWER SYSTEM

3.1 GENERAL

The controllability on one or more power flow arguments aroused the possibility to control active as well as reactive power flow in the transmission systems. The arguments referred in the power flow are line impedance, magnitude of voltages on both sending and receiving end and also the angles between voltages. [16]

In earlier times, power systems were designed to be self-sufficient and were very simple interconnected systems. The AC power flow between the power systems was rarely unusual as the AC transmission lines did not have the capability to handle dynamic changes in the system and these problems were usually solved by adapting generous stability margins. But now in today's world with the advent of high complex interconnected systems the system load ability and security can be increased to an extent by number of different approaches. The common practice is to install the shunt capacitors on the receiving end side to improve the voltage levels and also insertion of series capacitors to reduce transmission line reactance, which would eventually increase the power transfer capability of lines. To introduce an additional phase shift between sending and receiving end voltages, phase shifting transformers are applied. The variability of these parameters were regulated mechanically and therefore the regulation was slow. By mechanically varying the parameters was good enough for the steady state operation but with increase in complexity of the Power system dynamic operation was pre-dominant and the time response as in varying parameters mechanically is too slow to damp the transient oscillations. [18]

This concept and advances in the field of power electronics led to a new approach introduced by the Electric Power Research Institute (EPRI). Called Flexible AC Transmission Systems or simply FACTS, it was an answer to a call for a more efficient use of already existing resources in present power systems while maintaining and even improving power system security.

3.2 POWER SYSTEM STABILITY

Modern Electric Power system is a complex network of synchronous generators, transmission lines and loads. With changes in generation schedules and load, the system characterstics will vary. Electrical Utilities started as stand-alone systems and with increasing growth in the neighbouring utilities and upon their addition to the network began to form high interconnected systems. This facilitated the need to draw on each other's generation reserves in required times. The interconnection improved reliability but has given birth to instability issues as the disturbances can propagate through the system. Depending on the magnitude of disturbance the system can become transiently unstable. A good power system should have the ability to regain its normal operating conditions even after the disturbance, as the ability to supply uninterrupted electricity determines the quality of a power system. Stability of a power system is considered as a very important aspect for research.

Power system stability can be defined as the ability of synchronous machines to remain in synchronism with each other following a major disturbance. The possible disturbances being the line faults, generator, line outages, load switching and etc. Stability is characterized by the capability of power system to remain in synchronism for the possible disturbances. The stability studies are classified into steady state stability, transient stability and slowly growing stability depending on the order of magnitude and type of disturbance. The transient stability of a system can be improved by using FACT Controllers.

3.3 BASIC PRINCIPLE OF ACTIVE AND REACTIVE POWER FLOW CONTROL

Active (real) and reactive power in a transmission line depend on the voltage magnitudes and phase angles at the sending and receiving ends as well as line impedance. To understand the basic concept behind the FACTS controllers as simple model is considered in Fig 3.3.1.The sending and receiving end voltages are assumed to be fixed and can be interpreted as points in large power systems where voltages are "stiff". Assuming that the resistance of high voltage transmission lines are very small, there is equivalent reactance connected in between

sending and receiving ends. The receiving end is modelled as an infinite bus with a fixed angle of 0°. [16]

$$S_R = P_R + jQ_R = V_R I^*$$ .... (3.3.1)

$$P_R = \frac{V_S V_R}{X} \sin \delta$$ .... (3.3.2)

$$Q_R = \frac{V_S V_R \cos \delta - V_R^2}{X}$$ .... (3.3.3)

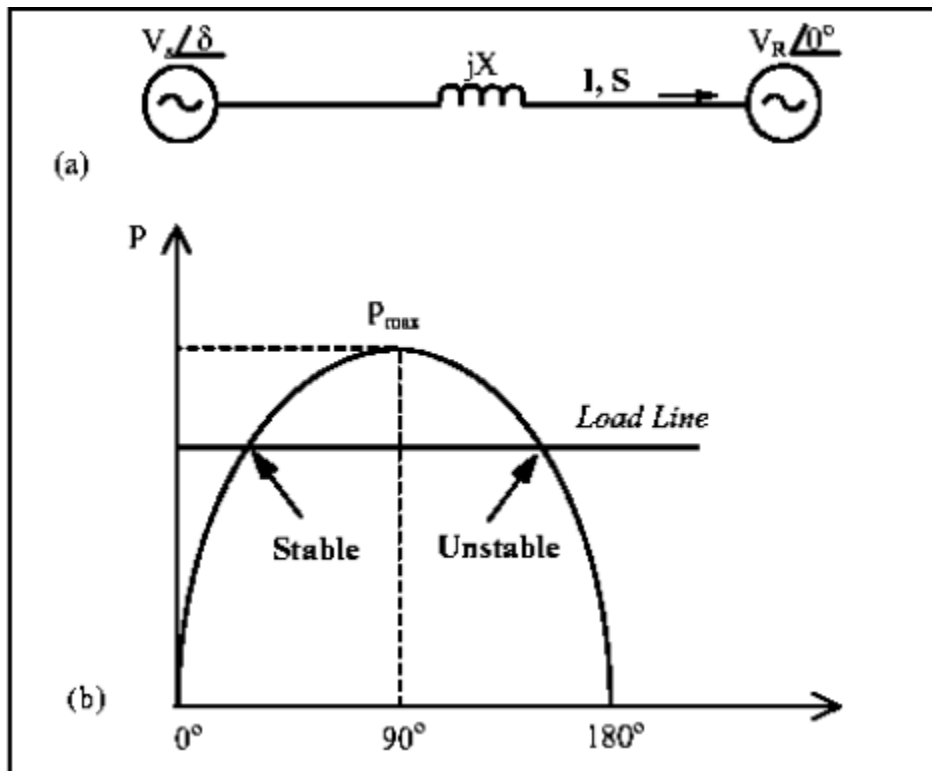
Fig 3.3.1: Model for Calculation of Real and Reactive Power flow [16]

Similarly, for the sending end:

$$P_S = \frac{V_S V_R}{X} \sin \delta - P_{max} \sin \delta$$ .... (3.3.4)

$$Q_S = \frac{V_S^2 - V_S V_R \cos\delta}{X} \qquad\qquad \text{............ (3.3.5)}$$

Where V_S and V_R are the magnitudes (in RMS values) of sending and receiving end voltages, respectively, where δ is the phase-shift between sending and receiving end voltages.

The system is assumed to be a lossless system and so the equations for sending and receiving active power flows, P_S and P_R, are equal. The maximum active power transfer occurs, for the given system, at a power or load angle δ equal to 90° which can be seen in the figure 3.3.1(a). Maximum power occurs at a different angle if the transmission losses are included. The system is stable or unstable depending on whether the derivative dP/dδ is positive or negative. The steady state limit is reached when the derivative is zero.

In practice, a transmission system is never allowed to operate close to its steady state limit, as certain margin must be left in power transfer in order for the system to be able to handle disturbances such as load changes, faults, and switching operations. The intersection between a load line representing sending end mechanical (turbine) power and the demand line defines the steady state value of δ. The angle can be increased by a small increase in mechanical power at the sending end. With increasing load demands the angle goes beyond 90° and results in less power transfer. This accelerates the generator and further increases the angle making the system unstable. However, the increased angle δ increases the electric power to correlate the mechanical increased power. The concepts of dynamic (small signal stability) or Transient (large signal stability) are used to determine the appropriate margin for the load angleδ. [16]

By the IEEE definition, "dynamic stability is the ability of the power system to maintain synchronism when subjected to a severe transient disturbance such as a fault or loss of generation". Typical power transfers correspond to power angles below 30°; to ensure steady state rotor angle stability, the angles across the transmission system are usually kept below 45°.Inspecting the equations little deeper reveals that the real or active power transfer depends mainly on the power angle and also reactive power requirements in both sending and receiving ends typically require high power transfers. From this information we can conclude that reactive power transfer depends mainly on voltage magnitudes, with flows from the highest voltage to the lowest voltage, while the direction of active power flow depends on the sign of the power angle.

Another interesting observation is on the dependability on reactance. The maximum power transfer P_{max} and the angle between two ends vary upon variation of reactance. The regulation of power flow is also possible by varying the sending and receiving end voltages. For a given power flow, a change of X also changes the angle between the two ends. Regulating the magnitudes of sending and receiving ends voltages, V_S and V_R, respectively, can also control power flow in a transmission line. From the equations of reactive power 3.3.4 & 3.3.5, it can be concluded that the regulation of voltage magnitude has much more influence over the reactive power flow than the active power flow.

3.4 FACTS CONTROLLERS

According to the IEEE definition, FACTS is defined as "The Flexible AC Transmission System(FACTS) is a new technology based on power electronic devices which offers an opportunity to enhance controllability, stability and power transfer capability of AC Transmission Systems" [2].

Flexible AC Transmission Systems (FACTS) devices as defined by IEEE as "power electronic based controllers and other static equipment which can regulate the power flow and transmission voltage through rapid control action". In earlier days power system control was only based on generator control and the controlling ability on the transmission lines was meager. With advent of FACTS controllability of transmission line impedance, both series and shunt was made possible. The performance of long distance AC transmission lines can be improved by using FACTS devices in the Power system. The technology was later developed using FACTS devices to regulate Power flow in the system as well. Power transmitted in a power system depends upon the impedance in lines and on the voltages and angles at both sending and receiving ends. Different FACTS controllers can influence these parameters to regulate the power flow in interconnected systems. STATCOM a shunt connected FACTS application can facilitate the fast voltage control and the reactive power control in a Power system.
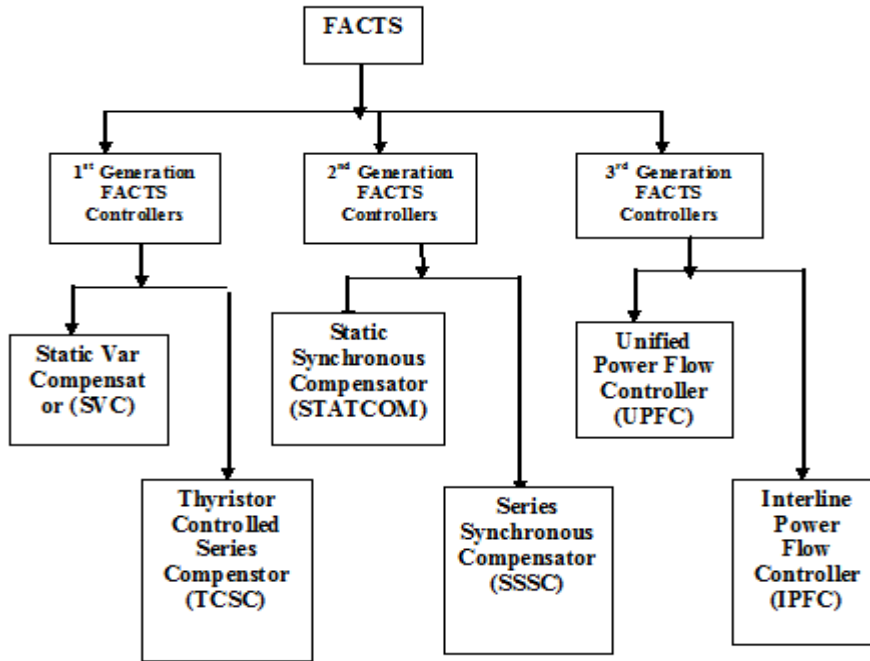
Figure 3.4.1: Block Diagram of FACTS Controllers

FACTS controllers are categorized as follows:

First Generation of FACTS Controllers: Static VAR Compensator (SVC) and Thyristor Controlled Series Compensator (TCSC)

Second Generation of FACTS Controllers: Static Synchronous Series Compensator (SSSC) and Static Synchronous Compensator (STATCOM)

Third Generation of FACTS Controllers: Unified Power Flow Controller (UPFC)

Fourth Generation of FACTS Controllers: Interline Power Flow Controller (IPFC) and Generalized Power Flow Controller (GUPFC)

3.5 DIFFERENT FACTS CONTROLLERS

First Generation of FACTS Controllers:

These categories of controllers are designed based on thyristor based FACTS technology.

3.5.1 Static VAR Compensator (SVC):

It is the first device in the first generation of FACTS controller introduced to provide fast-acting reactive power compensation in the transmission network.

Circuit Description: Static VAR Compensator as shown in Fig 3.5.1 composed of thyristor controlled reactor (TCR), thyristor switched capacitor (TSC) and harmonic filters connected in parallel to provide dynamic shunt compensation. The current in the thyristor controlled reactor is controlled by the thyristor valve that controls the fundamental current by changing the fire angle, ensuring the voltage limited to an acceptable range at the injected node. Current harmonics are inevitable during the operation of thyristor controlled rectifiers, thus it is essential to have filters to eliminate harmonics in the SVC system. The filter banks not only absorbs the risk harmonics but also produce the capacitive reactive power [19].
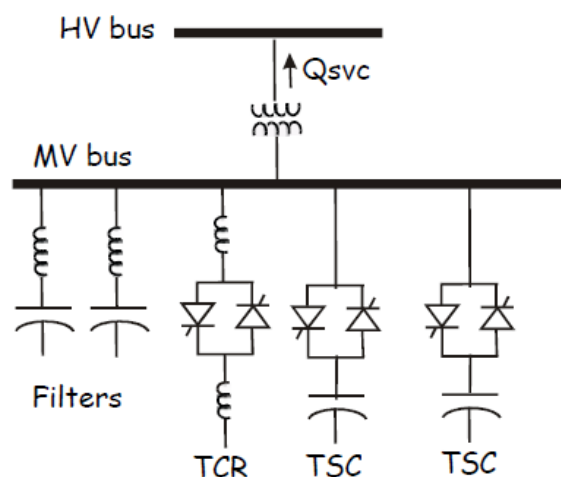
Figure 3.5.1: Circuit Diagram of Static VAR Compensator (SVC) [19]

Characteristics of SVC: SVC placed in a transmission network provides a dynamic voltage control to increase the transient stability, enhancing the damping power oscillations and improve the power flow control of the power systems.

 In real time scenario, it effectively controls the reactive power, improves the power factor, reduces the voltage levels caused by the nonlinear loads, improves the power quality and reduces the energy consumption [20].

The main advantage of SVC application is to maintain bus voltage approximately near a constant level in addition used to improve transient stability. It is widely used in metallurgy, electrified railway, wind power generation etc. [20].

3.5.2 Thyristor Controlled Series Compensator (TCSC):

It is designed based on the thyristor based FACTS technology that has the ability to control the line impedance with a thyristor-controlled capacitor placed in series with the transmission line. It is used to increase the transmission line capability by installing a series capacitor that reduces the net series impedance thus allowing additional power to be transferred [2].

Circuit Description: TCSC device consists of three main components: Capacitor bank, bypass inductor and bidirectional thyristors SCR1 and SCR2 as shown in the Fig 3.5.2.
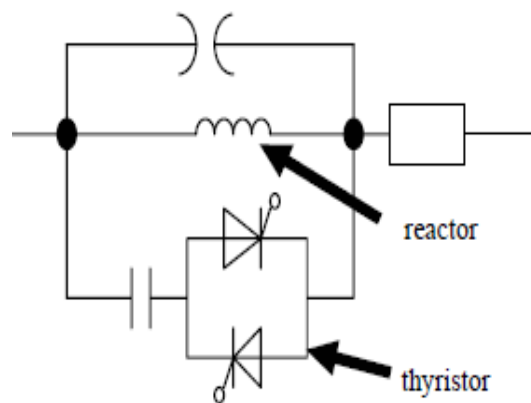
Figure 3.5.2: Circuit Diagram of Thyristor Controlled Series Compensator (TCSC) [21]

Characteristics of Thyristor Controlled Series Compensator (TCSC): TCSC placed in a transmission network provides the power flow control in a power system improving the damping power oscillation and reduces the net loss providing voltage support.

The thyristors in TCSC device offers a flexible adjustment with the ability to control the continuous line compensation. TCSC controllers effectively used for solving power system problems of transient stability, dynamic stability, steady state stability and voltage stability in long transmission lines[21].

Second Generation of FACTS Controllers:

These categories of controllers are designed based on voltage source converter FACTS technology.

3.5.3 Static Synchronous Series Compensator (SSSC):

Static Synchronous Series Compensator is based on solid-state voltage source converter designed to generate the desired voltage magnitude independent of line current.

Circuit Description: SSSC consists of a converter, DC bus (storage unit) and coupling transformer as shown in Figure 3.5.3. The dc bus uses the inverter to synthesize an ac voltage waveform that is inserted in series with transmission line through the transformer with an appropriate phase angle and line current. If the injected voltage is in phase with the line current it exchanges a real power and if the injected voltage is in quadrature with line current it exchanges a reactive power. Therefore, it has the ability to exchange both the real and reactive power in a transmission line.
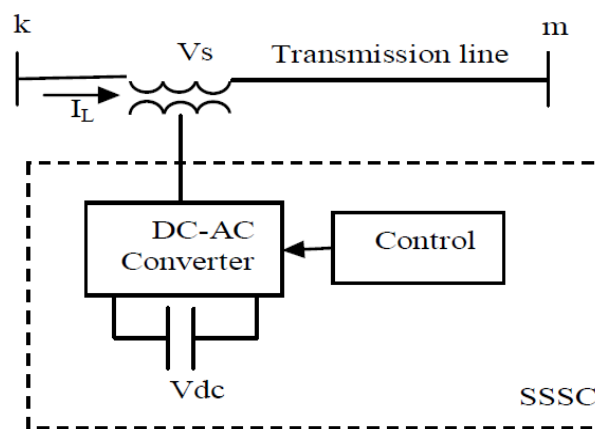
Figure 3.5.3: Block Diagram of Static Synchronous Series Compensator (SSSC) [22]

Characteristics of SSSC: SSSC in a transmission network generates a desired compensating voltage independent of the magnitude of line current, by modulating reactive line impedance and combining real and reactive compensation it can provide high damping of power oscillation.

The capability of SSSC to exchange both active and reactive power makes it possible to compensate both the reactive and the resistive voltage drop thereby maintains a high effective X/R ration independent of degree of series oscillation.

All the above features of SSSC attract the FACTS device for power flow control, damping of power oscillations and transient stability [22].

3.5.4 Static Synchronous Compensator (STATCOM):

It is designed based on Voltage source converter (VSC) electronic device with Gate turn off thyristor and dc capacitor coupled with a step down transformer tied to a transmission line as shown in Fig 3.5.4. It converts the dc input voltage into ac output voltages to compensate the active and reactive power of the system. STATCOM has better characteristics than SVC and it is used for voltage control and reactive power compensation.
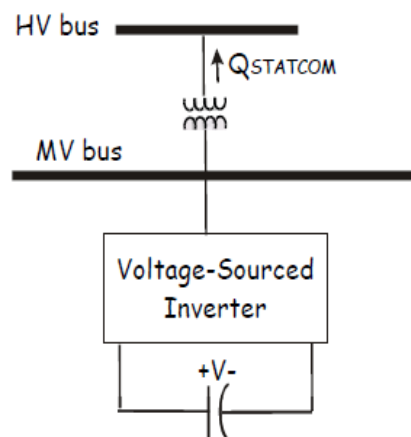
Figure 3.5.4: Circuit Diagram of Static Synchronous Compensator (STATCOM) [23]

Characteristics of Static Synchronous Compensator (STATCOM): STATCOM placed on a transmission network improve the voltage stability of a power system by controlling the voltage in transmission and distribution systems, improves the damping power oscillation in transmission system, provides the desired reactive power compensation of a power system[24].

Third Generation of FACTS Controllers:

The third generation of FACTS controllers is designed by combining the features of previous generation's series and shunt compensation FACTS controllers.

3.5.5 Unified Power Flow Controller (UPFC):

It is designed by combining the series compensator (SSSC) and shunt compensator (STATCOM) coupled with a common DC capacitor. It provides the ability to simultaneously control all the transmission parameters of power systems, i.e. voltage, impedance and phase angle.

Circuit Description: As shown in Fig 3.5.5 it consists of two converters – one connected in series with the transmission line through a series inserted transformer and the other one connected in shunt with the transmission line through a shunt transformer. The DC terminal of the two converters are connected together with a DC capacitor. The series converter control to inject voltage magnitude and phase angle in series with the line to control the active and reactive power flows on the transmission line. Hence the series converter will exchange active and reactive power with the line.
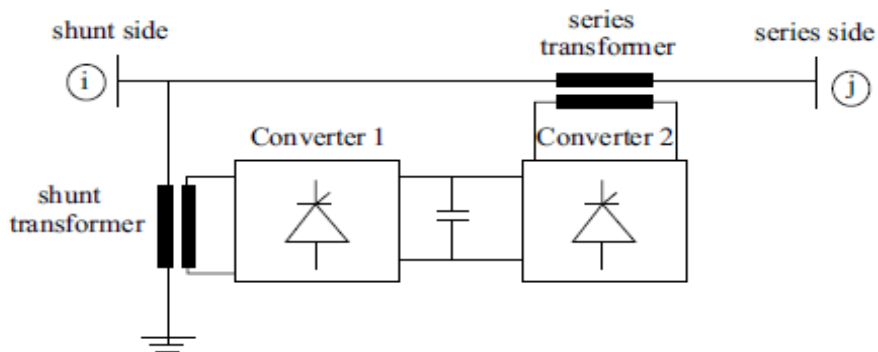
Figure 3.5.5: Circuit Diagram of Unified Power Flow Controller (UPFC) [24]

Characteristic of UPFC: The concept of UPFC makes it possible to handle practically all the power flow control and transmission lines compensation problems using solid-state

controllers that provide functional flexibility which are generally not obtained by thyristor-controlled controllers.

3.5.6 Convertible Static Compensator (CSC):

It is the latest generation and most recent development in the field of FACTS controllers. It has the ability to increase the power transfer capability and maximize the use of existing transmission line [25].

3.5.7 Interline Power Flow Controller (IPFC):

It is designed based on Convertible Static Compensator (CSC) of FACTS Controllers. As shown in Fig 3.5.6, IPFC consists of two series connected converters with two transmission lines. It is a device that provides a comprehensive power flow control for a multi-line transmission system and consists of multiple number of DC to AC converters, each providing series compensation for a different transmission line. The converters are linked together to their DC terminals and connected to the AC systems through their series coupling transformers. With this arrangement, it provides series reactive compensation in addition any converter can be controlled to supply active power to the common dc link from its own transmission line [25].
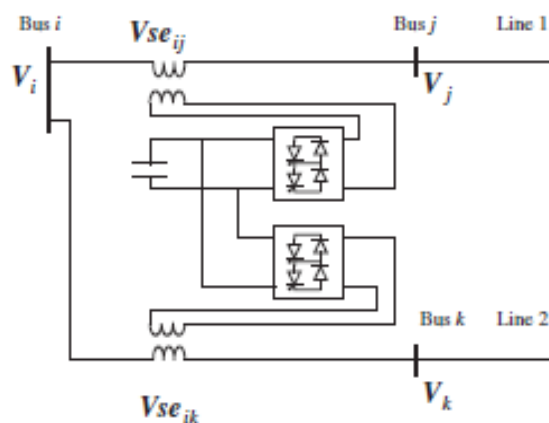
Figure 3.5.6: Circuit Diagram of Interline Power Flow Controller [25]

Characteristics of IPFC: To avoid the control of power flow problem in one system with synchronous of power in other system, installation of IPFC system in additional parallel inverter is required to meet the active power demand.

3.5.8 Generalized Unified Power Flow Controller (GUPFC):

It has been proposed to realize the simultaneous power flow control of several transmission lines. It is designed by combining three or more dc to ac converters working together extending the concepts of voltage and power flow control of the known two-converter UPFC controller to multi voltage and power flow control. The GUPFC shown in Fig 3.5.7 consists of three converters, one
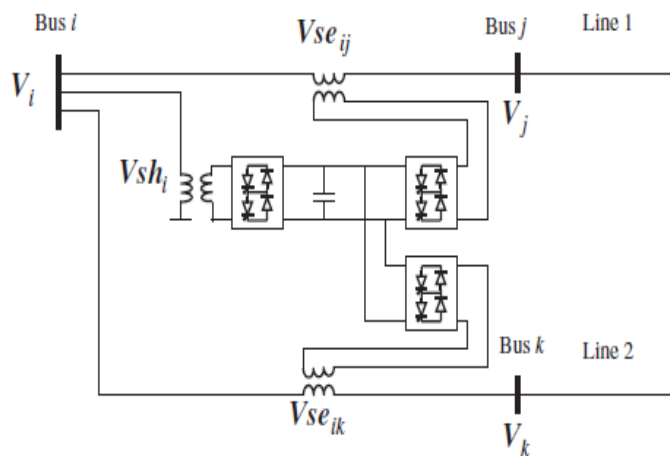
Figure 3.5.7: Circuit Diagram of Generalized UPFC [25]

3.6 OPPORTUNITIES FOR FACTS

The FACTS technology opens up new opportunities for controlling power and enhancing the usable capacity of present, as well as new and upgraded, lines. The FACTS controllers can enable a line to carry power closer to its thermal rating. FACTS device offers continuous control of power flow or voltage, against daily load changes. These opportunities arise through the ability of FACTS Controllers to control the interrelated parameters that govern the operation of transmission systems including series impedance, shunt impedance, current, voltage, phase angle, and the damping of oscillations at various frequencies below the rated

frequency. Within the basic system security guidelines, the FACTS devices enable the transmission system to obtain one or more of the following benefits [9-10, 2]:

1) Better utilization of existing transmission system assets:

Increasing the energy transfer capacity and controlling the load flow of transmission lines are is very important, especially in de-regulated power markets, where electricity supply and demand changes rapidly. Frequently, adding new transmission lines to meet increasing electricity demand is limited by economical and environmental constraints. FACTS devices help to meet these requirements with the existing transmission systems.

2) Increased quality of supply for sensitive Industries:

Modern industries depend upon high quality electricity supply including constant voltage, and frequency and no supply interruptions. FACTS devices can help provide the required quality of supply.

3) Increased Dynamic and Transient Stability:

Long transmission lines, interconnected grids, impacts of changing loads and line faults can create instabilities in transmission systems. These can lead to reduced line power flow, loop flows or even to line trips. FACTS devices stabilize transmission systems with resulting higher energy transfer capability and reduced risk of line trips.

4) Increased transmission system reliability and availability:

Transmission system reliability and availability is affected by many different factors. Although FACTS devices cannot prevent faults, they can mitigate the effects of faults and provide more secure electricity by reducing the number of line trips. For example, a major load rejection results in an over voltage of the line which can lead to a line trip. SVC's or STATCOM's counteract the over voltage and avoid line tripping.

5) Environmental Benefits:

FACTS devices are environmentally friendly. They contain no hazardous materials and produce no waste of pollutants.

The FACTS controllers can be used for various purposes to enhance power system performance during steady state and dynamic state resulted due to transients and

contingencies. Whereas, the conventional devices find little application during system transient or contingency condition [11-12].

3.7 APPLICATION OF FACTS UNDER STEADY STATE

Various steady state applications of FACTS controllers includes voltage control (low and high), increase of thermal loading, post-contingency voltage control, loop flows control, reduction in short circuit level and power flow control. The application of various FACTS controllers along with their conventional counterpart in addressing their limitations are summarized in Table 3.1. The primary advantage of FACTS controllers, over its conventional counterpart is the rapid control of current, voltage and/or impedance following disturbance. The conventional solutions are normally less expensive than FACTS devices, but limited in their dynamic behaviour. The steady state applications include-

- Reactive power and voltage control
- Increase thermal loading
- Post contingency and Voltage control
- Power flow balancing and control

REACTIVE POWER AND VOLTAGE CONTROL

Under steady-state conditions, high loading and low voltage can be a limiting factor. The proper corrective action is to supply reactive power so as to correct the load power factor and to compensate for the reactive losses in lines and transformers. Traditionally, mechanically switched shunt capacitors (MSC) and reactors (MSR) were used for voltage control.

INCREASE THERMAL LOADING

On a steady-state basis, equipment thermal limits represent a technical problem for which specific action is required. These hard limits can be removed only by adding transmission equipment or rearranging the network. Conventional solutions to transmission thermal overloads include a series reactor, series capacitors in parallel circuits.

POST-CONTINGENCY VOLTAGE CONTROL

Depending on the change in network configuration caused by the outage, unacceptably high or low voltage conditions can result and thermal limits may be exceeded. Low voltage following an outage is one of the most widespread causes of transmission limitations. Indeed, most major transmission line loading levels are set by the maximum acceptable voltage drop and/or the minimum voltage a line loss would cause at other locations in the network, if not in neighbouring systems. The voltage drop due to the loss of a major line can be accompanied by circuit overloads, at the same voltage or at lower voltage levels. If only the final under voltage problem is of concern, the proper corrective actions to supply reactive power from mechanically switched shunt capacitors or to switch off shunt reactors. A STATCOM may offer better voltage support than a SVC. If a rapid solution to the voltage drop is needed to prevent load loss, the preferred FACTS controllers are those capable of supplying reactive power and controlling flows including IPC, UPFC and TCSC. In the case of high post-contingency voltages, the rapid insertion of an overvoltage protective device such as the Thyristor Controlled Voltage Limiter (TCVL) may be the viable solution.

POWER FLOW BALANCING AND CONTROL

FACTS controllers, especially TCSC, SSSC and UPFC, enable the load flow on parallel circuits and different voltage levels to be optimized and controlled, with a minimum of power wheeling, the best possible utilization of the lines, and a minimizing of overall system losses at the same time.

3.8 APPLICATION OF FACTS UNDER DYNAMIC STATE

One of the most important capabilities expected of FACTS applications is to be able to reduce the impact of the primary disturbance. The impact reduction for contingencies can be achieved through dynamic voltage support (STATCOM), dynamic flow control (TCSC) or both with the use of UPFC. The typical applications in dynamic state include:

- Transient stability enhancement

- Oscillation damping

- Voltage stability enhancement

- SSR elimination

The above listed applications are explained briefly:

TRANSIENT STABILITY ENHANCEMENT:

Transient instability is caused by large disturbances such as tripping of a major transmission line or a generator and the problem can be seen from the first swing of the angle. The conventional solutions for increasing synchronizing torques have been to equip generators with high response exciters and to shorten equivalent transmission distances with series capacitors. However, series capacitor compensated transmission network could be facing sub-synchronous resonance (SSR) problem. This can be overcome through an installation of appropriate FACTS controllers.

A SVC and STATCOM, near the electrical centre of the sending and receiving system can hold voltage or even raise voltage above nominal to transiently increase synchronizing power transfer. A TCPAR could control the effective angle between the sending and the receiving systems to extend the period over which synchronizing power is high. A UPFC, depending on the control strategy, can provide the benefits of a TCSC, PAR, SVC or a STATCOM. Moreover, a UPFC could also limit fault current (when the fault is downstream of the UPFC) by applying a series voltage that mimics a series reactor.

OSCILLATION DAMPING

Electromechanical oscillations have been observed in many power systems worldwide and may lead to partial power interruption if not controlled. Initially, power system stabilizer (PSS) is used for oscillation damping in power system. Now this function can be more effectively handled by proper placement and setting of SVC, STATCOM and TCSC.

VOLTAGE STABILITY ENHANCEMENT

Voltage stability (instability/collapse) is a totally different form of power system dynamic problem. Contrary to the loss of electromechanical stability, voltage instability is a possible consequence of progressive increase in load until the point of collapse is reached, beyond which little can be done except to prepare for system restoration. The collapse phenomenon is typically slow, over several minutes, depending on the time-varying behaviour of the loads. The following conventional corrective actions are possible;

• Reserve reactive support must be used, i.e. switched shunt capacitors and SVCs.

• Network control actions: coordinate system LTCs, recluse lines automatically; use HVDC station reactive power control capabilities.

• Load control: automatic under-voltage load shedding or operator initiated load shedding.

• Generator control action: remove generation to mitigate a transmission system overload, add local generation or trade real power for reactive power on critical generation.

SSR ELIMINATION

Sub-synchronous resonance (SSR) is a phenomenon which can be associated with series compensation under certain adverse conditions. TCSC have dynamic characteristics that differ drastically from conventional series capacitors especially at frequencies outside the operating frequency range and hence is used for the elimination of SSR in the power system.

Table 3.1 Application of Various FACTS devices

Issues	Problem	Corrective Action	Conventional Solution	New Equipment (FACTS)
Voltage Limits	Low voltage at heavy load	Supply reactive power	Shunt capacitor, Series capacitor	TCSC, STATCOM
	High voltage at light load	Remove reactive power supply	Switch EHV line and/or shunt capacitor	TCSC, TCR
		Absorb reactive power	Switch shunt capacitor, shunt reactor,SVC	TCR, STATCOM
	High voltage following outage	Absorb reactive power	Add reactor	TCR
		Protect equipment	Add arrestor	TCVL
	Low voltage following outage	Supply reactive power limit	Switch, shunt capacitor, reactor, SVC, switch series capacitor	STATCOM, TCSC
		Prevent over load	Series reactor, PAR	IPC, TCPAR, TCSC
	Low voltage and overload;	Supply reactive power and limit over load	Combination of two or more equipment	IPC, TCSC, UPFC, STATCOM
Thermal Limits	Line/transformer overload	Reduce overload	Add line/transformer	TCSC, TCPAR, UPFC
			Add series reactor	TCR, IPC
	Tripping of parallel circuit	Limit circuit loading		IPC,TCR, UPFC
Short-circuit levels	Excessive breaker fault current	Limit short-circuit current	Add series reactor, fuses, new circuit breaker	TCR, IPC, UPFC
		Change circuit breaker	Add new circuit breaker	
		Rearrange network	Split bus	IPC

Chapter-4

LOAD FLOW INCLUDING STATCOM

4.1 POWER FLOW ANALYSIS WITH STATCOM

As discussed in the earlier chapter, we use a STATCOM for transmission voltage control by shunt compensation of reactive power. Usually, STATCOM consists of a coupling transformer, a converter and a DC capacitor, as shown in the figure below.
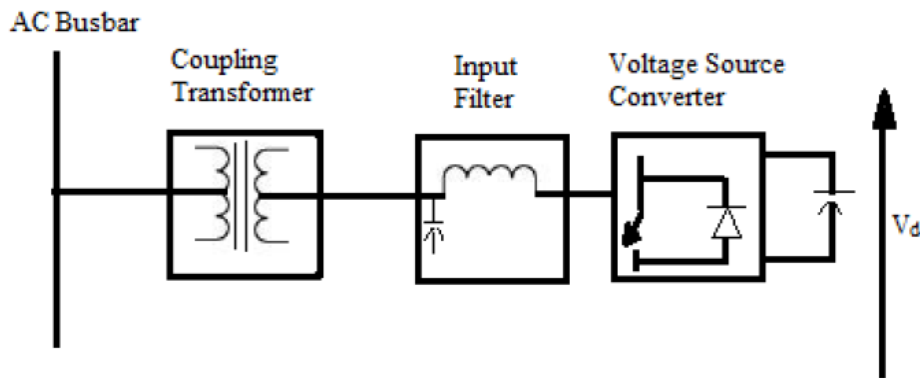
Fig 4.1
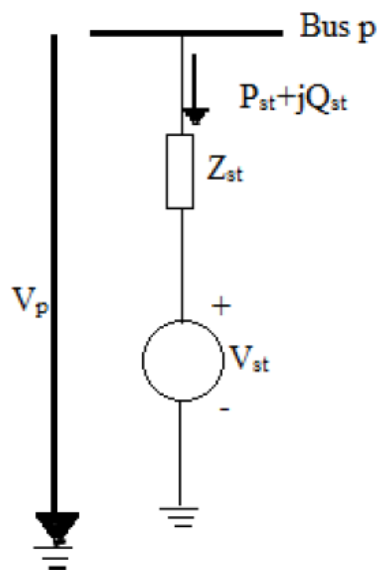
Fig 4.2

Supposing that the voltage across the STATCOM is $V_{st}\angle\ \delta_{st}$ and the voltage of the bus is $V_p\angle\ \delta_p$ then we have $Y_{st} = 1/\ Z_{st} = g_{st} + jb_{st}$

Then the power flow constraints of the STATCOM are given by

$$P_{st} = V_p{}^2\ g_{st} - V_pV_{st}(g_{st}\ \cos(\theta_p - \theta_{st}) + b_{st}\ \sin(\theta_p - \theta_{st}))\ \ .....(4.1)$$
$$Q_{st} = -V_p{}^2 b_{st} - V_pV_{st}(g_{st}\ \sin(\theta_p - \theta_{st}) - b_{st}\ \cos(\theta_p - \theta_{st}))\ \ .....(4.2)$$

In our case we are using the STATCOM to control the reactive power at one of the buses to see its effect on the performance of the transmission system and infer useful conclusions from this. This is done by the control of the voltage at the required bus.

The main constraint of the STATCOM while operating is that, the active power exchange via the DC link should be zero, i.e. $PEx = Re(V_{st}I_{St}{}^*) = 0$.

Where

$$Re(V_{st}I_{st}{}^*) = V_{st}{}^2 g_{st} - V_pV_{st}(g_{st}\ \cos(\theta_p - \theta_{st}) - b_{st}\ \sin(\theta_p - \theta_{st})\ \ ....(4.3)$$

4.2 CONTROL FUNCTION OF STATCOM:

The control of the STATCOM voltage magnitude should be such that the specified bus voltage and the STATCOM voltage should be equivalent and there should be no difference between them. By proper design procedure, knowing the limits of the variables and the parameters, but not exactly knowing the power system parameters, simultaneous DC and AC control can be achieved. We can ensure the stability of the power system by the proposed STATCOM controller design. Thus it can work along with the other controllers in the network. The bus control restraint will be

$$F = V_p\text{-}V_{sp} = 0$$

Where V_{sp} is the specified voltage for the bus.

4.3 IMPLEMENTATION OF STATCOM TO A BUS NETWORK:

The Newton power flow equations for a bus system containing n number of buses, including a STATCOM are developed as follows

$$
\begin{bmatrix}
\Delta P_2 \\ \Delta P_3 \\ . \\ . \\ \Delta P_n \\ \Delta Q_2 \\ \Delta Q_3 \\ . \\ . \\ \Delta Q_n \\ \Delta PE_x \\ \Delta F
\end{bmatrix}
=
\begin{bmatrix}
\frac{\partial P_2}{\partial e_2} & \frac{\partial P_2}{\partial e_3} & \cdots & \frac{\partial P_2}{\partial e_n} & \frac{\partial P_2}{\partial f_2} & \frac{\partial P_2}{\partial f_3} & \cdots & \frac{\partial P_2}{\partial f_n} \\
\frac{\partial P_3}{\partial e_2} & \frac{\partial P_3}{\partial e_3} & \cdots & \frac{\partial P_3}{\partial e_n} & \frac{\partial P_3}{\partial f_2} & \frac{\partial P_3}{\partial f_3} & \cdots & \frac{\partial P_3}{\partial f_n} \\
. & . & \cdots & . & . & . & \cdots & . \\
. & . & \cdots & . & . & . & \cdots & . \\
\frac{\partial P_n}{\partial e_2} & \frac{\partial P_n}{\partial e_3} & \cdots & \frac{\partial P_n}{\partial e_n} & \frac{\partial P_n}{\partial f_2} & \frac{\partial P_n}{\partial f_3} & \cdots & \frac{\partial P_n}{\partial f_n} \\
\frac{\partial Q_2}{\partial e_2} & \frac{\partial Q_2}{\partial e_3} & \cdots & \frac{\partial Q_2}{\partial e_n} & \frac{\partial Q_2}{\partial f_2} & \frac{\partial Q_2}{\partial f_3} & \cdots & \frac{\partial Q_2}{\partial f_n} \\
\frac{\partial Q_3}{\partial e_2} & \frac{\partial Q_3}{\partial e_3} & \cdots & \frac{\partial Q_3}{\partial e_n} & \frac{\partial Q_3}{\partial f_2} & \frac{\partial Q_3}{\partial f_3} & \cdots & \frac{\partial Q_3}{\partial f_n} \\
. & . & \cdots & . & . & . & \cdots & . \\
. & . & \cdots & . & . & . & \cdots & . \\
\frac{\partial Q_n}{\partial e_2} & \frac{\partial Q_n}{\partial e_3} & \cdots & \frac{\partial Q_n}{\partial e_n} & \frac{\partial Q_n}{\partial f_2} & \frac{\partial Q_n}{\partial f_3} & \cdots & \frac{\partial Q_n}{\partial f_n} \\
\frac{\partial PE_x}{\partial e_2} & \frac{\partial PE_x}{\partial e_3} & \cdots & \frac{\partial PE_x}{\partial e_n} & \frac{\partial PE_x}{\partial f_2} & \frac{\partial PE_x}{\partial f_3} & \cdots & \frac{\partial PE_x}{\partial f_n}
\end{bmatrix}
\begin{bmatrix}
\Delta e_2 \\ \Delta e_3 \\ . \\ . \\ \Delta e_n \\ \Delta f_2 \\ \Delta f_3 \\ . \\ . \\ \Delta f_n \\ \Delta V_{st} \\ \Delta \delta_{st}
\end{bmatrix}
\quad \text{....(4.4)}
$$

$$B = JC$$

Where V_{st} and δ_{st} are the two state variables of the STATCOM defined by the two equations given above. The Jacobian elements can be calculated by taking partial derivatives of the corresponding equations in the matrix. The STATCOM has two equality criterion and two state variables ΔV_{st} and $\Delta \delta_{st}$. The first equality is the real power balancing equation, given by:

$$PE_x = \mathrm{Re}(V_{st} I_{st}^*)$$

And the second equality for the control restraint of the STATCOM, given by:

$$F = V_p - V_{sp}$$

The Jacobian matrix elements can be found out by partially differentiating the corresponding equations.

Elements of the Jacobian Matrix:

The complex power injected at any bus p in a system is,

$$V_p I_p^* = V_p \left(\sum_{k=1}^n Y_{pk} V_k\right)^*$$

$$V_p I_p = V_p^* \left(\sum_{k=1}^n Y_{pk} V_k\right)$$

Considering

$$V_p = V_p(\cos\delta_i + j\sin\delta_i)$$

$$Y_{pk} = g_{pk} + jb_{pk}$$

$$V_k = V_k(\cos\delta_k + j\sin\delta_k)$$

Rewriting the previous equations as:

$$P_p - jQ_p = V_p^*(Y_{p1}V_1 + Y_{p2}V_2 + \cdots + Y_{pn}V_n)$$

$$= V_p^* Y_{p1} V_1 + V_p^* Y_{p2} V_2 + \ldots + V_p^* Y_{p2} V_2$$

$$= Y_{p1} V_1 V_k\{\cos(\delta_1 - \delta_k) + j\sin(\delta_1 - \delta_k)\} +$$
$$Y_{k2} V_2 V_k\left\{\cos(\delta_2 - \delta_k) + j\sin(\delta_2 - \delta_k) + \cdots +\right.$$
$$\left. Y_{pn} V_n V_p\{\cos(\delta_n - \delta_k) + j\sin(\delta_n - \delta_k)\}\right\}$$

$$= V_1 V_k[\{g_{k1}\cos(\delta_1 - \delta_k) - b_{k1}\sin(\delta_1 - \delta_k)\} +$$
$$j\{-g_{k1}(\delta_1 - \delta_k) + b_{k1}\cos(\delta_1 - \delta_k)\}] + \cdots +$$
$$V_n V_k[\{g_{kn}\cos(\delta_n - \delta_k) - b_{kn}\sin(\delta_n - \delta_k)\} +$$
$$j\{-g_{kn}(\delta_n - \delta_k) + b_{kn}\cos(\delta_n - \delta_k)\}]$$

Sorting out the real and imaginary parts, i.e. P_p and Q_p,

$$P_p = V_1 V_p\left[\{g_{p1}\cos(\delta_1 - \delta_p) - b_{p1}\sin(\delta_1 - \delta_p)\} + \cdots \right.$$
$$\left. + V_n V_p\{g_{pn}\cos(\delta_n - \delta_p) + b_{pn}\sin(\delta_n - \delta_p)\}\right] \quad \ldots (4.5)$$

$$Q_p = V_1 V_p \left[\{ g_{p1} \sin(\delta_1 - \delta_p) + b_{p1} \cos(\delta_1 - \delta_p) \} + \cdots + V_n V_p \{ g_{pn} \sin(\delta_n - \delta_p) + b_{pn} \cos(\delta_n - \delta_p) \} \right] \ \ldots(4.6)$$

Taking the derivatives of P_p and Q_p gives us the Jacobian matrix elements:

$$\frac{\partial P_p}{\partial \delta_k} = V_p V_k \left(g_{pk} \sin(\delta_p - \delta_k) - b_{pk} \cos(\delta_p - \delta_k) \right) \ \ldots (4.7)$$

$$\frac{\partial Q_p}{\partial \delta_k} = -V_p V_k \left(g_{pk} \sin(\delta_p - \delta_k) + b_{pk} \cos(\delta_p - \delta_k) \right) \ \ldots (4.8)$$

$$\frac{\partial P_p}{\partial V_k} = V_p \left(g_{pk} \cos(\delta_p - \delta_k) - b_{pk} \sin(\delta_p - \delta_k) \right) \ \ldots (4.9)$$

$$\frac{\partial Q_p}{\partial V_k} = V_p \left(g_{pk} \sin(\delta_p - \delta_k) - b_{pk} \cos(\delta_p - \delta_k) \right) \ \ldots (4.10)$$

The elements of the Jacobian can be found out from the above equations and put in the Newton-Raphson Power Flow solution.

4.4 ALGORITHM FOR LOAD FLOW WITH STATCOM

The steps to incorporate STATCOM are as follows:

Step 1: Read the system database.

Step 2: The system buses, at which STATCOM are assumed to be placed are made PV buses.

Step 3: The specified real power and reactive power at which STATCOM is placed is calculated using eq. (4.5) and eq. (4.6).

Step 4: On the buses with STATCOM, the specified voltage is set according to the desired voltage and upper and lower limits of reactive power are set according to the STATCOM ratings.

Step 5: Modify Jacobian elements as described in section 2.3 and using eq.(4.7) to eq.(4.10).

Step 6: Carry Newton-Raphson load flow with modified Jacobian elements

Step 7: Voltages and angles of system and STATCOM are updated.

Chapter-5

CASE STUDIES AND RESULTS

5.1 CASE STUDY OF 5-BUS NETWORK
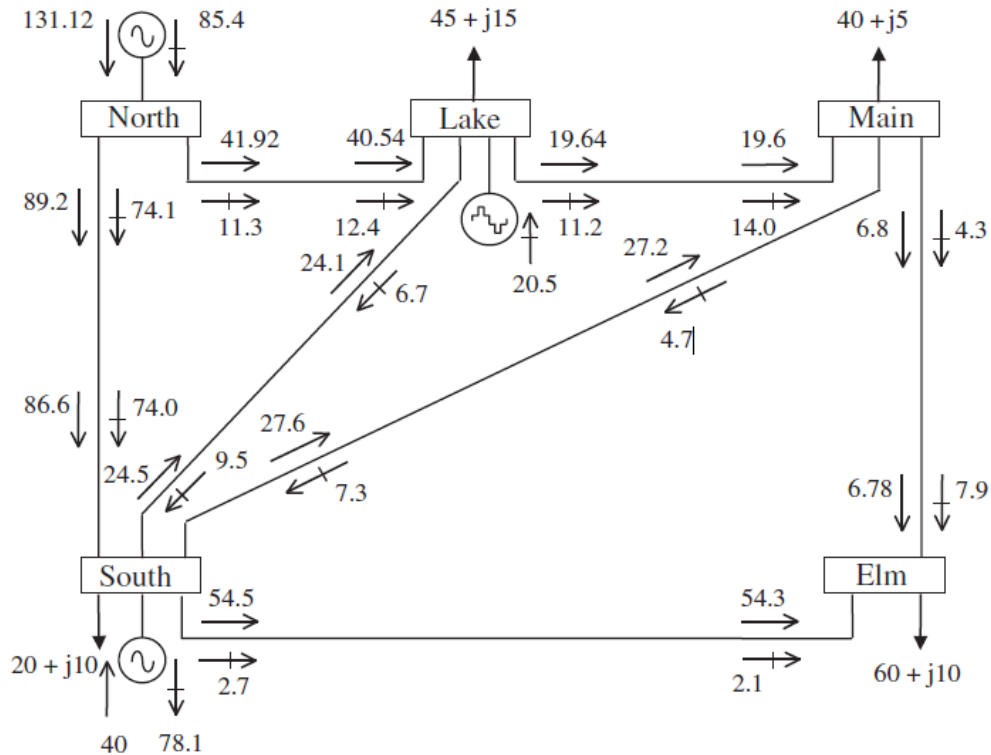
Figure 5.1: A Standard 5-Bus Network with STATCOM

In this project, I considered an IEEE standard 5- bus network with STATCOM to study the power flow of a power system. For the analysis as shown in Fig 5.1, bus 1(North) considered as slack bus, bus 2 (South) as voltage control bus and buses 3(Lake), 4(Main) and 5(Elm) as load buses. The five-bus network is modified to include one STATCOM connected at Lake, to maintain the nodal voltage magnitude at 1 p.u. The source impedance is X_{vr}=0.1 p.u. The power flow solution is shown in fig. 5.1 whereas nodal voltage magnitudes and phase angles

are given in Table 5.2.1convergence is achieved in six iterations to a power mismatch tolerance of 1e-12.

5.1.1 BUS DATA

Table 5.1.1 below displays the bus data characteristics of the transmission system discussed above. Column 1 of Table 5.1.1 outlines the bus number and column 2 contains the bus code. Columns 3 and 4 show the voltage magnitudes in p.u. and phase angle in degrees. Columns 5 and 6 outline the size of the active and reactive loads connected to the corresponding buses in MW and MVAR. Columns 7 through to 10 are MW, MVAR, minimum MVAR and maximum MVA of generation, in that order. The bus code entered in column 2 is used for identifying load, voltage-controlled, and slack buses as outlined below;

1 – This code is used for the slack bus.

2 – This code is used for the voltage controlled buses.

3 – This code is used for load buses.

5.1.2 LINE DATA

Table 5.1.2 below displays the line data characteristics of the transmission system discussed above. Columns 1 and 2 of Table 5.1.2 outline the corresponding line bus numbers. Columns 3 through to 5 contain the line resistance, reactance, and one half of the total line charging susceptance in per unit on the MVA base of 100MVA.

Table 5.1.1 Bus Data

Bus No.	Bus Code	Voltage Mag.	Angle Degree	Load MW	Load MVAR	Gen. MW	Gen MVAR	Qmin	Qmax
1	1	1.06	0	0.0	0.0	0.0	0.0	-500	500
2	2	1.0	0	20.0	10.0	40.0	0.0	-300	300
3	3	1.0	0	45.0	15.0	0.0	0.0	0	0
4	3	1.0	0	40.0	5.0	0.0	0.0	0	0
5	3	1.0	0	60.0	10.0	0.0	0.0	0	0

Table 5.1.2 Line Data

Bus nl	Bus nr	R	X	B
1	2	0.02	0.06	0.06
1	3	0.08	0.24	0.05
2	3	0.06	0.18	0.04
2	4	0.06	0.18	0.04
2	5	0.04	0.12	0.03
3	4	0.01	0.03	0.02
4	5	0.08	0.24	0.05

5.2 RESULTS:

5.2.1 A 5-Bus Network Bus Voltage without STATCOM

For iterations = 6

Table 5.2.1: Bus Voltage without STATCOM

	Bus Voltage without STATCOM				
Nodal Voltage	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5
Magnitude(p.u.)	1.06	1.00	0.98	0.98	0.97
Phase angle(deg)	0	-2.06	-4.63	-4.95	-5.76

5.2.2 A 5-Bus Network Bus Voltage with 1-STATCOM

For iterations = 5

Table 5.2.2: Bus Voltage with STATCOM

	Bus Voltage with STATCOM				
Nodal Voltage	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5
Magnitude(p.u.)	1.06	1.00	1.00	0.99	0.97
Phase angle(deg)	0	-2.05	-4.83	-5.10	-5.79

Table 5.2.3 Line Flow without STATCOM for the 5-bus Network:

Buses	Sending End		Receiving End	
	P (MW)	Q (MVAR)	P (MW)	Q (MVAR)
1-2	89.33	74.00	-86.85	-72.91
1-3	41.79	16.82	-40.27	-17.51
2-3	24.47	-2.52	-24.11	-0.35
2-4	27.71	-1.72	-27.25	-0.83
2-5	54.66	5.56	-53.44	-4.83
3-4	19.39	2.86	-19.35	-4.69
4-5	6.6	0.52	-6.56	-5.17

Table 5.2.4 Line Flow with STATCOM for the 5-bus Network:

Buses	Sending End		Receiving End	
	P (MW)	Q (MVAR)	P (MW)	Q (MVAR)
1-2	89.11	74.06	-86.63	-72.99
1-3	41.95	11.28	-40.55	-12.41
2-3	24.49	-9.51	-24.09	6.69
2-4	27.66	-7.32	-27.18	4.77
2-5	54.88	2.75	-53.29	-2.09
3-4	19.65	11.19	-19.59	-13.02
4-5	6.78	3.25	-6.71	-7.91

5.3 Case Study of IEEE-14 Bus test system:
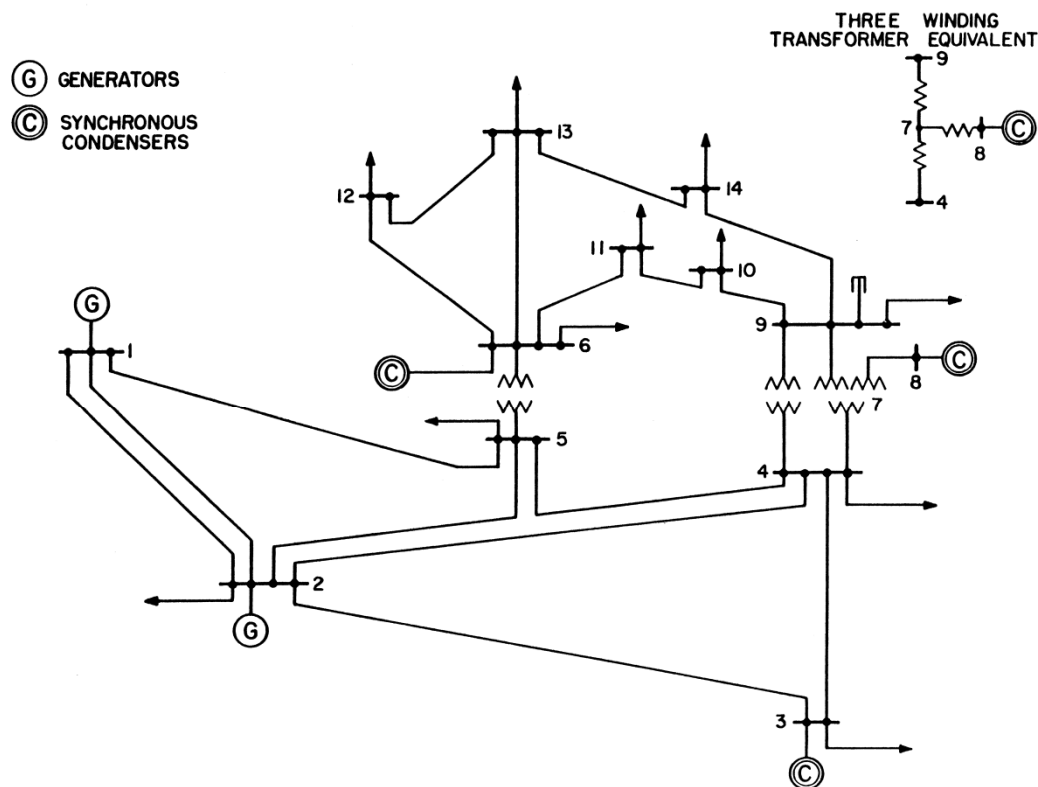
Figure 5.3: IEEE-14 bus test system

A single line diagram of IEEE-14 bus test system is shown in fig. 5.3. This system consists of four generator buses (bus no.-2,3,6,8,), one slack bus (bus no.-1) and twelve load buses (bus no.-2,3,4,5,6,7,9,10,11,12,13,14,).

5.3.1 BUS DATA

Table 5.3.1 below displays the bus data characteristics of the transmission system discussed above. Column 1 of Table 5.3.1 outlines the bus number and column 2 contains the bus code. Columns 3 and 4 show the voltage magnitudes in p.u. and phase angle in degrees. Columns 5 and 6 outline the size of the active and reactive loads connected to the corresponding buses in MW and MVAR. Columns 7 through to 10 are MW, MVAR, minimum MVAR and

maximum MVA of generation, in that order. The bus code entered in column 2 is used for identifying load, voltage-controlled, and slack buses as outlined below;

1 – This code is used for the slack bus.

2 – This code is used for the voltage controlled buses.

3 – This code is used for load buses.

5.3.2 LINE DATA

Table 5.3.2 below displays the line data characteristics of the transmission system discussed above. Columns 1 and 2 of Table 5.3.2 outline the corresponding line bus numbers. Columns 3 through to 5 contain the line resistance, reactance, and one half of the total line charging susceptance in per unit on the MVA base of 100MVA.

Table 5.3.1 Bus Data

Bus No.	Bus Code	Voltage Mag.	Angle Degree	Load MW	Load MVAR	Gen. MW	Gen MVAR	Qmin	Qmax
1	1	1.060	0	0.0	0.0	232.4	-16.9	0	0
2	2	1.045	0	21.70	12.7	40.0	42.4	-40	50
3	2	1.010	0	94.2	19.0	0.0	23.4	0	40
4	3	1.019	0	47.8	-3.9	0.0	0.0	0	0
5	3	1.020	0	7.6	1.6	0.0	0.0	0	0
6	2	1.070	0	11.2	7.5	0.0	12.2	-6	24
7	3	1.062	0	0.0	0.0	0.0	0.0	0	0
8	2	1.090	0	0.0	0.0	0.0	17.4	-6	24
9	3	1.056	0	29.5	16.6	0.0	0.0	0	0
10	3	1.051	0	9.0	5.8	0.0	0.0	0	0
11	3	1.057	0	3.5	1.8	0.0	0.0	0	0
12	3	1.055	0	6.1	1.6	0.0	0.0	0	0
13	3	1.050	0	13.5	5.8	0.0	0.0	0	0
14	3	1.036	0	14.9	5.0	0.0	0.0	0	0

Table 5.3.2 Line Data

Bus nl	Bus nr	R	X	B
1	2	0.01938	0.05917	0.0528
1	5	0.05403	0.22304	0.0492
2	3	0.04699	0.19797	0.0438
2	4	0.05811	0.17632	0.0340
2	5	0.05695	0.17388	0.0346
3	4	0.06701	0.17103	0.0128
4	5	0.01335	0.04211	0.0
4	7	0.0	0.20912	0.0
4	9	0.0	0.55618	0.0
5	6	0.0	0.25202	0.0
6	11	0.09498	0.19890	0.0
6	12	0.12291	0.25581	0.0
6	13	0.06615	0.13027	0.0
7	8	0.0	0.17615	0.0
7	9	0.0	0.11001	0.0
9	10	0.03181	0.08450	0.0
9	14	0.12711	0.27038	0.0
10	11	0.08205	0.19207	0.0
12	13	0.22092	0.19988	0.0
13	14	0.17093	0.34802	0.0

5.4 RESULTS:

5.4.1 IEEE-14 Bus test system without STATCOM

For iterations = 8

Table 5.4.1: Bus Voltage without STATCOM

	Bus Voltage without STATCOM			
Nodal Voltage	Bus 1	Bus 2	Bus 3	Bus 4
Magnitude(p.u.)	1.0600	1.0450	1.0100	1.0136
Phase angle(deg)	0	-4.98	-12.75	-10.25

Bus 5	Bus 6	Bus 7	Bus 8	Bus 9	Bus 10	Bus 11	Bus 12	Bus 13	Bus 14
1.0192	1.0154	1.0166	1.0566	0.9946	0.9904	0.9991	0.9992	0.9938	0.9751
-8.76	-14.85	-13.58	-13.58	-15.37	-15.59	-15.36	-15.79	-15.85	-16.70

5.4.2 IEEE-14 Bus test system with 2-STATCOM

For iterations = 7

Table 5.4.2: Bus Voltage with 2-STATCOM

	Bus Voltage with 2-STATCOM			
Nodal Voltage	Bus 1	Bus 2	Bus 3	Bus 4
Magnitude(p.u.)	1.0600	1.0450	1.0100	1.0233
Phase angle(deg)	0	-4.98	-12.67	-10.36

Bus 5	Bus 6	Bus 7	Bus 8	Bus 9	Bus 10	Bus 11	Bus 12	Bus 13	Bus 14
1.0306	1.0700	1.0360	1.0900	1.0101	1.0014	1.0000	1.0509	1.0422	1.0000
-8.98	-15.17	-13.42	-13.42	-15.05	-15.10	-14.45	-15.99	-15.94	-16.36

Table 5.4.3 Line Flow without STATCOM for IEEE-14 Bus test system:

Buses	Sending End		Receiving End	
	P(MW)	Q(MVAR)	P(MW)	Q(MVAR)
1-2	157.01	-20.43	-152.70	27.73
1-5	75.48	4.00	-72.72	2.08
2-3	73.44	3.54	-71.11	1.68
2-4	56.09	0.82	-54.41	0.67
2-5	41.47	1.36	-40.57	-2.29
3-4	-23.09	6.84	23.48	-7.16
4-5	-61.65	6.84	62.15	-5.26
4-7	28.62	-0.63	-28.62	2.30
4-9	16.16	4.18	-16.16	-2.68
5-6	43.54	3.87	-43.54	0.77
6-11	6.96	5.01	-6.89	-4.87
6-12	7.79	2.72	-7.71	-2.55
6-13	17.60	8.01	-17.36	-7.54
7-8	0.00	-23.09	-0.00	24.00
7-9	28.62	20.79	-28.62	-19.46
9-10	5.64	2.81	-5.63	-2.77
9-14	9.64	2.73	-9.51	-2.45
10-11	-3.37	-3.03	3.39	3.07
12-13	1.61	0.95	-1.60	-0.94
13-14	5.46	2.68	-5.39	-2.55

Table 5.4.4 Line Flow with 2-STATCOM for IEEE-14 Bus test system:

Buses	Sending End		Receiving End	
	P(MW)	Q(MVAR)	P(MW)	Q(MVAR)
1-2	156.81	-20.39	-152.52	27.65
1-5	76.79	-1.40	-73.96	7.73
2-3	72.84	3.60	-70.54	1.46

2-4	55.95	-4.74	-54.28	6.17
2-5	42.03	-5.50	-41.10	4.61
3-4	-23.66	1.28	24.03	-1.66
4-5	-59.83	1.83	60.29	-0.39
4-7	27.08	-5.49	-27.08	7.01
4-9	15.20	3.05	-15.20	-1.77
5-6	47.18	-13.55	-47.18	19.27
6-11	9.22	33.30	-8.23	-31.22
6-12	8.27	4.06	-8.18	-3.87
6-13	18.49	13.49	-18.19	-12.90
7-8	0.00	-31.78	-0.00	33.44
7-9	27.08	24.77	-27.08	-23.39
9-10	4.33	8.68	-4.30	-8.60
9-14	8.45	-0.12	-8.37	0.31
10-11	-4.70	2.80	4.73	-2.74
12-13	2.08	2.27	-2.06	-2.25
13-14	6.74	9.35	-6.53	-8.92

5.5 CASE STUDY OF IEEE-30 BUS TEST SYSTEM
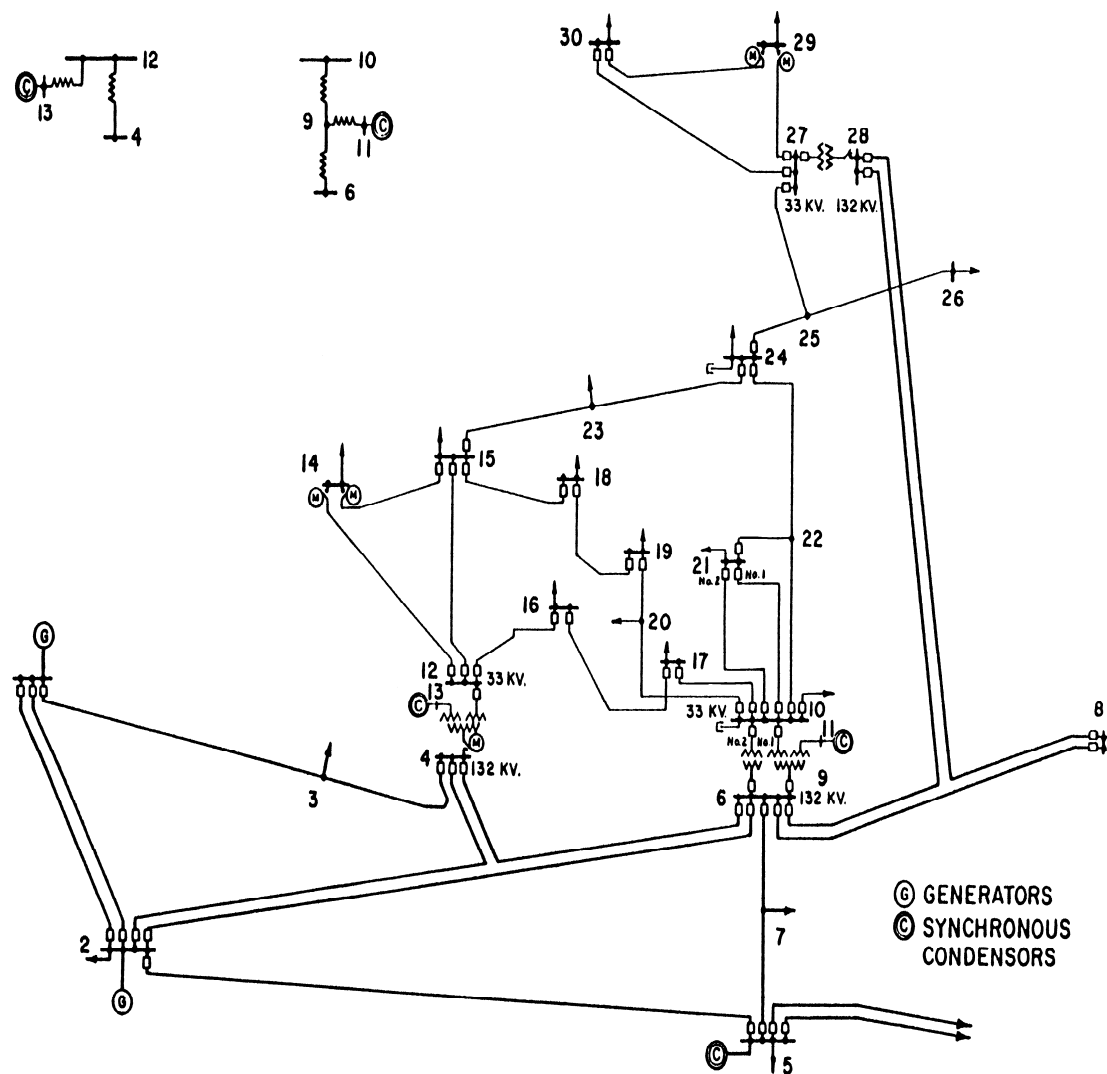
THREE WINDING TRANSFORMER EQUIVALENTS

Figure 5.5: IEEE-30 bus test system

A single line diagram of IEEE-30 bus test system is shown in fig. 5.5. This system consists of five generator buses (bus no.-2,5,8,11,13), one slack bus (bus no.-1) and twenty seven load buses (bus no.-2,3,4,5,6,7,8,9,10,12,14,15,16,17,18,19,20,21,22,23,24,25,26,27,28,29,30).

5.5.1 BUS DATA

Table 5.5.1 below displays the bus data characteristics of the transmission system discussed above. Column 1 of Table 5.5.1 outlines the bus number and column 2 contains the bus code. Columns 3 and 4 show the voltage magnitudes in p.u. and phase angle in degrees. Columns 5 and 6 outline the size of the active and reactive loads connected to the corresponding buses in MW and MVAR. Columns 7 through to 10 are MW, MVAR, minimum MVAR and maximum MVA of generation, in that order. The bus code entered in column 2 is used for identifying load, voltage-controlled, and slack buses as outlined below;

1 – This code is used for the slack bus.

2 – This code is used for the voltage controlled buses.

3 – This code is used for load buses.

5.5.2 LINE DATA

Table 5.5.2 below displays the line data characteristics of the transmission system discussed above. Columns 1 and 2 of Table 5.5.2 outline the corresponding line bus numbers. Columns 3 through to 5 contain the line resistance, reactance, and one half of the total line charging susceptance in per unit on the MVA base of 100MVA.

Table 5.5.1 Bus Data

Bus No.	Bus Code	Voltage Mag.	Angle Degree	Load MW	Load MVAR	Gen. MW	Gen MVAR	Qmin	Qmax
1	1	1.06	0	0.0	0.0	0.0	0.0	0	0
2	2	1.043	0	21.70	12.7	40.0	0.0	-40	50
3	3	1.0	0	2.4	1.2	0.0	0.0	0	0
4	3	1.06	0	7.6	1.6	0.0	0.0	0	0
5	2	1.01	0	94.2	19.0	0.0	0.0	-40	40
6	3	1.0	0	0.0	0.0	0.0	0.0	0	0
7	3	1.0	0	22.8	10.9	0.0	0.0	0	0
8	2	1.01	0	30.0	30.0	0.0	0.0	-10	40
9	3	1.0	0	0.0	0.0	0.0	0.0	0	0
10	3	1.0	0	5.8	2.0	0.0	0.0	0	0

11	2	1.082	0	0.0	0.0	0.0	0.0	-6	24
12	3	1.0	0	11.2	7.5	0.0	0.0	0.0	0.0
13	2	1.071	0	0.0	0.0	0.0	0.0	-6	24
14	3	1.0	0	6.2	1.6	0.0	0.0	0	0
15	3	1.0	0	8.2	2.5	0.0	0.0	0	0
16	3	1.0	0	3.5	1.8	0.0	0.0	0	0
17	3	1.0	0	9.0	5.8	0.0	0.0	0	0
18	3	1.0	0	3.2	0.9	0.0	0.0	0	0
19	3	1.0	0	9.5	3.4	0.0	0.0	0	0
20	3	1.0	0	2.2	0.7	0.0	0.0	0	0
21	3	1.0	0	17.5	11.2	0.0	0.0	0	0
22	3	1.0	0	0.0	0.0	0.0	0.0	0	0
23	3	1.0	0	3.2	1.6	0.0	0.0	0	0
24	3	1.0	0	8.7	6.7	0.0	0.0	0	0
25	3	1.0	0	0.0	0.0	0.0	0.0	0	0
26	3	1.0	0	3.5	2.3	0.0	0.0	0	0
27	3	1.0	0	0.0	0.0	0.0	0.0	0	0
28	3	1.0	0	0.0	0.0	0.0	0.0	0	0
29	3	1.0	0	2.4	0.9	0.0	0.0	0	0
30	3	1.0	0	10.6	1.9	0.0	0.0	0	0

Table 5.5.2 Line Data

Bus nl	Bus nr	R	X	½ B
1	2	0.0192	0.0575	0.0264
1	3	0.0452	0.1852	0.0204
2	4	0.0570	0.1737	0.1840
3	4	0.0132	0.0379	0.0042
2	5	0.0472	0.1983	0.0209
2	6	0.0581	0.1763	0.0187
4	6	0.0119	0.0414	0.0045

5	7	0.0460	0.1160	0.0102
6	7	0.0267	0.0820	0.0085
6	8	0.0120	0.0420	0.0045
6	9	0.0	0.2080	0.0
6	10	0.0	0.5560	0.0
9	11	0.0	0.2080	0.0
9	10	0.0	0.1100	0.0
4	12	0.0	0.2560	0.0
12	13	0.0	0.1400	0.0
12	14	0.1231	0.2559	0.0
12	15	0.0662	0.1304	0.0
12	16	0.0945	0.1987	0.0
14	15	0.2210	0.1997	0.0
16	17	0.0824	0.1923	0.0
15	18	0.1073	0.2185	0.0
18	19	0.0639	0.1292	0.0
19	20	0.0340	0.0680	0.0
10	20	0.0936	0.2090	0.0
10	17	0.0324	0.0845	0.0
10	21	0.0348	0.0749	0.0
10	22	0.0727	0.1499	0.0
21	22	0.0116	0.0236	0.0
15	23	0.1000	0.2020	0.0
22	24	0.1150	0.1790	0.0
23	24	0.1320	0.2700	0.0
24	25	0.1885	0.3292	0.0
25	26	0.2554	0.3800	0.0
25	27	0.1093	0.2087	0.0
28	27	0.0000	0.3960	0.0
27	29	0.2198	0.4153	0.0
27	30	0.3202	0.6027	0.0
29	30	0.2399	0.4533	0.0

8	28	0.0636	0.2000	0.0214
6	28	0.0169	0.0599	0.065

5.6 RESULTS:

5.6.1 IEEE-30 Bus test system without STATCOM

For iterations = 8

Table 5.6.1: Bus Voltage without STATCOM

	Bus Voltage without STATCOM				
Nodal Voltage	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5
Magnitude(p.u.)	1.0600	1.0430	1.0206	1.0122	1.0100
Phase angle(deg)	0	-5.50	-7.99	-9.65	-14.42

Bus 6	Bus 7	Bus 8	Bus 9	Bus 10	Bus 11	Bus 12	Bus 13	Bus 14	Bus 15
1.0082	1.0007	1.0100	1.0091	0.9860	1.0564	1.0051	1.0375	0.9884	0.9826
-11.36	-13.14	-12.15	-14.66	-16.44	-14.66	-15.91	-15.91	-16.86	-16.90

Bus 16	Bus 17	Bus 18	Bus 19	Bus 20	Bus 21	Bus 22	Bus 23	Bus 24	Bus 25
0.9895	0.9814	0.9709	0.9673	0.9712	0.9726	0.9730	0.9689	0.9596	0.9644
-16.43	-16.67	-17.51	-17.66	-17.42	-16.92	-16.90	-17.20	-17.22	-16.87

Bus 26	Bus 27	Bus 28	Bus 29	Bus 30
0.9458	0.9765	1.0045	0.9556	0.9435
-17.34	-16.36	-12.01	-17.72	-18.69

5.6.2 IEEE-30 Bus test system with 4-STATCOM

For iterations = 7

Table 5.6.2: Bus Voltage with 4-STATCOM

	Bus Voltage with STATCOM				
Nodal Voltage	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5
Magnitude(p.u.)	1.0600	1.0430	1.0105	1.0000	1.0100
Phase angle(deg)	0	-5.53	-7.88	-9.53	-14.47

Bus 6	Bus 7	Bus 8	Bus 9	Bus 10	Bus 11	Bus 12	Bus 13	Bus 14	Bus 15
1.0057	1.0000	1.0100	1.0208	0.9976	1.0820	1.0200	1.0710	1.0000	0.9964
-11.40	-13.20	-12.23	-14.61	-16.32	-14.61	-15.82	-15.82	-16.64	-16.77

Bus 16	Bus 17	Bus 18	Bus 19	Bus 20	Bus 21	Bus 22	Bus 23	Bus 24	Bus 25
1.0031	0.9937	0.9841	0.9801	0.9837	0.9849	0.9856	0.9834	0.9748	0.9847
-16.32	-16.55	-17.37	-17.52	-17.28	-16.80	-16.78	-17.09	-17.13	-16.88

Bus 26	Bus 27	Bus 28	Bus 29	Bus 30
0.9664	0.9997	1.0052	1.0000	0.9795
-17.33	-16.44	-12.11	-18.34	-18.97

Table 5.6.3 Line Flow without STATCOM for IEEE-30 Bus test system:

Buses	Sending End		Receiving End	
	P (MW)	Q (MVAR)	P (MW)	Q (MVAR)
1-2	178.10	-20.74	-172.62	34.24
1-3	83.17	6.80	-80.36	2.50

2-4	45.67	4.10	-44.56	-2.67
3-4	77.96	-3.70	-77.19	5.48
2-5	83.26	2.82	-80.24	7.64
2-6	61.99	2.29	-59.93	1.99
4-6	70.87	-9.59	-70.27	11.19
5-7	-13.96	13.36	14.13	-13.95
6-7	37.30	-2.78	-36.93	3.05
6-8	29.76	-12.94	-29.64	12.92
6-9	28.10	0.33	-28.10	1.29
6-10	15.81	4.71	-15.81	-3.22
9-11	0.00	-22.93	-0.00	24.00
9-10	28.10	21.64	-28.10	-20.28
4-12	43.29	5.18	-43.29	-0.43
12-13	-0.00	-23.25	0.00	24.00
12-14	7.84	2.91	-7.75	-2.73
12-15	17.44	8.60	-17.19	-8.11
12-16	6.81	4.68	-6.74	-4.54
14-15	1.55	1.13	-1.55	-1.12
16-17	3.24	2.74	-3.23	-2.71
15-18	5.87	2.39	-5.82	-2.30
18-19	2.62	1.40	-2.62	-1.39
19-20	-6.88	-2.01	6.90	2.05
10-20	9.19	2.95	-9.10	-2.75
10-17	5.79	3.13	-5.77	-3.09

10-21	15.62	10.51	-15.49	-10.23
10-22	7.51	4.92	-7.45	-4.80
21-22	-2.01	-0.97	2.01	0.97
15-23	4.67	4.34	-4.63	-4.26
22-24	5.44	3.83	-5.39	-3.74
23-24	1.43	2.66	-1.41	-2.63
24-25	-1.90	-0.33	1.90	0.34
25-26	3.55	2.37	-3.50	-2.30
25-27	-5.45	-2.71	5.50	2.80
28-27	18.81	7.81	-18.81	-6.18
27-29	6.20	1.69	-6.11	-1.51
27-30	7.11	1.69	-6.93	-1.36
29-30	3.71	0.61	-3.67	0.54
8-28	-0.36	1.80	0.37	-3.95
6-28	-19.24	-2.50	-19.18	-3.86

Table 5.6.4 Line Flow with 4-STATCOM for IEEE-30 Bus test system:

Buses	Sending End		Receiving End	
	P (MW)	Q (MVAR)	P (MW)	Q (MVAR)
1-2	178.97	-20.94	-173.44	34.61
1-3	82.65	12.48	-79.82	-3.11
2-4	45.85	11.23	-44.67	-9.56
3-4	77.42	1.91	-76.65	-0.10
2-5	83.53	2.80	-80.49	7.74

2-6	62.36	3.60	-60.27	0.78
4-6	70.01	-32.91	-69.30	34.93
5-7	-13.71	13.84	13.89	-14.42
6-7	37.05	-4.85	-36.69	5.13
6-8	29.84	-18.71	-29.69	18.76
6-9	27.65	-6.49	-27.65	8.15
6-10	15.49	2.14	-15.49	-0.80
9-11	0.00	-30.06	-0.00	31.68
9-10	27.65	21.91	-27.65	-20.60
4-12	43.71	-5.41	-43.71	10.38
12-13	-0.00	-37.15	0.00	39.01
12-14	7.72	4.36	-7.63	-4.16
12-15	17.74	9.56	-17.49	-9.06
12-16	7.05	5.36	-6.98	-5.21
14-15	1.43	0.23	-1.42	-0.22
16-17	3.48	3.41	-3.46	-3.36
15-18	6.01	2.67	-5.96	-2.58
18-19	2.76	1.68	-2.75	-1.67
19-20	-6.75	-1.73	6.76	1.77
10-20	9.05	2.66	-8.96	-2.47
10-17	5.56	2.47	-5.54	-2.44
10-21	15.38	9.80	-15.27	-9.55
10-22	7.35	4.46	-7.30	-4.35
21-22	-2.23	-1.65	2.23	1.65

15-23	4.70	4.10	-4.66	-4.02
22-24	5.07	2.70	-5.03	-2.64
23-24	1.46	2.42	-1.45	-2.40
24-25	-2.22	-1.66	2.24	1.68
25-26	3.55	2.37	-3.50	-2.30
25-27	-5.79	-4.05	5.84	4.16
28-27	19.16	2.12	-19.16	-0.67
27-29	6.26	-3.25	-6.15	3.46
27-30	7.06	-0.25	-6.90	0.55
29-30	3.75	2.54	-3.70	-2.45
8-28	-0.31	1.42	0.31	-3.58
6-28	19.54	-7.80	-19.47	1.46

Chapter-6

FUTURE SCOPE AND CONCLUSION

6.1 CONCLUSION

Power -flow problem, which is the determination of the voltage magnitude and angle at each bus of the power network under specified conditions of operation. The Newton- Raphson iterative procedure has been used for solving the power-flow problem.

The study of the basic principles of the STATCOM is carried out as well as the basics of reactive power compensation using a STATCOM. A power flow model of the STATCOM is attempted and it is seen that the modified load flow equations helps the system in better performance. The bus system shows improved plots and the thus we can conclude that the addition of a STATCOM controls the output of a bus in a robust manner.

Load flow results for all the three considered (5-bus, IEEE-14 and IEEE-30 bus test system) cases are shown in previous chapter. Also the load flow results for the same three cases with STATCOM are shown. We see that voltage magnitude of that particular bus at which STATCOM is placed is maintained at 1 p.u. This is possible because of reactive power compensation provided by STATCOM.

6.2 SCOPE FOR FURTHER RESEARCH

The completion of one research project opens the avenues for work in many other related areas. The following areas are identified for future work:

- The concept can be implemented to larger interconnected systems like IEEE-118 and IEEE-300 etc.
- Optimal location of STATCOM can be found out using Genetic Algorithm, Fuzzy Logic etc.

Appendix

MATLAB Program -1

Load flow in IEEE-30 bus test system without STATCOM

```
clear all
%load flow in IEEE-30 bus test system without STATCOM
%The following convention is used for the four types of buses available
%in conventional power flow studies:
%bustype = 1 is slack or swing bus
%bustype = 2 is generator PV bus
%bustype = 3 is load PQ bus
%bustype = 4 is generator PQ bus
%
%Bus data
%nbb = number of buses
%bustype = type of bus
%VM = nodal voltage magnitude
%VA = nodal voltage phase angle
nbb = 30 ;
bustype(1) = 1 ; VM(1) = 1.06 ; VA(1) =0 ;
bustype(2) = 2 ; VM(2) = 1.043 ; VA(2) =0 ;
bustype(3) = 3 ; VM(3) = 1.0 ; VA(3) =0 ;
bustype(4) = 3 ; VM(4) = 1.06 ; VA(4) =0 ;
bustype(5) = 2 ; VM(5) = 1.01 ; VA(5) =0 ;
bustype(6) = 3 ; VM(6) = 1.0 ; VA(6) =0;
bustype(7)  = 3 ; VM(7) = 1.0 ; VA(7) =0 ;
bustype(8)  = 2 ; VM(8) = 1.01 ; VA(8) =0 ;
bustype(9)  = 3 ; VM(9) = 1.0 ; VA(9) =0 ;
bustype(10) = 3 ; VM(10) = 1.0 ; VA(10) =0 ;
bustype(11) = 2 ; VM(11) = 1.082 ; VA(11) =0 ;
bustype(12) = 3 ; VM(12) = 1.0 ; VA(12) =0 ;
bustype(13) = 2 ; VM(13) = 1.071 ; VA(13) =0 ;
bustype(14) = 3 ; VM(14) = 1.0 ; VA(14) =0 ;
bustype(15) = 3 ; VM(15) = 1.0 ; VA(15) =0 ;
bustype(16) = 3 ; VM(16) = 1.0 ; VA(16) =0 ;
bustype(17) = 3 ; VM(17) = 1.0 ; VA(17) =0 ;
bustype(18) = 3 ; VM(18) = 1.0 ; VA(18) =0 ;
bustype(19) = 3 ; VM(19) = 1.0 ; VA(19) =0 ;
bustype(20) = 3 ; VM(20) = 1.0 ; VA(20) =0 ;
bustype(21) = 3 ; VM(21) = 1.0 ; VA(21) =0 ;
bustype(22) = 3 ; VM(22) = 1.0 ; VA(22) =0 ;
bustype(23) = 3 ; VM(23) = 1.0 ; VA(23) =0 ;
bustype(24) = 3 ; VM(24) = 1.0 ; VA(24) =0 ;
bustype(25) = 3 ; VM(25) = 1.0 ; VA(25) =0 ;
bustype(26) = 3 ; VM(26) = 1.0 ; VA(26) =0 ;
bustype(27) = 3 ; VM(27) = 1.0 ; VA(27) =0 ;
bustype(28) = 3 ; VM(28) = 1.0 ; VA(28) =0 ;
bustype(29) = 3 ; VM(29) = 1.0 ; VA(29) =0 ;
bustype(30) = 3 ; VM(30) = 1.0 ; VA(30) =0 ;
%
%Generator data
%ngn = number of generators
%genbus = generator bus number
%PGEN = scheduled active power contributed by the generator
%QGEN = scheduled reactive power contributed by the generator
```

```
%QMAX = generator reactive power upper limit
%QMIN = generator reactive power lower limit
ngn = 6 ;
genbus(1) = 1 ; PGEN(1) = 0 ; QGEN(1) = 0 ; QMAX(1) = 0 ; QMIN(1) = 0 ;
genbus(2) = 2 ; PGEN(2) = 0.40 ; QGEN(2) = 0.0 ; QMAX(2) = 0.50 ; QMIN(2) =
-0.40 ;
genbus(3) = 5 ; PGEN(3) = 0 ; QGEN(3) = 0 ; QMAX(3) = 0.40 ; QMIN(3) = -
0.40 ;
genbus(4) = 8 ; PGEN(4) = 0 ; QGEN(4) = 0 ; QMAX(4) = 0.40 ; QMIN(4) = -
0.10 ;
genbus(5) = 11 ; PGEN(5) = 0 ; QGEN(5) = 0 ; QMAX(5) = 0.24 ; QMIN(5) = -
0.06 ;
genbus(6) = 13 ; PGEN(6) = 0 ; QGEN(6) = 0 ; QMAX(6) = 0.24 ; QMIN(6) = -
0.06 ;
%
%Transmission line data
%ntl = number of transmission lines
%tlsend = sending end of transmission line
%tlrec = receiving end of transmission line
%tlresis = series resistance of transmission line
%tlreac = series reactance of transmission line
%tlcond = shunt conductance of transmission line
%tlsuscep = shunt susceptance of transmission line
ntl = 41 ;
tlsend(1) = 1 ; tlrec(1) = 2 ; tlresis(1) = 0.0192 ; tlreac(1) = 0.0575 ;
tlcond(1) = 0 ; tlsuscep(1) = 0.0264 ;
tlsend(2) = 1 ; tlrec(2) = 3 ; tlresis(2) = 0.0452 ; tlreac(2) = 0.1852 ;
tlcond(2) = 0 ; tlsuscep(2) = 0.0204 ;
tlsend(3) = 2 ; tlrec(3) = 4 ; tlresis(3) = 0.0570 ; tlreac(3) = 0.1737 ;
tlcond(3) = 0 ; tlsuscep(3) = 0.0184 ;
tlsend(4) = 3 ; tlrec(4) = 4 ; tlresis(4) = 0.0132 ; tlreac(4) = 0.0379 ;
tlcond(4) = 0 ; tlsuscep(4) = 0.0042 ;
tlsend(5) = 2 ; tlrec(5) = 5 ; tlresis(5) = 0.0472 ; tlreac(5) = 0.1983 ;
tlcond(5) = 0 ; tlsuscep(5) = 0.0209 ;
tlsend(6) = 2 ; tlrec(6) = 6 ; tlresis(6) = 0.0581 ; tlreac(6) = 0.1763 ;
tlcond(6) = 0 ; tlsuscep(6) = 0.0187 ;
tlsend(7) = 4 ; tlrec(7) = 6 ; tlresis(7) = 0.0119 ; tlreac(7) = 0.0414 ;
tlcond(7) = 0 ; tlsuscep(7) = 0.0045 ;
tlsend(8) = 5 ; tlrec(8) = 7 ; tlresis(8) = 0.0460 ; tlreac(8) = 0.1160 ;
tlcond(8) = 0 ; tlsuscep(8) = 0.0102 ;
tlsend(9) = 6 ; tlrec(9) = 7 ; tlresis(9) = 0.0267 ; tlreac(9) = 0.0820 ;
tlcond(9) = 0 ; tlsuscep(9) = 0.0085 ;
tlsend(10) = 6 ; tlrec(10) = 8 ; tlresis(10) = 0.0120 ; tlreac(10) = 0.0420
;
tlcond(10) = 0 ; tlsuscep(10) = 0.0045 ;
tlsend(11) = 6 ; tlrec(11) = 9 ; tlresis(11) = 0.0 ; tlreac(11) = 0.2080 ;
tlcond(11) = 0 ; tlsuscep(11) = 0.0 ;
tlsend(12) = 6 ; tlrec(12) = 10 ; tlresis(12) = 0.0 ; tlreac(12) = 0.556 ;
tlcond(12) = 0 ; tlsuscep(12) = 0.0 ;
tlsend(13) = 9 ; tlrec(13) = 11 ; tlresis(13) = 0.0 ; tlreac(13) = 0.208 ;
tlcond(13) = 0 ; tlsuscep(13) = 0.0 ;
tlsend(14) = 9 ; tlrec(14) = 10 ; tlresis(14) = 0.0 ; tlreac(14) = 0.1100 ;
tlcond(14) = 0 ; tlsuscep(14) = 0.0 ;
tlsend(15) = 4 ; tlrec(15) = 12 ; tlresis(15) = 0.0 ; tlreac(15) = 0.2560 ;
tlcond(15) = 0 ; tlsuscep(15) = 0.0 ;
tlsend(16) = 12 ; tlrec(16) = 13 ; tlresis(16) = 0.0 ; tlreac(16) = 0.1400
;
tlcond(16) = 0 ; tlsuscep(16) = 0.0 ;
tlsend(17) = 12 ; tlrec(17) = 14 ; tlresis(17) = 0.1213 ; tlreac(17) =
0.2559 ;
tlcond(17) = 0 ; tlsuscep(17) = 0.0 ;
```

```
tlsend(18) = 12 ; tlrec(18) = 15 ; tlresis(18) = 0.0662 ; tlreac(18) =
0.1304 ;
tlcond(18) = 0 ; tlsuscep(18) = 0.0 ;
tlsend(19) = 12 ; tlrec(19) = 16 ; tlresis(19) = 0.0945 ; tlreac(19) =
0.1987 ;
tlcond(19) = 0 ; tlsuscep(19) = 0.0 ;
tlsend(20) = 14 ; tlrec(20) = 15 ; tlresis(20) = 0.2210 ; tlreac(20) =
0.1997 ;
tlcond(20) = 0 ; tlsuscep(20) = 0.0 ;
tlsend(21) = 16 ; tlrec(21) = 17 ; tlresis(21) = 0.0824 ; tlreac(21) =
0.1923 ;
tlcond(21) = 0 ; tlsuscep(21) = 0.0 ;
tlsend(22) = 15 ; tlrec(22) = 18 ; tlresis(22) = 0.1073 ; tlreac(22) =
0.2185 ;
tlcond(22) = 0 ; tlsuscep(22) = 0.0 ;
tlsend(23) = 18 ; tlrec(23) = 19 ; tlresis(23) = 0.0639 ; tlreac(23) =
0.1292 ;
tlcond(23) = 0 ; tlsuscep(23) = 0.0 ;
tlsend(24) = 19 ; tlrec(24) = 20 ; tlresis(24) = 0.0340 ; tlreac(24) =
0.0680 ;
tlcond(24) = 0 ; tlsuscep(24) = 0.0 ;
tlsend(25) = 10 ; tlrec(25) = 20 ; tlresis(25) = 0.0936 ; tlreac(25) =
0.2090 ;
tlcond(25) = 0 ; tlsuscep(25) = 0.0 ;
tlsend(26) = 10 ; tlrec(26) = 17 ; tlresis(26) = 0.0324 ; tlreac(26) =
0.0845 ;
tlcond(26) = 0 ; tlsuscep(26) = 0.0 ;
tlsend(27) = 10 ; tlrec(27) = 21 ; tlresis(27) = 0.0348 ; tlreac(27) =
0.0749 ;
tlcond(27) = 0 ; tlsuscep(27) = 0.0 ;
tlsend(28) = 10 ; tlrec(28) = 22 ; tlresis(28) = 0.0727 ; tlreac(28) =
0.1499 ;
tlcond(28) = 0 ; tlsuscep(28) = 0.0 ;
tlsend(29) = 21 ; tlrec(29) = 22 ; tlresis(29) = 0.0116 ; tlreac(29) =
0.0236 ;
tlcond(29) = 0 ; tlsuscep(29) = 0.0 ;
tlsend(30) = 15 ; tlrec(30) = 23 ; tlresis(30) = 0.1000 ; tlreac(30) =
0.2020 ;
tlcond(30) = 0 ; tlsuscep(30) = 0.0 ;
tlsend(31) = 22 ; tlrec(31) = 24 ; tlresis(31) = 0.1150 ; tlreac(31) =
0.1790 ;
tlcond(31) = 0 ; tlsuscep(31) = 0.0 ;
tlsend(32) = 23 ; tlrec(32) = 24 ; tlresis(32) = 0.1320 ; tlreac(32) =
0.2700 ;
tlcond(32) = 0 ; tlsuscep(32) = 0.0 ;
tlsend(33) = 24 ; tlrec(33) = 25 ; tlresis(33) = 0.1885 ; tlreac(33) =
0.3292 ;
tlcond(33) = 0 ; tlsuscep(33) = 0.0 ;
tlsend(34) = 25 ; tlrec(34) = 26 ; tlresis(34) = 0.2544 ; tlreac(34) =
0.3800 ;
tlcond(34) = 0 ; tlsuscep(34) = 0.0 ;
tlsend(35) = 25 ; tlrec(35) = 27 ; tlresis(35) = 0.1093 ; tlreac(35) =
0.2087 ;
tlcond(35) = 0 ; tlsuscep(35) = 0.0 ;
tlsend(36) = 28 ; tlrec(36) = 27 ; tlresis(36) = 0.0000 ; tlreac(36) =
0.3960 ;
tlcond(36) = 0 ; tlsuscep(36) = 0.0 ;
tlsend(37) = 27 ; tlrec(37) = 29 ; tlresis(37) = 0.2198 ; tlreac(37) =
0.4153 ;
tlcond(37) = 0 ; tlsuscep(37) = 0.0 ;
```

```
tlsend(38) = 27 ; tlrec(38) = 30 ; tlresis(38) = 0.3202 ; tlreac(38) =
0.6027 ;
tlcond(38) = 0 ; tlsuscep(38) = 0.0 ;
tlsend(39) = 29 ; tlrec(39) = 30 ; tlresis(39) = 0.2399 ; tlreac(39) =
0.4533 ;
tlcond(39) = 0 ; tlsuscep(39) = 0.0 ;
tlsend(40) = 8 ; tlrec(40) = 28 ; tlresis(40) = 0.0636 ; tlreac(40) =
0.2000 ;
tlcond(40) = 0 ; tlsuscep(40) = 0.0214 ;
tlsend(41) = 6 ; tlrec(41) = 28 ; tlresis(41) = 0.0169 ; tlreac(41) =
0.0599 ;
tlcond(41) = 0 ; tlsuscep(41) = 0.065 ;
%
%Shunt data
%nsh = number of shunt elements
%shbus = shunt element bus number
%shresis = resistance of shunt element
%shreac = reactance of shunt element:
%+ve for inductive reactance and -ve for capacitive reactance
nsh = 0 ;
shbus(1) = 0 ; shresis(1) = 0 ; shreac(1) = 0 ;
%
%Load data
%nld = number of load elements
%loadbus = load element bus number
%PLOAD = scheduled active power consumed at the bus
%QLOAD = scheduled reactive power consumed at the bus
nld = 27 ;
loadbus(1) = 2 ; PLOAD(1) = 0.217 ; QLOAD(1) = 0.127 ;
loadbus(2) = 3 ; PLOAD(2) = 0.024 ; QLOAD(2) = 0.012 ;
loadbus(3) = 4 ; PLOAD(3) = 0.076 ; QLOAD(3) = 0.016 ;
loadbus(4) = 5 ; PLOAD(4) = 0.942 ; QLOAD(4) = 0.190 ;
loadbus(5) = 6 ; PLOAD(5) = 0.0 ; QLOAD(5) = 0.0 ;
loadbus(6) = 7 ; PLOAD(6) = 0.228 ; QLOAD(6) = 0.109 ;
loadbus(7) = 8 ; PLOAD(7) = 0.300 ; QLOAD(7) = 0.300 ;
loadbus(8) = 9 ; PLOAD(8) = 0.0 ; QLOAD(8) = 0.0 ;
loadbus(9) = 10 ; PLOAD(9) = 0.058 ; QLOAD(9) = 0.02 ;
loadbus(10) = 12 ; PLOAD(10) = 0.112 ; QLOAD(10) = 0.075 ;
loadbus(11) = 14 ; PLOAD(11) = 0.062 ; QLOAD(11) = 0.016 ;
loadbus(12) = 15 ; PLOAD(12) = 0.082 ; QLOAD(12) = 0.025 ;
loadbus(13) = 16 ; PLOAD(13) = 0.035 ; QLOAD(13) = 0.018 ;
loadbus(14) = 17 ; PLOAD(14) = 0.09 ; QLOAD(14) = 0.058 ;
loadbus(15) = 18 ; PLOAD(15) = 0.032 ; QLOAD(15) = 0.009 ;
loadbus(16) = 19 ; PLOAD(16) = 0.095 ; QLOAD(16) = 0.034 ;
loadbus(17) = 20 ; PLOAD(17) = 0.022 ; QLOAD(17) = 0.007 ;
loadbus(18) = 21 ; PLOAD(18) = 0.175 ; QLOAD(18) = 0.112 ;
loadbus(19) = 22 ; PLOAD(19) = 0.0 ; QLOAD(19) = 0.0 ;
loadbus(20) = 23 ; PLOAD(20) = 0.032 ; QLOAD(20) = 0.016 ;
loadbus(21) = 24 ; PLOAD(21) = 0.087 ; QLOAD(21) = 0.067 ;
loadbus(22) = 25 ; PLOAD(22) = 0.0 ; QLOAD(22) = 0.0 ;
loadbus(23) = 26 ; PLOAD(23) = 0.035 ; QLOAD(23) = 0.023 ;
loadbus(24) = 27 ; PLOAD(24) = 0.0 ; QLOAD(24) = 0.0 ;
loadbus(25) = 28 ; PLOAD(25) = 0.0 ; QLOAD(25) = 0.0 ;
loadbus(26) = 29 ; PLOAD(26) = 0.024 ; QLOAD(26) = 0.009 ;
loadbus(27) = 30 ; PLOAD(27) = 0.106 ; QLOAD(27) = 0.019 ;
%General parameters
%itmax = maximum number of iterations permitted before the iterative
%process is terminated - protection against infinite iterative loops
%tol = criterion tolerance to be met before the iterative solution is
%successfully brought to an end
itmax = 100;
```

```matlab
tol = 1e-12;
nmax = 2*nbb;
VA=VA*180/pi;
MVAbase=100; % base MVA
%Build up admittance matrix
YR=zeros(nbb,nbb);
YI=zeros(nbb,nbb);
% Transmission lines contribution
for kk = 1: ntl
ii = tlsend(kk);
jj = tlrec(kk);
denom = tlresis(kk)^2+tlreac(kk)^2;
YR(ii,ii) = YR(ii,ii) + tlresis(kk)/denom + 0.5*tlcond(kk);
YI(ii,ii) = YI(ii,ii) - tlreac(kk)/denom + 0.5*tlsuscep(kk);
YR(ii,jj) = YR(ii,jj) - tlresis(kk)/denom;
YI(ii,jj) = YI(ii,jj) + tlreac(kk)/denom;
YR(jj,ii) = YR(jj,ii) - tlresis(kk)/denom;
YI(jj,ii) = YI(jj,ii) + tlreac(kk)/denom;
YR(jj,jj) = YR(jj,jj) + tlresis(kk)/denom + 0.5*tlcond(kk);
YI(jj,jj) = YI(jj,jj) - tlreac(kk)/denom + 0.5*tlsuscep(kk);
end
% Shunt elements contribution
for kk = 1: nsh
ii = shbus(kk);
denom = shresis(kk)^2+shreac(kk)^2;
YR(ii,ii) = YR(ii,ii) + shresis(kk)/denom;
YI(ii,ii) = YI(ii,ii) - shreac(kk)/denom;
end
% End of function YBus
% GENERAL SETTINGS
D = zeros(1,nmax);
flag = 0;
it = 1;
% CALCULATE NET POWERS
%Function to calculate the net scheduled powers
PNET = zeros(1,nbb);
QNET = zeros(1,nbb);
for ii = 1: ngn
PNET(genbus(ii)) = PNET(genbus(ii)) + PGEN(ii);
QNET(genbus(ii)) = QNET(genbus(ii)) + QGEN(ii);
end
for ii = 1: nld
PNET(loadbus(ii)) = PNET(loadbus(ii)) - PLOAD(ii);
QNET(loadbus(ii)) = QNET(loadbus(ii)) - QLOAD(ii);
end
%End function NetPowers
while ( it < itmax & flag==0 )
% CALCULATED POWERS
%Function to calculate injected bus powers
% Include all entries
PCAL = zeros(1,nbb);
QCAL = zeros(1,nbb);
for ii = 1: nbb
PSUM = 0;
QSUM = 0;
for jj = 1: nbb
PSUM = PSUM + VM(ii)*VM(jj)*(YR(ii,jj)*cos(VA(ii)-VA(jj))
+YI(ii,jj)*sin(VA(ii)-VA(jj)));
QSUM = QSUM + VM(ii)*VM(jj)*(YR(ii,jj)*sin(VA(ii)-VA(jj)) -
YI(ii,jj)*cos(VA(ii)-VA(jj)));
end
```

```matlab
PCAL(ii) = PSUM;
QCAL(ii) = QSUM;
end
%End of functionCalculatePowers
% CHECK FOR POSSIBLE GENERATOR'S REACTIVE POWERS LIMITS VIOLATIONS
%Function to check whether or not solution is within generators limits
if it > 2
flag2 = 0;
for ii = 1: ngn
jj = genbus(ii);
if (bustype(jj) == 2)
if ( QCAL(jj) > QMAX(ii) )
QNET(genbus(ii)) = QMAX(ii);
bustype(jj) = 3;
flag2 = 1;
elseif ( QCAL(jj) < QMIN(ii) )
QNET(genbus(ii)) = QMIN(ii);
bustype(jj) = 3;
flag2 = 1;
end
if flag2 == 1
for ii = 1:nld
if loadbus(ii) == jj
QNET(loadbus(ii)) = QNET(loadbus(ii)) - QLOAD(ii)
end
end
end
end
end
end
%End function Generatorslimits
% POWER MISMATCHES
%Function to compute power mismatches
DPQ = zeros(1,nmax);
DP = zeros(1,nbb);
DQ = zeros(1,nbb);
DP = PNET - PCAL;
DQ = QNET - QCAL;
% To remove the active and reactive powers contributions of the slack
% bus and reactive power of all PV buses
for ii = 1: nbb
if (bustype(ii) == 1 )
DP(ii) = 0;
DQ(ii) = 0;
elseif (bustype(ii) == 2 )
DQ(ii) = 0;
end
end
% Re-arrange mismatch entries
kk = 1;
for ii = 1: nbb
DPQ(kk) = DP(ii);
DPQ(kk+1) = DQ(ii);
kk = kk + 2;
end
% Check for convergence
for ii = 1: nbb*2
if ( abs(DPQ) < tol)
flag = 1;
end
end
```

```matlab
%End function PowerMismatches
% JACOBIAN FORMATION
%Function to built the Jacobian matrix
% Include all entries
JAC = zeros(nmax,nmax);
iii = 1;
for ii = 1: nbb
jjj = 1;
for jj = 1: nbb
if ii == jj
JAC(iii,jjj) = -QCAL(ii) - VM(ii)^2*YI(ii,ii);
JAC(iii,jjj+1) = PCAL(ii) + VM(ii)^2*YR(ii,ii);
JAC(iii+1,jjj) = PCAL(ii) - VM(ii)^2*YR(ii,ii);
JAC(iii+1,jjj+1) = QCAL(ii) - VM(ii)^2*YI(ii,ii);
else
JAC(iii,jjj) = VM(ii)*VM(jj)*(YR(ii,jj)*sin(VA(ii)-VA(jj))-
YI(ii,jj)*cos(VA(ii)-VA(jj)));
JAC(iii+1,jjj) = -VM(ii)*VM(jj)*(YI(ii,jj)*sin(VA(ii)-
VA(jj))+YR(ii,jj)*cos(VA(ii)-VA(jj)));
JAC(iii,jjj+1) = -JAC(iii+1,jjj);
JAC(iii+1,jjj+1) = JAC(iii,jjj);
end
jjj = jjj + 2;
end
iii = iii + 2;
end
% Delete the voltage magnitude and phase angle equations of the slack
% bus and voltage magnitude equations corresponding to PV buses
for kk = 1: nbb
if (bustype(kk) == 1)
ii = kk*2-1;
for jj = 1: 2*nbb
if ii == jj
JAC(ii,ii) = 1;
else
JAC(ii,jj) = 0;
JAC(jj,ii) = 0;
end
end
end
if (bustype(kk) == 1) | (bustype(kk) == 2)
ii = kk*2;
for jj = 1: 2*nbb
if ii == jj
JAC(ii,ii) = 1;
else
JAC(ii,jj) = 0;
JAC(jj,ii) = 0;
end
end
end
end
%End of function NewtonRaphsonJacobian
% SOLVE FOR THE STATE VARIABLES VECTOR
D = JAC\DPQ';
% UPDATE STATE VARIABLES
%Function to update state variables
iii = 1;
for ii = 1: nbb
VA(ii) = VA(ii) + D(iii);
VM(ii) = VM(ii) + D(iii+1)*VM(ii);
```

```matlab
iii = iii + 2;
end
%End function StateVariableUpdating
it = it + 1;
end
% End function Newton-Raphson

%Function to calculate the power flows
PQsend = zeros(1,ntl);
PQrec = zeros(1,ntl);
% Calculate active and reactive powers at the sending and receiving
% ends of tranmsission lines
for ii = 1: ntl
Vsend = ( VM(tlsend(ii))*cos(VA(tlsend(ii))) +
VM(tlsend(ii))*sin(VA(tlsend(ii)))*i );
Vrec = ( VM(tlrec(ii))*cos(VA(tlrec(ii))) +
VM(tlrec(ii))*sin(VA(tlrec(ii)))*i );
tlimped = tlresis(ii) + tlreac(ii)*i;
current =(Vsend - Vrec) / tlimped + Vsend*( tlcond(ii) + tlsuscep(ii)*i
)*0.5 ;
PQsend(ii) = Vsend*conj(current);
current =(Vrec - Vsend) / tlimped + Vrec*( tlcond(ii) + tlsuscep(ii)*i
)*0.5 ;
PQrec(ii) = Vrec*conj(current);
PQloss(ii) = PQsend(ii) + PQrec(ii);
end
% Calculate active and reactive powers injections at buses
PQbus = zeros(1,nbb);
for ii = 1: ntl
PQbus(tlsend(ii)) = PQbus(tlsend(ii)) + PQsend(ii);
PQbus(tlrec(ii)) = PQbus(tlrec(ii)) + PQrec(ii);
end
% Make corrections at generator buses, where there is load, in order to
% get correct generators contributions
for ii = 1: nld
jj = loadbus(ii);
for kk = 1: ngn
ll = genbus(kk);
if jj == ll
PQbus(jj) = PQbus(jj) + ( PLOAD(ii) + QLOAD(ii)*i );
end
end
end
%End function PQflows
%Print results
it %Number of iterations
VM %Nodal voltage magnitude (p.u)
VA=VA*180/pi %Nodal voltage phase angles (deg)
PQsend %Sending active and reactive powers (p.u.)
PQrec %Receiving active and reactive powers (p.u.)
```

OUTPUT:

it = 8

VM =

Columns 1 through 16

1.0600   1.0430   1.0206   1.0122   1.0100   1.0082   1.0007   1.0100   1.0091   0.9860
1.0564   1.0051   1.0375   0.9884   0.9826   0.9895

Columns 17 through 30

0.9814   0.9709   0.9673   0.9712   0.9726   0.9730   0.9689   0.9596   0.9644   0.9458
0.9765   1.0045   0.9556   0.9435

VA =

Columns 1 through 16

 0   -5.5073   -7.9936   -9.6582   -14.4212   -11.3682   -13.1412   -12.1574   -14.6613   -16.4413   -
14.6613   -15.9113   -15.9113   -16.8648   -16.9005   -16.4360

Columns 17 through 30

 -16.6707   -17.5166   -17.6690   -17.4253   -16.9219   -16.9000   -17.2067   -17.2279   -16.8794   -
17.3473   -16.3674   -12.0126   -17.7205   -18.6950

PQsend =

Columns 1 through 8

1.7810 - 0.2074i   0.8317 + 0.0680i   0.4567 + 0.0410i   0.7796 - 0.0370i   0.8326 + 0.0282i
0.6199 + 0.0229i   0.7087 - 0.0959i -0.1396 + 0.1336i

 Columns 9 through 16

0.3730 - 0.0278i   0.2976 - 0.1294i   0.2810 + 0.0033i   0.1581 + 0.0471i   0.0000 - 0.2293i
0.2810 + 0.2164i   0.4329 + 0.0518i -0.0000 - 0.2325i

Columns 17 through 24

0.0784 + 0.0291i   0.1744 + 0.0860i   0.0681 + 0.0468i   0.0155 + 0.0113i   0.0324 + 0.0274i
0.0587 + 0.0239i   0.0262 + 0.0140i -0.0688 - 0.0201i

Columns 25 through 32

0.0919 + 0.0295i   0.0579 + 0.0313i   0.1562 + 0.1051i   0.0751 + 0.0492i -0.0201 - 0.0097i
0.0467 + 0.0434i   0.0544 + 0.0383i   0.0143 + 0.0266i

Columns 33 through 40

 -0.0190 - 0.0033i   0.0355 + 0.0237i -0.0545 - 0.0271i   0.1881 + 0.0781i   0.0620 + 0.0169i
0.0711 + 0.0169i   0.0371 + 0.0061i -0.0036 + 0.0180i

Column 41

0.1924 - 0.0250i

PQrec =

Columns 1 through 8

-1.7262 + 0.3424i   -0.8036 + 0.0250i   -0.4456 - 0.0267i   -0.7719 + 0.0548i   -0.8024 + 0.0764i   -0.5993 + 0.0199i   -0.7027 + 0.1119i   0.1413 - 0.1395i

Columns 9 through 16

-0.3693 + 0.0305i   -0.2964 + 0.1292i   -0.2810 + 0.0129i   -0.1581 - 0.0322i   -0.0000 + 0.2400i   -0.2810 - 0.2028i   -0.4329 - 0.0043i   0.0000 + 0.2400i

Columns 17 through 24

-0.0775 - 0.0273i   -0.1719 - 0.0811i   -0.0674 - 0.0454i   -0.0155 - 0.0112i   -0.0323 - 0.0271i   -0.0582 - 0.0230i   -0.0262 - 0.0139i   0.0690 + 0.0205i

Columns 25 through 32

-0.0910 - 0.0275i   -0.0577 - 0.0309i   -0.1549 - 0.1023i   -0.0745 - 0.0480i   0.0201 + 0.0097i   -0.0463 - 0.0426i   -0.0539 - 0.0374i   -0.0141 - 0.0263i

Columns 33 through 40

0.0190 + 0.0034i   -0.0350 - 0.0230i   0.0550 + 0.0280i   -0.1881 - 0.0618i   -0.0611 - 0.0151i   -0.0693 - 0.0136i   -0.0367 - 0.0054i   0.0037 - 0.0395i

Column 41

-0.1918 - 0.0386i

MATLAB Program -2

Load flow in IEEE-30 bus test system with STATCOM

```
clear all
%load flow in IEEE-30 bus test system with 4-STATCOM
% - - - Main STATCOM Program
%The following convention is used for the four types of buses available
%in conventional power flow studies:
%bustype = 1 is slack or swing bus
%bustype = 2 is generator PV bus
%bustype = 3 is load PQ bus
%
%Bus data
%nbb = number of buses
%bustype = type of bus
%VM = nodal voltage magnitude
%VA = nodal voltage phase angle
nbb = 30 ;
bustype(1) = 1 ; VM(1) = 1.06 ; VA(1) =0 ;
bustype(2) = 2 ; VM(2) = 1.043 ; VA(2) =0 ;
bustype(3) = 3 ; VM(3) = 1.0 ; VA(3) =0 ;
```

```
bustype(4)  = 3 ; VM(4) = 1.06 ; VA(4) =0 ;
bustype(5)  = 2 ; VM(5) = 1.01 ; VA(5) =0 ;
bustype(6)  = 3 ; VM(6) = 1.0 ; VA(6) =0;
bustype(7)  = 3 ; VM(7) = 1.0 ; VA(7) =0 ;
bustype(8)  = 2 ; VM(8) = 1.01 ; VA(8) =0 ;
bustype(9)  = 3 ; VM(9) = 1.0 ; VA(9) =0 ;
bustype(10) = 3 ; VM(10) = 1.0 ; VA(10) =0 ;
bustype(11) = 2 ; VM(11) = 1.082 ; VA(11) =0 ;
bustype(12) = 3 ; VM(12) = 1.0 ; VA(12) =0 ;
bustype(13) = 2 ; VM(13) = 1.071 ; VA(13) =0 ;
bustype(14) = 3 ; VM(14) = 1.0 ; VA(14) =0 ;
bustype(15) = 3 ; VM(15) = 1.0 ; VA(15) =0 ;
bustype(16) = 3 ; VM(16) = 1.0 ; VA(16) =0 ;
bustype(17) = 3 ; VM(17) = 1.0 ; VA(17) =0 ;
bustype(18) = 3 ; VM(18) = 1.0 ; VA(18) =0 ;
bustype(19) = 3 ; VM(19) = 1.0 ; VA(19) =0 ;
bustype(20) = 3 ; VM(20) = 1.0 ; VA(20) =0 ;
bustype(21) = 3 ; VM(21) = 1.0 ; VA(21) =0 ;
bustype(22) = 3 ; VM(22) = 1.0 ; VA(22) =0 ;
bustype(23) = 3 ; VM(23) = 1.0 ; VA(23) =0 ;
bustype(24) = 3 ; VM(24) = 1.0 ; VA(24) =0 ;
bustype(25) = 3 ; VM(25) = 1.0 ; VA(25) =0 ;
bustype(26) = 3 ; VM(26) = 1.0 ; VA(26) =0 ;
bustype(27) = 3 ; VM(27) = 1.0 ; VA(27) =0 ;
bustype(28) = 3 ; VM(28) = 1.0 ; VA(28) =0 ;
bustype(29) = 3 ; VM(29) = 1.0 ; VA(29) =0 ;
bustype(30) = 3 ; VM(30) = 1.0 ; VA(30) =0 ;
%
%Generator data
%ngn = number of generators
%genbus = generator bus number
%PGEN = scheduled active power contributed by the generator
%QGEN = scheduled reactive power contributed by the generator
%QMAX = generator reactive power upper limit
%QMIN = generator reactive power lower limit
ngn = 6 ;
genbus(1) = 1 ; PGEN(1) = 0 ; QGEN(1) = 0 ; QMAX(1) = 0 ; QMIN(1) = 0 ;
genbus(2) = 2 ; PGEN(2) = 0.40 ; QGEN(2) = 0.0 ; QMAX(2) = 0.50 ; QMIN(2) =
-0.40 ;
genbus(3) = 5 ; PGEN(3) = 0 ; QGEN(3) = 0 ; QMAX(3) = 0.40 ; QMIN(3) = -
0.40 ;
genbus(4) = 8 ; PGEN(4) = 0 ; QGEN(4) = 0 ; QMAX(4) = 0.40 ; QMIN(4) = -
0.10 ;
genbus(5) = 11 ; PGEN(5) = 0 ; QGEN(5) = 0 ; QMAX(5) = 0.24 ; QMIN(5) = -
0.06 ;
genbus(6) = 13 ; PGEN(6) = 0 ; QGEN(6) = 0 ; QMAX(6) = 0.24 ; QMIN(6) = -
0.06 ;
%
%Transmission line data
%ntl = number of transmission lines
%tlsend = sending end of transmission line
%tlrec = receiving end of transmission line
%tlresis = series resistance of transmission line
%tlreac = series reactance of transmission line
%tlcond = shunt conductance of transmission line
%tlsuscep = shunt susceptance of transmission line
ntl = 41 ;
tlsend(1) = 1 ; tlrec(1) = 2 ; tlresis(1) = 0.0192 ; tlreac(1) = 0.0575 ;
tlcond(1) = 0 ; tlsuscep(1) = 0.0264 ;
tlsend(2) = 1 ; tlrec(2) = 3 ; tlresis(2) = 0.0452 ; tlreac(2) = 0.1852 ;
tlcond(2) = 0 ; tlsuscep(2) = 0.0204 ;
```

```
tlsend(3) = 2 ; tlrec(3) = 4 ; tlresis(3) = 0.0570 ; tlreac(3) = 0.1737 ;
tlcond(3) = 0 ; tlsuscep(3) = 0.0184 ;
tlsend(4) = 3 ; tlrec(4) = 4 ; tlresis(4) = 0.0132 ; tlreac(4) = 0.0379 ;
tlcond(4) = 0 ; tlsuscep(4) = 0.0042 ;
tlsend(5) = 2 ; tlrec(5) = 5 ; tlresis(5) = 0.0472 ; tlreac(5) = 0.1983 ;
tlcond(5) = 0 ; tlsuscep(5) = 0.0209 ;
tlsend(6) = 2 ; tlrec(6) = 6 ; tlresis(6) = 0.0581 ; tlreac(6) = 0.1763 ;
tlcond(6) = 0 ; tlsuscep(6) = 0.0187 ;
tlsend(7) = 4 ; tlrec(7) = 6 ; tlresis(7) = 0.0119 ; tlreac(7) = 0.0414 ;
tlcond(7) = 0 ; tlsuscep(7) = 0.0045 ;
tlsend(8) = 5 ; tlrec(8) = 7 ; tlresis(8) = 0.0460 ; tlreac(8) = 0.1160 ;
tlcond(8) = 0 ; tlsuscep(8) = 0.0102 ;
tlsend(9) = 6 ; tlrec(9) = 7 ; tlresis(9) = 0.0267 ; tlreac(9) = 0.0820 ;
tlcond(9) = 0 ; tlsuscep(9) = 0.0085 ;
tlsend(10) = 6 ; tlrec(10) = 8 ; tlresis(10) = 0.0120 ; tlreac(10) = 0.0420
;
tlcond(10) = 0 ; tlsuscep(10) = 0.0045 ;
tlsend(11) = 6 ; tlrec(11) = 9 ; tlresis(11) = 0.0 ; tlreac(11) = 0.2080 ;
tlcond(11) = 0 ; tlsuscep(11) = 0.0 ;
tlsend(12) = 6 ; tlrec(12) = 10 ; tlresis(12) = 0.0 ; tlreac(12) = 0.556 ;
tlcond(12) = 0 ; tlsuscep(12) = 0.0 ;
tlsend(13) = 9 ; tlrec(13) = 11 ; tlresis(13) = 0.0 ; tlreac(13) = 0.208 ;
tlcond(13) = 0 ; tlsuscep(13) = 0.0 ;
tlsend(14) = 9 ; tlrec(14) = 10 ; tlresis(14) = 0.0 ; tlreac(14) = 0.1100 ;
tlcond(14) = 0 ; tlsuscep(14) = 0.0 ;
tlsend(15) = 4 ; tlrec(15) = 12 ; tlresis(15) = 0.0 ; tlreac(15) = 0.2560 ;
tlcond(15) = 0 ; tlsuscep(15) = 0.0 ;
tlsend(16) = 12 ; tlrec(16) = 13 ; tlresis(16) = 0.0 ; tlreac(16) = 0.1400
;
tlcond(16) = 0 ; tlsuscep(16) = 0.0 ;
tlsend(17) = 12 ; tlrec(17) = 14 ; tlresis(17) = 0.1213 ; tlreac(17) =
0.2559 ;
tlcond(17) = 0 ; tlsuscep(17) = 0.0 ;
tlsend(18) = 12 ; tlrec(18) = 15 ; tlresis(18) = 0.0662 ; tlreac(18) =
0.1304 ;
tlcond(18) = 0 ; tlsuscep(18) = 0.0 ;
tlsend(19) = 12 ; tlrec(19) = 16 ; tlresis(19) = 0.0945 ; tlreac(19) =
0.1987 ;
tlcond(19) = 0 ; tlsuscep(19) = 0.0 ;
tlsend(20) = 14 ; tlrec(20) = 15 ; tlresis(20) = 0.2210 ; tlreac(20) =
0.1997 ;
tlcond(20) = 0 ; tlsuscep(20) = 0.0 ;
tlsend(21) = 16 ; tlrec(21) = 17 ; tlresis(21) = 0.0824 ; tlreac(21) =
0.1923 ;
tlcond(21) = 0 ; tlsuscep(21) = 0.0 ;
tlsend(22) = 15 ; tlrec(22) = 18 ; tlresis(22) = 0.1073 ; tlreac(22) =
0.2185 ;
tlcond(22) = 0 ; tlsuscep(22) = 0.0 ;
tlsend(23) = 18 ; tlrec(23) = 19 ; tlresis(23) = 0.0639 ; tlreac(23) =
0.1292 ;
tlcond(23) = 0 ; tlsuscep(23) = 0.0 ;
tlsend(24) = 19 ; tlrec(24) = 20 ; tlresis(24) = 0.0340 ; tlreac(24) =
0.0680 ;
tlcond(24) = 0 ; tlsuscep(24) = 0.0 ;
tlsend(25) = 10 ; tlrec(25) = 20 ; tlresis(25) = 0.0936 ; tlreac(25) =
0.2090 ;
tlcond(25) = 0 ; tlsuscep(25) = 0.0 ;
tlsend(26) = 10 ; tlrec(26) = 17 ; tlresis(26) = 0.0324 ; tlreac(26) =
0.0845 ;
tlcond(26) = 0 ; tlsuscep(26) = 0.0 ;
```

```
tlsend(27) = 10 ; tlrec(27) = 21 ; tlresis(27) = 0.0348 ; tlreac(27) =
0.0749 ;
tlcond(27) = 0 ; tlsuscep(27) = 0.0 ;
tlsend(28) = 10 ; tlrec(28) = 22 ; tlresis(28) = 0.0727 ; tlreac(28) =
0.1499 ;
tlcond(28) = 0 ; tlsuscep(28) = 0.0 ;
tlsend(29) = 21 ; tlrec(29) = 22 ; tlresis(29) = 0.0116 ; tlreac(29) =
0.0236 ;
tlcond(29) = 0 ; tlsuscep(29) = 0.0 ;
tlsend(30) = 15 ; tlrec(30) = 23 ; tlresis(30) = 0.1000 ; tlreac(30) =
0.2020 ;
tlcond(30) = 0 ; tlsuscep(30) = 0.0 ;
tlsend(31) = 22 ; tlrec(31) = 24 ; tlresis(31) = 0.1150 ; tlreac(31) =
0.1790 ;
tlcond(31) = 0 ; tlsuscep(31) = 0.0 ;
tlsend(32) = 23 ; tlrec(32) = 24 ; tlresis(32) = 0.1320 ; tlreac(32) =
0.2700 ;
tlcond(32) = 0 ; tlsuscep(32) = 0.0 ;
tlsend(33) = 24 ; tlrec(33) = 25 ; tlresis(33) = 0.1885 ; tlreac(33) =
0.3292 ;
tlcond(33) = 0 ; tlsuscep(33) = 0.0 ;
tlsend(34) = 25 ; tlrec(34) = 26 ; tlresis(34) = 0.2544 ; tlreac(34) =
0.3800 ;
tlcond(34) = 0 ; tlsuscep(34) = 0.0 ;
tlsend(35) = 25 ; tlrec(35) = 27 ; tlresis(35) = 0.1093 ; tlreac(35) =
0.2087 ;
tlcond(35) = 0 ; tlsuscep(35) = 0.0 ;
tlsend(36) = 28 ; tlrec(36) = 27 ; tlresis(36) = 0.0000 ; tlreac(36) =
0.3960 ;
tlcond(36) = 0 ; tlsuscep(36) = 0.0 ;
tlsend(37) = 27 ; tlrec(37) = 29 ; tlresis(37) = 0.2198 ; tlreac(37) =
0.4153 ;
tlcond(37) = 0 ; tlsuscep(37) = 0.0 ;
tlsend(38) = 27 ; tlrec(38) = 30 ; tlresis(38) = 0.3202 ; tlreac(38) =
0.6027 ;
tlcond(38) = 0 ; tlsuscep(38) = 0.0 ;
tlsend(39) = 29 ; tlrec(39) = 30 ; tlresis(39) = 0.2399 ; tlreac(39) =
0.4533 ;
tlcond(39) = 0 ; tlsuscep(39) = 0.0 ;
tlsend(40) = 8 ; tlrec(40) = 28 ; tlresis(40) = 0.0636 ; tlreac(40) =
0.2000 ;
tlcond(40) = 0 ; tlsuscep(40) = 0.0214 ;
tlsend(41) = 6 ; tlrec(41) = 28 ; tlresis(41) = 0.0169 ; tlreac(41) =
0.0599 ;
tlcond(41) = 0 ; tlsuscep(41) = 0.065 ;
%
%Shunt data
%nsh = number of shunt elements
%shbus = shunt element bus number
%shresis = resistance of shunt element
%shreac = reactance of shunt element:
%+ve for inductive reactance and -ve for capacitive reactance
nsh = 0 ;
shbus(1) = 0 ; shresis(1) = 0 ; shreac(1) = 0 ;
%
%Load data
%nld = number of load elements
%loadbus = load element bus number
%PLOAD = scheduled active power consumed at the bus
%QLOAD = scheduled reactive power consumed at the bus
nld = 27 ;
```

```
loadbus(1)  = 2  ; PLOAD(1)  = 0.217 ; QLOAD(1)  = 0.127 ;
loadbus(2)  = 3  ; PLOAD(2)  = 0.024 ; QLOAD(2)  = 0.012 ;
loadbus(3)  = 4  ; PLOAD(3)  = 0.076 ; QLOAD(3)  = 0.016 ;
loadbus(4)  = 5  ; PLOAD(4)  = 0.942 ; QLOAD(4)  = 0.190 ;
loadbus(5)  = 6  ; PLOAD(5)  = 0.0   ; QLOAD(5)  = 0.0 ;
loadbus(6)  = 7  ; PLOAD(6)  = 0.228 ; QLOAD(6)  = 0.109 ;
loadbus(7)  = 8  ; PLOAD(7)  = 0.300 ; QLOAD(7)  = 0.300 ;
loadbus(8)  = 9  ; PLOAD(8)  = 0.0   ; QLOAD(8)  = 0.0 ;
loadbus(9)  = 10 ; PLOAD(9)  = 0.058 ; QLOAD(9)  = 0.02 ;
loadbus(10) = 12 ; PLOAD(10) = 0.112 ; QLOAD(10) = 0.075 ;
loadbus(11) = 14 ; PLOAD(11) = 0.062 ; QLOAD(11) = 0.016 ;
loadbus(12) = 15 ; PLOAD(12) = 0.082 ; QLOAD(12) = 0.025 ;
loadbus(13) = 16 ; PLOAD(13) = 0.035 ; QLOAD(13) = 0.018 ;
loadbus(14) = 17 ; PLOAD(14) = 0.09  ; QLOAD(14) = 0.058 ;
loadbus(15) = 18 ; PLOAD(15) = 0.032 ; QLOAD(15) = 0.009 ;
loadbus(16) = 19 ; PLOAD(16) = 0.095 ; QLOAD(16) = 0.034 ;
loadbus(17) = 20 ; PLOAD(17) = 0.022 ; QLOAD(17) = 0.007 ;
loadbus(18) = 21 ; PLOAD(18) = 0.175 ; QLOAD(18) = 0.112 ;
loadbus(19) = 22 ; PLOAD(19) = 0.0   ; QLOAD(19) = 0.0 ;
loadbus(20) = 23 ; PLOAD(20) = 0.032 ; QLOAD(20) = 0.016 ;
loadbus(21) = 24 ; PLOAD(21) = 0.087 ; QLOAD(21) = 0.067 ;
loadbus(22) = 25 ; PLOAD(22) = 0.0   ; QLOAD(22) = 0.0 ;
loadbus(23) = 26 ; PLOAD(23) = 0.035 ; QLOAD(23) = 0.023 ;
loadbus(24) = 27 ; PLOAD(24) = 0.0   ; QLOAD(24) = 0.0 ;
loadbus(25) = 28 ; PLOAD(25) = 0.0   ; QLOAD(25) = 0.0 ;
loadbus(26) = 29 ; PLOAD(26) = 0.024 ; QLOAD(26) = 0.009 ;
loadbus(27) = 30 ; PLOAD(27) = 0.106 ; QLOAD(27) = 0.019 ;
%General parameters
%itmax = maximum number of iterations permitted before the iterative
%process is terminated – protection against infinite iterative loops
%tol = criterion tolerance to be met before the iterative solution is
%successfully brought to an end
itmax = 100;
tol = 1e-12;
nmax = 2*nbb;
MVAbase=100; % base MVA
%End of function PowerFlowsData
%This function is used exclusively to enter data for:
%This function is used exclusively to enter data for:
% STATIC SYNCHRONOUS COMPENSATOR (STATCOM)
% NSSC : Number of STATCOM's
% SSCsend: STATCOM's bus
% Xvr : Converter's reactance (p.u.)
% TarVol: Target nodal voltage magnitude (p.u.)
% VSta : Indicate the control status over nodal voltage magnitude: 1 is
% on; 0 is off
% Psp : Target active power flow (p.u.)
% PSta : Indicate the control status over active power: 1 is on; 0 is off
% Qsp : Target reactive power flow (p.u.)
% QSta : Indicate the control status over reactive power:1 is on; 0 is off
% Vvr : Initial condition for the source voltage magnitude (p.u.)
% Tvr : Initial condition for the source voltage angle (deg)
% VvrHi : Lower limit source voltage magnitude (p.u.)
% VvrLo : higher limit source voltage magnitude (p.u.)
NSSC = 4;
SSCsend(1)=4; Xvr(1)=10; TarVol(1)=1.0; VSta(1)=1;
Psp(1)=0.0; PSta(1)=1; Qsp(1)=0.0; QSta(1)=0;
Vvr(1)=1.0; Tvr(1)=0.0; VvrHi(1)=1.1; VvrLo(1)=0.9;
SSCsend(2)=7; Xvr(2)=10; TarVol(2)=1.0; VSta(2)=1;
Psp(2)=0.0; PSta(2)=1; Qsp(2)=0.0; QSta(2)=0;
Vvr(2)=1.0; Tvr(2)=0.0; VvrHi(2)=1.1; VvrLo(2)=0.9;
```

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SSCsend(3)=14; Xvr(3)=10; TarVol(3)=1.0; VSta(3)=1;
Psp(3)=0.0; PSta(3)=1; Qsp(3)=0.0; QSta(3)=0;
Vvr(3)=1.0; Tvr(3)=0.0; VvrHi(3)=1.1; VvrLo(3)=0.9;
SSCsend(4)=29; Xvr(4)=10; TarVol(4)=1.0; VSta(4)=1;
Psp(4)=0.0; PSta(4)=1; Qsp(4)=0.0; QSta(4)=0;
Vvr(4)=1.0; Tvr(4)=0.0; VvrHi(4)=1.1; VvrLo(4)=0.9;
%Build up admittance matrix
YR=zeros(nbb,nbb);
YI=zeros(nbb,nbb);
% Transmission lines contribution
for kk = 1: ntl
ii = tlsend(kk);
jj = tlrec(kk);
denom = tlresis(kk)^2+tlreac(kk)^2;
YR(ii,ii) = YR(ii,ii) + tlresis(kk)/denom + 0.5*tlcond(kk);
YI(ii,ii) = YI(ii,ii) - tlreac(kk)/denom + 0.5*tlsuscep(kk);
YR(ii,jj) = YR(ii,jj) - tlresis(kk)/denom;
YI(ii,jj) = YI(ii,jj) + tlreac(kk)/denom;
YR(jj,ii) = YR(jj,ii) - tlresis(kk)/denom;
YI(jj,ii) = YI(jj,ii) + tlreac(kk)/denom;
YR(jj,jj) = YR(jj,jj) + tlresis(kk)/denom + 0.5*tlcond(kk);
YI(jj,jj) = YI(jj,jj) - tlreac(kk)/denom + 0.5*tlsuscep(kk);
end
% Shunt elements contribution
for kk = 1: nsh
ii = shbus(kk);
denom = shresis(kk)^2+shreac(kk)^2;
YR(ii,ii) = YR(ii,ii) + shresis(kk)/denom;
YI(ii,ii) = YI(ii,ii) - shreac(kk)/denom;
end
% End of function YBus


%Carry out iterative solution using the Newton-Raphson method

% GENERAL SETTINGS
flag = 0;
it = 1;
%Function to calculate the net scheduled powers
% CALCULATE NET POWERS
PNET = zeros(1,nbb);
QNET = zeros(1,nbb);
for ii = 1: ngn
PNET(genbus(ii)) = PNET(genbus(ii)) + PGEN(ii);
QNET(genbus(ii)) = QNET(genbus(ii)) + QGEN(ii);
end
for ii = 1: nld
PNET(loadbus(ii)) = PNET(loadbus(ii)) - PLOAD(ii);
QNET(loadbus(ii)) = QNET(loadbus(ii)) - QLOAD(ii);
end
%End function NetPowers
while ( it < itmax & flag==0 )
% CALCULATED POWERS
%Function to calculate injected bus powers
% Include all entries
PCAL = zeros(1,nbb);
QCAL = zeros(1,nbb);
for ii = 1: nbb
PSUM = 0;
QSUM = 0;
for jj = 1: nbb
```

```
PSUM = PSUM + VM(ii)*VM(jj)*(YR(ii,jj)*cos(VA(ii)-VA(jj))
+YI(ii,jj)*sin(VA(ii)-VA(jj)));
QSUM = QSUM + VM(ii)*VM(jj)*(YR(ii,jj)*sin(VA(ii)-VA(jj)) -
YI(ii,jj)*cos(VA(ii)-VA(jj)));
end
PCAL(ii) = PSUM;
QCAL(ii) = QSUM;
end
%End of functionCalculatePowers
%STATCOM CALCULATED POWERS
%Function to calculate injected bus powers by the STATCOM
for ii = 1 : NSSC
B(ii)=1/Xvr(ii);
A1 = Tvr(ii)-VA(SSCsend(ii));
A2 = VA(SSCsend(ii))-Tvr(ii);
PCAL(SSCsend(ii)) = PCAL(SSCsend(ii)) +
VM(SSCsend(ii))*Vvr(ii)*(B(ii)*sin(A2));
QCAL(SSCsend(ii)) = QCAL(SSCsend(ii)) + VM(SSCsend(ii))^2*B(ii) -
Vvr(ii)*VM(SSCsend(ii))*(B(ii)*cos(A2));
PSSC(ii) = Vvr(ii)*VM(SSCsend(ii))*(B(ii)*sin(A1));
QSSC(ii) = - Vvr(ii)^2*B(ii) + Vvr(ii)*VM(SSCsend(ii))*(B(ii)*cos(A1));
end
%power mismatches
%Function to compute power mismatches
% POWER MISMATCHES
DPQ = zeros(1,nmax);
DP = zeros(1,nbb);
DQ = zeros(1,nbb);
DP = PNET - PCAL;
DQ = QNET - QCAL;
% To remove the active and reactive powers contributions of the slack
% bus and reactive power of all PV buses
for ii = 1: nbb
if (bustype(ii) == 1 )
DP(ii) = 0;
DQ(ii) = 0;
elseif (bustype(ii) == 2 )
DQ(ii) = 0;
end
end
% Re-arrange mismatch entries
kk = 1;
for ii = 1: nbb
DPQ(kk) = DP(ii);
DPQ(kk+1) = DQ(ii);
kk = kk + 2;
end
% Check for convergence
for ii = 1: nbb*2
if ( abs(DPQ) < tol)
flag = 1;
end
end
%End function PowerMismatches
%STATCOM POWER MISMATCHES
%Function to compute power mismatches for the STATCOM
for ii = 1 : NSSC
B(ii)=1/Xvr(ii);
A1 = Tvr(ii)-VA(SSCsend(ii));
A2 = VA(SSCsend(ii))-Tvr(ii);
Pcal = VM(SSCsend(ii))*Vvr(ii)*(B(ii)*sin(A2));
```

```matlab
Qcal = - VM(SSCsend(ii))^2*B(ii) + Vvr(ii)*VM(SSCsend(ii))*(B(ii)*cos(A2));
DPQ(2*(nbb + ii)-1) = Pcal - Psp(ii);
if (QSta(ii) == 1)
DPQ(2*(nbb + ii)) = Qcal - Qsp(ii);
else
DPQ(2*(nbb + ii)) = 0;
end
end
% JACOBIAN FORMATION
%Function to built the Jacobian matrix
% JACOBIAN FORMATION
% Include all entries
JAC = zeros(nmax,nmax);
iii = 1;
for ii = 1: nbb
jjj = 1;
for jj = 1: nbb
if ii == jj
JAC(iii,jjj) = -QCAL(ii) - VM(ii)^2*YI(ii,ii);
JAC(iii,jjj+1) = PCAL(ii) + VM(ii)^2*YR(ii,ii);
JAC(iii+1,jjj) = PCAL(ii) - VM(ii)^2*YR(ii,ii);
JAC(iii+1,jjj+1) = QCAL(ii) - VM(ii)^2*YI(ii,ii);
else
JAC(iii,jjj) = VM(ii)*VM(jj)*(YR(ii,jj)*sin(VA(ii)-VA(jj))...
-YI(ii,jj)*cos(VA(ii)-VA(jj)));
JAC(iii+1,jjj) = -VM(ii)*VM(jj)*(YI(ii,jj)*sin(VA(ii)...
-VA(jj))+YR(ii,jj)*cos(VA(ii)-VA(jj)));
JAC(iii,jjj+1) = -JAC(iii+1,jjj);
JAC(iii+1,jjj+1) = JAC(iii,jjj);
end
jjj = jjj + 2;
end
iii = iii + 2;
end
% Delete the voltage magnitude and phase angle equations of the slack
% bus and voltage magnitude equations corresponding to PV buses
for kk = 1: nbb
if (bustype(kk) == 1)
ii = kk*2-1;
for jj = 1: 2*nbb
if ii == jj
JAC(ii,ii) = 1;
else
JAC(ii,jj) = 0;
JAC(jj,ii) = 0;
end
end
end
if (bustype(kk) == 1) || (bustype(kk) == 2)
ii = kk*2;
for jj = 1: 2*nbb
if ii == jj
JAC(ii,ii) = 1;
else
JAC(ii,jj) = 0;
JAC(jj,ii) = 0;
end
end
end
end
%End of function NewtonRaphsonJacobian
```

```matlab
% STATCOM JACOBIAN
%Function to add the STATCOM elements to Jacobian matrix
for ii = 1 : NSSC
B(ii)=1/Xvr(ii);
if VSta(ii) == 1
JAC(: , 2*SSCsend(ii) )=0;
end
JAC(2*(nbb + ii)-1,2*(nbb + ii)-1) = 1;
JAC(2*(nbb + ii),2*(nbb + ii)) = 1;
A1 = Tvr(ii)-VA(SSCsend(ii));
A2 = VA(SSCsend(ii))-Tvr(ii);
Pcal = - VM(SSCsend(ii))*Vvr(ii)*( + B(ii)*sin(A2));
DQcal = Vvr(ii)*VM(SSCsend(ii))*(B(ii)*cos(A2));
Pssc = - Vvr(ii)*VM(SSCsend(ii))*(B(ii)*sin(A1));
DQssc = Vvr(ii)*VM(SSCsend(ii))*(B(ii)*cos(A1));
JAC(2*SSCsend(ii)-1,2*SSCsend(ii)-1) = JAC(2*SSCsend(ii)-1,2*SSCsend(ii)-1)
+ VM(SSCsend(ii))^2*B(ii);
JAC(2*SSCsend(ii),2*SSCsend(ii)-1) = JAC(2*SSCsend(ii),2*SSCsend(ii)-1) -
Pcal;
if (QSta(ii) == 1 )
JAC(2*SSCsend(ii)-1,2*SSCsend(ii)) = JAC(2*SSCsend(ii)-1,2*SSCsend(ii)) -
Pcal;
JAC(2*SSCsend(ii),2*SSCsend(ii)) = JAC(2*SSCsend(ii),2*SSCsend(ii)) +
VM(SSCsend(ii))^2*B(ii);
else
JAC(2*SSCsend(ii)-1,2*SSCsend(ii)) = JAC(2*SSCsend(ii)-1,2*SSCsend(ii)) -
Pssc;
JAC(2*SSCsend(ii),2*SSCsend(ii)) = JAC(2*SSCsend(ii),2*SSCsend(ii)) -
DQssc;
end
if (PSta(ii) == 1)
JAC(2*(nbb + ii)-1,2*SSCsend(ii)-1) = JAC(2*(nbb + ii)-1, 2*SSCsend(ii)-1)
+ DQcal;
JAC(2*SSCsend(ii)-1,2*(nbb + ii)-1) = JAC(2*SSCsend(ii)-1,2*(nbb + ii)-1) -
DQssc;
JAC(2*SSCsend(ii),2*(nbb + ii)-1) = JAC(2*SSCsend(ii),2*(nbb + ii)-1) -
Pssc;
JAC(2*(nbb + ii)-1,2*(nbb + ii)-1) = - DQssc;
if (QSta == 1)
JAC(2*(nbb+ii),2*(nbb+ii)-1)=JAC(2*(nbb+ii),2*(nbb+ii)-1)-Pssc;
JAC(2*(nbb + ii)-1,2*SSCsend(ii)) = JAC(2*(nbb + ii)-1,2*SSCsend(ii)) -
Pcal;
else
JAC(2*(nbb + ii),2*(nbb + ii)-1) = 0.0;
JAC(2*(nbb + ii)-1,2*SSCsend(ii)) = JAC(2*(nbb + ii)-1,2*SSCsend(ii)) +
Pssc;
end
else
JAC(2*(nbb + ii)-1,2*(nbb + ii)-1) = 1.0;
end
if (QSta(ii) == 1)
JAC(2*(nbb + ii),2*SSCsend(ii)-1) = JAC(2*(nbb + ii),2*SSCsend(ii)-1)-
Pcal;
JAC(2*(nbb + ii),2*SSCsend(ii)) = JAC(2*(nbb + ii),2*SSCsend(ii))+ DQcal;
JAC(2*SSCsend(ii)-1,2*(nbb + ii)) = JAC(2*SSCsend(ii)-1,2*...
(nbb + ii)) + Pssc;
JAC(2*SSCsend(ii),2*(nbb + ii)) = JAC((nbb + ii),2*(nbb + ii)) - DQcal;
JAC(2*(nbb + ii),2*(nbb + ii)) = -2*Vvr(ii)^2*B(ii) + DQssc;
if (PSta(ii) == 1)
JAC(2*(nbb + ii)-1,2*(nbb + ii)) = JAC(2*(nbb + ii)-1,2*(nbb + ii)) - Pssc;
else
```

```matlab
JAC(2*(nbb + ii)-1,2*(nbb + ii)) = 0.0;
end
else
JAC(2*(nbb + ii),2*(nbb + ii)) = 1.0;
end
end

% SOLVE FOR THE STATE VARIABLES VECTOR
D = JAC\DPQ';
% UPDATE THE STATE VARIABLES VALUES, WITH TRUNCATED CORRECTIONS IF
% NECESSARY (VM increments < +-0.1 p.u. and VA inrements < +- 5 deg)
%Function to update state variables
iii = 1;
for ii = 1: nbb
VA(ii) = VA(ii) + D(iii);
VM(ii) = VM(ii) + D(iii+1)*VM(ii);
iii = iii + 2;
end
%End function StateVariableUpdating
%UPDATE STATCOM STATE VARIABLES
%Function to update STATCOM state variable
for ii = 1 : NSSC
if (VSta(ii) == 1)
% Adjust the Volatge Magnitud target
Vvr(ii) = Vvr(ii) + Vvr(ii)*D(2*SSCsend(ii));
VM(SSCsend(ii)) = TarVol(ii);
if (Psp(ii) == 0)
Tvr(ii) = VA(SSCsend(ii));
else
Tvr(ii) = Tvr(ii) + D(2*(nbb + ii)-1);
end
else
Vvr(ii) = Vvr(ii) + Vvr(ii)*D(2*(nbb + ii));
Tvr(ii) = VA(SSCsend(ii));
end
end
it = it + 1;
end
%CHECK VOLTAGE MAGNITUDE LIMITS
%Function to check source voltages limits in the STATCOM
for ii = 1 : NSSC
%Check STATCOM Vvr Limits
if (Vvr(ii) > VvrHi(ii))
Vvr(ii) = VvrHi(ii);
elseif (Vvr(ii) < VvrLo(ii))
Vvr(ii) = VvrLo(ii);
end
end

%Function to calculate the power flows
PQsend = zeros(1,ntl);
PQrec = zeros(1,ntl);
% Calculate active and reactive powers at the sending and receiving
% ends of tranmsission lines
for ii = 1: ntl
Vsend = ( VM(tlsend(ii))*cos(VA(tlsend(ii))) +
VM(tlsend(ii))*sin(VA(tlsend(ii)))*i );
Vrec = ( VM(tlrec(ii))*cos(VA(tlrec(ii))) +
VM(tlrec(ii))*sin(VA(tlrec(ii)))*i );
tlimped = tlresis(ii) + tlreac(ii)*i;
```

```matlab
current =(Vsend – Vrec) / tlimped + Vsend*( tlcond(ii) +tlsuscep(ii)*i
)*0.5 ;
PQsend(ii) = Vsend*conj(current);
current =(Vrec – Vsend) / tlimped + Vrec*( tlcond(ii) + tlsuscep(ii)*i
)*0.5 ;
PQrec(ii) = Vrec*conj(current);
PQloss(ii) = PQsend(ii) + PQrec(ii);
end
% Calculate active and reactive powers injections at buses
PQbus = zeros(1,nbb);
for ii = 1: ntl
PQbus(tlsend(ii)) = PQbus(tlsend(ii)) + PQsend(ii);
PQbus(tlrec(ii)) = PQbus(tlrec(ii)) + PQrec(ii);
end
% Make corrections at generator buses, where there is load, in order to
% get correct generators contributions
for ii = 1: nld
jj = loadbus(ii);
for kk = 1: ngn
ll = genbus(kk);
if jj == ll
PQbus(jj) = PQbus(jj) + ( PLOAD(ii) + QLOAD(ii)*i );
end
end
end
%End function PQflows

%Print results
it %Number of iterations
VM %Nodal voltage magnitude (p.u)
VA=VA*180/pi %Nodal voltage phase angles (Deg)
Vvr %Final voltage magnitude source (p.u.)
Tvr=Tvr*180/pi %Final voltage phase angle source (Deg)
PQSSC=PSSC + j*QSSC %Active and reactive powers in STACOM (p.u.)
PQsend
PQrec
% End of MAIN STATCOM PROGRAM
```

OUTPUT:

it =7

VM =

Columns 1 through 16
1.0600   1.0430   1.0105   1.0000   1.0100   1.0057   1.0000   1.0100   1.0208   0.9976
1.0820   1.0200   1.0710   1.0000   0.9964   1.0031

Columns 17 through 30
0.9937   0.9841   0.9801   0.9837   0.9849   0.9856   0.9834   0.9748   0.9847   0.9664
0.9997   1.0052   1.0000   0.9795

VA =

Columns 1 through 16
0 -5.5355 -7.8828 -9.5309 -14.4794 -11.4041 -13.2026 -12.2360 -14.6158 -16.3275 -14.6158 -15.8290 -15.8290 -16.6416 -16.7766 -16.3297

Columns 17 through 30
-16.5526 -17.3759 -17.5240 -17.2864 -16.8006 -16.7808 -17.0918 -17.1363 -16.8859 -17.3344 -16.4409 -12.1107 -18.3403 -18.9777

Vvr = 0.9000 1.1000 0.9000 1.1000

Tvr = -9.5309 -13.2026 -16.6416 -18.3403

PQSSC = 0 - 1.6871i 0 - 0.0187i 0 + 0.0179i 0 - 0.1166i

PQsend =

Columns 1 through 8
1.7897 - 0.2094i 0.8265 + 0.1248i 0.4585 + 0.1123i 0.7742 + 0.0191i 0.8353 + 0.0280i 0.6236 + 0.0360i 0.7001 - 0.3291i -0.1371 + 0.1384i

Columns 9 through 16
0.3705 - 0.0485i 0.2984 - 0.1871i 0.2765 - 0.0649i 0.1549 + 0.0214i 0.0000 - 0.3006i 0.2765 + 0.2191i 0.4371 - 0.0541i -0.0000 - 0.3715i

Columns 17 through 24
0.0772 + 0.0436i 0.1774 + 0.0956i 0.0705 + 0.0536i 0.0143 + 0.0023i 0.0348 + 0.0341i 0.0601 + 0.0267i 0.0276 + 0.0168i -0.0675 - 0.0173i

Columns 25 through 32
0.0905 + 0.0266i 0.0556 + 0.0247i 0.1538 + 0.0980i 0.0735 + 0.0446i -0.0223 - 0.0165i 0.0470 + 0.0410i 0.0507 + 0.0270i 0.0146 + 0.0242i

Columns 33 through 40
-0.0222 - 0.0166i 0.0355 + 0.0237i -0.0579 - 0.0405i 0.1916 + 0.0212i 0.0626 - 0.0325i 0.0706 - 0.0025i 0.0375 + 0.0254i -0.0031 + 0.0142i

Column 41
0.1954 - 0.0780i

PQrec =

Columns 1 through 8

-1.7344 + 0.3461i -0.7982 - 0.0311i -0.4467 - 0.0956i -0.7665 - 0.0010i -0.8049 + 0.0774i
-0.6027 + 0.0078i -0.6930 + 0.3493i   0.1389 - 0.1442i

Columns 9 through 16

-0.3669 + 0.0513i -0.2969 + 0.1876i -0.2765 + 0.0815i -0.1549 - 0.0080i -0.0000 +0.3186i
-0.2765 - 0.2060i -0.4371 + 0.1038i   0.0000 + 0.3901i
Columns 17 through 24

-0.0763 - 0.0416i -0.1749 - 0.0906i -0.0698 - 0.0521i -0.0142 - 0.0022i -0.0346 - 0.0336i -
0.0596 - 0.0258i -0.0275 - 0.0167i   0.0676 + 0.0177i

Columns 25 through 32

-0.0896 - 0.0247i -0.0554 - 0.0244i -0.1527 - 0.0955i -0.0730 - 0.0435i   0.0223 + 0.0165i
-0.0466 - 0.0402i -0.0503 - 0.0264i -0.0145 - 0.0240i

Columns 33 through 40

0.0224 + 0.0168i -0.0350 - 0.0230i   0.0584 + 0.0416i -0.1916 - 0.0067i -0.0615 + 0.0346i
-0.0690 + 0.0055i -0.0370 - 0.0245i   0.0031 - 0.0358i

Column 41
-0.1947 + 0.0146i

NOTE:- We can get load flow results with and without STATCOM for five bus and IEEE-14 bus by simply changing only the input data given in chapter-5. Rest MATLAB program for both the cases will remain same.

REFERENCES

[1] Y. H .Song and A. T. Johns, Flexible AC Transmission System, IEE Press London, 1999.

[2] N.G. Hingorani and L.Gyugi , "Understanding FACTS –Concepts and Technology of Flexible Ac Transmission Systems", Standard Publishers Distributors, IEEE Press, New York, 2001.

[3] A. A. Edris, R. Aapa, M. H. Baker, L. Bohman, K. Clark, "Proposed terms and definitions for Flexible AC Transmission Systems (FACTS)", IEEE Transactions on Power Delivery, vol. 12, no. 4, pp. 1848-1853, 1997.

[4] Hadi Saadat, "Power System Analysis (MATLAB concept)", Tata McGraw-Hill, Edition,2010.

[5] C.R. Fuerte-Esquivel, E. Acha and H. Ambriz-Perez, "FACTS Modelling and Simulation in Power Networks", John Willey & Sons, Ltd,2004.

[6] D. Gotham and G.T. Heydt, "Power Flow control and Power Flow Studies for Systems with FACTS devices", IEEE Transaction on Power Systems, vol.13, no.1, pp. 60-65, 1998.

[7] Rudra Pratap Singh, "Introduction to MATLAB", Ist Edition,2004

[8] M. Noorzian and G. Anderson, "Power flow control by use of controllable series components", IEEE Transactions on Power Systems, vol. 8, no. 3, pp. 1420-1429, 1993.

[9] J. Mutale and G. Strbac, "Transmission network reinforcement versus FACTS: an economic assessment", IEEE Transactions on Power Systems, vol. 15, no.
3, pp. 961-967, 2000.

[10] Y. Xia, Y. H. Song, C. C. Lier and Y. X. Sun, "Available Transfer Capability Enhancement using FACTS Devices", IEEE Transactions on Power Systems, vol. 18, no. 4, pp.305-312, 2003.

[11] P. Rao, M. L. Crow and Z. Yang, "STATCOM Control for system voltage control applications", IEEE Transactions on Power Delivery, vol. 15, no. 4, pp. 1311-1317 2000.

[12] Y. Lu and A. Abur, "Static security enhancement via optimal utilization of thyristor-controlled series capacitor", IEEE Transactions on Power Systems, vol 17, pp. 324-329, 2000.

[13] L. Gyugyi, C.D Shauder and K.K Sen, "Static Synchronous Series Compensator A solid state Approach to the series compensation of transmission line," IEEE Transactions on Power Delivery, vol. 12, no. 3, 1997.

[14] M. O. Hassan, S. J. Cheng and Z. A. Zakaria, "Steady-state modelling of static synchronous compensator and thyristor controlled series compensator for power flow analysis", Information Technology Journal, vol. 8, Issue 3, pp. 347-353, 2009.

[15] G.Radam and R.S Raje, "Power flow model/calculation for power systems with multiple FACTS controllers", Eletric Power System Research, vol. 77, Issue 12, pp.1521-1531,2007.

[16] Kalyan K.Sen, "STATCOM- Static Synchronous Compensator: Theory, Modelling & Applications" IEEE Transaction on power systems, 1988.

[17] N.G.Hingoroni, "Flexible AC transmission system". Fifth IEE international conference on AC and DC transmission (IEE-pub. no 345), pp 1-7 September 1991.

[18] N.G.Hingoroni, "Flexible AC transmission systems", IEEE spectrum (40-45) April 1993.

[19] M. Noroozian, C. W. Taylor, "Benefits of SVC and STATCOM for Electric Utility Application".

[20] Mark Ndubuka NWOHU, " Voltage Stability Improvement using Static VAR Compensator in Power Systems", Leonardo Journal of Sciences, Issue 14, p 167-172, January-June 2009.

[21] Mazilah Binti A Rahman, "Overview of Thyristor Controlled Series Capacitor (TCSC) In Power Transmission System".

[22] Nitus Voraphonpiput, Teratam Bunyagul and Somchai Chatratana, "Power Flow Control with Static Synchronous Series Compensator (SSSC)".

[23] M. Noroozian, C. W. Taylor, "Benefits of SVC and STATCOM for Electric Utility Application".

[24] Rusejla Sadikovic, "Power flow Control with UPFC".

[25] X.P. Zhang, "Robust modelling of the interline power flow controller and the generalized unified power flow controller with small impedances in power flow analysis", Electrical Engineering, Vol. 89, pp 1-9, 2006.

[26] C. L. Wadhwa, Electrical Power Systems, New Age International Publishers, 2006.