MAJOR PROJECT

POWER FLOW STUDY OF INTERCONNECTED POWER SYSTEM USING STATCOM

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CERTIFICATE

It is certified that this Major Project Thesis entitled as **“Power Flow Study of Interconnected Power System Using STATCOM”** submitted by **Bahadur Singh Pali** having Roll No. **10082,** in partial fulfilment of the requirement for the award of the Degree of “ Master of Engineering” (Control & Instrumentation) in Electrical Engineering from University of Delhi, Delhi is a true record of work undertaken by him as a part of curriculum under my guidance.

This dissertation is a bonafide record of work carried out by him under my guidance and supervision. The matter embodied in this thesis has not been submitted to any university or institute for award of any degree.

I wish him success in all his endeavours.

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ABSTRACT

An electric power system can be seen as the interconnection of generating sources and customer loads through a network of transmission lines, transformers and ancillary equipments. Its structure has many variations that are the result of a legacy of economic, political, engineering and environmental decisions. Independent of the structure of a power system, the power flows throughout the network are largely distributed as a function of transmission line impedance; a transmission line with low impedance enables larger power flows through it than does the transmission line with high impedance. This is not always the most desirable outcome because quite often it gives rise to a myriad of operational problems; the job of the system operator is to intervene to try to achieve power flow redistribution, but with limited success. Examples of operating problems to which unregulated active and reactive power flows may give rise are: loss of system stability, power flow loops, high transmission losses, voltage limit violations, an inability to utilise transmission line capability up to the thermal limit and cascade tripping. These problems have traditionally been solved by building new power plants and transmission lines, which is costly to implement and involves long construction time. A new solution to such operational problems is a new technological thinking that comes under the generic title of FACTS – flexible alternating current transmission system, which is based on the substantial incorporation of power electronic devices and methods into the high- voltage side of the network, to make it electronically controllable. Several kinds of FACTS controllers have been commissioned in various parts of the world. These controllers narrow the gap between the uncontrolled and the controlled power system mode of operation, providing additional degrees of freedom to control power flows and voltages at key locations of the network. This thesis presents the study of STATCOM – the static compensator, one of the most popular FACTS controllers. First, the basic theory of power flows is addressed. Building upon elementary concepts of circuit theory and complex algebra, equations for active and reactive powers injections at a bus are derived. A computer program in MATLAB code for Newton-Raphson method, which has been proved invaluable for decades in solving the power flow problem, is developed. Then, a power flow model of STATCOM is developed and its role in network-wide applications is assessed. The non- linear power flow equations of STATCOM have been linearised and included in the Newton-Raphson power flow algorithm. The state variables of STATCOM have been combined simultaneously with state variables of the network in the single frame of reference for unified iterative solution. The STATCOM computer program in MATLAB code is also developed. For the case study, a small five-bus network containing two generators and seven transmission lines is used. The power flow solutions in both uncontrolled and STATCOM controlled power system mode of operations are found and compared. After the conclusion, the scope for further work is also suggested in the last.

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1

INTRODUCTION

The main aim of a modern electrical power system is to satisfy continuously the electrical power contracted by all customers. This is a problem of great engineering complexity where the following operational policies must be observed :-

1. Nodal voltage magnitudes and system frequency must be kept within narrow boundaries.
2. The alternating current (AC) voltage and current waveforms must remain largely sinusoidal.
3. Transmission lines must be operated well below their thermal and stability limits.
4. Even short- term interruptions must be kept to a minimum.

To a large extent, several of these key issues in power system operation may be assessed quite effectively by resorting to power flow and derived studies. The main object of a power flow study is to determine the steady-state operating condition of electrical power network. The steady-state may be determined by finding out, for a given set of loading conditions, the flow of active and reactive powers throughout the network and the voltage magnitudes and phase angles at all buses of the network.

Expansion, planning and daily operation of power systems relies on extensive power flow studies. The information conveyed by such studies indicates whether or not the nodal voltage magnitudes and active and reactive power flows in transmission lines and transformers are within prescribed operating limits. If voltage magnitudes are outside bounds in one or more points of the network, then appropriate action is taken in order to regulate such voltage magnitudes. Similarly, if the study predicts that the power flow in a given transmission line is beyond the power carrying capacity of the line, then the control action is taken.

1.1 THE MAIN OBJECTS :

The key objectives of the power flow study of the inter-connected power system are given as bellow :

1. To increase transmission capacity allowing secure loading of the transmission lines upto their thermal capacities.
2. To enable better utilisation of available generation.
3. To contain outages from spreading to wider areas.

1.2 BASICS OF POWER FLOW

The power flow problem, is solved to determine the steady-state complex voltages at all buses of the network, from which the active and reactive power flows in every transmission line and transformer are calculated. The set of equations representing the power system are nonlinear. For most practical purposes, all power flow methods exploit the well-conformed nodal properties of the power network and equipment. In its most basic form, these equations are derived by assuming that a perfect symmetry exists between the phases of the three phase power system. Owing to the nonlinear nature of the power flow equations, the numerical solution is reached by iteration.

1.3 NECESSITIES OF POWER FLOW STUDIES

Power flow studies provide the following informations:

1. Informations regarding bus usage.
2. Informations regarding power flow theory and transmission lines, transformers and other elements of power system for a specified load demand subject to the regulating capabilities of the generators, condensers, tap changing transformers and phase shifting transformers.
3. Specified net interchange of power with adjoining power systems.
4. Power flow studies help in critically assessing alternating plans for system expansion to meet the ever increasing load demand.
5. Help the planning and operation engineers to meet contingency conditions such as loss of large generating unit or a major line outage due to thermal over loading of the line.
6. Help in determining best size and most favourable location for the power capacitors for improving the power factor as well as the usage profile of power system.
7. They are periodically executed for monitoring and controlling of power system.
8. Real time results of power flow computation may be used to determine the reactive compensation needed to establish bus voltages.

9. If these studies predict that the nodal voltage magnitudes, active and reactive power flows in transmission lines and transformers are not within limits, then control action is taken.

In practical system, there may be thousands of buses and transmission links. We shall concentrate mainly on transmission system with generators and loads modelled by the complex powers. Thus , the power flow study involves extensive calculations.

Before the advent of digital computers, the AC calculating boards were used for carrying out power flow studies. These studies were tedious and time consuming, but with the availability of fast and large sized digital computers, all kinds of power system studies, including power flow study can now be carried out conveniently.

1.4 MAIN PROBLEMS OF POWER FLOWS

In power flow studies load powers are assumed as constants. A given set of loads on the buses can be served from a given set of generators in an infinite number of power flow configuration.

Some of the main and important aspects of power flow studies are as follows:

The sum of real power injected at the generating buses must be equal, at each instant of time, the sum of total system load demand plus system losses. Their individual generator outputs must be closely maintained at the predetermined set points. As the load demand slowly changes throughout the day ,therefore these set points changes slowly with time. Thus the power flow results for a certain hour of the day may be quite different from that of the next hour.

The power transfer capability of a power transmission line is limited to the thermal loading limit and the stability limit. It must be seen that transmission line do not operate too close to their stability or thermal limits.

It is necessary to keep the voltage levels of certain buses within close tolerances. This can be achieved by proper scheduling of reactive powers.

The power system must fulfil the contractual scheduled interchange of power to neighbouring systems, if any , via its tie lines.

Power flow studies are very important in the planning stages of new networks or in addition to existing ones.

1.5 SUB-PROBLEMS OF POWER FLOWS

In addition to the main problems as discussed above, the following problems are also faced in power flow studies:-

1. Formulation of mathematical models that describe the relationship between voltages and powers in the inter-connected system.
2. Specification of power and voltage constraints that must apply to the various buses of the network.
3. The computation of the voltage magnitude and phase angle of each node or bus in a power system under balanced three phase steady-state conditions.

2

LITERATURE SURVEY

The flexible alternating-current transmission systems (FACTS) is a recent technological development in electrical power systems. IT builds on the great many advances achieved in high-current, high-power semiconductor device technology, digital control and signal conditioning. From the power systems engineering perspective, the wealth of experience gained with the commissioning and operation of high-voltage direct-current (HVDC) links and static VAR compensator (SVC) systems, over many decades, in various parts of the world, may have provided the driving force for searching deeper into the use of emerging power electronic equipments and techniques, as a means of alleviating long standing operational problems in both high-voltage transmission and low- voltage distribution systems. A large number of researchers had contributed to the rapid advancement of the FACTS technology, but the names N.G. Hingorani and L. Gyugyi stand out prominently. Their work on FACTS, synthesised in their book, Understanding FACTS - Concepts and Technology of Flexible AC Transmission Systems (Institute of Electronic and Electrical Engineers, New York, 2000) is a source of learning and inspiration.

2.1 SIGNIFICANT DEVELOPMENTS

The main aim of power flow studies is to make the electrical power system capable to satisfy continuously the electrical power contracted by all customers. This is a problem of great engineering complexity. Many significant developments have been made in the subject by researchers and engineers. To a large extent, several of these key issues in power system operation may be assessed quite effectively by resorting to power flow and derive studies (Stagg and El-Abiad, 1968; Wood and Wollenberg, 1984; Arrilaga and Arnold, 1990; Grainger and Stevenson, 1994). Expansion, planning and daily operation of power systems relies on extensive power flow studies (Weedy, 1987; Kundur, 1994).The power flow problem, is solved to determine the steady-state complex voltages at all buses of the network, from which active and reactive power flows in every transmission line and transformer are calculated (Stagg and El-Abiad, 1968). The set of equations representing the power system are nonlinear. For most practical purposes, all power flow models exploit the well confirmed nodal properties of the power network and equipment. In its most basic form, these equations are derived by assuming that a perfect symmetry exists between the phases of the three-phase power system (Arrilaga and Arnold, 1990). Owing to the nonlinear nature of the power flow equations, the numerical solution is reached by iterations (Grainger and Stevenson, 1994).

FACTS controllers narrow the gap between the uncontrolled and controlled power system mode of operation by providing additional degrees of freedom to control power flows and voltages at key locations of the network (Hingorani and Gyuagi, 2000). Key objectives of the technology are: to increase transmission capacity allowing secure loading of the transmission up to their thermal capacities; to enable better utilisation of available generation; and to contain outages from spreading to wider areas (Song and Johns, 1999).

In order to determine the effectiveness of this new generation of power system controllers on a network wide basis, it has become necessary to upgrade most of the analysis tools on which the power engineers rely to plan and to operate their system (IEEE/CIGRE, 1995). The power flow solutions are probably the most popular kind of computer-based calculations. The reliable solution of power flows in real life transmission and distribution networks is not a trivial matter and, over the years, owing to its very practical nature, many calculation methods have been put forward to solve this problem. Among them, Newton-Raphson type methods, with their strong convergence characteristics have proved the most successful (Tinny and Hart, 1967).

From the outset, interconnection was aided by the breakthrough in high-current, high-power semiconductor valve technology (Arrilaga, 1998). Thyristor-based high-voltage direct current (HVDC) converter installations provided a means for interconnecting power systems with different operating frequencies – e.g. 50/60 Hz, for interconnecting power systems separated by sea and for interconnecting weak and strong power systems (Hingorani, 1996). The most recent development in HVDC technology is the HVDC system based on solid-state voltage source converter, which enables independent, fast control of active and reactive powers (McMurray, 1987).

2.2 LITERATURE REVIEW

Another aspect of researches and developments has been towards the improvements techniques and procedures with which to access the steady-state operation of electrical power systems at the fundamental frequency. The power system application tool is termed “power flows”, and the most popular variants of the tool are presented in the literature; namely, positive sequence power flow [7], optimal power flow [8], and three phase power flow [9]. The first two applications deal with cases of balanced operation, for nonoptimal and optimal solutions, respectively. The third application deals with unbalanced operation induced by the imbalances present either in plant components or in system load.

Power electronic circuits using conventional thyristors have been widely used in power transmission applications since early 1970s [10]. The first application took place in the area of HVDC transmission, but shunt reactive power compensation using fast controllable inductors and capacitors soon gained general acceptance [11]. More recently, fast-acting series compensators using thyristors have been used to vary the electrical length of key transmission lines, with almost no delay, instead of classical series capacitor, which is mechanically controlled. In distribution system applications solid-state switches using thyristors are being used to enhance the reliability of supply to critical customer loads [12].

Power electronics is a technology that has affected every aspect of electrical power network. Deregulated markets are imposing further demands on generating plants, increasing their wear and tear and likelihood of generator instabilities of various kinds. To help to alleviate such problems, power electronic controllers have recently been developed to enable generators to operate more reliably. The thyristor-controlled series compensator (TCSC) is used to mitigate subsynchronous resonances (SSRs) and to damp power system oscillations (Larsen et al., 1992). However it may be argued that the primary function of the TCSC, like that of its mechanically controlled counterpart, the series capacitor bank, is to reduce the electrical length of the compensated transmission line. Hence the aim is still to increase power transfers significantly, but with increased transient stability margins.

For most practical purposes the thyristor-based static VAR compensator (SVC) have made the rotating synchronous compensator redundant, except where an increase in the short circuit level is required along with fast-acting reactive power support (Miller, 1982). However with development in technology, the replacement of SVC by a new breed of static compensators based on the use of VSCs is looming. They are known as STATCOMs and provide all the functions that the SVC can provide but at a higher speed (IEEE/CIGRE, 1995); it is more compact and requires only a fraction of land required by an SVC installation. The STATCOM is essentially a VSC is the basic building block of the new generation of power electronic controllers that have emerged from the FACTS and custom power initiatives (Hingorani and Gyugyi, 2000).

2.3 CONCLUSION

The exhaustive literature review has revealed that the research work carried out on FACTS controllers is largely influenced by the technological developments in power electronics – specially in thyristor based technology. Most of the developments in these fields are to replace the conventional mechanical power compensators by thyristor based FACTS controllers, among which, in high-voltage transmission , the most popular FACTS equipments are : the STATCOM , the unified power flow controller (UPFC) and the HVDC-VSC.

3

GENERAL POWER FLOW CONCEPTS

The power flow problem, is solved to determine the steady-state complex voltages at all buses of the network, from which the active and reactive power flows in every transmission line and transformer are calculated. The set of equations representing the power system are non-linear. For most practical purposes, all power flow methods exploits the well –confirmed nodal properties of the power network and equipment. In its most basic form, these equations are derived by assuming that a perfect symmetry exists between the phases of the three phase power system. Owing to the non-linear nature of the power flow equations, the numerical solution is reached by iteration.

3.1 BASIC FORMULATION

A popular approach to assess the steady-state operation of a power system is to write equations stipulating that at a given bus the generation, load and powers exchanged through the transmission elements connecting to the bus must add up to the zero, which applies to both active power and reactive power. These equations are termed mismatch power equations and at bus k they take the following form :

$$\Delta P_K = P_{GK} - P_{LK} - P_K^{cal} = P_K^{sch} - P_K^{cal} = 0 \qquad \text{. . . (1)}$$

$$\Delta Q_K = Q_{GK} - Q_{LK} - Q_K^{cal} = Q_K^{sch} - Q_K^{cal} = 0 \qquad \text{. . . (2)}$$

The terms ΔP_K and ΔQ_K are the mismatch active and reactive powers at bus k, respectively. P_{GK} *and* Q_{GK} represent, respectively ,the active and reactive powers injected by the generator at bus k, which are assumed to be controlled by the plant operator. P_{LK} *and* Q_{LK} represent the active and reactive powers drawn by the load at bus k, respectively. Under normal operation the customer has control of these variables, and in the power flow formulation they are assumed to be known variables.

In principles, at least, the generation and the load at bus k may be measured by the electric utility and, in the parlance of power system engineers, their net values are known as the scheduled active and reactive powers.

These scheduled active and reactive powers are :-

$$P_K^{sch} = P_{GK} - P_{LK} \qquad \ldots \quad (3)$$

$$Q_K^{sch} = Q_{GK} - Q_{LK} \qquad \ldots \quad (4)$$

The transmitted active and reactive powers, P_K^{cal} *and* Q_K^{cal} are functions of nodal voltages and network impedances and are computed using power flow equations. Provided the nodal voltages throughout the power network are known to a good degree of accuracy then the transmitted powers are easily and accurately calculated. In this situation, the corresponding mismatch powers are zero for any practical purpose and the power balance at each bus of the network is satisfied. However, if the nodal voltages are not known precisely then the calculated transmitted powers will have only approximated values and the corresponding mismatch powers are not zero.

The power flow solution takes the approach of successively correcting the calculated nodal voltages and, hence, the calculated transmitted powers until values accurate enough are arrived at, enabling the mismatch powers to be zero or fairly close to be zero. In modern power flow computer programs, it is normal for all mismatch equations to satisfy a tolerance as tight as 1e – 12 before the iterative solution can be considered successful. Upon convergence, the nodal voltage magnitude and angles yield useful information about the steady-state operating conditions of the power system and are known as state variables.

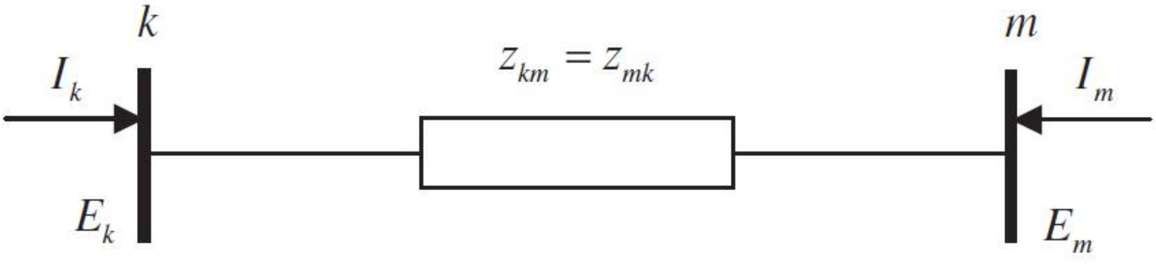

Figure 1 Equivalent Impedance

In order to develop suitable power flow equations, it is necessary to find relationships between injected bus currents and bus voltages. Based on Figure 1 the injected complex current at bus k, denoted by I_K may be expressed in terms of the complex bus voltages E_K *and* E_m as follows :

$$I_K = \frac{1}{Z_{Km}}\left(E_K - E_m\right) = y_{Km}\left(E_K - E_m\right) \qquad \ldots \quad (5)$$

Similarly for bus m,

$$I_m = \frac{1}{Z_{mK}}(E_m - E_K) = y_m(E_m - E_K) \quad \dots \quad (6)$$

The above equations can be written in matrix form as,

$$\left(\begin{bmatrix} I_K \\ I_m \end{bmatrix}\right) = \begin{bmatrix} y_{Km} & -y_{Km} \\ -y_{mK} & y_{mK} \end{bmatrix} \begin{bmatrix} E_K \\ E_m \end{bmatrix}, \quad \dots (7)$$

Or

$$\begin{bmatrix} I_K \\ I_m \end{bmatrix} = \begin{bmatrix} Y_{KK} & Y_{Km} \\ Y_{mK} & Y_{mm} \end{bmatrix} \begin{bmatrix} E_K \\ E_m \end{bmatrix}, \quad \dots (8)$$

Where the bus admittances and voltages can be expressed in more explicit form :

$$Y_{ij} = G_{ij} + jB_{ij} \quad \dots \quad (9)$$

$$E_i = V_i e^{j\theta_i} = V_i(\cos\theta_i + j\sin\theta_i) \quad \dots \quad (10)$$

Where I = k, m and j = k, m.

The complex power injected at bus k consists of an active and reactive component and nay be expressed as the function of the nodal voltage and injected current at the bus :

$$S_K = P_K + jQ_K = E_K I^*_K$$

$$= E_K(Y_{KK}E_K + Y_{Km}E_m)^* \quad \dots \quad (11)$$

Where I_K^* is the complex conjugate of the current injected at bus k.

The expression for P_K^{cal} *and* Q_K^{cal} can be determined by substituting Equation (9) and (10) into Equation (11), and separating into real and imaginary parts :

$$P_K^{cal} = V_K^2 G_{KK} + V_K V_m [G_{Km} \cos(\theta_K - \theta\ m) + B_{Km} \sin(\theta_K - \theta_m)] \quad . . . \ (12)$$

$$Q_K^{cal} = -V_K^2 B_{KK} + V_K V_m [G_{Km} \sin(\theta_K - \theta_m) - B_{Km} \cos(\theta_K - \theta_m)] \quad . . . \ (13)$$

For specified levels of power generation and power load at bus k, and according to Equation (1) and (2), the mismatch equations may be written down as :

$$\Delta P_K = P_{GK} - P_{LK} - \{V_K^2 G_{KK} + V_K V_m [G_{Km} \cos(\theta_K - \theta_m) + B_{Km} \sin(\theta_K - \theta_m)]\} = 0$$

. . . (14)

$$\Delta Q_K = Q_{GK} - Q_{LK} - \{-V_K^2 B_{KK} + V_K V_m [G_{Km} \sin(\theta_K - \theta_m) - B_{Km} \cos(\theta_K - \theta_m)]\} = 0$$

. .

. . . (15)

Similar equations may be obtained for bus m simple by exchanging subscripts k and m in Equations (14) and (15).

It should be marked that Equations (12) and (13) represent only the powers injected at bus k through *i*th transmission element, that is, $P_K^{i..cal}$ *and* $Q_K^{i..cal}$. However, a practical power system will consists of many buses and many transmission elements. This calls for Equations (12) and (13) to be expressed in more general terms, with net power flow injected at bus k expressed as the summation of the powers flowing at each one of the transmission elements terminating at this bus. This is illustrated in Figures 2(a) and 2(b) for cases of active and reactive powers, respectively.

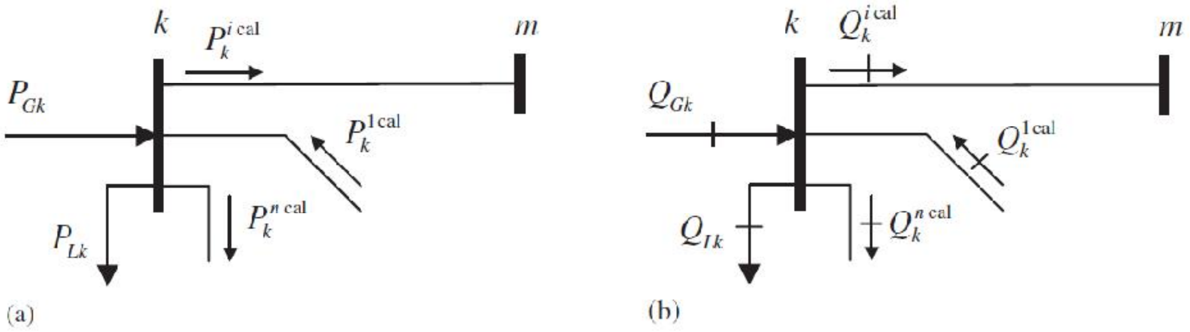

Figure 2 Power balance at bus k : (a) active power, (b) reactive power.

The generic net active and reactive powers injected at bus k are :

$$P_K^{cal} = \sum_{i=1}^{n} P_K^{i..cal} \quad . . . \quad (16)$$

$$Q_K^{cal} = \sum_{i=1}^{n} Q_K^{i..cal} \quad . . . \quad (17)$$

Where $P_K^{i..cal}$ *and* $Q_K^{i..cal}$ are computed by using Equations (12) and (13), respectively.

As an extension, the generic power mismatch equations at bus k are :

$$\Delta P_K = P_{GK} - P_{LK} - \sum_{i=1}^{n} P_K^{i..cal} = 0 \quad . . . \quad (18)$$

$$\Delta Q_K = Q_{GK} - Q_{LK} - \sum_{i=1}^{n} Q_K^{i..cal} = 0 \qquad . . . (19)$$

3.2 VARIABLES

In conventional power flow theory each bus is described by four variables : net active power, net reactive power, voltage magnitude and voltage phase angle.

Since there are only two equations per bus, two out of four variables must be specified in each bus in order to have a solvable problem. From a purely mathematical viewpoint, any two variables can be specified, however, in engineering terms the choice is based on which variables at the bus can be physically controlled through the availability of a nearby controller. In the broadest sense, one can think of voltage magnitudes and phase angles as the state variables, and active and reactive powers as control variables.

3.3 BUS CLASSIFICATION

Buses are classified according to which two out of the four variables are specified :

1. **Load PQ Bus** : No generator is connected to the bus, hence the controlled variables P_G and Q_G are zero. Furthermore the active and reactive powers drawn by the load $P_L \, and \, Q_L$ are known by available measurements. In these type of buses net active power and the net reactive power are specified, and voltage, V and phase angle, θ are computed.

2. **Generator PV Bus** : A generator source is connected to the bus ; the nodal voltage magnitude V is maintained at constant value by adjusting the field current of the generator and hence it generates and absorbs reactive power. Moreover, the generated active power P_G is also set at a specified value. The other two quantities phase angle, θ and generated reactive power Q_G are computed. Constant voltage operation is possible only if the generator reactive power design limits are not violated, that is, $Q_{G..\min} \angle Q_G \angle Q_{G..\max.}$
3. **Generator PQ Bus** : If the generator can not provide the necessary reactive power support to constrain the voltage magnitude at the specified value then the reactive power is fixed at the violated limit and the voltage magnitude is freed. In this case, the generated active power P_G and the reactive power Q_G are specified, and the nodal voltage magnitude V and the phase angle are computed.
4. **Slack (swing) Bus** : One of the generator buses is chosen to be the slack bus where the nodal voltage magnitude, V_{slack} , and phase angle, θ_{slack}, are specified. There is only one slack bus in the power system and the function of the slack generator is to produce sufficient power to provide for any unmet system load and for system losses, that are not known in advance of the power flow calculation. The voltage phase angle at the slack bus θ_{slack} is chosen as the reference against which all other voltage phase angles in the system are measured. It is normal to fix its value to zero.

4

METHODS OF POWER FLOW SOLUTION

4.1 EARLY POWER FLOW ALGORITHM:

From the mathematical modelling point of view, a power flow solution consists of solving the set of nonlinear algebraic equations that describes the electrical power network under steady-state conditions. Over the years, several approaches have been put forward for the solution of the power flow equations. Early approaches were based on loop equations and numerical methods using Gauss-type solutions. The method was laborious because the network loops have to be specified beforehand by the system engineer. Improved techniques saw the introduction of nodal analysis in favour of loop analysis, leading to a considerable reduction in data preparation, nevertheless, reliability towards convergence was still the main concern. Further developments led to the introduction of the Gauss-Seidel method with acceleration factors. The appeal of this generation power flow methods is their minimum storage requirements and the fact that they are easy to comprehend and to code in the computer programs. The drawback is that these algorithms exhibit poor convergence characteristics when applied to the solution of the networks of realistic size. Power flow solutions based on the nodal impedance matrix were briefly experimented with, but problem with computer storage and speed became insurmountable issues at the time. To overcome such limitations, the Newton-Raphson method and derived formulations were developed in the early 1970s and have since become firmly established throughout the power system industry.

4.2 THE NEWTON-RAPHSON ALGORITHM :

In large - scale power flow studies the Newton-Raphson method has proved most successful owing to its strong convergence characteristics. This approach uses iteration to solve the following set of nonlinear algebraic equations :

$$f_1(x_1, x_2, \ldots\ldots, x_N) = 0,$$

$$f_2(x_1, x_2, \ldots\ldots, x_N) = 0,$$

$$\vdots$$

$$f_N(x_1, x_2, \ldots\ldots x_N) = 0,$$

Or

$$\mathbf{F(X)} = \mathbf{0} \qquad \ldots \qquad \ldots \qquad (20)$$

Where **F** represent the set of n nonlinear equations and **X** is the vector of n unknown state variables.

The essence of the method consists of determining the vector of state variables **X** by performing a Taylor series expansion of **F(X)** about an initial estimate $X^{(0)}$:

$$\mathbf{F(X)} = \mathbf{F}[X^{(0)}] + \mathbf{J}[X^{(0)}][\mathbf{X} - X^{(0)}] + \text{higher-order terms}, \ldots \qquad (21)$$

Where **J**[$X^{(0)}$] is a matrix of first-order partial derivatives of **F** (**X**) with respect to **X**, termed the Jacobian, evaluated at **X** = $X^{(0)}$.

This expansion lends itself to a suitable formulation for calculating the vector of state variables X by assuming that $X^{(1)}$ is the value computed by the algorithm at iterative 1 and that this value is sufficiently close to the initial estimate $X^{(0)}$. Based on this premise, all higher-order derivative terms in equation (21) may be neglected. Hence,

$$\underbrace{\begin{bmatrix} f_1(\mathbf{X}^{(1)}) \\ f_2(\mathbf{X}^{(1)}) \\ \vdots \\ f_n(\mathbf{X}^{(1)}) \end{bmatrix}}_{\mathbf{F}(\mathbf{X}^{(1)})} \approx \underbrace{\begin{bmatrix} f_1(\mathbf{X}^{(0)}) \\ f_2(\mathbf{X}^{(0)}) \\ \vdots \\ f_n(\mathbf{X}^{(0)}) \end{bmatrix}}_{\mathbf{F}(\mathbf{X}^{(0)})} + \underbrace{\begin{bmatrix} \frac{\partial f_1(\mathbf{X})}{\partial x_1} & \frac{\partial f_1(\mathbf{X})}{\partial x_2} & \cdots & \frac{\partial f_1(\mathbf{X})}{\partial x_n} \\ \frac{\partial f_2(\mathbf{X})}{\partial x_1} & \frac{\partial f_2(\mathbf{X})}{\partial x_2} & \cdots & \frac{\partial f_2(\mathbf{X})}{\partial x_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial f_n(\mathbf{X})}{\partial x_1} & \frac{\partial f_n(\mathbf{X})}{\partial x_2} & \ddots & \frac{\partial f_n(\mathbf{X})}{\partial x_n} \end{bmatrix}\Bigg|_{\mathbf{X}=\mathbf{X}^{(0)}}}_{\mathbf{J}(\mathbf{X}^{(0)})} \underbrace{\begin{bmatrix} X_1^{(1)} - X_1^{(0)} \\ X_2^{(1)} - X_2^{(0)} \\ \vdots \\ X_n^{(1)} - X_n^{(0)} \end{bmatrix}}_{\mathbf{X}^{(1)} - \mathbf{X}^{(0)}}.$$

. . . (22)

In compact form, and generalising the power expression for the case of iteration (i),

$$F\left(X^{(i)}\right) \approx F\left(X^{i-1}\right) + J\left(X^{i-1}\right)\left(X^{i} - X^{i-1}\right), \qquad \ldots \qquad (23)$$

Where i = 1, 2, . . . Furthermore, if it is assumed that $X^{(i)}$ is sufficiently close to the solution $X^{(*)}$ then $F\left(X^{(i)}\right) \approx F\left(X^{(*)}\right) = 0,$ Hence , equation (23) becomes

$$F\left(X^{(i-1)}\right) + J\left(X^{(i-1)}\right)\left(X^{i(\ )} - X^{(i-1)}\right) = 0 \qquad \ldots \qquad (24)$$

and solving for $X^{(i)}$,

$$X^{(i)} = X^{(i-1)} - J^{-1}\left(X^{(i-1)}\right)F\left(X^{(i-1)}\right) \qquad \ldots \qquad (25)$$

The iterative solution can be expressed as a function of correction vector

$$\Delta X^{(i)} = X^{(i)} - X^{i-1},$$

$$\Delta X^{(i)} = -J^{-1}\left(X^{(i-1)}\right)F\left(X^{(i-1)}\right), \qquad \ldots \qquad (26)$$

And the initial estimates are updated using the following relation :

$$X^{(i)} = X^{(i-1)} + \Delta X^{(i)}, \qquad \ldots \qquad (27)$$

The calculations are repeated as many times as required using the most up-to-date values of X in equation (26). This is done until the mismatches ΔX are within a prescribed small tolerance (i.e. 1e – 12).

In order to apply the Newton-Raphson method to the power flow problem, the relevant equations must be expressed in the form of Equation (26) where **X** represents the set of unknown nodal voltage magnitudes and phase angles. The power mismatch equations ΔP and ΔQs are expanded around a base point $\left(\theta^{(0)}, V^{(0)}\right)$ and, hence, the power flow Newton-Raphson algorithm is expressed by the following relationship :

$$\underbrace{\begin{bmatrix}\Delta\mathbf{P}\\ \Delta\mathbf{Q}\end{bmatrix}^{(i)}}_{\mathbf{F}\left(\mathbf{X}^{(i-1)}\right)} = -\underbrace{\begin{bmatrix}\frac{\partial\mathbf{P}}{\partial\boldsymbol{\theta}} & \frac{\partial\mathbf{P}}{\partial\mathbf{V}}\mathbf{V}\\ \frac{\partial\mathbf{Q}}{\partial\boldsymbol{\theta}} & \frac{\partial\mathbf{Q}}{\partial\mathbf{V}}\mathbf{V}\end{bmatrix}^{(i)}}_{\mathbf{J}\left(\mathbf{X}^{(i-1)}\right)} \underbrace{\begin{bmatrix}\Delta\boldsymbol{\theta}\\ \frac{\Delta\mathbf{V}}{\mathbf{V}}\end{bmatrix}^{(i)}}_{\Delta\mathbf{X}^{(i)}} .$$

. . .   . . . (28)

The various matrices in the Jacobian may consists of up to (nb – 1) * (nb – 1) elements of the form :

$$\left.\begin{array}{ll} \dfrac{\partial P_k}{\partial \theta_m}, & \dfrac{\partial P_k}{\partial V_m}V_m, \\ \dfrac{\partial Q_k}{\partial \theta_m}, & \dfrac{\partial Q_k}{\partial V_m}V_m, \end{array}\right\}$$

. . .   . . .   (29)

Where k = 1, . . . , nb, and m = 1, . . . , nb but omitting the slack bus entries.

Also the rows and columns corresponding to the reactive power and voltage magnitude for the PV buses are discarded. Furthermore, when buses k and m are not directly linked by a transmission element, the corresponding k-m entry in the Jacobian is null. Owing to the low degree of connectivity that prevails in practical power systems, the Jacobian power flows are highly sparse. An additional characteristics is that they are symmetric in structure but not in value (Zollenkoff, 1970).

It must be pointed out that the correction terms ΔV_m are divided by V_m to compensate for the fact that Jacobian terms $\left(\partial P_K / \partial P_m\right) V_m$ and $(\partial Q_k / \partial V_m) V_m$ are multiplied by V_m. It is shown in the derivative terms given below that this artifice yields useful simplifying calculations.

Consider the lth element connected between the buses k and m in figure 1, for which self and mutual Jacobian terms are given below :

For $k \neq m$:

$$\frac{\partial P_{k,l}}{\partial \theta_{m,l}} = V_k V_m \left[G_{km} \sin(\theta_k - \theta_m) - B_{km} \cos(\theta_k - \theta_m)\right], \quad \ldots \quad \ldots \quad (30)$$

$$\frac{\partial P_{k,l}}{\partial V_{m,l}} V_{m,l} = V_k V_m \left[G_{km} \cos(\theta_k - \theta_m) + B_{km} \sin(\theta_k - \theta_m)\right], \quad \ldots \quad \ldots \quad (31)$$

$$\frac{\partial Q_{K,l}}{\partial \theta_{m,l}} = -\frac{\partial P_{K,l}}{\partial V_{m,l}} V_{m,l}, \quad \ldots \quad \ldots \quad (32)$$

$$\frac{\partial Q_{K,l}}{\partial V_{m,l}} V_{m,l} = \frac{\partial P_{K,l}}{\partial \theta_{m,l}}, \quad \ldots \quad \ldots \quad (33)$$

For k = m:

$$\frac{\partial P_{k,l}}{\partial \theta_{k,l}} = -Q_k^{cal} - V_k^2 B_{kk}, \quad . . . \qquad . . . \qquad (34)$$

$$\frac{\partial P_{k,l}}{\partial V_{k,l}} V_{k,l} = P_k^{cal} + V_k^2 G_{kk}, \quad . . . \qquad . . . \qquad (35)$$

$$\frac{\partial Q_{k,l}}{\partial \theta_{k,l}} = P_k^{cal} - V_k^2 G_{kk}, \quad . . . \qquad . . . \qquad (36)$$

$$\frac{\partial Q_{k,l}}{\partial V_{k,l}} V_{k,l} = Q_k^{cal} - V_k^2 B_{kk}, \quad . . . \qquad . . . \qquad (37)$$

In general, for a bus k containing n transmission elements l, the bus self-elements take the following form :

$$\frac{\partial P_k}{\partial \theta_k} = \sum_{l=1}^{n} \frac{\partial P_{k,l}}{\partial \theta_{k,l}}, \quad . . . \qquad . . . \qquad (38)$$

$$\frac{\partial P_k}{\partial V_k} V_k = \sum_{l=1}^{n} \frac{\partial P_{k,l}}{\partial V_{k,l}} V_{k,l}, \quad . . . \qquad . . . \qquad (39)$$

$$\frac{\partial Q_k}{\partial \theta_k} = \sum_{l=1}^{n} \frac{\partial Q_{k,l}}{\partial \theta_{k,l}}, \quad . . . \qquad . . . \qquad (40)$$

$$\frac{\partial Q_k}{\partial V_k} V_k = \sum_{l=1}^{n} \frac{\partial Q_{k,l}}{\partial V_{k,l}} V_{k,l}, \quad . . . \qquad . . . \qquad (41)$$

The mutual elements given by equation (30) – (33) remain the same whether we have one transmission element or n transmission elements terminating at bus k.

After the voltage magnitudes and phase angles have been calculated by iteration, active and reactive power flows throughout the transmission system are determined quite straightforwardly.

An important point to bear in mind is that the mismatch power equations $\Delta P and \Delta Q$ of the slack bus are not included in the equation (28) and the unknown variables $P_{slack} and Q_{slack}$ are computed once the system power flows and power losses have been determined. Also, Q_G in PV buses are calculated in each iteration in order to checkif the generators are within reactive power limits. However, the mismatch reactive power equations ΔQ of PV buses are not included in equation (28).

One of the main strengths of the Newton-Raphson method is its reliability towards convergence. For most practical situations, and provided the state variables, $X^{(0)}$, are suitably initialised, the method is said to exhibit a quadratic convergence characteristic; for example,

$$
\begin{aligned}
\mathrm{f}(X^{(1)}) &= 1\mathrm{e}-1, \\
\mathrm{f}(X^{(2)}) &= 1\mathrm{e}-2, \\
\mathrm{f}(X^{(3)}) &= 1\mathrm{e}-4, \\
\mathrm{f}(X^{(4)}) &= 1\mathrm{e}-8,
\end{aligned}
$$

for the maximum mismatch. Contrary to the non-Newton-Raphson solutions, such a characteristic is independent of the size of the network being solved and the number and the kinds of control equipment present in the power system. Aspects that may dent its quadratic convergence performance are reactive power limit violations in generator PV buses and extreme loading conditions.

4.3 STATE VARIABLE INITIALISATION :

The effectiveness of the Newton-Raphson method to achieve feasible iterative solution is dependent upon the selection of suitable initial values for all the state variables involved in the study.

The power flow solution of the networks that contain only conventional plat components is normally started with voltage magnitudes of 1 p.u. at all PQ buses. The slack and PV buses are given their specified values, which remain constant throughout the iterative solution if no generator reactive power limits are violated. The initial voltage phase angles are selected to be zero at all buses.

4.4 GENERATOR REACTIVE POWER LIMITS :

Even though the mismatch reactive power equation ΔQ_K of PV bus k is not required in Equation (28), solution of equation (17) for the PV bus is still carried out at each iterative step to assess whether or not the calculated reactive power Q_K^{cal} is within the generator reactive power limits :

$$Q_{G.\min.K} < Q_{GK} < Q_{G.\max.K}, \quad . \; . \; . \qquad . \; . \; . \qquad (42)$$

If either of the following conditions occur during the iterative process :

$$\left.\begin{aligned} Q_k^{\mathrm{cal}} &\geq Q_{G\max k}, \\ Q_k^{\mathrm{cal}} &\leq Q_{G\min k}, \end{aligned}\right\} \quad \ldots \quad \ldots (43)$$

Bus k becomes a generator PQ bus with either of the following mismatch power equations incorporated in equation (28) :

$$\left.\begin{aligned} \Delta Q_k &= Q_{G\max k} - Q_{Lk} - Q_k^{\mathrm{cal}}, \\ \Delta Q_k &= Q_{G\min k} - Q_{Lk} - Q_k^{\mathrm{cal}}, \end{aligned}\right\}$$

$$\ldots \quad \ldots \quad (44)$$

depending on the violated limit, together with the relevant Jacobian entries. The nodal voltage magnitude at bus k is allowed to vary and V_K becomes a state variables.

It should be remarked that bus k may revert to being a generator PV bus at some point during the iterative process if better estimates of Q_K^{cal}, calculated with more accurate nodal voltages, indicate that the reactive power requirements at bus k can, after all be met by the generator connected at bus k. Hence reactive power limit checking is carried out at each iteration. Programming wisdom indicates that limit checking should start after the first or second iteration, since nodal voltage values computed at the beginning of the iterative process may be quite inaccurate leading to misleading reactive power requirements. The switching of buses from PV to PQ and vice versa impose additional numerical demands on the iterative solution and retard convergence.

4.5 LINEARISED FRAME OF REFERANCE :

In order to illustrate how network components may be processed in the linearised frame of reference afforded by Newton-Raphson method, consider the simple 3-bus system shown in Figure 3. Bus 1 is selected to be the slack bus and bus 2 is the generator bus. Bus 3 contains no generation and becomes the load bus. A transformer and a transmission line link buses 1 and 2 and buses 2 and 3, respectively. One shunt element and one load are connected at bus 3.

The concept of 'power balance at a node' may be used to great effect to account for bus power injections in the Newton-Raphson solution. At a given bus, the power balance is obtained by adding the contribution of each plant component connected to that bus.

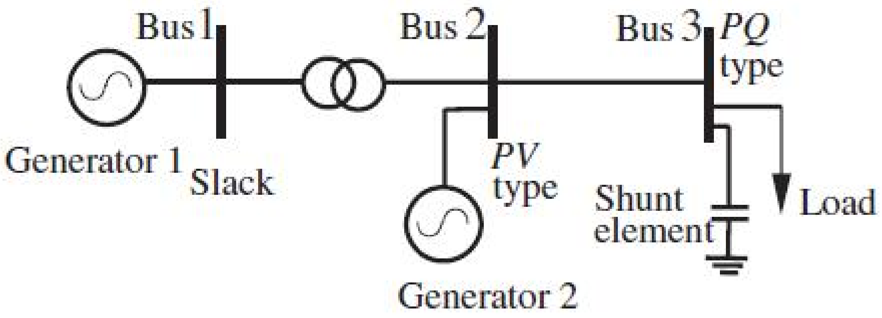

Figure 3 Tree-Bus Network

This is illustrated in Figure 4 with reference to Figure 3. The contribution of all three buses is shown in this example for completeness, but it should remembered that in actual calculations active and reactive mismatch entries are not required for the slack bus. Likewise, the reactive power mismatch entry is not required for generator PV bus.

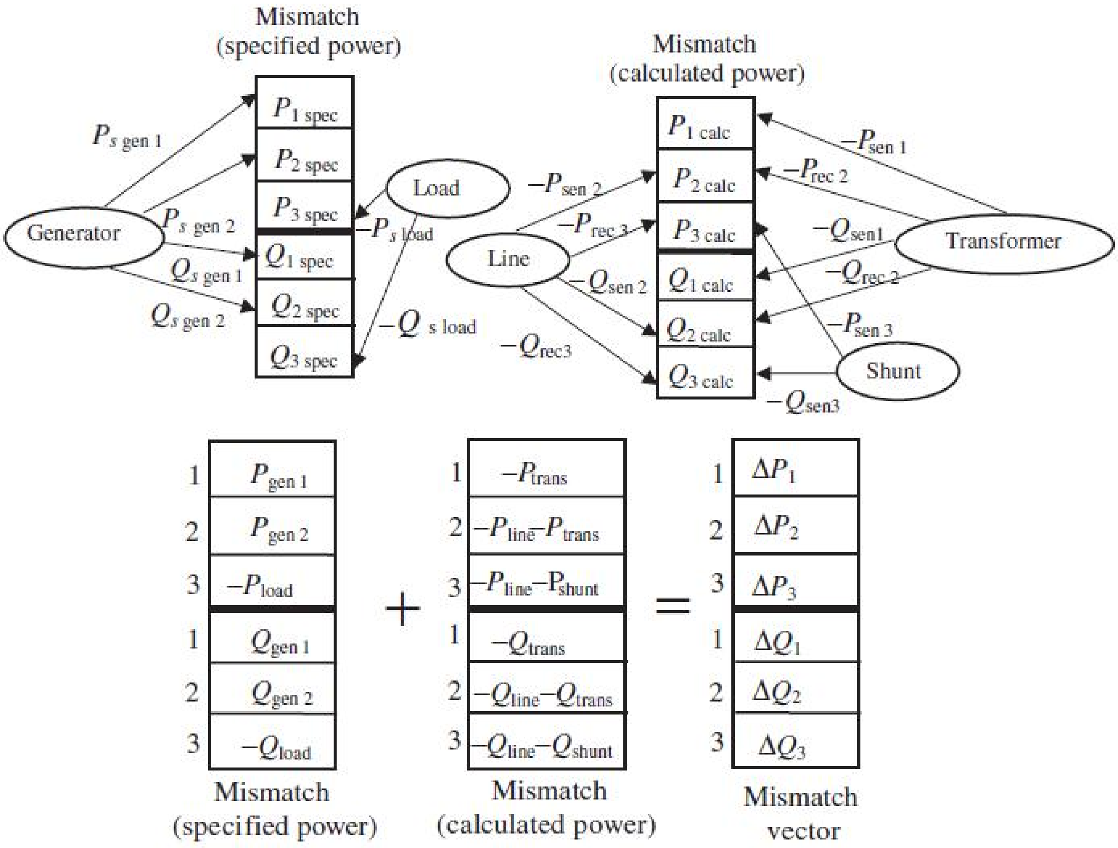

Figure 4 Power mismatch vector; subscripts ‘sen’ and ‘rec’ indicate the sending and receiving ends.

The construction of the Jacobian matrix is slightly more involved owing to the need to evaluate self and mutual Jacobian terms, and finding their location in the matrix. Nevertheless, the basic procedure illustrated above, based on superposition, will also apply to the formation of the Jacobian. For each plant component, relevant Jacobian equations are chosen based on the type of buses to which the plant component is connected. These buses determine the location of the individual Jacobian terms in the overall Jacobian structure. The contributions of the line, transformer, and shunt components to the Jacobian are shown in Figure 5. It should be noted that entries for the slack bus and the reactive power entry of the generator bus are not considered in the Jacibian structure.

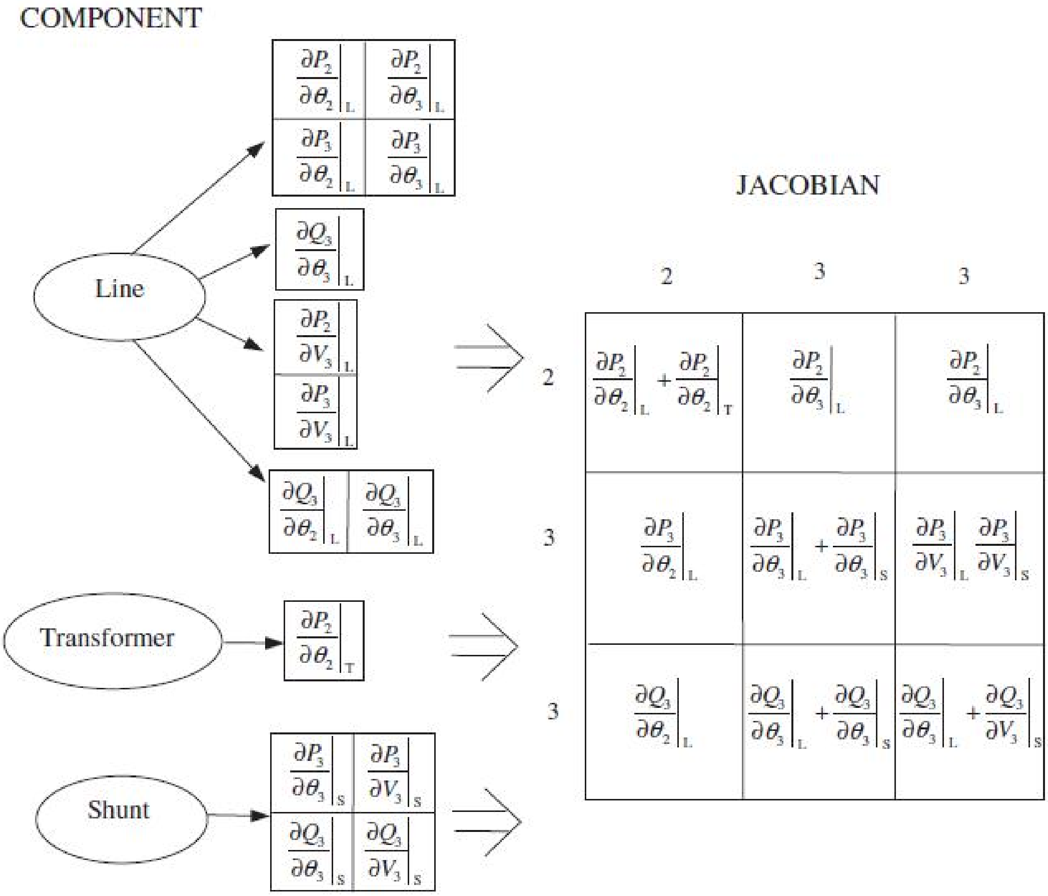

Figure 5 Jacobian structure

5

STATIC COMPENSATOR (STATCOM)

The STATCOM – an acronym for static compensator is one of the most popular FACTS controllers, which are used to narrow the gap between the uncontrolled and controlled power system mode of operation, by providing additional degrees of freedom to control power flows and voltages at key locations of the network. The number of FACTS controllers have been commissioned. Most of them perform a useful role during both steady-state and transient operation, but some are specifically designed to operate only under transient conditions. The various FACTS controllers other than STATCOM are listed below –

1. Thyristor-controlled phase shifter (PS)
2. Load tap changer (LTC)
3. Thyristor-controlled reactor (TCR)
4. Thyristo-controlled series capacitor (TCSC)
5. Interphase power controller (IPC)
6. Solid-state series controller (SSSC)
7. Unified power flow controller (UPFC)
8. Static VAR compensator (SVC)

5.1 REPRESENTATION OF STATCOM

The STATCOM consists of one voltage source converter (VSC) and its associated shunt connected transformer. It is a solid-state synchronous condenser connected in shunt with the AC system. The output current is adjusted to control either the nodal voltage magnitude or the reactive power injected at the bus. Hence it is a static counterpart of the rotating synchronous condenser but it generates or absorbs reactive power at a faster rate because no moving parts are involved.

In principle, it performs the same voltage regulation function as the static VAR compensator but in a more robust manner, unlike the SVC. Its operation is not impaired by the presence of low voltages. A schematic representation of the STATCOM is shown in Figure 6

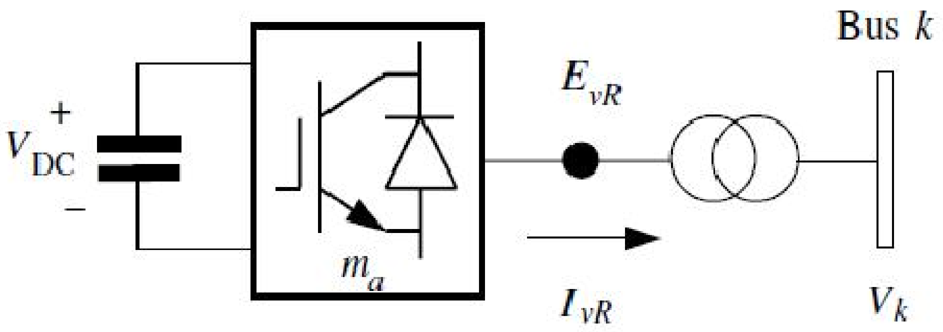

Figure 6 STATCOM system

In steady-state fundamental frequency studies the STATCOM may be represented in the same way as a synchronous condenser, which in most cases is the model of a synchronous generator with zero active power generation. A more flexible model may be realised by representing the STATCOM as a variable voltage source ?? , for which the magnitude and phase angle may be adjusted, using a suitable iterative algorithm, to satisfy a specified voltage magnitude at the point of connection with the AC network. The shunt voltage source of the three phase STATCOM may be represented by:

$$E_{vR}^{\rho} = V_{vR}^{\rho}(\cos \delta_{vR}^{\rho} + \mathrm{j} \sin \delta_{vR}^{\rho}),$$

Where indicates phase quantities, a, b and c.

The voltage magnitude, V_{vR}^{ρ} is given maximum and minimum limits, which are a function of the STATCOM capacitor rating. However, δ_{vR}^{ρ} may take any value between 0 and 2 π radians.

5.2 EQUIVALENT CIRCUIT OF STATCOM

Following on the STATCOM operational characteristics as discussed in previous para, it is reasonable to expect that for the purpose of positive sequence power flow analysis the STATCOM will be well represented by a synchronous voltage source with maximum and minimum voltage magnitude limits. The synchronous voltage source represents the fundamental Fourier series component of the switched voltage waveform at the AC converter terminal of the STATCOM. Its equivalent circuit is shown in Figure 7. The STATCOM equivalent circuit corresponds to the Thevenin equivalent as seen from bus k, with voltage source E_{vR} being the fundamental frequency component of the VSC output voltage, resulting from the product of V_{DC} and M_2 .

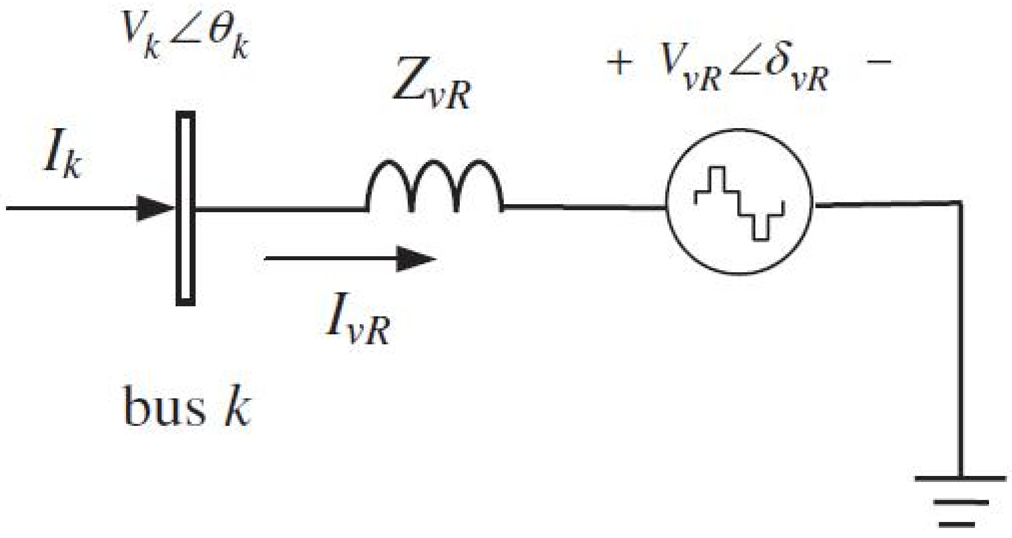

Figure 7 Equivalent circuit of the STATCOM

The bus at which the STATCOM is connected is represented as a PVS bus, which may change to a PQ bus in the events of limits being violated. In such a case, the generated or absorbed reactive power would correspond to the violated limit. Unlike the SVC, the STATCOM is represented as a voltage source for the full range of operation, enabling a more robust voltage support mechanism.

5.3 POWER FLOW MODEL OF STATCOM

The STATCOM equivalent circuit shown in Figure 7 is used to derive the mathematical model of the controller for inclusion in power flow algorithm. The power flow equations for the STATCOM are derived below from first principles and assuming the following voltage source representation:

$$E_{vR} = V_{vR}(\cos\delta_{vR} + \mathrm{j}\sin\delta_{vR}).$$

Based on the shunt connection shown in Figure 7, the following may be written –

$$S_{vR} = V_{vR}I_{vR}^{*} = V_{vR}Y_{vR}^{*}\left(V_{vR}^{*} - V_{k}^{*}\right).$$

After performing some complex operations, the following active and reactive power equations are obtained for the converter and bus k, respectively –

$$\begin{aligned}
P_{vR} &= V_{vR}^{2}G_{vR} + V_{vR}V_{k}\left[G_{vR}\cos(\delta_{vR} - \theta_{k}) + B_{vR}\sin(\delta_{vR} - \theta_{k})\right],\\
Q_{vR} &= -V_{vR}^{2}B_{vR} + V_{vR}V_{k}[G_{vR}\sin(\delta_{vR} - \theta_{k}) - B_{vR}\cos(\delta_{vR} - \theta_{k})],\\
P_{k} &= V_{k}^{2}\,G_{vR} + V_{k}V_{vR}[G_{vR}\cos(\theta_{k} - \delta_{vR}) + B_{vR}\sin(\theta_{k} - \delta_{vR})],\\
Q_{k} &= -V_{k}^{2}\,B_{vR} + V_{k}V_{vR}[G_{vR}\sin(\theta_{k} - \delta_{vR}) - B_{vR}\cos(\theta_{k} - \delta_{vR})].
\end{aligned}$$

Using these power equations, the linearised STATCOM model is given below, where the voltage magnitude ?? and phase angle ?? are taken to be the state variables –

$$\begin{bmatrix} \Delta P_k \\ \Delta Q_k \\ \Delta P_{vR} \\ \Delta Q_{vR} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_k}{\partial \theta_k} & \frac{\partial P_k}{\partial V_k} V_k & \frac{\partial P_k}{\partial \delta_{vR}} & \frac{\partial P_k}{\partial V_{vR}} V_{vR} \\ \frac{\partial Q_k}{\partial \theta_k} & \frac{\partial Q_k}{\partial V_k} V_k & \frac{\partial Q_k}{\partial \delta_{vR}} & \frac{\partial Q_k}{\partial V_{vR}} V_{vR} \\ \frac{\partial P_{vR}}{\partial \theta_k} & \frac{\partial P_{vR}}{\partial V_k} V_k & \frac{\partial P_{vR}}{\partial \delta_{vR}} & \frac{\partial P_{vR}}{\partial V_{vR}} V_{vR} \\ \frac{\partial Q_{vR}}{\partial \theta_k} & \frac{\partial Q_{vR}}{\partial V_k} V_k & \frac{\partial Q_{vR}}{\partial \delta_{vR}} & \frac{\partial Q_{vR}}{\partial V_{vR}} V_{vR} \end{bmatrix} \begin{bmatrix} \Delta \theta_k \\ \frac{\Delta V_k}{V_k} \\ \Delta \delta_{vR} \\ \frac{\Delta V_{vR}}{V_{vR}} \end{bmatrix} .$$

6

NEWTON-RAPHSON COMPUTER PROGRAM IN MATLAB CODE

A computer programme suitable for the power flow study of interconnected power system of small and medium-sized is given below. The program is general, as far as the topology of the network is concerned, and caters for any numbers of PQ and PV buses. Moreover, any bus in the network may be designated to be the slack bus. Provisions are made for generator reactive limit checking and to accommodate fix shunt compensations. No transformers are represented in this base program and no sparsity techniques (Zollenkoff, 1970) are incorporated.

6.1 MAIN PROGRAM:

```
PowerFlowsData
%***- - - Main Program
PowerFlowsData; %Read system data
[YR,YI] =
YBus(tlsend,tlrec,tlresis,tlreac,tlsuscep,tlcond,shbus,shresis,shreac,ntl
,nbb,nsh);
[VM,VA,it] =
NewtonRaphson(nmax,tol,itmax,ngn,nld,nbb,bustype,genbus,loadbus,PGEN,QGEN
,QMAX,QMIN,PLOAD,QLOAD,YR,YI,VM,VA);
[PQsend,PQrec,PQloss,PQbus] =
PQflows(nbb,ngn,ntl,nld,genbus,loadbus,tlsend,tlrec,tlresis,tlreac,tlcond
,tlsuscep,PLOAD,QLOAD,VM,VA);
it%Iteration number
VM %Nodal voltage magnitude (p.u.)
```

```
VA = VA*180/pi %Nodal voltage phase angle(Deg)
PQsend%Sending active and reactive powers (p.u.)
PQrec%Receiving active and reactive powers (p.u.)
%End Main Program
```

6.2 THE ADMITTANCE MATRIX :

```
%Build up admittance matrix
function [YR,YI] =
YBus(tlsend,tlrec,tlresis,tlreac,tlsuscep,tlcond,shbus,shresis,shreac,ntl
,
nbb,nsh);
YR=zeros(nbb,nbb);
YI=zeros(nbb,nbb);
% Transmission lines contribution
forkk = 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
forkk = 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
```

6.3 THE ITERATIVE SOLUTION :

```
%Carry out iterative solution using the Newton-Raphson method
function [VM,VA,it] = NewtonRaphson(nmax,tol,itmax,ngn,nld,nbb,bustype,
genbus,loadbus,PGEN,QGEN,QMAX,QMIN,PLOAD,QLOAD,YR,YI,VM,VA)
% GENERAL SETTINGS
D = zeros(1,nmax);
flag = 0;
it = 1;
% CALCULATE NET POWERS
[PNET,QNET] =
NetPowers(nbb,ngn,nld,genbus,loadbus,PGEN,QGEN,PLOAD,QLOAD);
while ( it <itmax& flag==0 )
% CALCULATED POWERS
[PCAL,QCAL] = CalculatedPowers(nbb,VM,VA,YR,YI);
% CHECK FOR POSSIBLE GENERATOR’S REACTIVE POWERS LIMITS VIOLATIONS
[QNET,bustype] =
GeneratorsLimits(ngn,genbus,bustype,QGEN,QMAX,QMIN,QCAL,QNET, QLOAD, it,
VM, nld, loadbus);
% POWER MISMATCHES
[DPQ,DP,DQ,flag] =
PowerMismatches(nmax,nbb,tol,bustype,flag,PNET,QNET,PCAL,QCAL);
% JACOBIAN FORMATION
[JAC] = NewtonRaphsonJacobian(nmax,nbb,bustype,PCAL,QCAL,VM,VA,YR,YI);
% SOLVE FOR THE STATE VARIABLES VECTOR
D = JAC\DPQ';
% UPDATE STATE VARIABLES
[VA,VM] = StateVariablesUpdates(nbb,D,VA,VM);
it = it + 1;
end
% End function Newton-Raphson
```

6.4 NET SCHEDULED POWER CALCULATIONS :

```
%Function to calculate the net scheduled powers
function [PNET,QNET] = NetPowers(nbb,ngn,nld,genbus,loadbus,PGEN,QGEN,
PLOAD,QLOAD);
% 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
```

6.5 INJECTED BUS POWER CALCULATIONS

```
%Function to calculate injected bus powers
function [PCAL,QCAL] = CalculatedPowers(nbb,VM,VA,YR,YI)
% Include all entries
PCAL = zeros(1,nbb);
QCAL = zeros(1,nbb);
for ii = 1: nbb
PSUM = 0;
QSUM = 0;
forjj = 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
```

6.6 GENERATOR LIMITS :

```
%Function to check whether or not solution is within generators limits
function [QNET,bustype] =
GeneratorsLimits(ngn,genbus,bustype,QGEN,QMAX,QMIN,QCAL,QNET, QLOAD, it,
VM, nld, loadbus)
% CHECK FOR POSSIBLE GENERATOR'S REACTIVE POWERS LIMITS VIOLATIONS
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
ifloadbus(ii) == jj
QNET(loadbus(ii)) = QNET(loadbus(ii)) - QLOAD(ii)
```

```
end
end
end



end
end
end
%End function Generatorslimits
```

6.7 COMPUTATION OF POWER MISMATCHES

```
%Function to compute power mismatches
function [DPQ,DP,DQ,flag] =
PowerMismatches(nmax,nbb,tol,bustype,flag,PNET,QNET,PCAL,QCAL);
% 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
```

6.8 THE JACOBIAN MATRIX :

```
%Function to built the Jacobian matrix
function [JAC] =
NewtonRaphsonJacobian(nmax,nbb,bustype,PCAL,QCAL,VM,VA,YR,YI);
% JACOBIAN FORMATION
% Include all entries
JAC = zeros(nmax,nmax);
iii = 1;
for ii = 1: nbb
jjj = 1;
forjj = 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
forkk = 1: nbb
if (bustype(kk) == 1)
ii = kk*2-1;
forjj = 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;
forjj = 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
```

6.9 STATE VARIABLE UPDATING :

```
%Function to update state variables
function [VA,VM] = StateVariablesUpdates(nbb,D,VA,VM)
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
```

6.10 CALCULATION OF POWER FLOWS :

```
%Function to calculate the power flows
function [PQsend,PQrec,PQloss,PQbus] =
PQflows(nbb,ngn,ntl,nld,genbus,loadbus,tlsend,tlrec,tlresis,tlreac,tlcond
,tlsuscep,PLOAD,QLOAD,VM,VA);
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);
forkk = 1: ngn
ll = genbus(kk);
ifjj == ll
PQbus(jj) = PQbus(jj) + ( PLOAD(ii) + QLOAD(ii)*i );
end
end
end
%End function PQflows
```

7

STATCOM COMPUTER PROGRAM IN MATLAB CODE :

Following is the program written in MATLAB Code to incorporate the static compensator (STATCOM) within the Newton-Raphson power flow algorithm.

7.1 STATCOM MAIN PROGRAM :

```
% - - - Main STATCOM Program
PowerFlowsData %Function to read network data
SSCData; %Function to read the STATCOM data
[YR,YI] = YBus(tlsend,tlrec,tlresis,tlreac,tlsuscep,tlcond,ntl,nbb);
[VM,VA,it,Vvr,Tvr] = SSCNewtonRaphson(tol,itmax,ngn,nld,nbb,...
bustype,genbus,loadbus,PGEN,QGEN,QMAX,QMIN,PLOAD,QLOAD,YR,YI,VM,...
VA,NSSC,SSCsend, Xvr,TarVol,VSta,Psp,PSta,Qsp,QSta,Vvr,Tvr,VvrHi,...
VvrLo);
[PQsend,PQrec,PQloss,PQbus] = PQflows(nbb,ngn,ntl,nld,genbus,...
loadbus,tlsend,tlrec,tlresis,tlreac,tlcond,tlsuscep,PLOAD,QLOAD,...
VM,VA);
[Psend,Qsend,PSSC,QSSC] = SSCPQPowers(VM,VA,NSSC,SSCsend,Xvr,Vvr,...
Tvr);
%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)
PQsend=Psend + j*Qsend %Active and reactive powers in bus (p.u.)
PQSSC=PSSC + j*QSSC %Active and reactive powers in STACOM (p.u.)
% End of MAIN STATCOM PROGRAM
```

7.2 STATCOM CALCULATED POWERS :

```
%Function to calculate injected bus powers by the STATCOM
function [PCAL,QCAL,PSSC,QSSC] = SSCCalculatePowers(PCAL,QCAL,VM,...
```

```
VA,NSSC, SSCsend,Xvr,Vvr,Tvr);
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
```

7.3 POWER MISMATCHES FOR STATCOM

```
%Function to compute power mismatches
function [DPQ,DP,DQ,flag] =
PowerMismatches(nbb,tol,bustype,flag,PNET,QNET,PCAL,QCAL);
% POWER MISMATCHES
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
```

7.4 STATCOM ELEMENTS TO JACOBIAN MATRIX

```
%Function to add the STATCOM elements to Jacobian matrix
function [JAC] = SSCJacobian(nbb,JAC,VM,VA,NSSC,SSCsend,Xvr,TarVol,...
VSta,Psp,PSta,Qsp,QSta,Vvr,Tvr);
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
JAC(2*(nbb + ii)-1,2*(nbb + ii)) = 0.0;
end
else
JAC(2*(nbb + ii),2*(nbb + ii)) = 1.0;
end
end
```

7.5 STATCOM STATE VARIABLES UPDATING :

```
%Function to update STATCOM state variable
function [VM,Vvr,Tvr] = SSCUpdating(nbb,D,VM,VA,NSSC,SSCsend,...
TarVol,VSta, Psp,Vvr,Tvr);
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
```

7.6 SOUERCE VOLTAGES LIMITS IN THE STATCOM :

```
%Function to check source voltages limits in the STATCOM
function [Vvr] = SSCLimits(NSSC,Vvr,VvrHi,VvrLo);
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
```

7.7 CALCULATION OF THE POWER FLOWS IN THE STATCOM :

```
%Function to calculate the power flows in the STATCOM
function [Psend,Qsend,PSSC,QSSC] = SSCPQPowers(VM,VA,NSSC,SSCsend,...
Xvr,Vvr,Tvr);
for ii = 1 : NSSC
B(ii)=1/Xvr;
A1 = Tvr(ii)-VA(SSCsend(ii));
A2 = VA(SSCsend(ii))-Tvr(ii);
```

```
Psend(ii) = VM(SSCsend(ii))*Vvr(ii)*(B(ii)*sin(A2));
Qsend(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
```

8

CASE STUDIES :

8.1 THE TEST CASE :

A five-bus network containing two generators and seven transmission lines is shown in Figure 6. The network connectivity and transmission line data are given in Table 1, while generator data and load data are given in Tables 2 and 3 respectively. The power flow solution of this network is obtained by using the Newton-Raphson method. The power flow results are superimposed on the one line diagram of the network, and the bus voltage magnitudes and phase angles are given in Table 4. The STATCOM-upgraded test network and power flow results are shown in Figure 9. The STATCOM is installed at the bus lake.

Table 1 Network connectivity and transmission line data

Sending Node	Receiving Node	R (p.u.)	X (p.u.)	B (p.u.)
North	South	0.02	0.06	0.06
North	Lake	0.08	0.24	0.05
South	Lake	0.06	0.18	0.04
South	Main	0.06	0.18	0.04
South	Elm	0.04	0.12	0.03
Lake	Main	0.01	0.03	0.02
Main	Elm	0.08	0.24	0.05

Table 2 Generator data

Node	P_G (MW)	$Q_{\min}$ (MVAr)	$Q_{\max}$ (MVAr)	|V|(p.u.)
South	40	-300	300	1.0

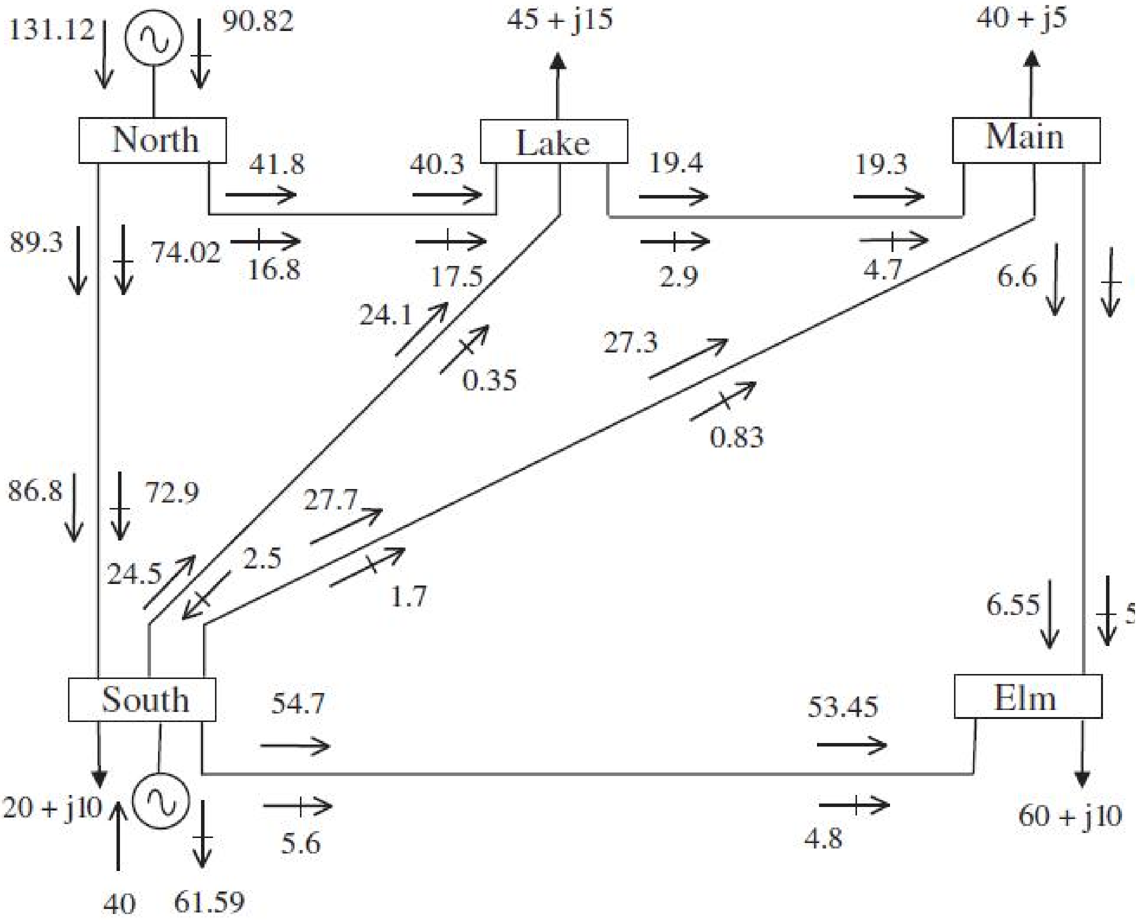

Figure 8 The five-bus test network containing two generators and seven transmission lines, and power flow results (The base case without STATCOM)

Table 3 Load data

Node	P_{load} (MW)	Q_{load} (MVAr)
South	20	10
Lake	45	15
Main	40	5
Elm	60	10

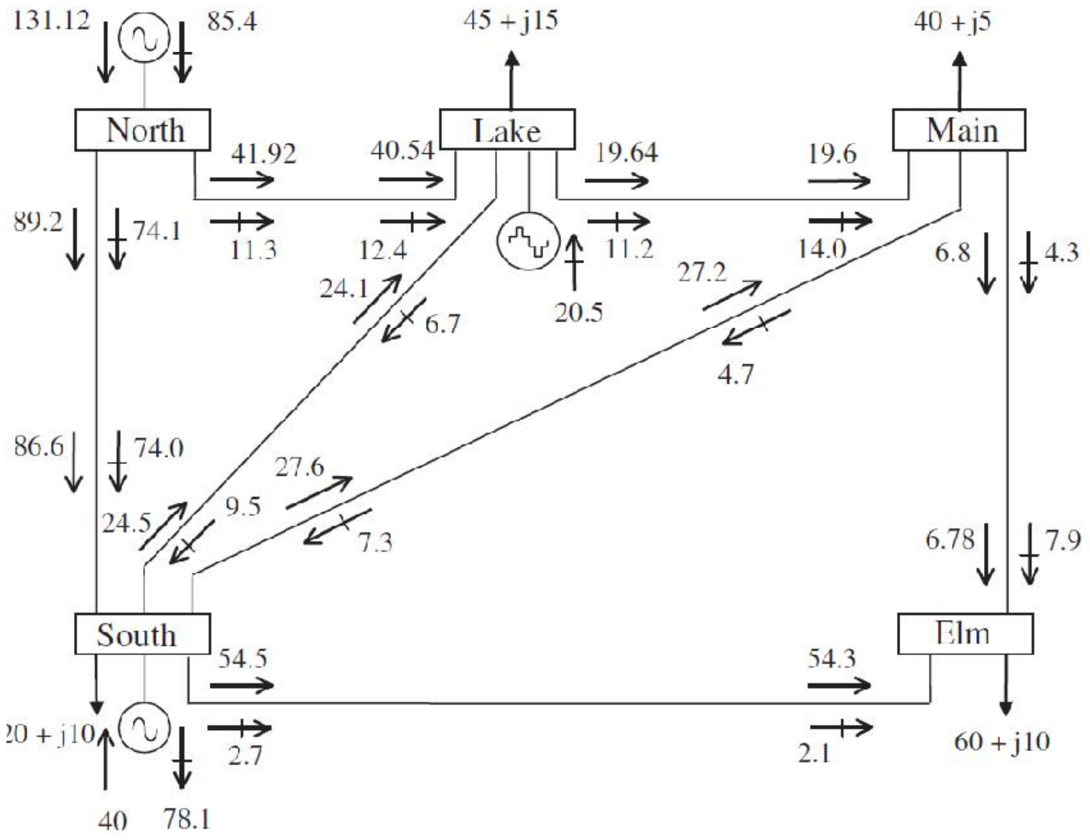

Figure 9 STATCOM –upgraded test network and power flow results

8.2 THE TEST CASE DATA :

The data of the test case are given below in the function PowerFlowsData which are suitable for use with the Newton-Raphson Matlab program.

```
%Function PowerFlowsData, to read data for the five-bus test network, is
as follows:
%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
%
%The five buses in the network shown in Figure 4.6 are numbered for the
% purpose of the power flow solution, as follows:
```

```
%North = 1
%South = 2
%Lake = 3
%Main = 4
%Elm = 5
%
%Bus data
%nbb = number of buses
%bustype = type of bus
%VM = nodal voltage magnitude
%VA = nodal voltage phase angle



nbb = 5 ;
bustype(1) = 1 ; VM(1) = 1.06 ; VA(1) =0 ;
bustype(2) = 2 ; VM(2) = 1 ; VA(2) =0 ;
bustype(3) = 3 ; VM(3) = 1 ; VA(3) =0 ;
bustype(4) = 3 ; VM(4) = 1 ; VA(4) =0 ;
bustype(5) = 3 ; VM(5) = 1 ; VA(5) =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 = 2 ;
genbus(1) = 1 ; PGEN(1) = 0 ; QGEN(1) = 0 ; QMAX(1) = 5 ; QMIN(1) = -5 ;
genbus(2) = 2 ; PGEN(2) = 0.4 ; QGEN(2) = 0 ; QMAX(2) = 3 ; QMIN(2) = -3
;
%
%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 = 7 ;
tlsend(1) = 1 ; tlrec(1) = 2 ; tlresis(1) = 0.02 ; tlreac(1) = 0.06 ;
tlcond(1) = 0 ; tlsuscep(1) = 0.06 ;
tlsend(2) = 1 ; tlrec(2) = 3 ; tlresis(2) = 0.08 ; tlreac(2) = 0.24 ;
tlcond(2) = 0 ; tlsuscep(2) = 0.05 ;
tlsend(3) = 2 ; tlrec(3) = 3 ; tlresis(3) = 0.06 ; tlreac(3) = 0.18 ;
tlcond(3) = 0 ; tlsuscep(3) = 0.04 ;
tlsend(4) = 2 ; tlrec(4) = 4 ; tlresis(4) = 0.06 ; tlreac(4) = 0.18 ;
tlcond(4) = 0 ; tlsuscep(4) = 0.04 ;
tlsend(5) = 2 ; tlrec(5) = 5 ; tlresis(5) = 0.04 ; tlreac(5) = 0.12 ;
tlcond(5) = 0 ; tlsuscep(5) = 0.03 ;
tlsend(6) = 3 ; tlrec(6) = 4 ; tlresis(6) = 0.01 ; tlreac(6) = 0.03 ;
tlcond(6) = 0 ; tlsuscep(6) = 0.02 ;
tlsend(7) = 4 ; tlrec(7) = 5 ; tlresis(7) = 0.08 ; tlreac(7) = 0.24 ;
tlcond(7) = 0 ; tlsuscep(7) = 0.05 ;
%
%Shunt data
%nsh = number of shunt elements
%shbus = shunt element bus number
%shresis = resistance of shunt element
%shreac = reactance

%+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 = 4 ;
loadbus(1) = 2 ; PLOAD(1) = 0.2 ; QLOAD(1) = 0.1 ;
loadbus(2) = 3 ; PLOAD(2) = 0.45 ; QLOAD(2) = 0.15 ;
loadbus(3) = 4 ; PLOAD(3) = 0.4 ; QLOAD(3) = 0.05 ;
loadbus(4) = 5 ; PLOAD(4) = 0.6 ; QLOAD(4) = 0.1 ;
```

```
%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;
%End of function PowerFlowsDat
```

8.3 STATCOM DATA :

```
%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 = 1;
SSCsend(1)=3; 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;

%Bus data
%nbb = number of buses
%bustype = type of bus
%VM = nodal voltage magnitude
%VA = nodal voltage phase angle

nbb = 5 ;
bustype(1) = 1 ; VM(1) = 1.06 ; VA(1) =0 ;
bustype(2) = 2 ; VM(2) = 1 ; VA(2) =0 ;
bustype(3) = 3 ; VM(3) = 1 ; VA(3) =0 ;
bustype(4) = 3 ; VM(4) = 1 ; VA(4) =0 ;
bustype(5) = 3 ; VM(5) = 1 ; VA(5) =0 ;
```

9

RESULTS

9.1 THE BASE CASE WITHOUT STATCOM

The power flows study results of the uncontrolled interconnected power system test case without connecting STATCOM obtained by using Newton-Raphson method are shown below :

```
it =

        6

VM =

        1.0600    1.0000    0.9872    0.9841    0.9717

VA =

                    0   -2.0612   -4.6367   -4.9570   -5.7649

PQsend =

 0.8933 + 0.7400i   0.4179 + 0.1682i   0.2447 - 0.0252i   0.2771 -      0.0172i
0.5466 + 0.0556i   0.1939 + 0.0286i   0.0660 + 0.0052i
```

```
PQrec =

  -0.8685 - 0.7291i  -0.4027 - 0.1751i  -0.2411 - 0.0035i  -0.2725 - 0.0083i  -
0.5344 - 0.0483i  -0.1935 - 0.0469i  -0.0656 - 0.0517i

>>
```

9.2 WITH STATCOM

```
>> StatcomPower


it =

          100

 VM =

             1.0600    1.0000    1.0000    1.0000    1.0000

VA =

          0         0    0.1421         0         0


Vvr =

           1.0032

Tvr =

         0.1421
```

```
PQsend =

             0 +3.2221e-004i

PQSSC =

             0 -3.2325e-004i

>>
```

9.3 COMPARISION OF RESULTS OF WITH AND WITH OUT STATCOM

The power flow results with and without connecting the STATCOM in the interconnected electric power system are shown in Table 4. The voltage magnitude in p.u. and phase angles in degrees at each bus is shown in table. On comparing the power flow results, it is seen that when the STATCOM is connected in power system, the voltage magnitudes are maintained at 1.00 p.u. at each bus while the phase

Table 4 Nodal voltages (p.u.) and phase angles (dgrees)

Network bus	Voltage magnitude (p.u.) base case	Phase angle (degrees) base case	Voltage magnitude (p.u.)with STATCOM	Phase angle (degrees) with STATCOM
North	1.0600	0	1.0600	0
South	1.0000	- 2.0612	1.0000	0
Lake	0.9872	- 4.6367	1.0000	0.1421
Main	0.9841	- 4.9570	1.0000	0
Elm	0.9717	- 5.7649	1.0000	0

angles are also maintained at 0 degree at each bus except the lake bus. At lake the phase angle is improved to 0.1421 degrees from - 4.6367 degrees – the phase angle of uncontrolled power system mode of operation.

9.4 COMMENTS

The results of power flow solution as solved by using Newton-Raphson method are given above. The method takes 6 iterations to converge. It can be observed from the results that all nodal voltages are within accepted voltage magnitude limits (i.e. 100± 6%). The largest power flow takes place in the transmission line connecting two generator buses : 89.3 MW and 74.02 MVAR leave North, and 86.8 MW and 72.9 MVAR arrive at south. This is also the transmission line that incurs higher active power loss (i.e. 2.5 MW). The active power system loss is 6.12 MW.

The operating conditions demand a large amount of reactive power generation by the generator connected at north (i.e. 90.82 MVAR). This amount is well in excess of the reactive power drawn by the system loads (i.e. 40 MVAR). The generator at south draws the excess of reactive power in the network (i.e. 61.59 MVAR). This amount includes the net reactive power produced by several of the transmission lines.

The power flow result indicates that the STATCOM generates 20.5 MVAR in order to keep the voltage magnitudes at 1.00 p.u. at each bus. Hence, the use of the STATCOM results in an improved network voltage profile.

The slack generator reduces its reactive power generation compared with the base case, and reactive power exported from North to lake reduces. The largest reactive power flow takes place in the transmission line connecting

North and South, where 74.1 MVAR leaves North and 74 MVAR arrives at South. In general, more reactive power is available in the network than in the base case, and the generator connected at South increases its share of reactive power absorption compared with the base case. As expected, active power flows are only marginally affected by the STATCOM installation.

9.5 CONCLUSION AND RECOMMENDATIONS :

This project addresses the basic theory of power flows. Building upon elementary concepts afforded by circuit theory and complex algebra, the equations for active and reactive power injections at a bus are derived. The mathematical model that describes its operation during steady-state is non-linear. For most practical situations, the power network is a very large scale system. Hence, the solutions for the non-linear set of equations, which must be reached by iteration, requires a robust and efficient numerical technique. For several decades Newton-Raphson method, with its quadratic convergence characteristics, has proved invaluable in solving the power flow problems. The additional burden imposed on the numerical solution by many constraint actions resulting from the various power system controllers in the network does not impair the ability of the Newton-Raphson method to converge in quadratic fashion. The relevant equations making up Newton-Raphson method have been coded in MatLab and the programs used to solve a classical test case. The test system is small and yet it provides sufficient realism and flexibility to explore different loading scenarios, active power generator schedules, and transmission- line parameters. This is something which certainly encourages the user to do. Hence, the Newton-Raphson method, with their strong convergence characteristics, have proved the most successful and have been warmly embraced by the industry. For improving the network voltage profile, the STATCOM stands amongst the most popular high-transmission FACTS controllers.

9.6 SUGGESTIONS FOR FURTHER WORK

The STATCOM uses the VSC as its basis building. It has been emphasised that all of the power electronic controllers produce harmonic distortion, which is an undesirable side –effect, as part of their normal operation. The various means of harmonic cancellation open to system engineers have been mentioned, such as switching control, multilevel configuration, three-phase connections, and, as a last resort, filtering equipment. This harmonic distortion cancellation is a topic for future work. In the present work, it is assumed that harmonic distortion is effectively contained at source. The mathematical modelling conducted for the STATCOM reflects this fact.

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MAJOR PROJECT

POWER FLOW STUDY OF INTERCONNECTED POWER SYSTEM USING STATCOM

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE AWARD

OF THE DEGREE OF

MASTER OF ENGINEERING IN ELECTRCAL ENGINEERING

(CONTROL & INSTRUMENTATION)

By

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CERTIFICATE

It is certified that this Major Project Thesis entitled as **“Power Flow Study of Interconnected Power System Using STATCOM”** submitted by **Bahadur Singh Pali** having Roll No. **10082,** in partial fulfilment of the requirement for the award of the Degree of “ Master of Engineering” (Control & Instrumentation) in Electrical Engineering from University of Delhi, Delhi is a true record of work undertaken by him as a part of curriculum under my guidance.

This dissertation is a bonafide record of work carried out by him under my guidance and supervision. The matter embodied in this thesis has not been submitted to any university or institute for award of any degree.

I wish him success in all his endeavours.

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ABSTRACT

An electric power system can be seen as the interconnection of generating sources and customer loads through a network of transmission lines, transformers and ancillary equipments. Its structure has many variations that are the result of a legacy of economic, political, engineering and environmental decisions. Independent of the structure of a power system, the power flows throughout the network are largely distributed as a function of transmission line impedance; a transmission line with low impedance enables larger power flows through it than does the transmission line with high impedance. This is not always the most desirable outcome because quite often it gives rise to a myriad of operational problems; the job of the system operator is to intervene to try to achieve power flow redistribution, but with limited success. Examples of operating problems to which unregulated active and reactive power flows may give rise are: loss of system stability, power flow loops, high transmission losses, voltage limit violations, an inability to utilise transmission line capability up to the thermal limit and cascade tripping. These problems have traditionally been solved by building new power plants and transmission lines, which is costly to implement and involves long construction time. A new solution to such operational problems is a new technological thinking that comes under the generic title of FACTS – flexible alternating current transmission system, which is based on the substantial incorporation of power electronic devices and methods into the high- voltage side of the network, to make it

electronically controllable. Several kinds of FACTS controllers have been commissioned in various parts of the world. These controllers narrow the gap between the uncontrolled and the controlled power system mode of operation, providing additional degrees of freedom to control power flows and voltages at key locations of the network. This thesis presents the study of STATCOM – the static compensator, one of the most popular FACTS controllers. First, the basic theory of power flows is addressed. Building upon elementary concepts of circuit theory and complex algebra, equations for active and reactive powers injections at a bus are derived. A computer program in MATLAB code for Newton-Raphson method, which has been proved invaluable for decades in solving the power flow problem, is developed. Then, a power flow model of STATCOM is developed and its role in network-wide applications is assessed. The non- linear power flow equations of STATCOM have been linearised and included in the Newton-Raphson power flow algorithm. The state variables of STATCOM have been combined simultaneously with state variables of the network in the single frame of reference for unified iterative solution. The STATCOM computer program in MATLAB code is also developed. For the case study, a small five-bus network containing two generators and seven transmission lines is used. The power flow solutions in both uncontrolled and STATCOM controlled power system mode of operations are found and compared. After the conclusion, the scope for further work is also suggested in the last.

CONTENTS

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Abstract

1

INTRODUCTION

The main aim of a modern electrical power system is to satisfy continuously the electrical power contracted by all customers. This is a problem of great engineering complexity where the following operational policies must be observed :-

1. Nodal voltage magnitudes and system frequency must be kept within narrow boundaries.
2. The alternating current (AC) voltage and current waveforms must remain largely sinusoidal.
3. Transmission lines must be operated well below their thermal and stability limits.
4. Even short- term interruptions must be kept to a minimum.

To a large extent, several of these key issues in power system operation may be assessed quite effectively by resorting to power flow and derived studies. The main object of a power flow study is to determine the steady-state operating condition of electrical power network. The steady-state may be determined by finding out, for a given set of loading conditions, the flow of active and reactive powers throughout the network and the voltage magnitudes and phase angles at all buses of the network.

Expansion, planning and daily operation of power systems relies on extensive power flow studies. The information conveyed by such studies indicates whether or not the nodal voltage magnitudes and active and reactive power flows in transmission lines and transformers are within prescribed operating limits. If voltage magnitudes are outside bounds in one or more points of the network, then appropriate action is taken in order to regulate such voltage magnitudes. Similarly, if the study predicts that the power flow in a given transmission line is beyond the power carrying capacity of the line, then the control action is taken.

1.1 THE MAIN OBJECTS :

The key objectives of the power flow study of the inter-connected power system are given as bellow :

1. To increase transmission capacity allowing secure loading of the transmission lines upto their thermal capacities.
2. To enable better utilisation of available generation.
3. To contain outages from spreading to wider areas.

1.2 BASICS OF POWER FLOW

The power flow problem, is solved to determine the steady-state complex voltages at all buses of the network, from which the active and reactive power flows in every transmission line and transformer are calculated. The set of equations representing the power system are nonlinear. For most practical purposes, all power flow methods exploit the well-conformed nodal properties of the power network and equipment. In its most basic form, these equations are derived by assuming that a perfect symmetry exists between the phases of the three phase power system. Owing to the nonlinear nature of the power flow equations, the numerical solution is reached by iteration.

1.3 NECESSITIES OF POWER FLOW STUDIES

Power flow studies provide the following informations:

1. Informations regarding bus usage.
2. Informations regarding power flow theory and transmission lines, transformers and other elements of power system for a specified load demand subject to the regulating capabilities of the generators, condensers, tap changing transformers and phase shifting transformers.
3. Specified net interchange of power with adjoining power systems.
4. Power flow studies help in critically assessing alternating plans for system expansion to meet the ever increasing load demand.
5. Help the planning and operation engineers to meet contingency conditions such as loss of large generating unit or a major line outage due to thermal over loading of the line.
6. Help in determining best size and most favourable location for the power capacitors for improving the power factor as well as the usage profile of power system.
7. They are periodically executed for monitoring and controlling of power system.
8. Real time results of power flow computation may be used to determine the reactive compensation needed to establish bus voltages.

9. If these studies predict that the nodal voltage magnitudes, active and reactive power flows in transmission lines and transformers are not within limits, then control action is taken.

In practical system, there may be thousands of buses and transmission links. We shall concentrate mainly on transmission system with generators and loads modelled by the complex powers. Thus , the power flow study involves extensive calculations.

Before the advent of digital computers, the AC calculating boards were used for carrying out power flow studies. These studies were tedious and time consuming, but with the availability of fast and large sized digital computers, all kinds of power system studies, including power flow study can now be carried out conveniently.

1.4 MAIN PROBLEMS OF POWER FLOWS

In power flow studies load powers are assumed as constants. A given set of loads on the buses can be served from a given set of generators in an infinite number of power flow configuration.

Some of the main and important aspects of power flow studies are as follows:

The sum of real power injected at the generating buses must be equal, at each instant of time, the sum of total system load demand plus system losses. Their individual generator outputs must be closely maintained at the predetermined set points. As the load demand slowly changes throughout the day ,therefore these set points changes slowly with time. Thus the power flow results for a certain hour of the day may be quite different from that of the next hour.

The power transfer capability of a power transmission line is limited to the thermal loading limit and the stability limit. It must be seen that transmission line do not operate too close to their stability or thermal limits.

It is necessary to keep the voltage levels of certain buses within close tolerances. This can be achieved by proper scheduling of reactive powers.

The power system must fulfil the contractual scheduled interchange of power to neighbouring systems, if any , via its tie lines.

Power flow studies are very important in the planning stages of new networks or in addition to existing ones.

1.5 SUB-PROBLEMS OF POWER FLOWS

In addition to the main problems as discussed above, the following problems are also faced in power flow studies:-

1. Formulation of mathematical models that describe the relationship between voltages and powers in the inter-connected system.
2. Specification of power and voltage constraints that must apply to the various buses of the network.
3. The computation of the voltage magnitude and phase angle of each node or bus in a power system under balanced three phase steady-state conditions.

2

LITERATURE SURVEY

The flexible alternating-current transmission systems (FACTS) is a recent technological development in electrical power systems. IT builds on the great many advances achieved in high-current, high-power semiconductor device technology, digital control and signal conditioning. From the power systems engineering perspective, the wealth of experience gained with the commissioning and operation of high-voltage direct-current (HVDC) links and static VAR compensator (SVC) systems, over many decades, in various parts of the world, may have provided the driving force for searching deeper into the use of emerging power electronic equipments and techniques, as a means of alleviating long standing operational problems in both high-voltage transmission and low- voltage distribution systems. A large number of researchers had contributed to the rapid advancement of the FACTS technology, but the names N.G. Hingorani and L. Gyugyi stand out prominently. Their work on FACTS, synthesised in their book, Understanding FACTS - Concepts and Technology of Flexible AC Transmission Systems (Institute of Electronic and Electrical Engineers, New York, 2000) is a source of learning and inspiration.

2.1 SIGNIFICANT DEVELOPMENTS

The main aim of power flow studies is to make the electrical power system capable to satisfy continuously the electrical power contracted by all customers. This is a problem of great engineering complexity. Many significant developments have been made in the subject by researchers and engineers. To a large extent, several of these key issues in power system operation may be assessed quite effectively by resorting to power flow and derive studies (Stagg and El-Abiad, 1968; Wood and Wollenberg, 1984; Arrilaga and Arnold, 1990; Grainger and Stevenson, 1994). Expansion, planning and daily operation of power systems relies on extensive power flow studies (Weedy, 1987; Kundur, 1994).The power flow problem, is solved to determine the steady-state complex voltages at all buses of the network, from which active and reactive power flows in every transmission line and transformer are calculated (Stagg and El-Abiad, 1968). The set of equations representing the power system are nonlinear. For most practical purposes, all power flow models exploit the well confirmed nodal properties of the power network and equipment. In its most basic form, these equations are derived by assuming that a perfect symmetry exists between the phases of the three-phase power system (Arrilaga and Arnold, 1990). Owing to the nonlinear nature of the power flow equations, the numerical solution is reached by iterations (Grainger and Stevenson, 1994).

FACTS controllers narrow the gap between the uncontrolled and controlled power system mode of operation by providing additional degrees of freedom to control power flows and voltages at key locations of the network (Hingorani and Gyuagi, 2000). Key objectives of the technology are: to increase transmission capacity allowing secure loading of the transmission up to their thermal capacities; to enable better utilisation of available generation; and to contain outages from spreading to wider areas (Song and Johns, 1999).

In order to determine the effectiveness of this new generation of power system controllers on a network wide basis, it has become necessary to upgrade most of the analysis tools on which the power engineers rely to plan and to operate their system (IEEE/CIGRE, 1995). The power flow solutions are probably the most popular kind of computer-based calculations. The reliable solution of power flows in real life transmission and distribution networks is not a trivial matter and, over the years, owing to its very practical nature, many calculation methods have been put forward to solve this problem. Among them, Newton-Raphson type methods, with their strong convergence characteristics have proved the most successful (Tinny and Hart, 1967).

From the outset, interconnection was aided by the breakthrough in high-current, high-power semiconductor valve technology (Arrilaga, 1998). Thyristor-based high-voltage direct current (HVDC) converter installations provided a means for interconnecting power systems with different operating frequencies – e.g. 50/60 Hz, for interconnecting power systems separated by sea and for interconnecting weak and strong power systems (Hingorani, 1996). The most recent development in HVDC technology is the HVDC system based on solid-state voltage source converter, which enables independent, fast control of active and reactive powers (McMurray, 1987).

2.2 LITERATURE REVIEW

Another aspect of researches and developments has been towards the improvements techniques and procedures with which to access the steady-state operation of electrical power systems at the fundamental frequency. The power system application tool is termed “power flows”, and the most popular variants of the tool are presented in the literature; namely, positive sequence power flow [7], optimal power flow [8], and three phase power flow [9]. The first two applications deal with cases of balanced operation, for nonoptimal and optimal solutions, respectively. The third application deals with unbalanced operation induced by the imbalances present either in plant components or in system load.

Power electronic circuits using conventional thyristors have been widely used in power transmission applications since early 1970s [10]. The first application took place in the area of HVDC transmission, but shunt reactive power compensation using fast controllable inductors and capacitors soon gained general acceptance [11]. More recently, fast-acting series compensators using thyristors have been used to vary the electrical length of key transmission lines, with almost no delay, instead of classical series capacitor, which is mechanically controlled. In distribution system applications solid-state switches using thyristors are being used to enhance the reliability of supply to critical customer loads [12].

Power electronics is a technology that has affected every aspect of electrical power network. Deregulated markets are imposing further demands on generating plants, increasing their wear and tear and likelihood of generator instabilities of various kinds. To help to alleviate such problems, power electronic controllers have recently been developed to enable generators to operate more reliably. The thyristor-controlled series compensator (TCSC) is used to mitigate subsynchronous resonances (SSRs) and to damp power system oscillations (Larsen et al., 1992). However it may be argued that the primary function of the TCSC, like that of its mechanically controlled counterpart, the series capacitor bank, is to reduce the electrical length of the compensated transmission line. Hence the aim is still to increase power transfers significantly, but with increased transient stability margins.

For most practical purposes the thyristor-based static VAR compensator (SVC) have made the rotating synchronous compensator redundant, except where an increase in the short circuit level is required along with fast-acting reactive power support (Miller, 1982). However with development in technology, the replacement of SVC by a new breed of static compensators based on the use of VSCs is looming. They are known as STATCOMs and provide all the functions that the SVC can provide but at a higher speed (IEEE/CIGRE, 1995); it is more compact and requires only a fraction of land required by an SVC installation. The STATCOM is essentially a VSC is the basic building block of the new generation of power electronic controllers that have emerged from the FACTS and custom power initiatives (Hingorani and Gyugyi, 2000).

2.3 CONCLUSION

The exhaustive literature review has revealed that the research work carried out on FACTS controllers is largely influenced by the technological developments in power electronics – specially in thyristor based technology. Most of the developments in these fields are to replace the conventional mechanical power compensators by thyristor based FACTS controllers, among which, in high-voltage transmission , the most popular FACTS equipments are : the STATCOM , the unified power flow controller (UPFC) and the HVDC-VSC.

3

GENERAL POWER FLOW CONCEPTS

The power flow problem, is solved to determine the steady-state complex voltages at all buses of the network, from which the active and reactive power flows in every transmission line and transformer are calculated. The set of equations representing the power system are non-linear. For most practical purposes, all power flow methods exploits the well –confirmed nodal properties of the power network and equipment. In its most basic form, these equations are derived by assuming that a perfect symmetry exists between the phases of the three phase power system. Owing to the non-linear nature of the power flow equations, the numerical solution is reached by iteration.

3.1 BASIC FORMULATION

A popular approach to assess the steady-state operation of a power system is to write equations stipulating that at a given bus the generation, load and powers exchanged through the transmission elements connecting to the bus must add up to the zero, which applies to both active power and reactive power. These equations are termed mismatch power equations and at bus k they take the following form :

$$\Delta P_K = P_{GK} - P_{LK} - P_K^{cal} = P_K^{sch} - P_K^{cal} = 0 \qquad \ldots \ (1)$$

$$\Delta Q_K = Q_{GK} - Q_{LK} - Q_K^{cal} = Q_K^{sch} - Q_K^{cal} = 0 \qquad \ldots \ (2)$$

The terms ΔP_K and ΔQ_K are the mismatch active and reactive powers at bus k, respectively. P_{GK} *and* Q_{GK} represent, respectively ,the active and reactive powers injected by the generator at bus k, which are assumed to be controlled by the plant operator. P_{LK} *and* Q_{LK} represent the active and reactive powers drawn by the load at bus k, respectively. Under normal operation the customer has control of these variables, and in the power flow formulation they are assumed to be known variables.

In principles, at least, the generation and the load at bus k may be measured by the electric utility and, in the parlance of power system engineers, their net values are known as the scheduled active and reactive powers.

These scheduled active and reactive powers are :-

$$P_K^{sch} = P_{GK} - P_{LK} \qquad \ldots \quad (3)$$

$$Q_K^{sch} = Q_{GK} - Q_{LK} \qquad \ldots \quad (4)$$

The transmitted active and reactive powers, P_K^{cal} *and* Q_K^{cal} are functions of nodal voltages and network impedances and are computed using power flow equations. Provided the nodal voltages throughout the power network are known to a good degree of accuracy then the transmitted powers are easily and accurately calculated. In this situation, the corresponding mismatch powers are zero for any practical purpose and the power balance at each bus of the network is satisfied. However, if the nodal voltages are not known precisely then the calculated transmitted powers will have only approximated values and the corresponding mismatch powers are not zero.

The power flow solution takes the approach of successively correcting the calculated nodal voltages and, hence, the calculated transmitted powers until values accurate enough are arrived at, enabling the mismatch powers to be zero or fairly close to be zero. In modern power flow computer programs, it is normal for all mismatch equations to satisfy a tolerance as tight as 1e – 12 before the iterative solution can be considered successful. Upon convergence, the nodal voltage magnitude and angles yield useful information about the steady-state operating conditions of the power system and are known as state variables.

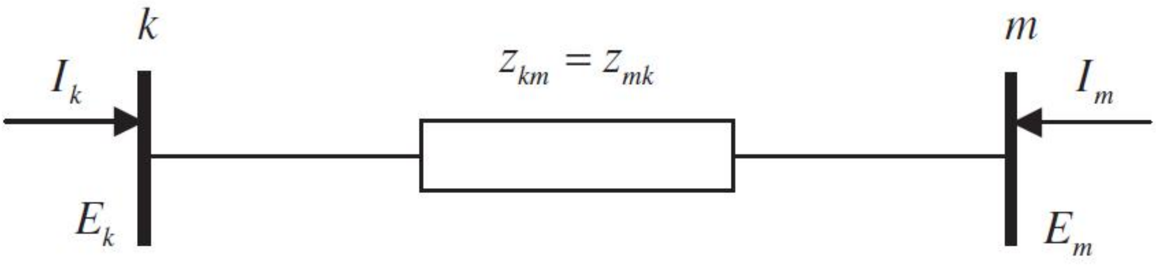

Figure 1 Equivalent Impedance

In order to develop suitable power flow equations, it is necessary to find relationships between injected bus currents and bus voltages. Based on Figure 1 the injected complex current at bus k, denoted by I_K may be expressed in terms of the complex bus voltages E_K *and* E_m as follows :

$$I_K = \frac{1}{Z_{Km}}(E_K - E_m) = y_{Km}(E_K - E_m) \qquad \ldots \quad (5)$$

Similarly for bus m,

$$I_m = \frac{1}{Z_{mK}}(E_m - E_K) = y_m(E_m - E_K). \qquad \ldots \quad (6)$$

The above equations can be written in matrix form as,

$$\left(\begin{bmatrix} I_K \\ I_m \end{bmatrix}\right) = \begin{bmatrix} y_{Km} & -y_{Km} \\ -y_{mK} & y_{mK} \end{bmatrix} \begin{bmatrix} E_K \\ E_m \end{bmatrix}, \qquad \ldots (7)$$

Or

$$\begin{bmatrix} I_K \\ I_m \end{bmatrix} = \begin{bmatrix} Y_{KK} & Y_{Km} \\ Y_{mK} & Y_{mm} \end{bmatrix} \begin{bmatrix} E_K \\ E_m \end{bmatrix}, \qquad \ldots (8)$$

Where the bus admittances and voltages can be expressed in more explicit form :

$$Y_{ij} = G_{ij} + jB_{ij} \qquad \ldots \quad (9)$$

$$E_i = V_i e^{j\theta_i} = V_i(\cos\theta_i + j\sin\theta_i) \qquad \ldots \quad (10)$$

Where I = k, m and j = k, m.

The complex power injected at bus k consists of an active and reactive component and nay be expressed as the function of the nodal voltage and injected current at the bus :

$$S_K = P_K + jQ_K = E_K I^*_K$$

$$= E_K (Y_{KK} E_K + Y_{Km} E_m)^* \qquad \ldots \quad (11)$$

Where I_K^* is the complex conjugate of the current injected at bus k.

The expression for $P_K^{cal}\ and\ Q_K^{cal}$ can be determined by substituting Equation (9) and (10) into Equation (11), and separating into real and imaginary parts :

$$P_K^{cal} = V_K^2 G_{KK} + V_K V_m \left[G_{Km} \cos(\theta_K - \theta\ m) + B_{Km} \sin(\theta_K - \theta_m)\right] \quad . . . \quad (12)$$

$$Q_K^{cal} = -V_K^2 B_{KK} + V_K V_m \left[G_{Km} \sin(\theta_K - \theta_m) - B_{Km} \cos(\theta_K - \theta_m)\right] \quad . . . \quad (13)$$

For specified levels of power generation and power load at bus k, and according to Equation (1) and (2), the mismatch equations may be written down as :

$$\Delta P_K = P_{GK} - P_{LK} - \left\{V_K^2 G_{KK} + V_K V_m \left[G_{Km} \cos(\theta_K - \theta_m) + B_{Km} \sin(\theta_K - \theta_m)\right]\right\} = 0$$

$$. . . \quad (14)$$

$$\Delta Q_K = Q_{GK} - Q_{LK} - \left\{-V_K^2 B_{KK} + V_K V_m \left[G_{Km} \sin(\theta_K - \theta_m) - B_{Km} \cos(\theta_K - \theta_m)\right]\right\} = 0$$

. .

$$. . . \quad (15)$$

Similar equations may be obtained for bus m simple by exchanging subscripts k and m in Equations (14) and (15).

It should be marked that Equations (12) and (13) represent only the powers injected at bus k through *i*th transmission element, that is, $P_K^{i..cal}\ and\ Q_K^{i..cal}$. However, a practical power system will consists of many buses and many transmission elements. This calls for Equations (12) and (13) to be expressed in more general terms, with net power flow injected at bus k expressed as the summation of the powers flowing at each one of the transmission elements terminating at this bus. This is illustrated in Figures 2(a) and 2(b) for cases of active and reactive powers, respectively.

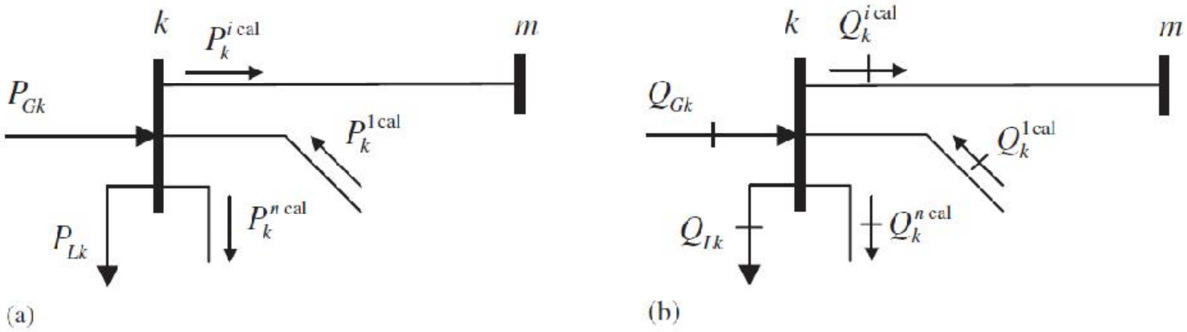

Figure 2 Power balance at bus k : (a) active power, (b) reactive power.

The generic net active and reactive powers injected at bus k are :

$$P_K^{cal} = \sum_{i=1}^{n} P_K^{i..cal} \qquad \dots \qquad (16)$$

$$Q_K^{cal} = \sum_{i=1}^{n} Q_K^{i..cal} \qquad \dots \qquad (17)$$

Where $P_K^{i..cal}$ *and* $Q_K^{i..cal}$ are computed by using Equations (12) and (13), respectively.

As an extension, the generic power mismatch equations at bus k are :

$$\Delta P_K = P_{GK} - P_{LK} - \sum_{i=1}^{n} P_K^{i..cal} = 0 \qquad \dots \qquad (18)$$

$$\Delta Q_K = Q_{GK} - Q_{LK} - \sum_{i=1}^{n} Q_K^{i..cal} = 0 \qquad . \; . \; . \; (19)$$

3.2 VARIABLES

In conventional power flow theory each bus is described by four variables : net active power, net reactive power, voltage magnitude and voltage phase angle.

Since there are only two equations per bus, two out of four variables must be specified in each bus in order to have a solvable problem. From a purely mathematical viewpoint, any two variables can be specified, however, in engineering terms the choice is based on which variables at the bus can be physically controlled through the availability of a nearby controller. In the broadest sense, one can think of voltage magnitudes and phase angles as the state variables, and active and reactive powers as control variables.

3.3 BUS CLASSIFICATION

Buses are classified according to which two out of the four variables are specified :

1. **Load PQ Bus** : No generator is connected to the bus, hence the controlled variables P_G and Q_G are zero. Furthermore the active and reactive powers drawn by the load $P_L \, and \, Q_L$ are known by available measurements. In these type of buses net active power and the net reactive power are specified, and voltage, V and phase angle, θ are computed.

2. **Generator PV Bus** : A generator source is connected to the bus ; the nodal voltage magnitude V is maintained at constant value by adjusting the field current of the generator and hence it generates and absorbs reactive power. Moreover, the generated active power P_G is also set at a specified value. The other two quantities phase angle, θ and generated reactive power Q_G are computed. Constant voltage operation is possible only if the generator reactive power design limits are not violated, that is, $Q_{G..\min} \angle Q_G \angle Q_{G..\max.}$
3. **Generator PQ Bus** : If the generator can not provide the necessary reactive power support to constrain the voltage magnitude at the specified value then the reactive power is fixed at the violated limit and the voltage magnitude is freed. In this case, the generated active power P_G and the reactive power Q_G are specified, and the nodal voltage magnitude V and the phase angle are computed.
4. **Slack (swing) Bus** : One of the generator buses is chosen to be the slack bus where the nodal voltage magnitude, V_{slack} , and phase angle, θ_{slack}, are specified. There is only one slack bus in the power system and the function of the slack generator is to produce sufficient power to provide for any unmet system load and for system losses, that are not known in advance of the power flow calculation. The voltage phase angle at the slack bus θ_{slack} is chosen as the reference against which all other voltage phase angles in the system are measured. It is normal to fix its value to zero.

4

METHODS OF POWER FLOW SOLUTION

4.1 EARLY POWER FLOW ALGORITHM:

From the mathematical modelling point of view, a power flow solution consists of solving the set of nonlinear algebraic equations that describes the electrical power network under steady-state conditions. Over the years, several approaches have been put forward for the solution of the power flow equations. Early approaches were based on loop equations and numerical methods using Gauss-type solutions. The method was laborious because the network loops have to be specified beforehand by the system engineer. Improved techniques saw the introduction of nodal analysis in favour of loop analysis, leading to a considerable reduction in data preparation, nevertheless, reliability towards convergence was still the main concern. Further developments led to the introduction of the Gauss-Seidel method with acceleration factors. The appeal of this generation power flow methods is their minimum storage requirements and the fact that they are easy to comprehend and to code in the computer programs. The drawback is that these algorithms exhibit poor convergence characteristics when applied to the solution of the networks of realistic size. Power flow solutions based on the nodal impedance matrix were briefly experimented with, but problem with computer storage and speed became insurmountable issues at the time. To overcome such limitations, the Newton-Raphson method and derived formulations were developed in the early 1970s and have since become firmly established throughout the power system industry.

4.2 THE NEWTON-RAPHSON ALGORITHM :

In large - scale power flow studies the Newton-Raphson method has proved most successful owing to its strong convergence characteristics. This approach uses iteration to solve the following set of nonlinear algebraic equations :

$$f_1(x_1, x_2, \ldots\ldots, x_N) = 0,$$

$$f_2(x_1, x_2, \ldots\ldots, x_N) = 0,$$

$$\vdots$$

$$f_N(x_1, x_2, \ldots\ldots x_N) = 0,$$

Or

$$\mathbf{F(X)} = \mathbf{0} \qquad \ldots \qquad \ldots \qquad (20)$$

Where **F** represent the set of n nonlinear equations and **X** is the vector of n unknown state variables.

The essence of the method consists of determining the vector of state variables **X** by performing a Taylor series expansion of **F(X)** about an initial estimate $X^{(0)}$:

F(X) = **F**[$X^{(0)}$] + **J**[$X^{(0)}$][**X** - $X^{(0)}$] + higher-order terms, . . . (21)

Where **J**[$X^{(0)}$] is a matrix of first-order partial derivatives of **F** (**X**) with respect to **X** , termed the Jacobian, evaluated at **X** = $X^{(0)}$.

This expansion lends itself to a suitable formulation for calculating the vector of state variables X by assuming that $X^{(1)}$ is the value computed by the algorithm at iterative 1 and that this value is sufficiently close to the initial estimate $X^{(0)}$. Based on this premise, all higher-order derivative terms in equation (21) may be neglected. Hence,

$$\underbrace{\begin{bmatrix} f_1(\mathbf{X}^{(1)}) \\ f_2(\mathbf{X}^{(1)}) \\ \vdots \\ f_n(\mathbf{X}^{(1)}) \end{bmatrix}}_{\mathbf{F}(\mathbf{X}^{(1)})} \approx \underbrace{\begin{bmatrix} f_1(\mathbf{X}^{(0)}) \\ f_2(\mathbf{X}^{(0)}) \\ \vdots \\ f_n(\mathbf{X}^{(0)}) \end{bmatrix}}_{\mathbf{F}(\mathbf{X}^{(0)})} + \underbrace{\begin{bmatrix} \frac{\partial f_1(\mathbf{X})}{\partial x_1} & \frac{\partial f_1(\mathbf{X})}{\partial x_2} & \cdots & \frac{\partial f_1(\mathbf{X})}{\partial x_n} \\ \frac{\partial f_2(\mathbf{X})}{\partial x_1} & \frac{\partial f_2(\mathbf{X})}{\partial x_2} & \cdots & \frac{\partial f_2(\mathbf{X})}{\partial x_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial f_n(\mathbf{X})}{\partial x_1} & \frac{\partial f_n(\mathbf{X})}{\partial x_2} & \ddots & \frac{\partial f_n(\mathbf{X})}{\partial x_n} \end{bmatrix}\Bigg|_{\mathbf{X}=\mathbf{X}^{(0)}}}_{\mathbf{J}(\mathbf{X}^{(0)})} \underbrace{\begin{bmatrix} X_1^{(1)} - X_1^{(0)} \\ X_2^{(1)} - X_2^{(0)} \\ \vdots \\ X_n^{(1)} - X_n^{(0)} \end{bmatrix}}_{\mathbf{X}^{(1)}-\mathbf{X}^{(0)}} .$$

. . . (22)

In compact form, and generalising the power expression for the case of iteration (i),

$$F\left(X^{(i)}\right) \approx F\left(X^{i-1}\right) + J\left(X^{i-1}\right)\left(X^{i} - X^{i-1}\right), \qquad . . . \qquad (23)$$

Where i = 1, 2, . . . Furthermore, if it is assumed that $X^{(i)}$ is sufficiently close to the solution $X^{(*)}$ then $F\left(X^{(i)}\right) \approx F\left(X^{(*)}\right) = 0,$ Hence , equation (23) becomes

$$F\left(X^{(i-1)}\right) + J\left(X^{(i-1)}\right)\left(X^{i(\ )} - X^{(i-1)}\right) = 0 \qquad . . . \qquad (24)$$

and solving for $X^{(i)}$,

$$X^{(i)} = X^{(i-1)} - J^{-1}\left(X^{(i-1)}\right)F\left(X^{(i-1)}\right) \qquad . \; . \; . \qquad (25)$$

The iterative solution can be expressed as a function of correction vector

$$\Delta X^{(i)} = X^{(i)} - X^{i-1},$$

$$\Delta X^{(i)} = -J^{-1}\left(X^{(i-1)}\right)F\left(X^{(i-1)}\right), \qquad . \; . \; . \qquad (26)$$

And the initial estimates are updated using the following relation :

$$X^{(i)} = X^{(i-1)} + \Delta X^{(i)}, \qquad . \; . \; . \qquad (27)$$

The calculations are repeated as many times as required using the most up-to-date values of X in equation (26). This is done until the mismatches ΔX are within a prescribed small tolerance (i.e. 1e – 12).

In order to apply the Newton-Raphson method to the power flow problem, the relevant equations must be expressed in the form of Equation (26) where **X** represents the set of unknown nodal voltage magnitudes and phase angles. The power mismatch equations ΔP and ΔQs are expanded around a base point $\left(\theta^{(0)}, V^{(0)}\right)$ and, hence, the power flow Newton-Raphson algorithm is expressed by the following relationship :

$$\underbrace{\begin{bmatrix} \Delta \mathbf{P} \\ \Delta \mathbf{Q} \end{bmatrix}^{(i)}}_{\mathbf{F}\left(\mathbf{X}^{(i-1)}\right)} = -\underbrace{\begin{bmatrix} \dfrac{\partial \mathbf{P}}{\partial \boldsymbol{\theta}} & \dfrac{\partial \mathbf{P}}{\partial \mathbf{V}}\mathbf{V} \\ \dfrac{\partial \mathbf{Q}}{\partial \boldsymbol{\theta}} & \dfrac{\partial \mathbf{Q}}{\partial \mathbf{V}}\mathbf{V} \end{bmatrix}^{(i)}}_{\mathbf{J}\left(\mathbf{X}^{(i-1)}\right)} \underbrace{\begin{bmatrix} \Delta \boldsymbol{\theta} \\ \dfrac{\Delta \mathbf{V}}{\mathbf{V}} \end{bmatrix}^{(i)}}_{\Delta \mathbf{X}^{(i)}} .$$

. . .   . . . (28)

The various matrices in the Jacobian may consists of up to (nb – 1) * (nb – 1) elements of the form :

$$\left.\begin{matrix} \dfrac{\partial P_k}{\partial \theta_m}, & \dfrac{\partial P_k}{\partial V_m} V_m, \\ \dfrac{\partial Q_k}{\partial \theta_m}, & \dfrac{\partial Q_k}{\partial V_m} V_m, \end{matrix}\right\}$$

. . .   . . .   (29)

Where k = 1, . . . , nb, and m = 1, . . . , nb but omitting the slack bus entries.

Also the rows and columns corresponding to the reactive power and voltage magnitude for the PV buses are discarded. Furthermore, when buses k and m are not directly linked by a transmission element, the corresponding k-m entry in the Jacobian is null. Owing to the low degree of connectivity that prevails in practical power systems, the Jacobian power flows are highly sparse. An additional characteristics is that they are symmetric in structure but not in value (Zollenkoff, 1970).

It must be pointed out that the correction terms ΔV_m are divided by V_m to compensate for the fact that Jacobian terms $\left(\partial P_K / \partial P_m \right) V_m$ and $(\partial Q_k / \partial V_m) V_m$ are multiplied by V_m. It is shown in the derivative terms given below that this artifice yields useful simplifying calculations.

Consider the lth element connected between the buses k and m in figure 1, for which self and mutual Jacobian terms are given below :

For $k \neq m$:

$$\frac{\partial P_{k,l}}{\partial \theta_{m,l}} = V_k V_m \left[G_{km} \sin(\theta_k - \theta_m) - B_{km} \cos(\theta_k - \theta_m) \right], \quad \ldots \quad \ldots \quad (30)$$

$$\frac{\partial P_{k,l}}{\partial V_{m,l}} V_{m,l} = V_k V_m \left[G_{km} \cos(\theta_k - \theta_m) + B_{km} \sin(\theta_k - \theta_m) \right], \quad \ldots \quad \ldots \quad (31)$$

$$\frac{\partial Q_{K,l}}{\partial \theta_{m,l}} = -\frac{\partial P_{K,l}}{\partial V_{m,l}} V_{m,l}, \quad \ldots \quad \ldots \quad (32)$$

$$\frac{\partial Q_{K,l}}{\partial V_{m,l}} V_{m,l} = \frac{\partial P_{K,l}}{\partial \theta_{m,l}}, \quad \ldots \quad \ldots \quad (33)$$

For k = m:

$$\frac{\partial P_{k,l}}{\partial \theta_{k,l}} = -Q_k^{cal} - V_k^2 B_{kk}, \quad \ldots \quad \ldots \qquad (34)$$

$$\frac{\partial P_{k,l}}{\partial V_{k,l}} V_{k,l} = P_k^{cal} + V_k^2 G_{kk}, \quad \ldots \quad \ldots \qquad (35)$$

$$\frac{\partial Q_{k,l}}{\partial \theta_{k,l}} = P_k^{cal} - V_k^2 G_{kk}, \quad \ldots \quad \ldots \qquad (36)$$

$$\frac{\partial Q_{k,l}}{\partial V_{k,l}} V_{k,l} = Q_k^{cal} - V_k^2 B_{kk}, \quad \ldots \quad \ldots \qquad (37)$$

In general, for a bus k containing n transmission elements l, the bus self-elements take the following form :

$$\frac{\partial P_k}{\partial \theta_k} = \sum_{l=1}^{n} \frac{\partial P_{k,l}}{\partial \theta_{k,l}}, \quad \ldots \quad \ldots \qquad (38)$$

$$\frac{\partial P_k}{\partial V_k} V_k = \sum_{l=1}^{n} \frac{\partial P_{k,l}}{\partial V_{k,l}} V_{k,l}, \quad \ldots \quad \ldots \qquad (39)$$

$$\frac{\partial Q_k}{\partial \theta_k} = \sum_{l=1}^{n} \frac{\partial Q_{k,l}}{\partial \theta_{k,l}}, \quad \ldots \quad \ldots \qquad (40)$$

$$\frac{\partial Q_k}{\partial V_k} V_k = \sum_{l=1}^{n} \frac{\partial Q_{k,l}}{\partial V_{k,l}} V_{k,l}, \quad \ldots \quad \ldots \qquad (41)$$

The mutual elements given by equation (30) – (33) remain the same whether we have one transmission element or n transmission elements terminating at bus k.

After the voltage magnitudes and phase angles have been calculated by iteration, active and reactive power flows throughout the transmission system are determined quite straightforwardly.

An important point to bear in mind is that the mismatch power equations $\Delta P and \Delta Q$ of the slack bus are not included in the equation (28) and the unknown variables $P_{slack} and Q_{slack}$ are computed once the system power flows and power losses have been determined. Also, Q_G in PV buses are calculated in each iteration in order to checkif the generators are within reactive power limits. However, the mismatch reactive power equations ΔQ of PV buses are not included in equation (28).

One of the main strengths of the Newton-Raphson method is its reliability towards convergence. For most practical situations, and provided the state variables, $X^{(0)}$, are suitably initialised, the method is said to exhibit a quadratic convergence characteristic; for example,

$$
\begin{aligned}
\mathrm{f}(X^{(1)}) &= 1\mathrm{e}-1, \\
\mathrm{f}(X^{(2)}) &= 1\mathrm{e}-2, \\
\mathrm{f}(X^{(3)}) &= 1\mathrm{e}-4, \\
\mathrm{f}(X^{(4)}) &= 1\mathrm{e}-8,
\end{aligned}
$$

for the maximum mismatch. Contrary to the non-Newton-Raphson solutions, such a characteristic is independent of the size of the network being solved and the number and the kinds of control equipment present in the power system. Aspects that may dent its quadratic convergence performance are reactive power limit violations in generator PV buses and extreme loading conditions.

4.3 STATE VARIABLE INITIALISATION :

The effectiveness of the Newton-Raphson method to achieve feasible iterative solution is dependent upon the selection of suitable initial values for all the state variables involved in the study.

The power flow solution of the networks that contain only conventional plat components is normally started with voltage magnitudes of 1 p.u. at all PQ buses. The slack and PV buses are given their specified values, which remain constant throughout the iterative solution if no generator reactive power limits are violated. The initial voltage phase angles are selected to be zero at all buses.

4.4 GENERATOR REACTIVE POWER LIMITS :

Even though the mismatch reactive power equation ΔQ_K of PV bus k is not required in Equation (28), solution of equation (17) for the PV bus is still carried out at each iterative step to assess whether or not the calculated reactive power Q_K^{cal} is within the generator reactive power limits :

$$Q_{G.\min.K} < Q_{GK} < Q_{G.\max.K}, \quad . \; . \; . \qquad . \; . \; . \qquad (42)$$

If either of the following conditions occur during the iterative process :

$$\left.\begin{aligned} Q_k^{\mathrm{cal}} &\geq Q_{G\max k}, \\ Q_k^{\mathrm{cal}} &\leq Q_{G\min k}, \end{aligned}\right\} \qquad \ldots \quad \ldots \ (43)$$

Bus k becomes a generator PQ bus with either of the following mismatch power equations incorporated in equation (28) :

$$\left.\begin{aligned} \Delta Q_k &= Q_{G\max k} - Q_{Lk} - Q_k^{\mathrm{cal}}, \\ \Delta Q_k &= Q_{G\min k} - Q_{Lk} - Q_k^{\mathrm{cal}}, \end{aligned}\right\} \qquad \ldots \quad \ldots \quad (44)$$

depending on the violated limit, together with the relevant Jacobian entries. The nodal voltage magnitude at bus k is allowed to vary and V_K becomes a state variables.

It should be remarked that bus k may revert to being a generator PV bus at some point during the iterative process if better estimates of Q_K^{cal}, calculated with more accurate nodal voltages, indicate that the reactive power requirements at bus k can, after all be met by the generator connected at bus k. Hence reactive power limit checking is carried out at each iteration. Programming wisdom indicates that limit checking should start after the first or second iteration, since nodal voltage values computed at the beginning of the iterative process may be quite inaccurate leading to misleading reactive power requirements. The switching of buses from PV to PQ and vice versa impose additional numerical demands on the iterative solution and retard convergence.

4.5 LINEARISED FRAME OF REFERANCE :

In order to illustrate how network components may be processed in the linearised frame of reference afforded by Newton-Raphson method, consider the simple 3-bus system shown in Figure 3. Bus 1 is selected to be the slack bus and bus 2 is the generator bus. Bus 3 contains no generation and becomes the load bus. A transformer and a transmission line link buses 1 and 2 and buses 2 and 3, respectively. One shunt element and one load are connected at bus 3.

The concept of 'power balance at a node' may be used to great effect to account for bus power injections in the Newton-Raphson solution. At a given bus, the power balance is obtained by adding the contribution of each plant component connected to that bus.

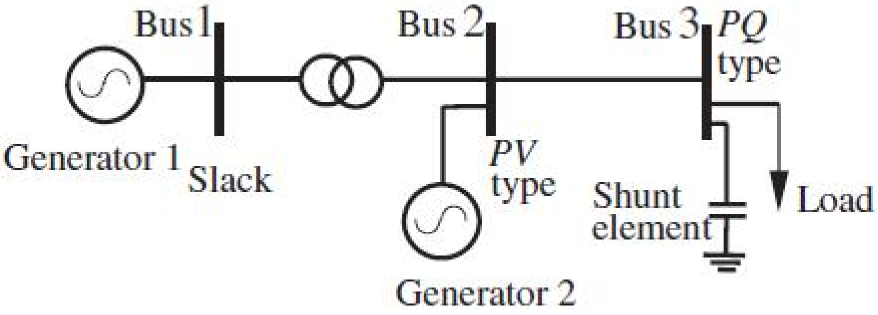

Figure 3 Tree-Bus Network

This is illustrated in Figure 4 with reference to Figure 3. The contribution of all three buses is shown in this example for completeness, but it should remembered that in actual calculations active and reactive mismatch entries are not required for the slack bus. Likewise, the reactive power mismatch entry is not required for generator PV bus.

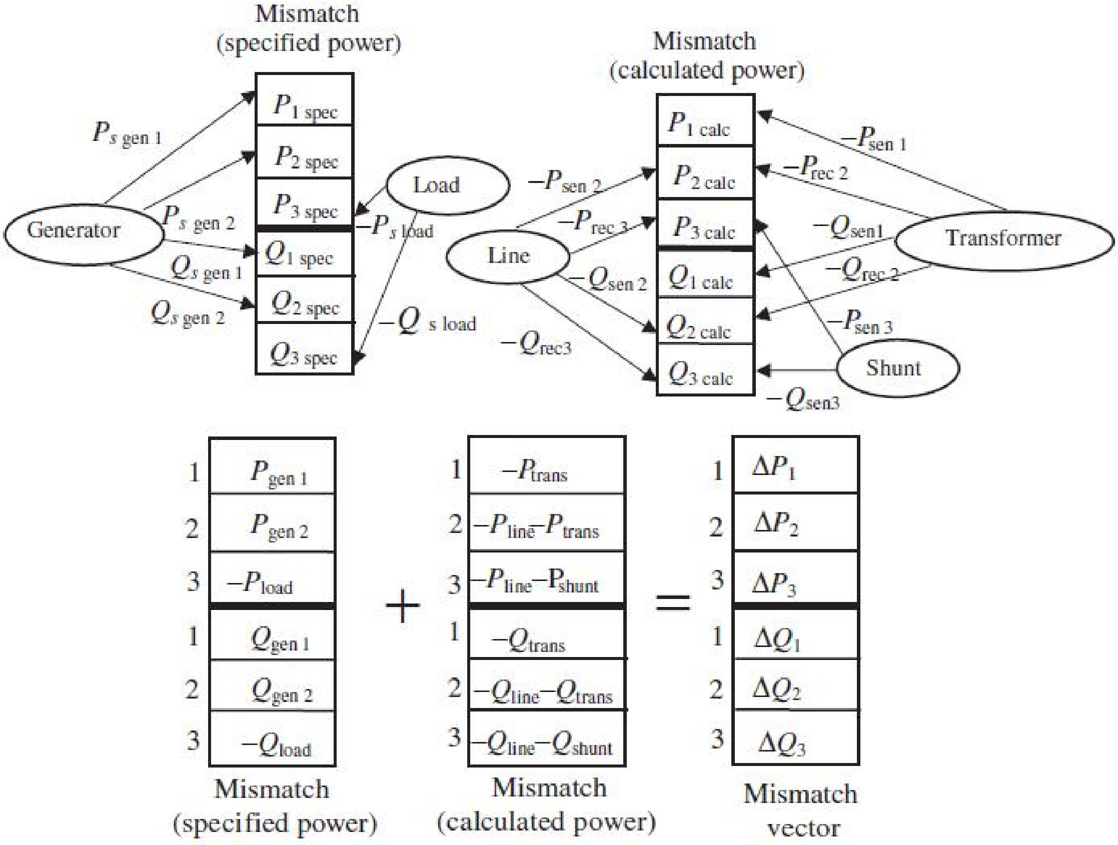

Figure 4 Power mismatch vector; subscripts ‘sen’ and ‘rec’ indicate the sending and receiving ends.

The construction of the Jacobian matrix is slightly more involved owing to the need to evaluate self and mutual Jacobian terms, and finding their location in the matrix. Nevertheless, the basic procedure illustrated above, based on superposition, will also apply to the formation of the Jacobian. For each plant component, relevant Jacobian equations are chosen based on the type of buses to which the plant component is connected. These buses determine the location of the individual Jacobian terms in the overall Jacobian structure. The contributions of the line, transformer, and shunt components to the Jacobian are shown in Figure 5. It should be noted that entries for the slack bus and the reactive power entry of the generator bus are not considered in the Jacibian structure.

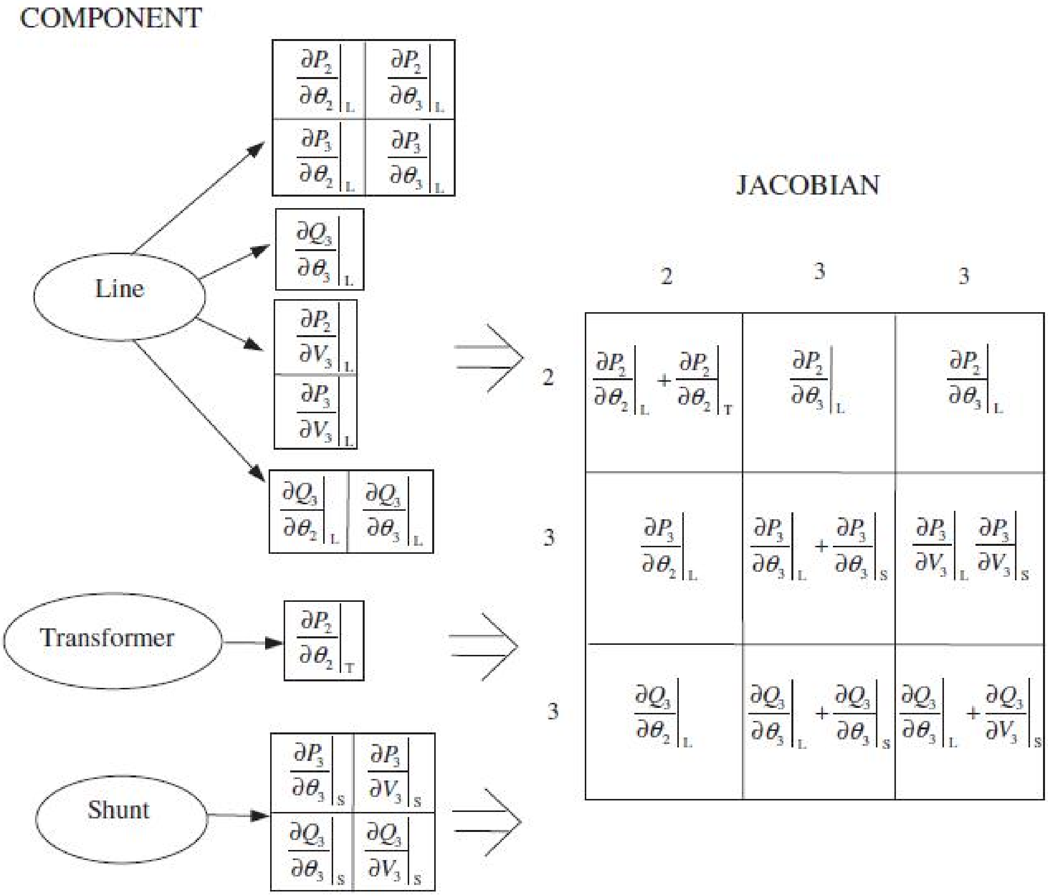

Figure 5 Jacobian structure

5

STATIC COMPENSATOR (STATCOM)

The STATCOM – an acronym for static compensator is one of the most popular FACTS controllers, which are used to narrow the gap between the uncontrolled and controlled power system mode of operation, by providing additional degrees of freedom to control power flows and voltages at key locations of the network. The number of FACTS controllers have been commissioned. Most of them perform a useful role during both steady-state and transient operation, but some are specifically designed to operate only under transient conditions. The various FACTS controllers other than STATCOM are listed below –

1. Thyristor-controlled phase shifter (PS)
2. Load tap changer (LTC)
3. Thyristor-controlled reactor (TCR)
4. Thyristo-controlled series capacitor (TCSC)
5. Interphase power controller (IPC)
6. Solid-state series controller (SSSC)
7. Unified power flow controller (UPFC)
8. Static VAR compensator (SVC)

5.1 REPRESENTATION OF STATCOM

The STATCOM consists of one voltage source converter (VSC) and its associated shunt connected transformer. It is a solid-state synchronous condenser connected in shunt with the AC system. The output current is adjusted to control either the nodal voltage magnitude or the reactive power injected at the bus. Hence it is a static counterpart of the rotating synchronous condenser but it generates or absorbs reactive power at a faster rate because no moving parts are involved.

In principle, it performs the same voltage regulation function as the static VAR compensator but in a more robust manner, unlike the SVC. Its operation is not impaired by the presence of low voltages. A schematic representation of the STATCOM is shown in Figure 6

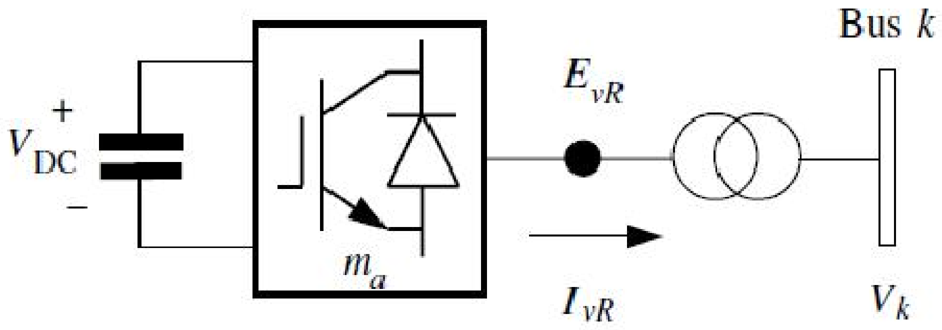

Figure 6 STATCOM system

In steady-state fundamental frequency studies the STATCOM may be represented in the same way as a synchronous condenser, which in most cases is the model of a synchronous generator with zero active power generation. A more flexible model may be realised by representing the STATCOM as a variable voltage source ?? , for which the magnitude and phase angle may be adjusted, using a suitable iterative algorithm, to satisfy a specified voltage magnitude at the point of connection with the AC network. The shunt voltage source of the three phase STATCOM may be represented by:

$$E_{vR}^{\rho} = V_{vR}^{\rho}(\cos\delta_{vR}^{\rho} + \mathrm{j}\sin\delta_{vR}^{\rho}),$$

Where indicates phase quantities, a, b and c.

The voltage magnitude, V_{vR}^{ρ} is given maximum and minimum limits, which are a function of the STATCOM capacitor rating. However, δ_{vR}^{ρ} may take any value between 0 and 2 π radians.

5.2 EQUIVALENT CIRCUIT OF STATCOM

Following on the STATCOM operational characteristics as discussed in previous para, it is reasonable to expect that for the purpose of positive sequence power flow analysis the STATCOM will be well represented by a synchronous voltage source with maximum and minimum voltage magnitude limits. The synchronous voltage source represents the fundamental Fourier series component of the switched voltage waveform at the AC converter terminal of the STATCOM. Its equivalent circuit is shown in Figure 7. The STATCOM equivalent circuit corresponds to the Thevenin equivalent as seen from bus k, with voltage source E_{vR} being the fundamental frequency component of the VSC output voltage, resulting from the product of V_{DC} and M_2 .

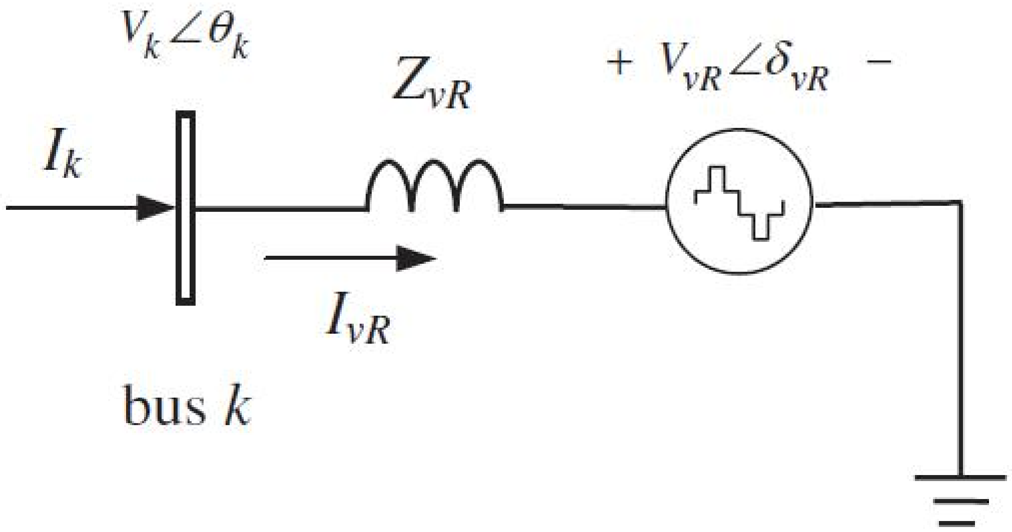

Figure 7 Equivalent circuit of the STATCOM

The bus at which the STATCOM is connected is represented as a PVS bus, which may change to a PQ bus in the events of limits being violated. In such a case, the generated or absorbed reactive power would correspond to the violated limit. Unlike the SVC, the STATCOM is represented as a voltage source for the full range of operation, enabling a more robust voltage support mechanism.

5.3 POWER FLOW MODEL OF STATCOM

The STATCOM equivalent circuit shown in Figure 7 is used to derive the mathematical model of the controller for inclusion in power flow algorithm. The power flow equations for the STATCOM are derived below from first principles and assuming the following voltage source representation:

$$E_{vR} = V_{vR}(\cos\delta_{vR} + \mathrm{j}\sin\delta_{vR}).$$

Based on the shunt connection shown in Figure 7, the following may be written –

$$S_{vR} = V_{vR}I_{vR}^{*} = V_{vR}Y_{vR}^{*}\left(V_{vR}^{*} - V_{k}^{*}\right).$$

After performing some complex operations, the following active and reactive power equations are obtained for the converter and bus k, respectively –

$$\begin{aligned}
P_{vR} &= V_{vR}^{2}G_{vR} + V_{vR}V_{k}\left[G_{vR}\cos(\delta_{vR} - \theta_{k}) + B_{vR}\sin(\delta_{vR} - \theta_{k})\right],\\
Q_{vR} &= -V_{vR}^{2}B_{vR} + V_{vR}V_{k}[G_{vR}\sin(\delta_{vR} - \theta_{k}) - B_{vR}\cos(\delta_{vR} - \theta_{k})],\\
P_{k} &= V_{k}^{2}\,G_{vR} + V_{k}V_{vR}[G_{vR}\cos(\theta_{k} - \delta_{vR}) + B_{vR}\sin(\theta_{k} - \delta_{vR})],\\
Q_{k} &= -V_{k}^{2}\,B_{vR} + V_{k}V_{vR}[G_{vR}\sin(\theta_{k} - \delta_{vR}) - B_{vR}\cos(\theta_{k} - \delta_{vR})].
\end{aligned}$$

Using these power equations, the linearised STATCOM model is given below, where the voltage magnitude ?? and phase angle ?? are taken to be the state variables –

$$\begin{bmatrix} \Delta P_k \\ \Delta Q_k \\ \Delta P_{vR} \\ \Delta Q_{vR} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_k}{\partial \theta_k} & \frac{\partial P_k}{\partial V_k} V_k & \frac{\partial P_k}{\partial \delta_{vR}} & \frac{\partial P_k}{\partial V_{vR}} V_{vR} \\ \frac{\partial Q_k}{\partial \theta_k} & \frac{\partial Q_k}{\partial V_k} V_k & \frac{\partial Q_k}{\partial \delta_{vR}} & \frac{\partial Q_k}{\partial V_{vR}} V_{vR} \\ \frac{\partial P_{vR}}{\partial \theta_k} & \frac{\partial P_{vR}}{\partial V_k} V_k & \frac{\partial P_{vR}}{\partial \delta_{vR}} & \frac{\partial P_{vR}}{\partial V_{vR}} V_{vR} \\ \frac{\partial Q_{vR}}{\partial \theta_k} & \frac{\partial Q_{vR}}{\partial V_k} V_k & \frac{\partial Q_{vR}}{\partial \delta_{vR}} & \frac{\partial Q_{vR}}{\partial V_{vR}} V_{vR} \end{bmatrix} \begin{bmatrix} \Delta \theta_k \\ \frac{\Delta V_k}{V_k} \\ \Delta \delta_{vR} \\ \frac{\Delta V_{vR}}{V_{vR}} \end{bmatrix} .$$

6

NEWTON-RAPHSON COMPUTER PROGRAM IN MATLAB CODE

A computer programme suitable for the power flow study of interconnected power system of small and medium-sized is given below. The program is general, as far as the topology of the network is concerned, and caters for any numbers of PQ and PV buses. Moreover, any bus in the network may be designated to be the slack bus. Provisions are made for generator reactive limit checking and to accommodate fix shunt compensations. No transformers are represented in this base program and no sparsity techniques (Zollenkoff, 1970) are incorporated.

6.1 MAIN PROGRAM:

```
PowerFlowsData
%***- - - Main Program
PowerFlowsData; %Read system data
[YR,YI] =
YBus(tlsend,tlrec,tlresis,tlreac,tlsuscep,tlcond,shbus,shresis,shreac,ntl
,nbb,nsh);
[VM,VA,it] =
NewtonRaphson(nmax,tol,itmax,ngn,nld,nbb,bustype,genbus,loadbus,PGEN,QGEN
,QMAX,QMIN,PLOAD,QLOAD,YR,YI,VM,VA);
[PQsend,PQrec,PQloss,PQbus] =
PQflows(nbb,ngn,ntl,nld,genbus,loadbus,tlsend,tlrec,tlresis,tlreac,tlcond
,tlsuscep,PLOAD,QLOAD,VM,VA);
it%Iteration number
VM %Nodal voltage magnitude (p.u.)
```

```
VA = VA*180/pi %Nodal voltage phase angle(Deg)
PQsend%Sending active and reactive powers (p.u.)
PQrec%Receiving active and reactive powers (p.u.)
%End Main Program
```

6.2 THE ADMITTANCE MATRIX :

```
%Build up admittance matrix
function [YR,YI] =
YBus(tlsend,tlrec,tlresis,tlreac,tlsuscep,tlcond,shbus,shresis,shreac,ntl
,
nbb,nsh);
YR=zeros(nbb,nbb);
YI=zeros(nbb,nbb);
% Transmission lines contribution
forkk = 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
forkk = 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
```

6.3 THE ITERATIVE SOLUTION :

```
%Carry out iterative solution using the Newton-Raphson method
function [VM,VA,it] = NewtonRaphson(nmax,tol,itmax,ngn,nld,nbb,bustype,
genbus,loadbus,PGEN,QGEN,QMAX,QMIN,PLOAD,QLOAD,YR,YI,VM,VA)
% GENERAL SETTINGS
D = zeros(1,nmax);
flag = 0;
it = 1;
% CALCULATE NET POWERS
[PNET,QNET] =
NetPowers(nbb,ngn,nld,genbus,loadbus,PGEN,QGEN,PLOAD,QLOAD);
while ( it <itmax& flag==0 )
% CALCULATED POWERS
[PCAL,QCAL] = CalculatedPowers(nbb,VM,VA,YR,YI);
% CHECK FOR POSSIBLE GENERATOR’S REACTIVE POWERS LIMITS VIOLATIONS
[QNET,bustype] =
GeneratorsLimits(ngn,genbus,bustype,QGEN,QMAX,QMIN,QCAL,QNET, QLOAD, it,
VM, nld, loadbus);
% POWER MISMATCHES
[DPQ,DP,DQ,flag] =
PowerMismatches(nmax,nbb,tol,bustype,flag,PNET,QNET,PCAL,QCAL);
% JACOBIAN FORMATION
[JAC] = NewtonRaphsonJacobian(nmax,nbb,bustype,PCAL,QCAL,VM,VA,YR,YI);
% SOLVE FOR THE STATE VARIABLES VECTOR
D = JAC\DPQ';
% UPDATE STATE VARIABLES
[VA,VM] = StateVariablesUpdates(nbb,D,VA,VM);
it = it + 1;
end
% End function Newton-Raphson
```

6.4 NET SCHEDULED POWER CALCULATIONS :

```
%Function to calculate the net scheduled powers
function [PNET,QNET] = NetPowers(nbb,ngn,nld,genbus,loadbus,PGEN,QGEN,
PLOAD,QLOAD);
% 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
```

6.5 INJECTED BUS POWER CALCULATIONS

```
%Function to calculate injected bus powers
function [PCAL,QCAL] = CalculatedPowers(nbb,VM,VA,YR,YI)
% Include all entries
PCAL = zeros(1,nbb);
QCAL = zeros(1,nbb);
for ii = 1: nbb
PSUM = 0;
QSUM = 0;
forjj = 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
```

6.6 GENERATOR LIMITS :

```
%Function to check whether or not solution is within generators limits
function [QNET,bustype] =
GeneratorsLimits(ngn,genbus,bustype,QGEN,QMAX,QMIN,QCAL,QNET, QLOAD, it,
VM, nld, loadbus)
% CHECK FOR POSSIBLE GENERATOR'S REACTIVE POWERS LIMITS VIOLATIONS
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
ifloadbus(ii) == jj
QNET(loadbus(ii)) = QNET(loadbus(ii)) - QLOAD(ii)
```

```
end
end
end
```

```
end
end
end
%End function Generatorslimits
```

6.7 COMPUTATION OF POWER MISMATCHES

```
%Function to compute power mismatches
function [DPQ,DP,DQ,flag] =
PowerMismatches(nmax,nbb,tol,bustype,flag,PNET,QNET,PCAL,QCAL);
% 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
```

6.8 THE JACOBIAN MATRIX :

```
%Function to built the Jacobian matrix
function [JAC] =
NewtonRaphsonJacobian(nmax,nbb,bustype,PCAL,QCAL,VM,VA,YR,YI);
% JACOBIAN FORMATION
% Include all entries
JAC = zeros(nmax,nmax);
iii = 1;
for ii = 1: nbb
jjj = 1;
forjj = 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
forkk = 1: nbb
if (bustype(kk) == 1)
ii = kk*2-1;
forjj = 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;
forjj = 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
```

6.9 STATE VARIABLE UPDATING :

```
%Function to update state variables
function [VA,VM] = StateVariablesUpdates(nbb,D,VA,VM)
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
```

6.10 CALCULATION OF POWER FLOWS :

```
%Function to calculate the power flows
function [PQsend,PQrec,PQloss,PQbus] =
PQflows(nbb,ngn,ntl,nld,genbus,loadbus,tlsend,tlrec,tlresis,tlreac,tlcond
,tlsuscep,PLOAD,QLOAD,VM,VA);
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);
forkk = 1: ngn
ll = genbus(kk);
ifjj == ll
PQbus(jj) = PQbus(jj) + ( PLOAD(ii) + QLOAD(ii)*i );
end
end
end
%End function PQflows
```

7

STATCOM COMPUTER PROGRAM IN MATLAB CODE :

Following is the program written in MATLAB Code to incorporate the static compensator (STATCOM) within the Newton-Raphson power flow algorithm.

7.1 STATCOM MAIN PROGRAM :

```
% - - - Main STATCOM Program
PowerFlowsData %Function to read network data
SSCData; %Function to read the STATCOM data
[YR,YI] = YBus(tlsend,tlrec,tlresis,tlreac,tlsuscep,tlcond,ntl,nbb);
[VM,VA,it,Vvr,Tvr] = SSCNewtonRaphson(tol,itmax,ngn,nld,nbb,...
bustype,genbus,loadbus,PGEN,QGEN,QMAX,QMIN,PLOAD,QLOAD,YR,YI,VM,...
VA,NSSC,SSCsend, Xvr,TarVol,VSta,Psp,PSta,Qsp,QSta,Vvr,Tvr,VvrHi,...
VvrLo);
[PQsend,PQrec,PQloss,PQbus] = PQflows(nbb,ngn,ntl,nld,genbus,...
loadbus,tlsend,tlrec,tlresis,tlreac,tlcond,tlsuscep,PLOAD,QLOAD,...
VM,VA);
[Psend,Qsend,PSSC,QSSC] = SSCPQPowers(VM,VA,NSSC,SSCsend,Xvr,Vvr,...
Tvr);
%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)
PQsend=Psend + j*Qsend %Active and reactive powers in bus (p.u.)
PQSSC=PSSC + j*QSSC %Active and reactive powers in STACOM (p.u.)
% End of MAIN STATCOM PROGRAM
```

7.2 STATCOM CALCULATED POWERS :

```
%Function to calculate injected bus powers by the STATCOM
function [PCAL,QCAL,PSSC,QSSC] = SSCCalculatePowers(PCAL,QCAL,VM,...
```

```
VA,NSSC, SSCsend,Xvr,Vvr,Tvr);
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
```

7.3 POWER MISMATCHES FOR STATCOM

```
%Function to compute power mismatches
function [DPQ,DP,DQ,flag] =
PowerMismatches(nbb,tol,bustype,flag,PNET,QNET,PCAL,QCAL);
% POWER MISMATCHES
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
```

7.4 STATCOM ELEMENTS TO JACOBIAN MATRIX

```
%Function to add the STATCOM elements to Jacobian matrix
function [JAC] = SSCJacobian(nbb,JAC,VM,VA,NSSC,SSCsend,Xvr,TarVol,...
VSta,Psp,PSta,Qsp,QSta,Vvr,Tvr);
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
JAC(2*(nbb + ii)-1,2*(nbb + ii)) = 0.0;
end
else
JAC(2*(nbb + ii),2*(nbb + ii)) = 1.0;
end
end
```

7.5 STATCOM STATE VARIABLES UPDATING :

```
%Function to update STATCOM state variable
function [VM,Vvr,Tvr] = SSCUpdating(nbb,D,VM,VA,NSSC,SSCsend,...
TarVol,VSta, Psp,Vvr,Tvr);
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
```

7.6 SOUERCE VOLTAGES LIMITS IN THE STATCOM :

```
%Function to check source voltages limits in the STATCOM
function [Vvr] = SSCLimits(NSSC,Vvr,VvrHi,VvrLo);
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
```

7.7 CALCULATION OF THE POWER FLOWS IN THE STATCOM :

```
%Function to calculate the power flows in the STATCOM
function [Psend,Qsend,PSSC,QSSC] = SSCPQPowers(VM,VA,NSSC,SSCsend,...
Xvr,Vvr,Tvr);
for ii = 1 : NSSC
B(ii)=1/Xvr;
A1 = Tvr(ii)-VA(SSCsend(ii));
A2 = VA(SSCsend(ii))-Tvr(ii);
```

```
Psend(ii) = VM(SSCsend(ii))*Vvr(ii)*(B(ii)*sin(A2));
Qsend(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
```

8

CASE STUDIES :

8.1 THE TEST CASE :

A five-bus network containing two generators and seven transmission lines is shown in Figure 6. The network connectivity and transmission line data are given in Table 1, while generator data and load data are given in Tables 2 and 3 respectively. The power flow solution of this network is obtained by using the Newton-Raphson method. The power flow results are superimposed on the one line diagram of the network, and the bus voltage magnitudes and phase angles are given in Table 4. The STATCOM-upgraded test network and power flow results are shown in Figure 9. The STATCOM is installed at the bus lake.

Table 1 Network connectivity and transmission line data

Sending Node	Receiving Node	R (p.u.)	X (p.u.)	B (p.u.)
North	South	0.02	0.06	0.06
North	Lake	0.08	0.24	0.05
South	Lake	0.06	0.18	0.04
South	Main	0.06	0.18	0.04
South	Elm	0.04	0.12	0.03
Lake	Main	0.01	0.03	0.02
Main	Elm	0.08	0.24	0.05

Table 2 Generator data

Node	P_G (MW)	$Q_{\min}$ (MVAr)	$Q_{\max}$ (MVAr)	|V|(p.u.)
South	40	-300	300	1.0

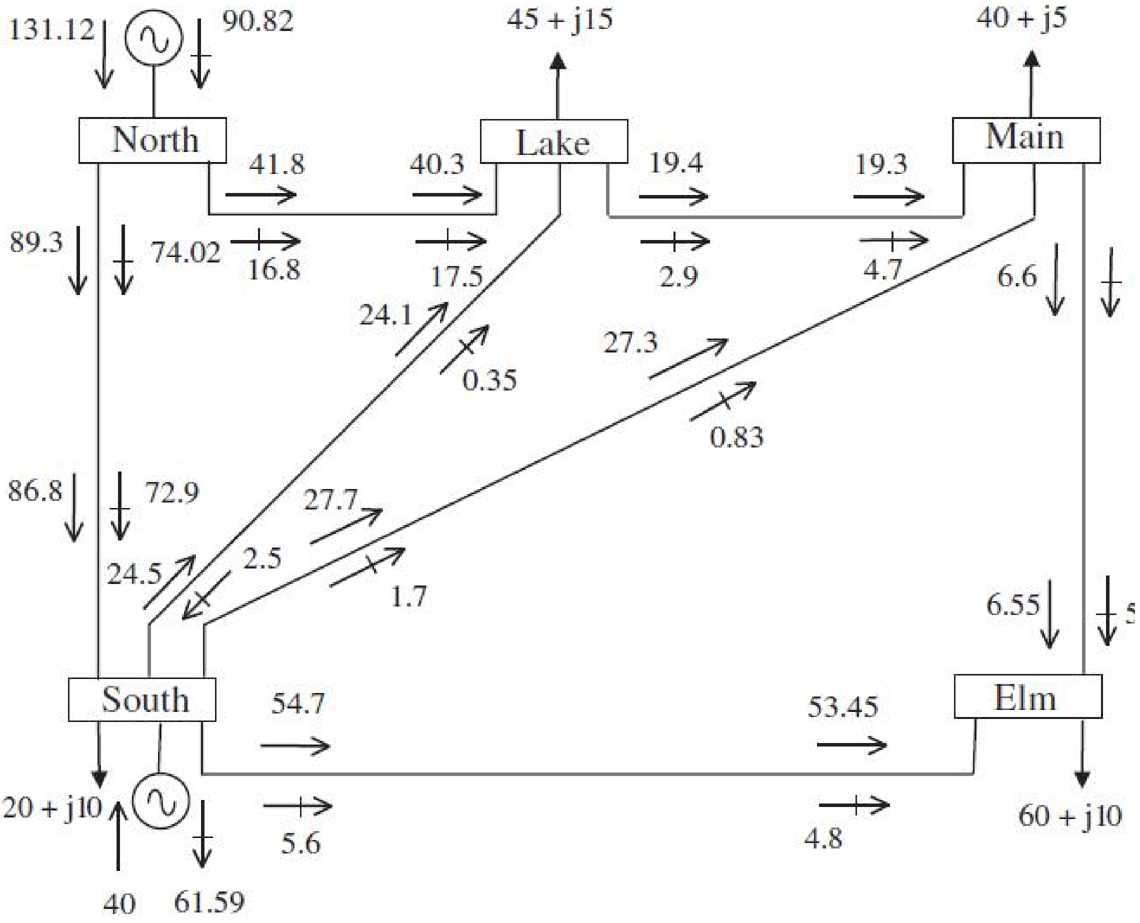

Figure 8 The five-bus test network containing two generators and seven transmission lines, and power flow results (The base case without STATCOM)

Table 3 Load data

Node	P_{load} (MW)	Q_{load} (MVAr)
South	20	10
Lake	45	15
Main	40	5
Elm	60	10

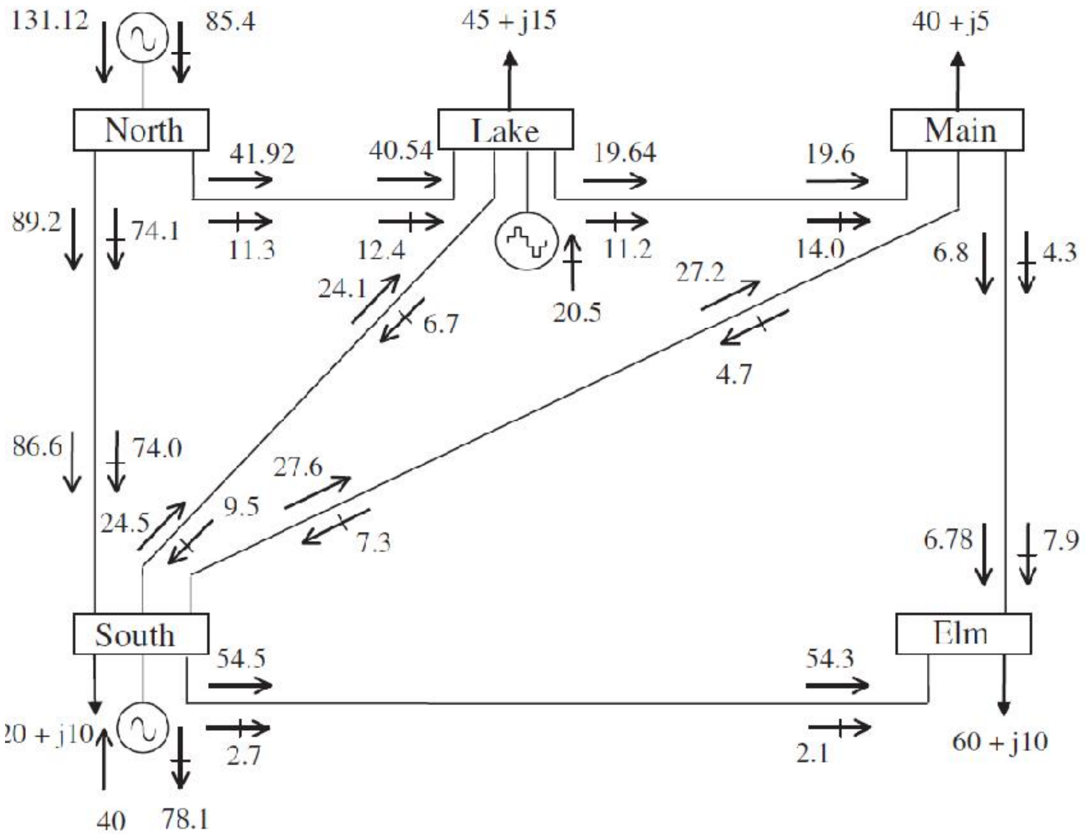

Figure 9 STATCOM –upgraded test network and power flow results

8.2 THE TEST CASE DATA :

The data of the test case are given below in the function PowerFlowsData which are suitable for use with the Newton-Raphson Matlab program.

```
%Function PowerFlowsData, to read data for the five-bus test network, is
as follows:
%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
%
%The five buses in the network shown in Figure 4.6 are numbered for the
% purpose of the power flow solution, as follows:
```

```
%North = 1
%South = 2
%Lake = 3
%Main = 4
%Elm = 5
%
%Bus data
%nbb = number of buses
%bustype = type of bus
%VM = nodal voltage magnitude
%VA = nodal voltage phase angle

nbb = 5 ;
bustype(1) = 1 ; VM(1) = 1.06 ; VA(1) =0 ;
bustype(2) = 2 ; VM(2) = 1 ; VA(2) =0 ;
bustype(3) = 3 ; VM(3) = 1 ; VA(3) =0 ;
bustype(4) = 3 ; VM(4) = 1 ; VA(4) =0 ;
bustype(5) = 3 ; VM(5) = 1 ; VA(5) =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 = 2 ;
genbus(1) = 1 ; PGEN(1) = 0 ; QGEN(1) = 0 ; QMAX(1) = 5 ; QMIN(1) = -5 ;
genbus(2) = 2 ; PGEN(2) = 0.4 ; QGEN(2) = 0 ; QMAX(2) = 3 ; QMIN(2) = -3
;
%
%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 = 7 ;
tlsend(1) = 1 ; tlrec(1) = 2 ; tlresis(1) = 0.02 ; tlreac(1) = 0.06 ;
tlcond(1) = 0 ; tlsuscep(1) = 0.06 ;
tlsend(2) = 1 ; tlrec(2) = 3 ; tlresis(2) = 0.08 ; tlreac(2) = 0.24 ;
tlcond(2) = 0 ; tlsuscep(2) = 0.05 ;
tlsend(3) = 2 ; tlrec(3) = 3 ; tlresis(3) = 0.06 ; tlreac(3) = 0.18 ;
tlcond(3) = 0 ; tlsuscep(3) = 0.04 ;
tlsend(4) = 2 ; tlrec(4) = 4 ; tlresis(4) = 0.06 ; tlreac(4) = 0.18 ;
tlcond(4) = 0 ; tlsuscep(4) = 0.04 ;
tlsend(5) = 2 ; tlrec(5) = 5 ; tlresis(5) = 0.04 ; tlreac(5) = 0.12 ;
tlcond(5) = 0 ; tlsuscep(5) = 0.03 ;
tlsend(6) = 3 ; tlrec(6) = 4 ; tlresis(6) = 0.01 ; tlreac(6) = 0.03 ;
tlcond(6) = 0 ; tlsuscep(6) = 0.02 ;
tlsend(7) = 4 ; tlrec(7) = 5 ; tlresis(7) = 0.08 ; tlreac(7) = 0.24 ;
tlcond(7) = 0 ; tlsuscep(7) = 0.05 ;
%
%Shunt data
%nsh = number of shunt elements
%shbus = shunt element bus number
%shresis = resistance of shunt element
%shreac = reactance

%+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 = 4 ;
loadbus(1) = 2 ; PLOAD(1) = 0.2 ; QLOAD(1) = 0.1 ;
loadbus(2) = 3 ; PLOAD(2) = 0.45 ; QLOAD(2) = 0.15 ;
loadbus(3) = 4 ; PLOAD(3) = 0.4 ; QLOAD(3) = 0.05 ;
loadbus(4) = 5 ; PLOAD(4) = 0.6 ; QLOAD(4) = 0.1 ;
```

```
%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;
%End of function PowerFlowsDat
```

8.3 STATCOM DATA :

```
%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 = 1;
SSCsend(1)=3; 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;

%Bus data
%nbb = number of buses
%bustype = type of bus
%VM = nodal voltage magnitude
%VA = nodal voltage phase angle

nbb = 5 ;
bustype(1) = 1 ; VM(1) = 1.06 ; VA(1) =0 ;
bustype(2) = 2 ; VM(2) = 1 ; VA(2) =0 ;
bustype(3) = 3 ; VM(3) = 1 ; VA(3) =0 ;
bustype(4) = 3 ; VM(4) = 1 ; VA(4) =0 ;
bustype(5) = 3 ; VM(5) = 1 ; VA(5) =0 ;
```

9

RESULTS

9.1 THE BASE CASE WITHOUT STATCOM

The power flows study results of the uncontrolled interconnected power system test case without connecting STATCOM obtained by using Newton-Raphson method are shown below :

```
it =

      6

VM =

      1.0600    1.0000    0.9872    0.9841    0.9717

VA =

                  0   -2.0612   -4.6367   -4.9570   -5.7649

PQsend =

 0.8933 + 0.7400i   0.4179 + 0.1682i   0.2447 - 0.0252i   0.2771 -      0.0172i
0.5466 + 0.0556i   0.1939 + 0.0286i   0.0660 + 0.0052i
```

```
PQrec =

  -0.8685 - 0.7291i  -0.4027 - 0.1751i  -0.2411 - 0.0035i  -0.2725 - 0.0083i  -
0.5344 - 0.0483i  -0.1935 - 0.0469i  -0.0656 - 0.0517i

>>
```

9.2 WITH STATCOM

```
>> StatcomPower


it =

          100

 VM =

            1.0600    1.0000    1.0000    1.0000    1.0000

VA =

           0         0    0.1421         0         0


Vvr =

           1.0032

Tvr =

         0.1421
```

```
PQsend =

                  0 +3.2221e-004i

PQSSC =

                 0 -3.2325e-004i

>>
```

9.3 COMPARISION OF RESULTS OF WITH AND WITH OUT STATCOM

The power flow results with and without connecting the STATCOM in the interconnected electric power system are shown in Table 4. The voltage magnitude in p.u. and phase angles in degrees at each bus is shown in table. On comparing the power flow results, it is seen that when the STATCOM is connected in power system, the voltage magnitudes are maintained at 1.00 p.u. at each bus while the phase

Table 4 Nodal voltages (p.u.) and phase angles (dgrees)

Network bus	Voltage magnitude (p.u.) base case	Phase angle (degrees) base case	Voltage magnitude (p.u.)with STATCOM	Phase angle (degrees) with STATCOM
North	1.0600	0	1.0600	0
South	1.0000	- 2.0612	1.0000	0
Lake	0.9872	- 4.6367	1.0000	0.1421
Main	0.9841	- 4.9570	1.0000	0
Elm	0.9717	- 5.7649	1.0000	0

angles are also maintained at 0 degree at each bus except the lake bus. At lake the phase angle is improved to 0.1421 degrees from - 4.6367 degrees – the phase angle of uncontrolled power system mode of operation.

9.4 COMMENTS

The results of power flow solution as solved by using Newton-Raphson method are given above. The method takes 6 iterations to converge. It can be observed from the results that all nodal voltages are within accepted voltage magnitude limits (i.e. 100± 6%). The largest power flow takes place in the transmission line connecting two generator buses : 89.3 MW and 74.02 MVAR leave North, and 86.8 MW and 72.9 MVAR arrive at south. This is also the transmission line that incurs higher active power loss (i.e. 2.5 MW). The active power system loss is 6.12 MW.

The operating conditions demand a large amount of reactive power generation by the generator connected at north (i.e. 90.82 MVAR). This amount is well in excess of the reactive power drawn by the system loads (i.e. 40 MVAR). The generator at south draws the excess of reactive power in the network (i.e. 61.59 MVAR). This amount includes the net reactive power produced by several of the transmission lines.

The power flow result indicates that the STATCOM generates 20.5 MVAR in order to keep the voltage magnitudes at 1.00 p.u. at each bus. Hence, the use of the STATCOM results in an improved network voltage profile.

The slack generator reduces its reactive power generation compared with the base case, and reactive power exported from North to lake reduces. The largest reactive power flow takes place in the transmission line connecting

North and South, where 74.1 MVAR leaves North and 74 MVAR arrives at South. In general, more reactive power is available in the network than in the base case, and the generator connected at South increases its share of reactive power absorption compared with the base case. As expected, active power flows are only marginally affected by the STATCOM installation.

9.5 CONCLUSION AND RECOMMENDATIONS :

This project addresses the basic theory of power flows. Building upon elementary concepts afforded by circuit theory and complex algebra, the equations for active and reactive power injections at a bus are derived. The mathematical model that describes its operation during steady-state is non-linear. For most practical situations, the power network is a very large scale system. Hence, the solutions for the non-linear set of equations, which must be reached by iteration, requires a robust and efficient numerical technique. For several decades Newton-Raphson method, with its quadratic convergence characteristics, has proved invaluable in solving the power flow problems. The additional burden imposed on the numerical solution by many constraint actions resulting from the various power system controllers in the network does not impair the ability of the Newton-Raphson method to converge in quadratic fashion. The relevant equations making up Newton-Raphson method have been coded in MatLab and the programs used to solve a classical test case. The test system is small and yet it provides sufficient realism and flexibility to explore different loading scenarios, active power generator schedules, and transmission- line parameters. This is something which certainly encourages the user to do. Hence, the Newton-Raphson method, with their strong convergence characteristics, have proved the most successful and have been warmly embraced by the industry. For improving the network voltage profile, the STATCOM stands amongst the most popular high-transmission FACTS controllers.

9.6 SUGGESTIONS FOR FURTHER WORK

The STATCOM uses the VSC as its basis building. It has been emphasised that all of the power electronic controllers produce harmonic distortion, which is an undesirable side –effect, as part of their normal operation. The various means of harmonic cancellation open to system engineers have been mentioned, such as switching control, multilevel configuration, three-phase connections, and, as a last resort, filtering equipment. This harmonic distortion cancellation is a topic for future work. In the present work, it is assumed that harmonic distortion is effectively contained at source. The mathematical modelling conducted for the STATCOM reflects this fact.

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