EEE-160004

# Electrical Power System

A Dissertation Submitted to The Department of Electrical and Electronics Engineering of Sonargaon University in Patiala Fulfillment of the Requirements for the Degree of Bachelor of Science in Engineering.

# SONARGAON UNIVERSITY

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## Candidates' Declaration

It is declared hereby that this thesis paper or any part of it has not been submitted to anywhere else for the award of any degree.

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## Certificate

This is to certify that the thesis entitled "Power Flow Analysis and Micro-Controller Based Reactive Power Compensation" by Md. Faruk Hossain (1403003100) Mostfiz (1403003109) Protab sen (1403003079) Korban ali (1403003110) have been carried out under my supervision.

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# Abstract

In high voltage ac system, the system voltage and frequency changes rapidly with the variation of load. The reactive power also changes with the variation of load which affects the system voltage therefore it is necessary to analyze the power system in order to determine system parameters and its variation under various load conditions In this thesis work, in order to get an idea about the power flow nature of the transmission system of Bangladesh, 42 buses are considered. The fast decoupled method is used for analyzing the power flow of 42 buses and later MATLAB coding is used for determining the buses having problem in reference system voltage. The proposed decoupled method is faster and easier than the conventional method. For reactive power compensation, the required capacitive or inductive bank is determined by using logical flow chart. The size of the reactor bank is calculated by conventional method and the thryristor based switching technique is used for connecting the reactor bank with the transmission line according to the system requirement. Since fast switching is required for maintaining the system voltage constant under various load conditions therefore Microcontroller is used for controlling the switching devices. The Microcontroller provides necessary gate pulses to the Triacs which perform the switching action for connecting either the capacitor or inductor bank with the system. The connected capacitor and inductor also acts as a harmonic suppressor in case of harmonic effect in the transmission line. The proposed method of power flow analysis and reactive power compensation can be applied in any complicated power system network.

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# Introduction

VAR compensation is defined as the management of reactive power to improve the performance of ac power systems [1]. The concept of VAR compensation embraces a wide and diverse field of both system and customer problems, especially related with power quality issues, since most of power quality problems can be attenuated or solved with an adequate control of reactive power [1]. In general, the problem of reactive power compensation is viewed from two aspects: load compensation and voltage support [9]. In load compensation the objectives are to increase the value of the system power factor, to balance the real power drawn from the ac supply, compensate voltage regulation and to eliminate current harmonic components produced by large and fluctuating nonlinear industrial loads [2], [3]. Voltage support is generally required to reduce voltage fluctuation of a transmission line. Reactive power compensation in transmission systems also improves the stability of the ac system by increasing the maximum active power that can be transmitted [4].

The most of the power plant is situated in east zone of Bangladesh due to available fuel like natural gas [23]. On the other hand when the power is transmitted in the west zone or other long distance the angle between voltage and current is increased due to reactance of the transmission line [5]. Moreover the rapid change of load is caused the leading current and lagging current on the transmission line. The identified 42 buses of Bangladesh are analyzed by the MATLAB of fast decoupled method. The size of the capacitor bank and inductor bank is determined by normal phasor diagram of transmission line [3]. The proposed method is more efficient to analysis the power flow than the traditional method. Where the capacitor bank is used to compensate the lagging current and inductor bank is used to compensate the leading current [10].

In order to rapid change of voltage of the bus, the Triac is used to switch inductor and capacitor bank of the transmission line [9]. Generally the electromechanically switch is used to switch the capacitor bank and inductor bank in the transmission line which causes the harmonics effect of the voltage and current signal [10]. On the other hand the electromechanical switch needs more time to switch. In static VAR system (SVS) the Triac is used for smart switching [11]. And the switching of capacitor bank and inductor bank depends on the voltage of the transmission line. The Microcontroller takes the decision to switch the capacitor bank or inductor bank. The Microcontroller switching techniques is more acceptable due to less external circuit to switch the

Triac and it is programmable device [12]. The flow chart of proposed method is applied for selected 4- bus system. The result is more efficient than the traditional method. Again the proposed method is applied to selected 7-bus system where the proposed method is more efficient than the traditional method. The proposed method can be applied to analysis power flow in more complicated power system. It is very simple and easy to analysis the power flow. The modern SVS system provides quality power where the voltage and frequency is in stable condition [25]. The most common method for this compensation is to add capacitor banks and inductor banks to the system.

# Chapter 1: Power and Power System

Generally energy exists in different forms in nature but the most important form is the electrical energy. When this energy is worked with respect to the time then it is called electrical power. So power is the rate of the transferred energy by the system [3]. There are basically three types of power which are real, reactive and apparent power. Any power system network comprises of generation, transmission and distribution system. The fuel for electricity generation comes from conventional and unconventional sources. The conventional sources are petroleum oil, coal, propane, and natural gas whereas the unconventional sources are bio-diesel, bio-alcohol, non-fossil methane, non-fossil natural gas and renewable like solar, wind, geothermal and others [24]. Most of the power plants in Bangladesh are either steam turbine or gas turbine based. In order to ensure quality power it's necessary to keep the system voltage and frequency constant irrespective of the variation of load. Moreover for the sake of system stability, the rated voltage, current, frequency, real power and reactive power need to be controlled within rated values. The variation of load greatly affects the system voltage which is also related with the real and reactive power of the system [22].

## 1.1 Power and Power Related Terminology

**Power:** Electric power is the rate at which electrical energy is transferred by an electric circuit [23]. For any system such as in figure 1.1, the power delivered to a load at any instant is defined by the product of the applied voltage and the resulting current; that is,

$$p = vi \tag{1.1}$$

In the case, since $i$ and $v$ are sinusoidal quantities, where

$$v = V_m \sin(\omega t + \theta) \tag{1.2}$$

$$i = I_m \sin \omega t \tag{1.3}$$

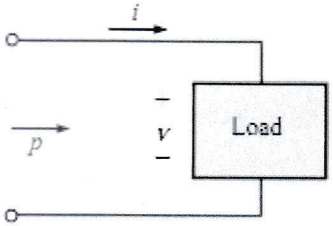



Figure 1.1: Power delivering to load

When the load is purely resistive,$\theta$ is equal to zero degree whereas in case of purely inductive and capacitive load $\theta$ is positive 90 degree or negative 90 degree, respectively. For an inductive electrical network current lags voltage by 90 degree and for a capacitive electrical network current lead voltage by 90 degree. Substituting the above equations for $v$ and $i$ into the power equation results in

$$p = V_m I_m \sin\omega t \sin(\omega t + \theta) \tag{1.4}$$

Applying a number of trigonometric identities, the following form for the power equation results.

$$p = VI\cos\theta\,(1 - \cos 2\omega t) + VI\sin\theta\,(\sin 2\omega t) \tag{1.5}$$

Where$V$ and$I$ are the rms values. The conversion from peak values$V_m$ and$I_m$to rms values resulted from the operations performed using the trigonometric identities. Form the equation (1.5) it is expended to the form

$$p = \underbrace{VI\cos\theta}_{Average} - \underbrace{VI\cos\theta}_{Peak}\underbrace{VI\cos 2\omega t}_{2x} + \underbrace{VI\sin\theta}_{Peak}\underbrace{VI\sin 2\omega t}_{2x} \tag{1.6}$$

There are two obvious points that can be made. First, the average power still appears as an isolated term that is time independent. Second, both terms that follow vary are a frequency twice that of the applied voltage of current, with peak values having a very similar format. There are three types of power which are mentioned as follows.

**Real Power:** From equation (1.6) avoiding time dependent part, there is a time independent part of$VI\cos\theta$. Due to change the magnitude of corresponding current and voltage with respect to time must be avoided for purely resistive load [23]. In more details, for a purely resistive circuit which is shown in Fig. 1.2 where $v$ and $i$ are in phase and$\theta = 0°$. So according to the equation (1.5),

$$p_R = VI\cos(0°)\,(1 - \cos 2\omega t) + VI\sin(0°)(\sin 2\omega t)$$

Or $\quad p_R = VI(1 - \cos 2\omega t)$

Or $\quad p_R = VI(1 - \cos 2\omega t)$ (1.7)

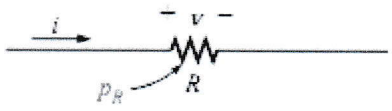



Figure 1.2: Power is delivering to a purely resistive load.

Where$VI$the average or dc is is term and$-\cos 2\omega t$is a negative cosine wave with twice the frequency of either input quantity ($v$or $i$) and a peak value of$VI$. The total power delivered to a resistor will be dissipated in the form of heat.

$$P = VI\cos\theta \tag{1.8}$$

But it is recommended to any appliance, the real power is the simply product of current and corresponding voltage of cosine. Where $\cos\theta$ denotes the power factor.

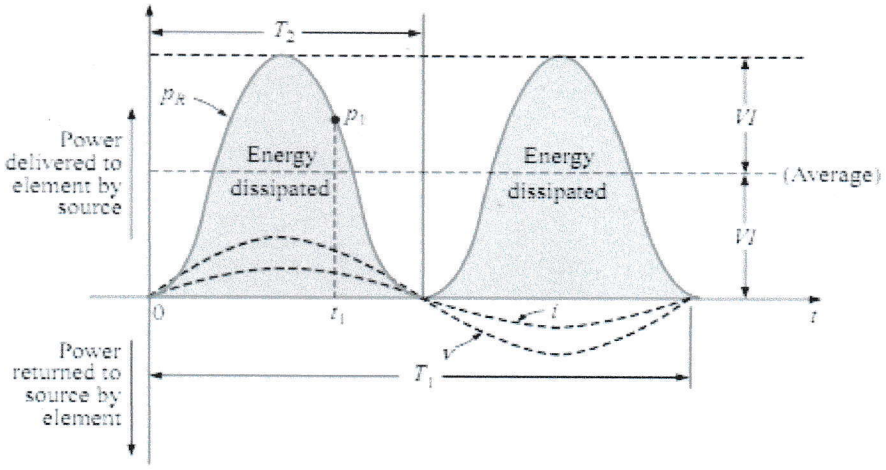



Figure 1.3: Power versus time for a purely resistive load.

Plotting the waveform for $p_R$ which is shown in the figure 1.3, It is seen that

$T_1$ =Period of input quantities

$T_2$ =Period of power curve $p_R$

Note that in figure 1.3 the power curve passes through two cycles about its average value of $VI$ for each cycle of either ($v$ or $i$) ($T_1 = 2T_2$ or$f_2 = 2f_1$). Since the peak and average values of the power curve are the same, the curve is always above the horizontal axis. This indicates that the total power delivered to a resistor is dissipated in the form of heat. The power returned to the source is represented by the portion of the curve below the axis, which is zero in this case [23]. The power dissipated by the resistor at any instant of time $t_1$can be found by simply substituting the time $t_1$into equation (1.7) to find $p_1$indicated in figure 1.3.

**Reactive power:** For a purely inductive circuit which is shown in the figure 1.4 where $v$ leads $i$ by 90 degree, therefore in equation (1.5) $\theta = 90°$. Substituting $\theta = 90°$ into the equation yields

$$p_L = VI\cos(90°)\,(1 - \cos 2\omega t) + VI\sin(90°)\,(\sin 2\omega t)$$

$$p_L = VI\sin 2\omega t \qquad (1.9)$$

Where$VI\sin 2\omega t$is a sine wave with twice the frequency of either input quantity ($v$ or $i$) and a peak value of$VI$



Figure 1.4: Delivering the power for a purely inductive load.

Note that over one full cycle of $p_L(T_2)$, the area above the horizontal axis in Figure 1.5 is exactly equal to that below the axis. This indicates that over a full cycle of $p_L$, the power delivered by the source to the inductor is exactly equal to that returned to the source by the inductor. The net flow of power to the pure (ideal) inductor is zero over a full cycle, and no energy is lost in the transaction.

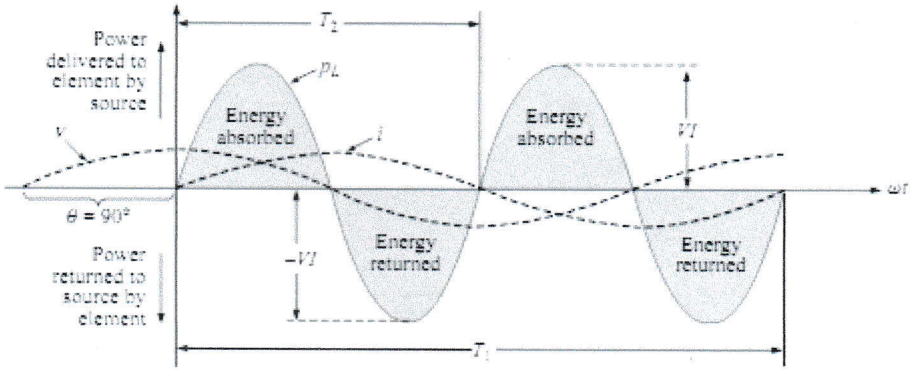



Figure 1.5: The power curve for a purely inductive load.

Plotting the waveform for $p_R$ which is shown in the figure 1.5, It is seen that

$T_1$ =Period of input quantities

$T_2$ =Period of$p_L$curve

The power is absorbed or returned by the inductor at any instant of time$t_1$ is found simply by substituting$t_1$ into equation (1.9). The peak value of the curve$VI$ is defined as the reactive power associated with a pure inductor. In general, reactive power associated with any circuit is defined to be $VI \sin\theta$, a factor appearing in the second terms of equation (1.5).

$$Q = VI \sin\theta \tag{1.10}$$

Note that it is the peak value of that term of the total power equation that produces no net transfer of energy. The symbol for reactive power is $Q$, and its unit is volt-ampere reactive (VAR). Where $\theta$ is the phase angle between $V$and $I$.

**Apparent Power:** The apparent power is the actual power delivered to the load is determined by the product of the applied voltage and current [23]. However, the power factor$(\cos\theta)$of the load affects the power dissipated to the loads. The apparent power is represented symbolically by$S$. Sicne it is simply the product of voltage and current, its units are volt-amperes (VA). Its magnitude is determined by

$$S = VI \tag{1.11}$$

**The Relationship among the Real, Reactive and Apparent Power**

In alternating current circuits, energy storage elements such as inductance and capacitance may result in periodic reversals of the direction of energy flow. The portion of power flow that, averaged over a complete cycle of the AC waveform, results in net transfer of energy in one direction is known as real power (also referred to as active power). That portion of power flow due to stored energy that returns to the source in each cycle is known as reactive power.

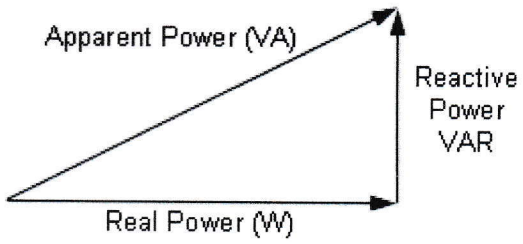



Figure 1.7: Power Triangle.

Figure 1.7 shows relationship among real power, reactive power and apparent power can be expressed by representing the quantities as vectors. Real power is represented as a horizontal vector and reactive power is represented as a vertical vector [3]. The apparent power vector is the hypotenuse of a right triangle formed by connecting the real and reactive power vectors. This representation is often called the power triangle. Using the Pythagorean Theorem, the relationship among real, reactive and apparent power is

$$(Apparent\ power)^2 = (Real\ power)^2 + (Reactive\ power)^2 \quad (1.12)$$

Real and reactive powers can also be calculated directly from the apparent power, when the current and voltage are both sinusoids with a known phase angle between them

$$(Real\ power) = (Apparent\ power)\cos\theta \quad (1.13)$$

$$(Reactive\ power) = (Apparent\ power)\sin\theta \quad (1.14)$$

The ratio of real power to apparent power is called power factor and is a number always between 0 and 1. Where the currents and voltages have non-sinusoidal forms, power factor is generalized to include the effects of distortion. Thus the above relation can be expressed as

$$S = P + jQ \quad (1.15)$$

## 1.2 Power System Network

**Generation:** Electricity generation is the process of generating electricity from other forms of energy. The fundamental principles of electricity generation are discovered during the 1820s and early 1830s by the British scientist Michael Faraday. The electricity is generated by the movement of a loop of wire, or disc of copper between the poles of a magnet [18]. For electric utilities, it is the

first process in the delivery of electricity to consumers. The other processes, electricity transmission, distribution, and electrical power storage and recovery using pumped storage methods are normally carried out by the electrical power industry. Electrical power flow starts from the power plant. It is assembly of equipment that produces and delivers mechanical and electrical energy. A generating station essentially employs a prime mover coupled to an alternator for the production of electric power. The prime mover (e.g. steam turbine, water turbine, etc.) converts energy form other form into mechanical energy. The alternator converts energy of the prime mover into electrical energy. The electrical energy produced by the generating station transmitted and distributed with the help of conductors to various consumers. The electrical equipments of a power station include generator, exciter, transformer, reactor, switchboard and control board.

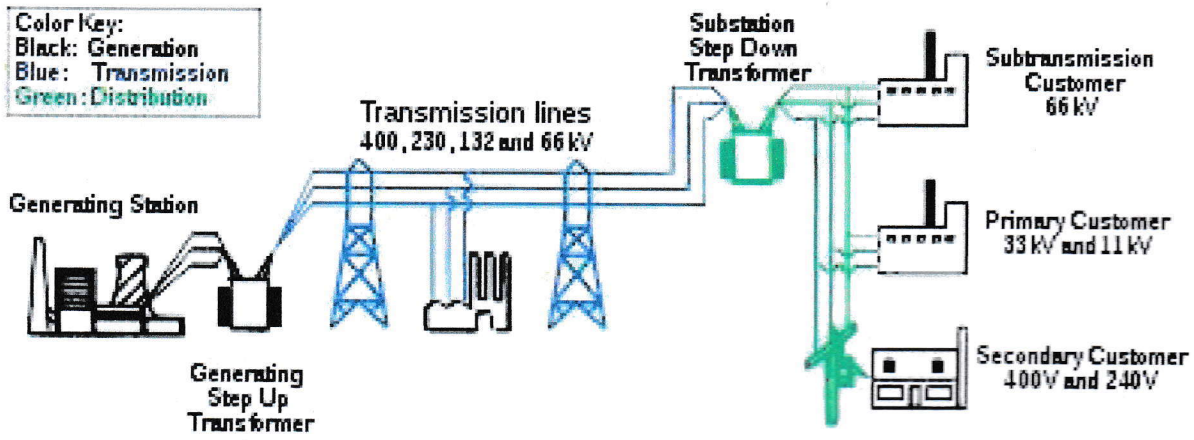



Figure 1.8: General power system with generation transmission and distribution

Step up transformer is used for step up the generating voltage to transmission voltage [19]. At the transmission substation the voltage is stepped down to medium voltage. The feeders carry power to the distribution substation [7]. At the distribution substation the voltage is steped down to low distribution voltage. Distributors are used to supply power to the consumers. A general feature of power system is shown in figure 1.8. The voltage is stepped up for long transmission line. Here generally the voltage levels are the 400kV/230kV/132kV. But for 230kV to 760kV transmission line is already implemented in USA it is known as extra high voltage transmission line [2]. And also another 760kV line is already found in Europe, which is known as ultra high voltage transmission line. However the high voltage is stepped down in substation for sub-transmission line. Here a lot of large consumers are connected with 66kV or 33kV line. But this voltage level is not suitable for household or small industries, for that reason it is need to step down to 400V or 240V again.

Again there are different types of generation plant. And for those purpose different types of fuel is used.

**Conventional Fuel**

Conventional fuels include: fossil fuels petroleum oil, coal, propane, and natural gas etc, nuclear materials and artificial radioisotope fuels that are used in nuclear reactors[3].

**Diesel Power Station:** A generating station in which diesel engine is used as the prime mover for the generation of electrical energy is known as diesel power station [3]. In a diesel power station, diesel engine is used as the prime mover. The diesel burns inside the engine and the products of this combustion act as the working fluid to produce mechanical energy [3]. The diesel engine drives the alternator which converts mechanical energy into electrical energy. As the generation cost is considerable due to high price of diesel, therefore, such power stations are only used to produce small power. Although steam power stations and hydro-electric plants are invariably used to generate bulk power at cheaper cost, yet diesel power stations are finding favor at places where demand of power is less, sufficient quantity of coal and water is not available and the transportation facilities are inadequate. These plants are also used as standby sets for continuity of supply to important points such as hospitals, radio stations, cinema houses and telephone exchanges.

**Gas Turbine Power Station:** A generating station which employs gas turbine as the prime mover for the generation of electrical energy is known as gas turbine power plant [3]. In a gas turbine power plant, air is used as the working fluid. The air is compressed by the compressor is led to the combustion chamber where heat is added to air, thus raising its temperature. Heat is added to the compressed air either by burning fuel in the chamber or by the use of air heaters. The hot and high pressure air from the combustion chamber is then passed to the gas turbine where it expands and does the mechanical work. The gas turbine drives the alternator which converts mechanical energy into electrical energy. It may be mentioned here that compressor, gas turbine and the alternator are mounted on the same shaft so that a part of mechanical power of the turbine can be utilized for the operation of the compressor. Gas turbine power plants are being used as standby plants for hydro-electric stations, as a starting plant for driving auxiliaries in power plants etc.

**Coal Power Stations**: A generating station which converts heat energy of coal combustion into electrical energy is known as a steam power station. Steam is produced in the boiler by utilizing the heat of coal combustion. The steam is then expanded in the prime mover and is condensed in a condenser to be fed into the boiler again. The steam turbine drives the alternator which converts

mechanical energy of the turbine into electrical energy. This type of power station is suitable where coal and water are available in abundance and a large amount electric power is to be generated.

**Nuclear Power Station:** The nuclear energy is converted into electrical energy. In nuclear power station, heavy elements such as Uranium ($U^{235}$) or Thorium ($Th^{232}$) are subjected to nuclear fission in a special apparatus known as a reactor. The heat energy thus released is utilized in raising steam at high temperature and pressure. The steam runs the steam turbine which converts steam energy into mechanical energy into electrical energy. The most important feature of a nuclear power station is that huge amount of electrical energy can be produced from a relatively small amount of nuclear fuel as compared to other conventional types of power stations. It is found that complete fission of 1 kg of Uranium ($U^{235}$) can produce as much energy as can be produced by the burning of 4500 tons of high coal. Although the recovery of principle nuclear fuels (i.e. Uranium ($U^{235}$) and Thorium ($Th^{232}$) is difficult and expensive, yet the total energy content of the estimated world reserves of these fuels are considerably higher than those of conventional fuels namely coal, oil and gas.

**Nonconventional Fuel**

Alternative fuels, known as non-conventional or advanced fuels, are any materials or substances that can be used as fuels, Some well-known alternative fuels include water, biodiesel, bioalcohol(methanol, ethanol, butanol), chemically stored electricity (batteries and fuel cells), hydrogen, non-fossil methane, non-fossil natural gas, vegetable oil and other biomass sources.

**Solar Energy:** Every day, the sun radiates an enormous amount of energy called solar energy. It radiates more energy in one second than the world has used since time began. This energy comes from within the sun itself. Like most stars, the sun is a big gas ball made up mostly of hydrogen and helium gas. The sun makes energy in its inner core in a process called nuclear fusion. Solar energy can also be used to produce electricity. Two ways to make electricity from solar energy are photo-voltaic and solar thermal systems. Photovoltaic comes from the words photo meaning light and volt, a measurement of electricity. Solar cells are made up of silicon, the same substance that makes up sand. Silicon is the second most common substance on Earth. Solar cells can supply energy to anything that is powered by batteries or electrical power. Electricity is produced when sunlight strikes the solar cell, causing the electrons to move around. The action of the electrons starts an electric current. Like solar cells, solar thermal systems also called concentrated solar power (CSP) which uses solar energy to produce electricity in a different way. Most solar thermal systems use a solar collector with a mirrored surface to focus sunlight onto a receiver that heats a liquid. The

super-heated liquid is used to make steam to produce electricity in the same way that coal plants do. There are nine solar thermal power plants in the Mojave Desert that together produce 360 MW of electricity.

**Wind Energy:** Wind is simply air in motion. Like old-fashioned windmills, today's wind turbines use blades to capture the wind's kinetic energy [25]. Wind turbines work because they slow down the speed of the wind. When the wind blows, it pushes against the blades of the wind turbine, making them spin. They power a generator to produce electricity. Generally the wind turbines comprises of blades, shafts, gears, a generator, and a cable. These parts work together to convert the wind's energy into electricity. The wind blows and pushes against the blades on top of the tower, making them spin. The turbine blades are connected to a low-speed drive shaft. When the blades spin, the shaft turns. The shaft is connected to a gearbox. The gears in the gearbox increase the speed of the spinning motion on a high-speed drive shaft. The high-speed drive shaft is connected to a generator. As the shaft turns inside the generator, it produces electricity. The electricity is sent through a cable down the turbine tower to a transmission line. The amount of electricity that a turbine produces depends on its size and the speed of the wind. Wind turbines come in many different sizes.

**Hydro-Electric Power Station:** It is power generation station where potential energy of water is utilized as a high level for the generation of electrical energy is known as a hydro-electric power station [3]. Hydro-electric power stations are generally located in hilly areas where dams can be built contently and large water reserves can be obtained. In a hydro-electric power station, water height is created by constructing a dam across a river or a lake. From the dam, water is led to a water turbine which converts hydraulic energy (i.e. product of head and flow of water) into mechanical energy

**Transmission:** The transmission system of an area is known as grid. The different grids are interconnected through tie lines to form a regional grid and the different regional grids are further interconnected to form a national grid. Each grid operates independently. However, power can be transmitted from one grid to another over the tie lines, under conditions of the sudden loss of generation or increase in load. The three-phase power leaves the generator and enters a transmissionsubstation at the power plant. This substation uses large transformers to convert the generator's voltage (which is at the thousands of volts level) up to extremely high voltages for long-distance transmission on the transmission grid.

**Distribution:** For power to be useful in a home or business, it comes off the transmission grid and is stepped-down to the distribution grid. This may happen in several phases. The place where the conversion from transmission to distribution occurs is in a power substation. A power substation typically does two or three things: It has transformers that step transmission voltages (in the tens or hundreds of thousands of volts range) down to distribution voltages (typically less than 10,000 volts). It has a bus that can split the distribution power off in multiple directions. It often has circuit breakers and switches so that the substation can be disconnected from the transmission grid or separate distribution lines can be disconnected from the substation when necessary. The secondary substation the voltage stepped down to 33kV, 11kV and power is fed into the primary distribution system. The 33kV or 11kV distribution lines (usually known as feeders) originate from the secondary substation and terminate in distribution substation. The distribution substation consists of pole-mounted transformers located on the road side in large multi-stored buildings, the distribution transformers are located within the building itself. These transformers step down the voltage to 400V. The 400V distribution lines (or distributor) are laid along the roads and service connections to the consumers are tapped off from the distributors. A single phase circuit requires two conductors. A 3-phase ac circuit, using the same size conductors as the single phase circuit, can carry three times the power which can be carried by a single phase circuit and use three conductors for the 3-phase and the one conductor for the neutral. In fact, a balanced 3-phase circuit does not require the neutral conductor but in un-balanced system the neutral conductor is required. The distributor's 3-phase 4-wire circuits because a neutral wire is necessary to supply the single phase loads of domestic and commercial consumers.

## 1.3 Overall Power Systems Scenario of Bangladesh

Figure 1.9 shows the layout of ac power supply network of Bangladesh by a block diagram electrical energy is generated by three-phase synchronous generators. The generation voltages are usually 11kV. This voltage is too low for transmission over long distance. It is therefore, stepped upon 220kV or more by means of step-up transformer. At that voltage, the electrical energy is transmitted to a bulk power substation where energy is supplied from several power stations. The voltage at these substations is stepped down to 66kV in Bangladesh and fed to the sub-transmission system for onward transmission and distribution sub-stations. These substations are located in the vicinity of the load. The voltage is further stepped down to 33kV and 11kV. Large industrial consumers are supplied at the primary distribution level of 33kV while smaller industrial consumers are supplied at 11kV.

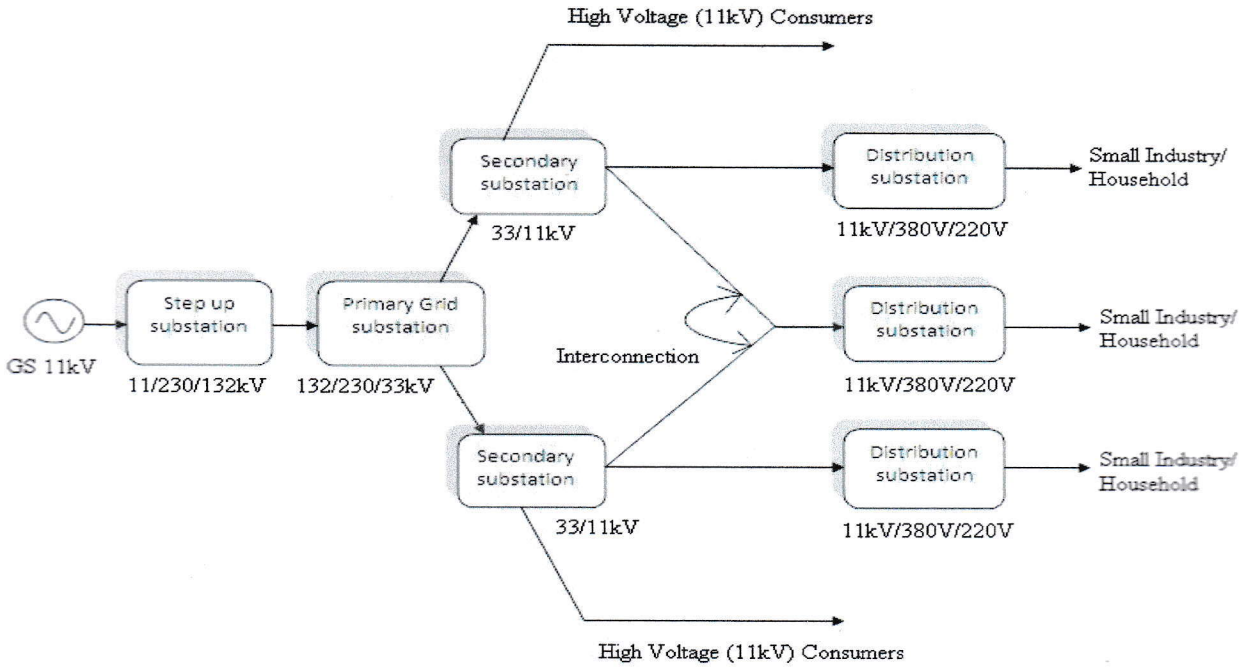



Figure 1.9: Overall Power system of Bangladesh.

The voltage is stepped down further by distribution transformers located in residential and commercial areas, where it is supplied to household and small industrial consumers at the secondary distribution level of 220V and 380V respectively [24].

## 1.4Stability Problem in Power System

Stability studies which evaluate the impact of disturbances on the electromechanical dynamic behavior of power system are of two types' transient and steady state. Transient stability studies are very commonly undertaken by electric planning departments responsible for ensuring proper dynamic performance of the system. The system models used in such studies are extensive because present day power systems are vast, heavily interconnected system with hundreds of machines which can interact through the medium of their extra-high-voltage and ultra-high-voltage networks [1]. These machines have associated excitation systems and turbines-governing control system which in some but not all cases are modeled in order to reflect properly correct dynamic performance of the system. When the resultant nonlinear differential and algebraic equations of the overall system are to be solved, then either direct methods or iterative step-by-step procedures must be used. In this chapter it is emphasized that transient stability consideration and introduce basic iterative procedures used in transient stability studies encountered in stability analysis.

A power system is in a steady-state operating condition when all the measured (or calculated) physical quantities describing the operation condition of the system can be considered constant for

purpose of analysis. When operating in a steady-state condition when a sudden change or sequence of changes occurs in one or more of the parameters of the system, or in one or more of its operating quantities, it is said that the system has undergone a disturbance from its steady-state operating condition [5]. Disturbances can belarge or small depending of their origin. Transmission system faults, sudden load changes, loss of generating units, and line switching are example of large disturbances. When the power system is operating in a steady-state condition and it undergoes change which can be properly analyzed by its dynamic and algebraic equations, it is said that a small disturbances has occurred. A change in the gain of the automatic of voltage regulator in the excitation system of a large generating unit could be an example of a small disturbance. The power system is steady-state stable for a particular steady-state operating condition of following a small disturbance, it returns to essentially the same steady-state condition of operation. However, when following a large disturbance, a significantly different but acceptable steady-state operating condition is attained, it is called transient stable.

Steady-state stability studies are usually less extensive in scope than transient stability studies and often involve a single machine operating into an infinite bus or just a few machines undergoing one or more small disturbances. Thus, steady-state stability studies examine the stability of the system under small incremental variations in parameters or operating conditions about a steady-state equilibrium point. The nonlinear differential and algebraic equations of the system are replaced by a set of linear equations which are then solved by methods of linear analysis to determine when the system is steady-state stable.

Since transient stability studies involve large disturbance, linearization of the system equations is not permitted. Transient stability is sometimes studied on a first-swing rather than a multiswing basis. Firsts-wing transient stability studies use a reasonably simple generator model consisting of the transient internal voltage $E'_i$ behind transient reactance $X'_d$; in such studies the excitation system and turbine-governing control systems of the generating units are not represented. Usually, the time period under study is the first second following a system fault or other large disturbance. When the machine of the system is regarded as being transiently stable. Multiswing stability studies extend over a longer study period, and considered since those can affect the dynamic performance of the units during the extended period. Machine models of greater sophistication are than needed to properly reflect the behavior of the system.

Thus, excitation system and turbine-governing control systems may or may not be represented in steady-state and transient stability studies depending on the objectives. In all stability studies the

objectives is to determine whether or not the rotors of the machines being perturbed returns to constant speed operation. Obviously, this means that the rotor speeds have departed at least temporarily from synchronous speed. To facilitate consumption, three fundamental assumptions therefore are made in all stability studies.

Only synchronous frequency currents and voltage are considered in the stator winding and the power system. Consequently, dc offset currents and harmonic components are neglected. Symmetrical components are used in the representation of unbalanced faults. Generated voltage is considered unaffected by machine speed variations.

These assumptions permit the use of phasor algebra for the transmission network and solution by power-flow techniques using 50Hz parameters. Also negative and zero-sequences networks can be incorporated into the positive sequence network at the fault point. As the three-phase balanced faults are generally considered. However, in some special studies circuit-breaker clearing operation may be such that consideration of unbalanced conditions is unavoidable.

## 1.5 Power System Analysis for Quality Power

The word quality power means the proper combination of real power and reactive power and also frequency. In the view of household consumers for normal household appliances need proper active power with stable frequency [6]. And for small rotating machine like motors need both real and reactive power for producing magnetic flux. The reactance is much greater than resistance of the transmission line. For no load or lightly loaded long transmission line, the receiving end voltage is higher than sending end voltage due to transmission line capacitance. It is known as Ferranti effect [2]. As a result the connected load can be destroyed due to over voltage. Again due to connect lots of inductive load with line it can cause the high reactive power. From power triangle analysis it is observed that when reactive is increased in a system the active power must be decreased where the total apparent power is constant in the system. Another effect is power factor; the power factor is defined as the ratio of the active power and volt-amperes.

$$powerfactor = \frac{P}{S} = \frac{P}{VI} \tag{1.16}$$

The power factor is the cosine of the phase angle $\varphi$ between voltage and current for sinusoidal waveforms.

$$powerfactor = \cos\varphi$$

Therefore from equation (1.16) it can be written

$$\cos\varphi = \frac{P}{VI}$$

Or $P = VI\cos\varphi$

Or $I = \frac{P}{V\cos\varphi}$ (1.17)

Equation (1.17) shows that the current is affected by the power factor. The supply voltage $V$ is kept fairly constant. When given power $P$ rquired by the load, the current $I$ taken by the load varies inversely as the load power factor $\cos\varphi$. It is observed that a given load taken more current at a low power factor than it does at a high power factor. The undesirable effects of operating a load at a low power factor are due to larger current required at low power factor. The important disadvantages of low power factor are higher currents require larger cables, switchgears, transformers, alternators etc [7]. As a result the capital cost of the equipment is increased. This is, uneconomical from the supplier's point of view. Higher currents give rise to higher copper losses in the system and therefore the efficiency of the systems is reduced. Also, the cost of energy loss in the system is increased. Higher currents produce larger voltage drop in cables and other apparatus. This results in poor voltage regulation. The voltage regulation is defined as the change in voltage between the no-load and full-load conditions. To keep the consumer's voltage within the prescribed limits, the cost of the apparatus for compensating voltage drop increase.

# Chapter 2: Reactive Power Compensation for Power Stability

The real and reactive power is the cosine and sine components of the active power. Basically the real and reactive power is consumed by the real and reactive components of the load [23]. The consumption of real and reactive power varies with the variation of load which also affects the system voltage and frequency. In any alternating current system, when the voltage and current go up and down at the same time, only real power is transmitted and when there is a time shift between voltage and current both active and reactive power are transmitted [3]. For system stability its necessary to control the reactive power within the rated value however the reactive power is necessary for producing revolving magnetic field for rotating machine [16]. The series compensation, shunt compensation and synchronous condenser are the traditional methods to compensate the reactive power in the transmission line [9]. In the modern technique, the static VAR compensation (SVC) is used to compensate reactive power, whereas thyristor is used for harmonics free switching action. In static VAR system (SVS), the Thyristor Switched Capacitor (TSC), Thyristor-Controlled Reactor (TCR), Combined TSC and TCR are used to compensate the reactive power [10].

## 2.1 Reactive Power and Reactive Power Compensation

Electrical Power is transmitted from generating stations to consumers via transmission network. The reactive power is required to generate the magnetic field of rotating machines [21]. However the reactive power is required to keep to a minimum level for the system stability. The inductive reactive-power requirement of an asynchronous machine can be compensated with a capacitor bank, a synchronous machine or a special current converter (power factor correction) [6]. This is defined as reactive power compensation. The energy required for generating the magnetic field no longer flows in the supply network to the generator but only between the asynchronous machine and the capacitor bank or synchronous machine [1]. In practice, it is difficult to maintain the balance of reactive powers because of the varied unpredictable demand of the consumers. Therefore an unbalance always exists between the supply and demand conditions of reactive power which causes the variation of supply voltage [2]. Where active power is only supplied by generators, reactive power is supplied from several sources. A list of generators and consumers of reactive power is as follows:

1. Generators of $Q$
   (a) Synchronous generators and synchronous motors
   (b) Static capacitors

(c) Distributed capacitance of overhead lines and cables

2. Consumers of $Q$

   (a) Synchronous machines

   (b) Inductive static loads

   (c) Inductive motors

   (d) Distributed inductances of overhead lines and cables

   (e) Transformers inductance

Lightly loaded transmission lines or lines under no-load conditions supply reactive power because of their shunt capacitance. When the lines are fully loaded, they absorb reactive power. Transformers absorb low reactive power under no-load conditions. Fully loaded transformers are absorbed high values of reactive power [2]. Inductive reactors absorb reactive power [2]. And it is connected in series of parallel with the networks. The series reactors are used for limiting the fault currents, shunt reactors are used for reactive power control. Shunt reactors are connected in the transmission circuit during light-load condition. Capacitors generate reactive power and connected in series or parallel with the system. Series capacitors compensate the line reactance in long overhead lines and thus improve the stability limit. Shunt capacitors are used for reactive compensation. The voltage at the receiving end of short lines is maintained nearly constant by adjusting the field excitation of the alternators at the sending end. For long lines this method not suitable as it results in greater line losses and voltage drop.

## 2.2 Reactive Power Compensation for Quality Power

When the synchronous machines are connected to an infinite bus, its speed and terminal voltage are fixed and unalterable. Two controllable variables, however, are the field current and the mechanical torque on the shaft. The variation of the field current $I_f$ referred to as excitation system control, is applied to either a generator or a motor to supply or absorb a variable amount of reactive power. Because the synchronous machine runs at constant speed, the only means of varying the real power is through control of the torque imposed on the shaft by either the prime mover in the case of a generator and changing mechanical loads in the case of a motor. It is convenient to neglect resistance which is considered reactive power control of the round-rotor generator. Assume that the generator is delivering power so that a certain angle $\delta$ exists between the terminal voltage $V_t$ and the generated voltage $E_i$ of the machine [1]. The complex power delivered to the system by the generator is given in per unit by

$$S = P + jQ = V_t + I_a^* = |V_t||I_a|\,(\cos\theta + j\sin\theta) \qquad (2.1)$$

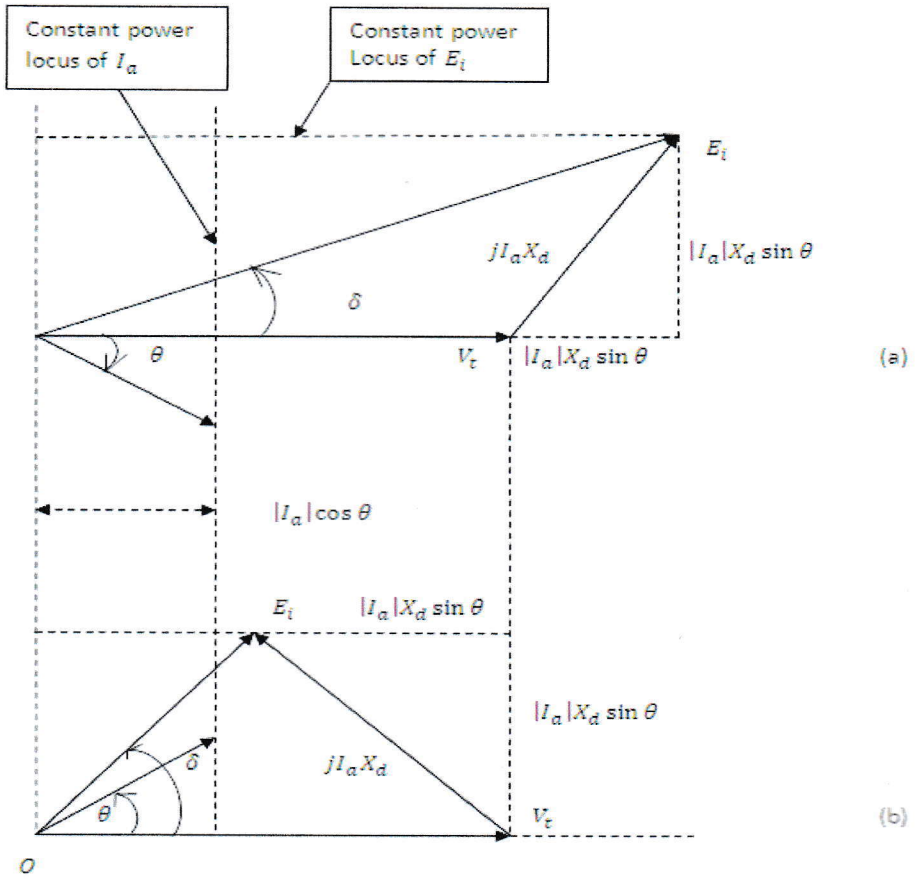



Figure 2.1: Phasor diagrams showing constant-power loci of an (a) overexcited generator delivering reactive power to the system. (b) under-excited generator receiving reactive power from the system. The power delivered by the generator is the same in both cases.

Equating real and imaginary quantities in this equation, it is obtained

$$P = |V_t||I_a|\cos\theta \qquad Q = |V_t||I_a|\sin\theta \tag{2.2}$$

It is noted that $Q$ is positive for lagging power factors since the angle $\theta$ is numerically positive. In order to maintain a certain power delivery $P$ from the generator to the constant voltage system, it is clear from equations (2.2) that $|I_a|\cos\theta$ must remain constant.

As the dc current $I_f$ is varied under these conditions, the generated voltage $E_i$ varies proportionally but always so as to keep $|I_a|\cos\theta$ constant, as shown by the loci of figure 2.1(a). Normal excitation is defined as the condition when

$$|E_i|\cos\theta = |V_t| \tag{2.3}$$

And, the machine is said to be either overexcited or under-excited according to whether $|E_i|\cos\theta > |V_t|$ or $|E_i|\cos\theta < |V_t|$. For the condition of figure 2.1(a) the generator is overexcited and supplies reactive power $Q$ to the system. Thus, from the system viewpoint the machine is acting like a capacitor. Figure 2.2(b) is for an underexcited generator supplying the same amount of

real power and a leading current the system, or it may be considered to be drawing lagging current from the system.

## 2.3 Methods of Reactive Power Compensation

The reactive power at different buses of the power system varies with the changes in load. The reactive power is normally high at light-load conditions and low at heavy-load conditions. To keep reactive power within permissible limits, means must be provided to control the reactive power, that is, to increase the circuit reactive power when it is too low. The followings methods are used for reactive power compensation in power system:

### a. Shunt Compensation

Shunt capacitors are the capacitors connected in parallel with the lines. Capacitors are installed near the load terminals, in receiving-end substations, distribution substations and in switching substations [23]. Shunt capacitors injected leading volt amperes (VAR) to counteract some or all of lagging inductive VAR at the point of installation. Capacitors are arranged in three-phase banks. A serious disadvantage with shunt capacitors that are no load or light load, the receiving-end voltage is greater than the sending-end voltage, which is called Ferranti effect. To remove this difficulty the capacitors bank is provided with fixed and variable elements. When the voltage rises the variable elements are removed from the bank to decrees the capacitance. With the fall of voltage the variable elements added to the bank to increase the capacitance, shunt capacitors first rate switched in during heavy, low power factor loads [4]. In transmission lines shut capacitors are connected either to the tertiary winding of the power transmission or to the bus bars. Most of the industrial loads like induction motor, wielding equipment furnace transformers etc draw inductive currents of poor power factor [17]. Shunt capacitors are used with individual equipment to improve power factor. The improve power factors reduces the kVA drawn from the supply. The power losses are reduced and the efficiency is increased. The smaller voltage and reactive power flows are the points where capacitors are installed [9]. Figure 2.2 shows the principles and theoretical effects of shunt reactive power compensation in a basic ac system, which comprises a source$V_1$, a power line and a typical inductive load. Figure 2.2(a) shows the system without compensation, and its associated phasor diagram. In the phasor diagram, the phase angle of the current has been related to the load side, which means that the active current$I_P$ is in phase with the load voltage$V_2$. When reactive power is supplied near the load, the line current can be reduced or minimized, reducing power losses and improving voltage regulation at the load terminals. This can be done in three ways: a) With a capacitor, b) With a voltage source, or c) With a current source. In Figure 2.2(b) a current source device is being used to compensate the reactive component of the load current$I_Q$.

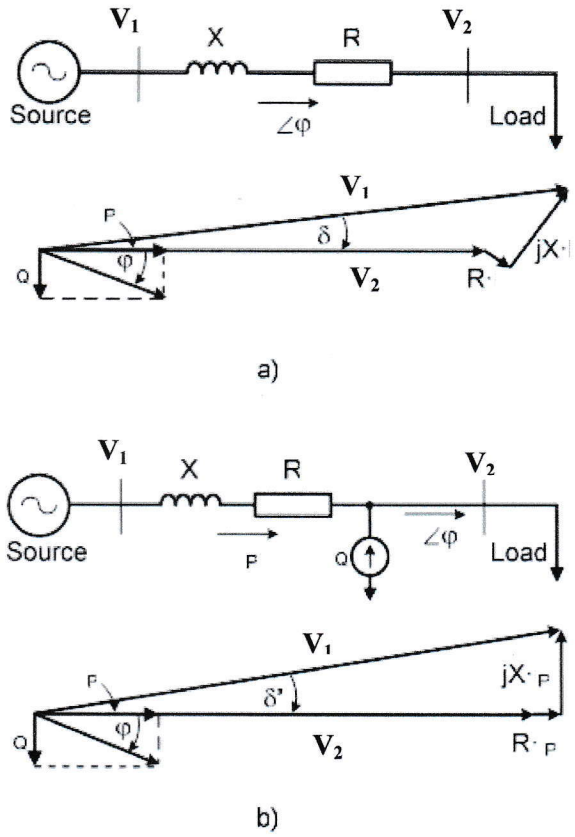



Figure 2.2: Principles of shunt compensation in a radial ac system. (a) Without reactive compensation. (b) Shunt compensation with a current source.

As a result, the system voltage regulation is improved and the reactive current component from the source is reduced or almost eliminated. When the load needs leading compensation, then an inductor would be required. Also a current source or a voltage source can be used for inductive shunt compensation. The main advantages of using voltage or current source VAR generators (instead of inductors or capacitors) is that the reactive power generated is independent of the voltage at the point of connection.

**b. Series Compensation**

Capacitors are connected in series with the line at suitable location. Series capacitors increase transmission capacity, improve system stability, control voltage regulation and ensure proper load division among parallel feeders [3].Series compensation with capacitors is the most common strategy. Series Capacitor is installed in series with a transmission line. On this platform, the main capacitor is located together with over voltage protection circuits.

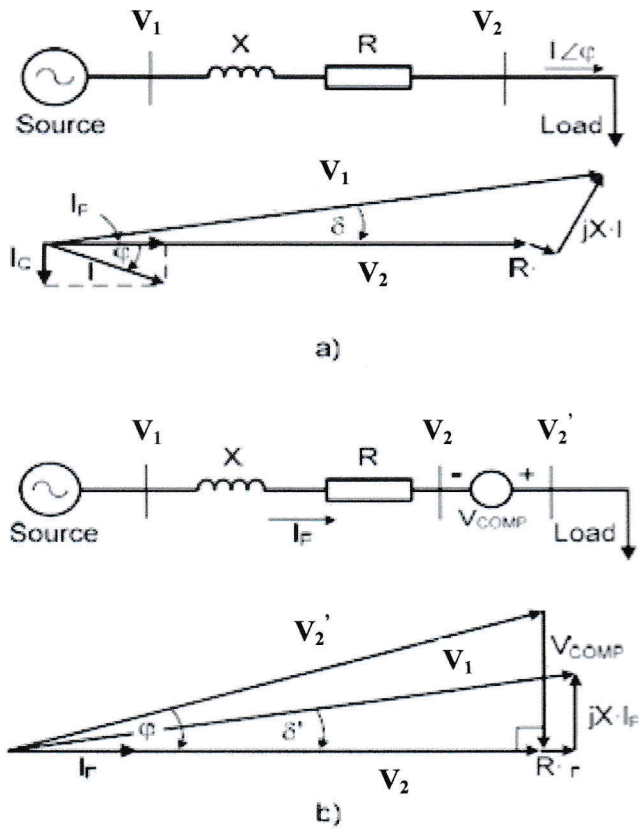



Figure 2.3: Principles of series compensation. (a) Without compensation. (b) Series compensation with a voltage source.

The figure 2.3 shows that the series compensation of the reactive power compensation method. The over voltage protection is a key design factor as the capacitor bank has to withstand the throughput fault current, even at a severe nearby fault.

### c. Synchronous Condensers

Synchronous condensers are playing a major role in voltage and reactive power control for more than 50 years. Functionally, a synchronous condenser is simply a synchronous machine connected to the power system. After the unit is synchronized, the field current is adjusted to either generate or absorb reactive power as required by the ac system. The machine can provide continuous reactive power control when used with the proper automatic exciter circuit. Synchronous condensers have been used at both distribution and transmission voltage levels to improve stability and to maintain voltages within desired limits under varying load conditions and contingency situations [2]. However, synchronous condensers are rarely used today because they require substantial foundations and a significant amount of starting and protective equipment. It does also contribute to the short circuit current and they cannot be controlled fast enough to compensate for rapid load changes. Moreover, their losses are much higher than those associated with static

compensators, and the cost is much higher compared with static compensators. Their advantage lies in their high temporary overload capability

## 2.4 Shunt Reactive Power Compensation and its Applications

The basic function of capacitors, whether these are series or shunt, installed as a single unit or as a bank, is to regulate the voltage and reactive power flows are the point where capacitors are installed. The shunt capacitor does it by changing the power factor of the load, whereas the series capacitor does it by directly reducing the inductive reactance of the line. A series capacitor provides for a voltage rise which increase automatically and instantaneously with the increase of the load current. Also, a series capacitor produces more net voltage rise than a shunt capacitors at lower power factor which produces more voltage drop. However, a series capacitor improves the system power factor much less than a shunt capacitor and has a little effect on source current

### Static VAR System

In EHV (Extra High Voltage) transmission practice, when the voltage at a bus falls below the reference value, capacitive VARs are to be injective. When the bus voltage becomes higher than the reference value, inductive VARs are supplied to lower the bus voltage. In conventional methods of shunt compensation, shunt reactors are connected during low loads, and shunt capacitors are connected during heavy loads or low lagging power factor load, such switching operations are very slow because of the greater time required for the operation of the circuit breakers [7]. Moreover, circuit breakers are not suitable for frequent switching during voltage variations. These limitations have been overcome by static car systems (SVS). In a static VAR system, thyristor are sued as switching devices instead of circuit breakers. Thyristor switching is faster than mechanical switching and also it is possible to have transient-free operation by controlling the instant of switching. The advantage of high-speed, high-current switching made possible by thyristors has introduced a new concept is providing reactive compensation for optimum EHV/UHV (Extra High Voltage/ Ultra High Voltage) system performance [7]. The static VAR compensators (SVC) use shunt reactor and shunt capacitor combinations with high voltage high current thyristor control for obtaining fast and accurate control of reactive power flow [2] and [9]. The static VAR compensation (SVC) is also known as static VAR system (SVS). Many SVS schemes are in operation. Some of the commonly used schemes are as follows.

**Thyristor Switched Capacitor (TSC)**

Figure 2.4 shows the basic scheme of a static compensator of the thyristor-switched capacitor (TSC) type. The shunt capacitor bank is split up into appropriately small steps, which are individually switched in and out using bidirectional thyristor switches.

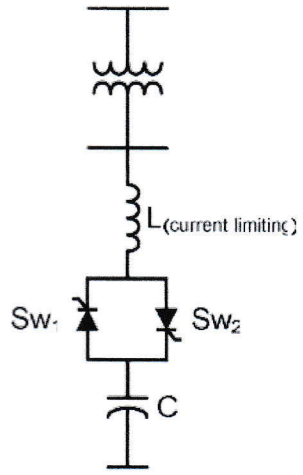



Figure 2.4: The thyristor-switched capacitor (TCS) configuration.

Each single-phase branch consists of two major parts, the capacitor C and the thyristor switches $Sw_1$ and $Sw_2$. In addition, there is a minor component, the inductor L, whose purpose is to limit the rate of rise of the current through the thyristors and to prevent resonance with the network (normally 6% with respect to $X_c$). The capacitor can be switched with a minimum of transients when the thyristor is turned on at the instant while the capacitor voltage and the network voltage is in the same value [10]. Static compensators of the TSC type have the following properties: stepwise control, average delay of one half a cycle (maximum one cycle), and no generation of harmonics since current transient component can be attenuated effectively

**Thyristor-Controlled Reactor (TCR)**

Figure 2.5 shows the scheme of a static compensator of the thyristor controlled reactor (TCR) type. In most cases, the compensator also includes a fixed capacitor and a filter for low order harmonics, which is not show in this figure. Each of the three phase branches includes an inductor L, and the thyristor switches $Sw_1$ and $Sw_2$. Reactors can be both switched and phase-angle controlled. When phase-angle control is used, a continuous range of reactive power consumption is obtained. It results, however, in the generation of odd harmonic current components during the control process. Full conduction is achieved with a gating angle of 90°.Partial conduction is obtained with gating

angles between 90° and 180°, as shown in figure 2.5. By increasing the thyristor gating angle, the fundamental component of the current reactor is reduced [22].

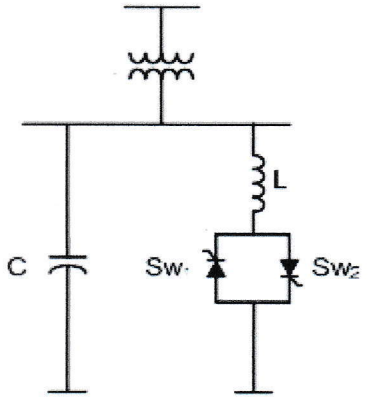



Figure 2.5: The thyristor-controlled reactor (TCR) configuration.

This is equivalent to increase the inductance, reducing the reactive power absorbed by the reactor. However, it should be pointed out that the change in the reactor current may only take place at discrete points of time, which means that adjustments cannot be made more frequently than once per half-cycle. Static compensators of the TCR type are characterized by the ability to perform continuous control, maximum delay of one half cycle and practically no transients. The principal disadvantages of this configuration are the generation of low frequency harmonic current components, and higher losses when working in the inductive region.

**Combined TSC and TCR**

Irrespective of the reactive power control range required, any static compensator can be built up from one or both of the above mentioned schemes (i.e. TSC and TCR), as shown in figure 2.6 . In those cases where the system with switched capacitors is used, the reactive power is divided into a suitable number of steps and the variation will therefore take place stepwise [2]. Continuous control may be obtained with the addition of a thyristor-controlled reactor. When it is required to absorb reactive power, the entire capacitor bank is disconnected and the equalizing reactor becomes responsible for the absorption. By coordinating the control between the reactor and the capacitor steps, it is possible to obtain fully step less control. Static compensators of the combined TSC and TCR type are characterized by a continuous control, practically no transients, low generation of harmonics (because the controlled reactor rating is small compared to the total reactive power), and flexibility in control and operation. An obvious disadvantage of the TSC-TCR as compared with TCR and TSC type compensators is the higher cost. Smaller TCR rating results in some savings, but these savings are more than absorbed by the cost of the capacitor switches and the more complex control system. A static VAR system provides a fast, smooth and step-less

variation of compensation of reactive power injected into the line. It ensures an accurate voltage control of buses over a wide range of loads. The static VAR systems are used to control the reactive power demand of large fluctuation loads such as rolling mills, arc, furnace etc. when a large load is switched off, the voltage at the sending end of the line increases (Ferranti effect). The static VAR system provides a fast change in the reactive power compensation to regulate the voltage.

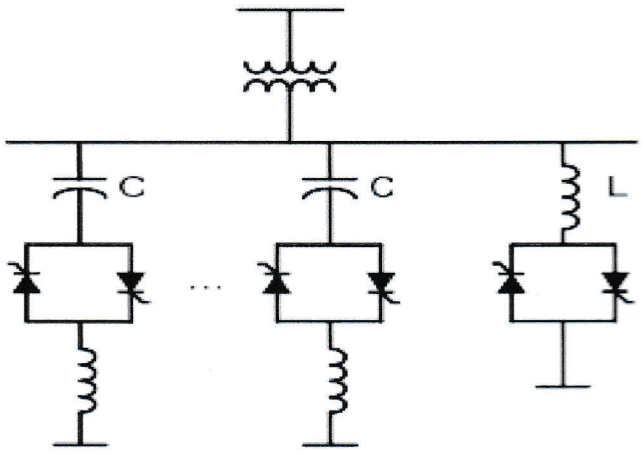



Figure 2.6: Combined TSC and TCR configuration.

In other words, the SVS provides control of dynamic overvoltage caused by load rejection. In HVDC converter stations, the provision of the static VAR system mainly helps to have fast control of reactive power flow [9]. Voltage fluctuations are controlled and the problem of instability is overcome.

## 2.5 Power System Stability and Reactive Power Compensation

For a short transmission line, the magnitude of voltage drops in the line is

$$|\Delta V| = |V_s| - |V_r| \tag{2.4}$$

Where $V_s$ and $V_r$ are the sending end voltage and receiving end voltage of line respectively.

$$|\Delta V| = |IR\cos\varphi_r| - |IX\sin\varphi_r|$$

$$|\Delta V| = \frac{1}{V_r}[(V_r I\cos\varphi_r)R + (V_r I\sin\varphi_r)X]$$

$$|\Delta V| = \frac{RP_r + XQ_r}{V_r}$$

For a transmission line, $X \gg R$ and $R$ is negligible small. Therefore

$$|\Delta V| = \frac{XQ_r}{V_r} \qquad Q_r = \frac{V_r}{X}|\Delta V| \tag{2.5}$$

This relation shows that the reactive power $Q_r$ is proportional to the voltage drop in the line. Thus voltage control and reactive power control are interrelated. The voltage at the consumer terminals

must be maintained constant within prescribed limits irrespective of the type and magnitude of the load. The maintenance of constant voltage is a complicated problem due to fact that the system is supplied from many sources and it supplies many loads at several voltage levels. In order to maintain the voltages at their prescribed values at all times, it is necessary to maintain the balance of reactive power in the system [14]. In other words, the reactive power generation is exactly equal to the power consumed (absorbed). Any mismatch in the reactive power balance affects the bus voltage magnitudes without much affecting the system frequency.

# Chapter 3: Power Flow Analysis

Modern power system comprises of complex generation, transmission and distribution network where the nature of generation and consumption changes rapidly with increasing demand of load [1]. Generally in power system, generators and loads are interconnected through transmission network with complex bus system [3]. In order to identify the nature of any power system, power flow analysis is required of that power system. Moreover power flow analysis gives information about different system parameters like system voltage, frequency, current, real power, reactive power and relative phase angle [7]. There are various methods for power flow analysis. Among conventional methods there are Gaussian Elimination, Gauss-Siedel and Newton-Raphson and Decoupled method [1]. However power flow analysis softwares like Power World Simulator, PSAF and others make the power flow analysis faster and easier than the conventional methods [25]. The conventional methods calculate the real, reactive power and phase angle by using bus impedance or bus admittance in the form of voltage or current equation. However the power flow analysis softwares also use bus impedance or bus admittance matrix as the basis for power flow analysis. The short circuit current analysis is used to calculate the voltage difference between before and after short circuit and then the reactive power can be calculated from the voltage difference.

## 3.1 Bus and its Classifications

In power system bus can be defined as a junction where power coming in and going out.

1. Load bus (PQ bus) – a bus at which the real and reactive power are specified, and for which the bus voltage will be calculated. Real and reactive powers supplied to a power system are defined to be positive, while the powers consumed from the system are defined to be negative. All busses having no generators are load busses.

2. Generator bus or voltage-controlled bus (PV bus) – a bus at which the magnitude of the voltage is kept constant by adjusting the field current of a synchronous generator on the bus. It is assumed that the field current is adjusted to maintain a constant terminal voltage$V_t$. Which is also known as increasing the prime mover's governor set points increases the power that generator supplies to the power system. Therefore, the supplied bus voltage and real power can be controlled.

3. Slack bus (swing bus) – a special generator bus serving as the reference bus for the power system. Its voltage is assumed to be fixed in both magnitude and phase (for instance, $1\angle 0^{\circ}$ per

unit). The real and reactive powers are uncontrolled: the bus supplies whatever real or reactive power is necessary to make the power flows in the system balance.

## 3.2 Power Flow of a Typical Bus

Either the bus self and mutual admittances which compose the bus admittance matrix $Y_{bus}$ or the driving-point and transfer impedances which compose $Z_{bus}$ may be used in solving the power-flow problem [2]. It is confined our study to methods using admittances. The starting point in obtaining the data which must be furnished to the computer is the single-line diagram of the system. Transmission lines are represented by their per-phase nominal-$\pi$ equivalent circuits like that shown figure (3.1).

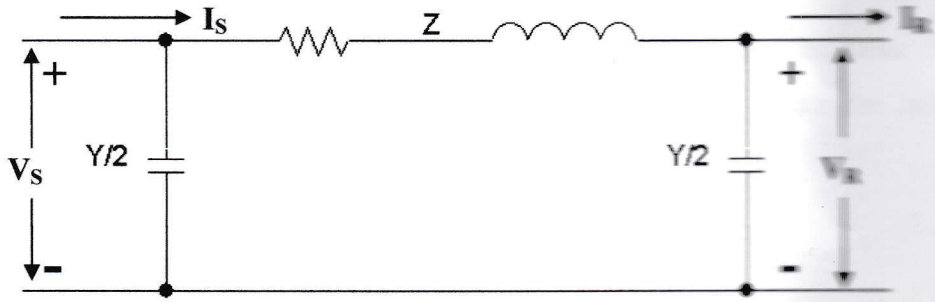



Figure 3.1: Nominal-$\pi$ circuit of a medium-length transmission line.

For each line numerical values for the series impedance $Z$ and the total line charging admittances $Y$ are necessary so that the computer can determine all the elements of the $N \times N$ bus admittance matrix of which the typical element $Y_{ij}$ is

$$Y_{ij} = |Y_{ij}|\angle\theta_{ij} = |Y_{ij}|\cos\theta + j|Y_{ij}|\sin\theta_{ij} = G_{ij} + jB_{ij} \quad (3.1)$$

Other essential information includes transformer ratings and impedance, shunt capacitor ratings and transformer tap settings. In advance of each power-flow study certain bus voltages and power injections must be given known values. The voltages at typical bus (i) of the system is given in polar coordinates by

$$V_i = |V_i|\angle\delta_i = |V_i|(\cos\delta_i + j\ \sin\delta_i) \quad (3.2)$$

And the voltage at another bus (i) is similarly written by changing the subscript from *i*and *j*. the net current injected into the network at bus (i) in terms of the elements $Y_{in}$of $Y_{bus}$ is given by the summation

$$I_i = Y_{i1}V_1 + Y_{i2}V_1 + \ldots\ldots\ldots + Y_{iN}V_{N1} = \sum_{n=1}^{N} Y_{in}V_n \quad (3.3)$$

Let $P_i$ and $Q_i$denote the net real and reactive power entering the network at the bus (i). Then, the complex conjugate of the power injected at bus (i) is

$$P_i - jQ_i = V_i^* \sum_{n=1}^{N} Y_{in} V_n \quad (3.4)$$

In which substituting from equation (3.1) and (3.2) to obtain

$$P_i - jQ_i = \sum_{n=1}^{N} |Y_{in} V_i V_n| \angle(\theta_{in} + \delta_n - \delta_i) \quad (3.5)$$

Expanding this equation and equating real and reactive parts, it is obtained

$$P_i = \sum_{n=1}^{N} |Y_{in} V_i V_n| \cos(\theta_{in} + \delta_n - \delta_i) \quad (3.6)$$

$$Q_i = -\sum_{n=1}^{N} |Y_{in} V_i V_n| \sin\cos(\theta_{in} + \delta_n - \delta_i) \quad (3.7)$$

Equations (3.6) and (3.7) constitute the polar form of the power-flow equations; they provided calculated values for the net real power $P_i$ and reactive power $Q_i$ entering the network at typical bus (i). Let $P_{gi}$ denote the schedule power being generated at bus (i) and $P_{di}$ denote the schedule power demand of the load at that bus. Then, $P_{i,sch} = P_{gi} - P_{di}$ is the net schedule power being injected into the network at bus (i), as illustrated in figure 3.2(a). Denoting the, calculated value of $P_i$ by $P_{i,cale}$ leads to be definition of mismatch $\Delta P_i$ as the schedule value $P_{i,sch}$ minus the calculated value $P_{i,cale}$,

$$\Delta P_i = P_{i,sch} - P_{i,cale} = (P_{gi} - P_{di}) - P_{i,cale} \quad (3.8)$$

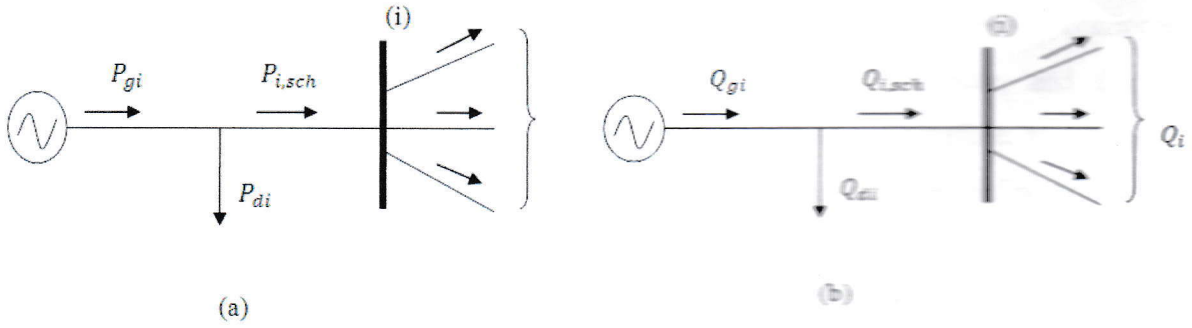



Figure 3.2: Notation for (a) active and (b) reactive power at a typical bus (i) in power-flow studies.

Likewise, for reactive power t bus (i) we have

$$\Delta Q_i = Q_{i,sch} - Q_{i,cale} = (Q_{gi} - Q_{di}) - Q_{i,cale} \quad (3.9)$$

As shown in figure 3.2(b). Mismatches occur in the course of solving of solving a power-flow problem when calculated values of $P_i$ and $Q_i$ do not coincide with the scheduled values. When the calculated values $P_{i,cale}$ and $Q_{i,cale}$ match the scheduled values $P_{i,sch}$ and $Q_{i,sch}$ perfectly, then it is said the mismatches $\Delta P_i$ and $\Delta Q_i$ are zero at bus (i), and we write the power-balanced equations

$$g_{i'} = P_i - P_{i,sch} = P_i - (P_{gi} - P_{di}) = 0 \quad (3.10)$$

$$g_{i''} = Q_i - Q_{i,sch} = Q_i - (Q_{gi} - Q_{si}) = 0 \qquad (3.11)$$

Four potentially unknown quantities associated with each bus (i) are $P_i, Q_i$, voltage angle $\delta_i$ and voltage magnitude$|V_i|$. At most there are two equations (3.10) and (3.11) available for each node and so it must consider how the number of unknown quantities can be reduced to agree with the number of available equations before beginning to solve the power-flow problem. The general practice in power-flow studies is to identify three types of buses in the network.

1. Load buses: At each nongenerator bus, called a load bus, both $P_{gi}$ and $Q_{gi}$ are zero and the real power $P_{di}$ and reactive power $Q_{di}$drawn from the system by the load ( negative impulse into the system ) are known from historical record, load forecast of measurement. Quite often in practice only real power is known and the reactive power is then based on an assumed power factor such as 0.85 or higher. A load bus (i) is often called a $P$-$Q$ bus because the scheduled values $P_{i,sch} = -P_{di}$ and $Q_{i,sch} = -Q_{di}$ are known mismatches $\Delta P_i$ and $\Delta Q_i$ can be defined. The corresponding power balanced equation (3.10) and (3.11) are explicitly include in the statement of the power-flow problem and the two unknown quantities to be determined for the bus are $\delta_i$and $|V_i|$.

2. Voltage-controlled buses: any bus of the system at which the voltage magnitude is kept constant is said to be voltage controlled. At each bus to which there is a generator connected the megawatt generation can be controlled by adjusting the prime mover, and the voltage magnitude can be controlled by adjusting the generator excitation. Therefore, at each generator bus (i) It may properly specify $P_{gi}$and$|V_i|$. With $P_{di}$ also known, it can be defined mismatch $\Delta P_i$ according to equation (3.8). Generator reactive power $Q_{gi}$ required to scheduled voltage $|V_i|$ cannot be known in advance, and so mismatch $\Delta Q_i$ is not defined. Therefore, at a generator bus (i) voltage angle $\delta_i$ is known quantity to be determined and equation (3.10) for $P_i$ is the available equation. After the power-flow problem is solved $Q_i$ can be calculated from equation (3.7).For obvious reasons a generator bus is usually called a voltage controlled or$PV$ bus. Certain buses without generators may have voltage-control capability; such buses are also designated-voltage buses at which the real power generation is simply zero.

3. Slack-bus: for convenience through this chapter bus (i) is almost always designated as the slack bus. The voltage angle of the slack bus serves as reference for the angles of all other bus voltages. The particular angle assigned to the slack bus voltage is not important because voltage-angle differences determine the calculated values of $P_i$ and $Q_i$ in equations (3.6) and (3.7). The usual practice is to set$\delta_1 = 0^0$. Mismatches are not defined for the lack bys as

explained below, and so voltage magnitude $|V_1|$is specified as the other known quantity along with$\delta_1 = 0^0$. Then, there is no requirement to include withers equation (3.10) or equation (3.11) for the slack bus in the power-flow problem.

To understand why $P_1$and $Q_1$are not scheduled at the slack bus, consider that at each is the $N$ buses of the system an equation similar to equation (3.10) can be written by letting $i$ range from 1 to $N$. When the resulting$N$ equation are added together, it can obtained

$$P_L = \sum_{i=1}^{N} P_i = \sum_{i=1}^{N} P_{gi} - \sum_{i=1}^{N} P_{di} \qquad (3.12)$$

The term $P_L$ in this equation is evidently the total $I^2R$ loss in the transmission lines and transformers of the network. The individual currents in the variation transmission lines of the network cannot be calculated until after the voltage magnitude and angle are known at every bus of the system.

Therefore, $P_L$ is initially unknown and it is not possible to represent all the quantities in the summations of equation (3.12). In the formulation of the power-flow problem, the slack bus, at which $P_g$ is not scheduled of otherwise pre-specified. After the power-flow problem has been solved, the difference (slack) between the total specified $P$ going into the system at all the other buses and the total output $P$ plus $I^2R$ losses are assigned to the slack bus. For thisreason a generator bus must be selected as the slack bus. The difference between the total megavars supplied by the generators at the buses and the megavars received by the loads is given by

$$\sum_{i=1}^{N} Q_i = \sum_{i=1}^{N} Q_{gi} - \sum_{i=1}^{N} Q_{di} \qquad (3.13)$$

This equation is specified on an individual bus basisi by satisfying equation (3.11) at each bus (i) in the course of solving the power-flow problem. Individual $Q_i$can be evaluated from equation (3.7) after the power-flow solution becomes available. Thus, the quantity on the left-hand side of equation (3.13) accounts for the combined megavars associated with line charging, shunt capacitors and reactors installed at the buses and the so-called $I^2X$ loss in the series reactance of the transmission lines.

## 3.3 Methods of Power-Flow Analysis

The function $P_i$and $Q_i$ of equations (3.6) and (3.7) are nonlinear functions of the state variables $\delta_i$and$|V_i|$. Hence, power-flow calculations usually employ iterative techniques such as the Gauss-Seidel and Newton-Raphson procedures, which are described in this chapter. The Newton-Raphson methods solves the polar form of the power-flow equations until the $\Delta P$ and$\Delta Q$ mismatches at all busses fail within specified tolerances. The Gauss-Seidel method solves the power-flow equations

in rectangular (complex variable) coordinates until differences in bus voltages from one iteration to another are sufficiently small [5]. Both methods are based on bus admittance equations [4].

**The Gauss-Seidel Method**

The complex of obtaining a formal solution for power flow in a power system aries because of the differences in type of data specified for the different kinds of busses. Although the formulation of sufficient equations to match the number of unknown sate variables is not difficult, as it is seen, the closed form of solution is not practical. Digital solutions of the power-flow problems follow an iterative process by assigning estimated values to the unknown bus voltages by calculating a new value for each bus voltage from the estimated values at the other buses and the real and reactive power specified [1]. A new set of values for the voltage a each bus is thus obtained and used to calculate still another set of bus voltage. Each calculation of a new set of voltages it called iteration. The iterative process is repeated until the changes at each bus are less than a specified minimum value.

To derive equations for a four-bus system and write the general equations later. With the slack bus designed as number 1, computations (2). When $P_{2,sch}$ and $Q_{2,sch}$ are the scheduled real and reactive power, respectively, entering the network at bus (2), it follows from equation (3.9) with iset equal to 2 and N equal to 4 that

$$\frac{P_{2,sch}-jQ_{2,sch}}{V_2^*} = Y_{21}V_1 + Y_{22}V_2 + Y_{23}V_3 + Y_{24}V_4 \qquad (3.14)$$

Solving for $V_2$ gives

$$V_2 = \frac{1}{Y_{22}}\left[\frac{P_{2,sch}-Q_{2,sch}}{V_2^*} - (Y_{21}V_1 + Y_{23}V_3 + Y_{24}V_4)\right] \qquad (3.15)$$

For now let us assume that buses (3) and (4) are also load buses with real and reactive power specified. Expressions similar to that in equation (3.15) may be written for each bus. At bus (3) it can be written.

$$V_3 = \frac{1}{Y_{33}}\left[\frac{P_{3,sch}-Q_{3,sch}}{V_3^*} - (Y_{31}V_1 + Y_{32}V_2 + Y_{34}V_4)\right] \qquad (3.16)$$

Equating real and imaginary parts of equations (3.15) and (3.16) and the similar equation of bus (4). Six equation can be obtained in the six state variables $\delta_2$ to $\delta_4$ and $|V_2|$ to $|V_4|$. However it can be solve for the complex voltages directly from the equations as they appear. The solution proceeds by iteration based in the scheduled real and reactive power at buses (2), (3) and (4), the scheduled slack bus voltage $V_i = |V_i|\angle\delta_i$, and initial voltage estimates $V_2^{(0)}$, $V_3^{(0)}$ and $V_4^{(0)}$ at the other buses. Solution of equation (3.15) gives the corrected voltage $V_2^{(1)}$ calculated from

$$V_2^{(1)} = \frac{1}{Y_{22}}\left[\frac{P_{2,sch}-Q_{2,sch}}{V_2^*} - \left(Y_{21}V_1 + Y_{23}V_3^{(0)} + Y_{24}V_4^{(0)}\right)\right] \qquad (3.17)$$

In which all quantities in the right-hand side expression are either fixed specifications or initial estimates. The calculated value $V_2^{(1)}$ and the estimated value $V_2^{(0)}$ will not agree. Agreement would be reached to a good degree of accuracy after several iterations and would be the correct value for $V_2$ with the estimated voltage but without regard to power at the other buses. This value would not be the solution for $V_2$ for the specific power-flow conditions, however, because the voltages on which this calculations for $V_2$ depends are the estimated values $V_3^{(0)}$ and $V_4^{(0)}$ at the other buses, and the actual voltages are not yet known.

As the corrected voltage is found at each bus, it is used to calculate the corrected voltage at the next bus. Therefore, substituting $V_2^{(1)}$ in equation (3.16). it can be obtained for the first calculated value at bus (3)

$$V_3^{(1)} = \frac{1}{Y_{33}}\left[\frac{P_{3,sch}-Q_{3,sch}}{V_3^*} - \left(Y_{31}V_1 + Y_{32}V_3^{(1)} + Y_{34}V_4^{(0)}\right)\right]$$

The process is repeated at bus (4) and at each bus consecutively throughout the network (except at the slack bus) to complete the first iteration in which calculated values are found for each state variable. Then, the entire process is carried out again until the amount of correction in voltage at every bus is less than some predetermined precision index. This process of solving the power-flow equations is known as the Gauss-Seidel iterative method.

Convergence upon an erroneous solution is usually avoided when the initial values are of reasonable magnitude and do not differ too widely in phase. It is common practice to set the initial estimates of the unknown voltages at all load buses equal to 1.0∠0° per unit. Such initialization is called a flat start because of the uniform voltage profile assumed. For a system of N buses the general equation for the calculated voltage at any bus (i) where P and Q are scheduled is

$$V_i^{(k)} = \frac{1}{Y_{ii}}\left[\frac{P_{3,sch}-Q_{i,sch}}{V_i^{(k-1)}} - \sum_{j=1}^{i-1} Y_{ij}V_j^{(k)} - \sum_{j=i+1}^{N} Y_{ij}V_j^{(k-1)}\right] \qquad (3.19)$$

The superscript (k) denotes the number of the iteration in which the voltage is currently being calculated and $(k-1)$ indicates the number of the preceding iteration. Thus, it is seen that the values for the voltage on the right-hand of this equation are the most recently calculated values for the corresponding buses (or the estimated voltage when k is 1 and no iteration has yet been made at that particular bus). Since equation (3.16) applies only at load buses real and reactive power specified, an additional step is necessary at voltage-controlled buses where voltage magnitude is to remain constant.

Experience with the Gauss-Seidel method of solution of power-flow problems has shown that the number of iterations required may be reduced considerably when the correction in voltage at each bus is multiplied by some constant that increases the amount of correction to bring the voltage closer to the value it is approaching. The multiplier that accomplishes this improved convergence is called an acceleration factor. The difference between the newly calculated voltage and the best previous voltage at the bus is multiplied by the appropriate acceleration factor to obtain a better correction to be added to the previous value. For example bus (2) in the first iteration it has been seen the accelerated value $V_{2,acc}^{(1)}$ defined by the straight-line formula

$$V_{2,acc}^{(1)} = (1-\alpha)V_2^{(0)} + \alpha V_2^{(1)} = V_2^{(0)} + \alpha(V_2^{(1)} - V_2^{(0)}) \tag{3.20}$$

In which $\alpha$ is the acceleration factor. More generally, for bus (i) during iteration $k$ the accelerated value is given by

$$V_{2,acc}^{(k)} = (1-\alpha)V_{i,acc}^{(k-1)} + \alpha V_{i,acc}^{(k)} = V_{i,acc}^{(k-1)} + \alpha(V_i^{(k)} - V_{i.acc}^{(k-1)} \tag{3.21}$$

When$\alpha = 1$, then the Gauss-Seidel computed value of $V_i$ is stored as the current value. When$0 < \alpha < 1$, then the value to be stored is a weighted average of the Gauss-Seidel value and the value stored from the previous iteration. When$0 < \alpha < 2$ then the value to be stored is essentially an extrapolated value. In power-flow studies $\alpha$ is generally set at about 1.6 and cannot exceed 2 when convergence is to occur.

The acceleration factor the real component of the correction may differ from that for the imaginary component. For any system optimum values for acceleration factors exist, and poor choice of factors may results of 1.6 for both the real and imaginary components is usually a good but studies may be made to determine the best choice for a particular system.

**Voltage-Controlled Buses:** when voltage magnitude rather than reactive power is specified at bus (i), the real and imaginary components of the voltage for each iteration are found by first computing a value for the reactive power. From equation (3.4) it can be written

$$Q_i = -Im\{V_i^* \textstyle\sum_{j=1}^{N} Y_{ij}V_j\} \tag{3.22}$$

This has the equivalent algorithmic expression

$$Q_i^{(k)} = -Im\{V_i^{(k-1)*}[\textstyle\sum_{j=1}^{i-1} Y_{ij}V_j^{(k)} + \sum_{j=i}^{N} Y_{ij}V_j^{(k-1)}]\} \tag{3.23}$$

When Im means "imaginary part of" and the superscripts indicate the relavent iteration. Reactive power $Q_i^{(k)}$ is evaluated by equation (3.23) for the best previous voltage values at the buses, and this value of $Q_i^{(k)}$is substitute in equation (3.19) to find a new value of $V_i^{(k)}$. The components of the new $V_i^{(k)}$ are then multiplied by the ratio of the specified constant magnitude $|V_i|$ to the magnitude

of $V_i^{(k)}$ found by equation (3.19). The result is the corrected complex voltage of the specified magnitude. In the four-bus example when bus (4) is voltage controlled, equation (3.23) yields the calculated value

$$Q_4^{(k)} = -Im\left\{V_4^{(o)*}(Y_{41}V_1 + Y_{42}V_{2,acc}^{(1)} + Y_{43}V_{3,acc}^{(1)} + Y_{44}V_4^{(0)})\right\} \quad (3.24)$$

Wherein the calculated voltage of buses (2) and (3) are accelerated values of the first iteration. Substituting $Q_4^{(1)} for Q_{4,sch}$ in the equivalent of equation (3.19) for bus (4) yields

$$V_4^{(1)} = \frac{1}{Y_{44}}\left[\frac{P_{4,sch}-Q_{4,sch}}{V_4^{(0)*}} - Y_{41}V_1 + Y_{42}V_{2,acc}^{(1)} + Y_{43}V_{3,acc}^{(1)}\right] \quad (3.25)$$

And all quantities on the right-hand side are now known. Since $|V_4|$is specified, the magnitude is $V_4^{(1)}$ as follows.

$$V_{4,corr}^{(1)} = |V_4|\frac{V_4^{(1)}}{|V_4^{(1)}|} \quad (3.26)$$

And proceed to the next step with stored value $V_{4,corr}^{(1)}$ of bus (4) voltage having the specified magnitude in the remaining calculation of the iteration.

Either voltage magnitude or reactive power is specified at every bus except the slack bus, where voltage is specified by both voltage magnitude and angle. At buses with generation the voltage magnitude is specified as well as the real power $P_g$ supplied by the generator. The reactive power $Q_g$entering the network from the generation is then determined by the computer in solving the power-flow problem. From a practical viewpoint the $Q_g$output of the generation must be within definite limits given by the inequality

$$Q_{min} \geq Q_g \geq Q_{max}$$

Where $Q_{min}$ is the minimum and $Q_{max}$ is the maximum limit imposed on the reactive power output of the generator at the bus. In the course of power-flow solution when the calculated value of $Q_g$is outside either limit, then $Q_g$is set equal to the limit violated, the originally specified voltage magnitude a the bus is relaxed, and the bus is then treated as a $P-Q$ bus for which a new voltage is calculated by the computer program. In subsequence iteration the program endeavors to sustain the originally specified voltage at the bus while ensuring that $Q_g$ is within the permitted range of values. This could well be possible since other changes may occur elsewhere in the system to support the local action of the generator excitation as it adjusts to satisfy the specified terminal voltage.

**The Newton-Raphson Method**

Taylor's series for a function for two or more variables is the basis for the Newton-Raphson method of solving the power-flow problem [1]. The study of the method begins by a discussion of the solution of a problem involving only two variables. Then, it is seen how to extend the analysis to the solution of power-flow equations.

Let us consider the equation of a function of a function $h_1$of two variables $x_1$ and $x_2$ equal to a constant $b_1$ expressed as

$$g_1(x_1, x_2, u) = h_1(x_1, x_2, u) - b_1 = 0 \tag{3.27}$$

And a second equation involving another function $h_2$ such that

$$g_2(x_1, x_2, u) = h_2(x_1, x_2, u) - b_2 = 0 \tag{3.28}$$

Where $b_2$ is also a constant. The symbol $u$ represents an independent control, which is considered constant in theis chapter. As in equation (3.9) and (3.10), the function $g_1$ and $g_2$ are introduced for conveniences to allow us to discuss the difference between calculated values of $h_1$ and $h_2$ and their respective specified values $b_1$and $b_2$.

For a specified value of $u$ let us estimate the solution of these equations to be $x_1^{(0)}$and $x_2^{(0)}$. The zero superscripts indicate that these values are initial estimate and not the actual solutions $x_1^*$and $x_2^*$. It is designated the corrections $\Delta x_1^{(0)}$ and $\Delta x_2^{(0)}$ as the values to be added to $x_1^{(0)}$ and $x_2^{(0)}$ to yield the correct solutions $x_1^*$and $x_2^*$. So it can be written

$$g_1(x_1^*, x_2^*, \mathrm{u}) = g_1\left(x_1^{(0)} + \Delta x_1^{(0)}, x_2^{(0)} + \Delta x_2^{(0)}, \mathrm{u}\right) = 0 \tag{3.29}$$

$$g_2(x_1^*, x_2^*, \mathrm{u}) = g_2\left(x_1^{(0)} + \Delta x_1^{(0)}, x_2^{(0)} + \Delta x_2^{(0)}, \mathrm{u}\right) = 0 \tag{3.30}$$

The problem is now to solve for $\Delta x_1^{(0)}$and $\Delta x_2^{(0)}$, which it is done by expanding equations (3.29) and (3.30) in Taylor's series about the assumed solution to give

$$g_1(x_1^*, x_2^*, \mathrm{u}) = g_1\left(x_1^{(0)}, x_2^{(0)}, \mathrm{u}\right) + \Delta x_1^{(0)} \frac{\partial g_1}{\partial x_1}\Big|^{(0)} + \Delta x_2^{(0)} \frac{\partial g_1}{\partial x_2}\Big|^{(0)} + \cdots\cdots = 0 \tag{3.31}$$

$$g_2(x_1^*, x_2^*, \mathrm{u}) = g_2\left(x_1^{(0)}, x_2^{(0)}, \mathrm{u}\right) + \Delta x_1^{(0)} \frac{\partial g_2}{\partial x_1}\Big|^{(0)} + \Delta x_2^{(0)} \frac{\partial g_2}{\partial x_1}\Big|^{(0)} + \cdots\cdots = 0 \tag{3.32}$$

Where the partial derivatives of order greater than 1 in the series of terms of the expansion have not been listed. The term $\delta g_1/\delta x_1|^{(0)}$ indicates that the partial derivatives is evaluated for the estimated values of $x_1^{(0)}$and $x_2^{(0)}$. Other such terms are evaluated similarly.

It the partial derivatives is neglected of order greater than 1, it can be written equations (3.31) and (3.32) in matrix form.

$$\underbrace{\begin{bmatrix} \frac{\partial g_1}{\partial x_1} & \frac{\partial g_1}{\partial x_2} \\ \frac{\partial g_2}{\partial x_1} & \frac{\partial g_2}{\partial x_1} \end{bmatrix}^{(0)}}_{J^{(0)}} \begin{bmatrix} \Delta x_1^{(0)} \\ \Delta x_2^{(0)} \end{bmatrix} = \begin{bmatrix} 0 - g_1\left(x_1^{(0)}, x_2^{(0)}, \mathrm{u}\right) \\ 0 - g_2\left(x_1^{(0)}, x_2^{(0)}, \mathrm{u}\right) \end{bmatrix} = \begin{bmatrix} b_1 - h_1\left(x_1^{(0)}, x_2^{(0)}, \mathrm{u}\right) \\ b_2 - h\left(x_1^{(0)}, x_2^{(0)}, \mathrm{u}\right) \end{bmatrix} \tag{3.33}$$

Where the square matrix of partial derivatives is called the jacobian J or in this case $J^{(0)}$ to indicate that the initial estimates $x_1^{(0)}$ and $x_2^{(0)}$ have been used to compute the numerical values of the partial derivatives. It is noticed that $g_1\left(x_1^{(0)}, x_2^{(0)}, \mathrm{u}\right)$ is the calculated value of $g_1$ based in the estimated values of $x_1^{(0)}$ and$x_2^{(0)}$, but this calculated value is not the zero value specified by equation (3.27) unless the estimated values $x_1^{(0)}$ and $x_2^{(0)}$ are correct. As before it is designated the specified value of $g_1$ minus the calculated value of $g_1$ as the mismatch $\Delta g_1^{(0)}$ and define the mismatch $\Delta g_2^{(0)}$ similarly. The mismatch equation can be expressed

$$J^{(0)} \begin{bmatrix} \Delta x_1^{(0)} \\ \Delta x_2^{(0)} \end{bmatrix} = \begin{bmatrix} \Delta g_1^{(0)} \\ \Delta g_2^{(0)} \end{bmatrix} \tag{3.34}$$

By solving the mismatch equation either by triangular factorization of the jacobian of (for very small problems) by finding its inverse, it can be determined $\Delta x_1^{(0)}$and $\Delta x_2^{(0)}$.

$$x_1^{(1)} = x_1^{(0)} + \Delta x_1^{(0)}; \qquad x_2^{(1)} = x_2^{(0)} + \Delta x_2^{(0)} \tag{3.35}$$

It is repeated the process until the corrections become so small in magnitude that they satisfy a chosen precision index $\varepsilon < 0$; that is, until $|\Delta x_1|$ and $|\Delta x_2|$ are both less than $\varepsilon$.

**The Newton-Raphson Power-Flow Solution**

To apply the Newton-Raphsonmethodto the solution of the power-flow equations, it is expressed bus voltages and line admittances in polar form [4]. When $n$ is set equal to $i$ in equations (3.6) and (3.7) and the corresponding terms are separated from the summations, it is obtained

$$P_i = |V_i|^2 G_{ii} + \sum_{\substack{n=1 \\ n \neq i}}^{N} |Y_{in} V_i V_n| \cos(\theta_{in} + \delta_n - \delta_i) \tag{3.38}$$

$$Q_i = -|V_i|^2 B_{ii} - \sum_{\substack{n=1 \\ i \neq 1}}^{N} |Y_{in} V_i V_n| \sin(\theta_{in} + \delta_n - \delta_i) \tag{3.39}$$

These equations can be readily differentiated with respect to voltage angles and magnitudes. The terms involving $G_{ii}$ and $B_{ii}$come from the definition of $Y_{ij}$ in equation (3.1) and the fact that the angle $(\delta_n - \delta_i)$ is zero when$n = i$.

Let us postpone consideration of voltage-controlled buses for now and regard all buses (expect the slack bus) as load buses with known demands $P_{di}$and $Q_{di}$. The slack bus has specified values for $\delta_i$and $|V_i|$, and each of the other buses in the network has the two state variables $\delta_i$ and $|V_i|$ to be calculated in the power-flow solution. The known values of$P_{di}$ and $Q_{di}$ correspond to the negative

of the constants shown in equations (3.27) and (3.28). At each of the non-slack buses estimated values of $\delta_i$ and $|V_i|$ correspond to the estimates $x_1^{(0)}$ and $x_2^{(0)}$ in the preceding section. Corresponding to the $\Delta g$ mismatches of equation (3.34) follows from equations (3.8) and (3.9) by writing the power mismatches for typical load bus (i),

$$\Delta P_i = P_{i,sch} - P_{i,cale} \tag{3.40}$$

$$\Delta Q_i = Q_{i,sch} - Q_{i,cale} \tag{3.41}$$

For simplicity sake, it is written mismatch equations for a four-bus system, and it will become obvious how to extend those equations to system with more than four buses. For real power $P_i$ it can be expressed

$$\Delta P_i = \frac{\partial P_i}{\partial \delta_2}\Delta\delta_2 + \frac{\partial P_i}{\partial \delta_3}\Delta\delta_3 + \frac{\partial P_i}{\partial \delta_4}\Delta\delta_4 + \frac{\partial P_i}{\partial |V_2|}\Delta|V_2| + \frac{\partial P_i}{\partial |V_3|}\Delta|V_3| + \frac{\partial P_i}{\partial |V_4|}\Delta|V_4| \tag{3.42}$$

The last three terms can be multiplied and divided by their respective voltage magnitudes without alternating their values, and so it is obtained

$$\Delta P_i = \frac{\partial P_i}{\partial \delta_2}\Delta\delta_2 + \frac{\partial P_i}{\partial \delta_3}\Delta\delta_3 + \frac{\partial P_i}{\partial \delta_4}\Delta\delta_4 + |V_2|\frac{\partial P_i}{\partial |V_2|}\frac{\Delta|V_2|}{|V_2|} + |V_3|\frac{\partial P_i}{\partial |V_3|}\frac{\Delta|V_3|}{|V_3|} + |V_4|\frac{\partial P_i}{\partial |V_4|}\frac{\Delta|V_4|}{|V_4|} \tag{3.43}$$

There are advantages to this form of the equation it is seen at previous section. A similar mismatch equation can be written for reactive power $Q_i$,

$$\Delta Q_i = \frac{\partial Q_i}{\partial \delta_2}\Delta\delta_2 + \frac{\partial Q_i}{\partial \delta_3}\Delta\delta_3 + \frac{\partial Q_i}{\partial \delta_4}\Delta\delta_4 + |V_2|\frac{\partial Q_i}{\partial |V_2|}\frac{\Delta|V_2|}{|V_2|} + |V_3|\frac{\partial Q_i}{\partial |V_3|}\frac{\Delta|V_3|}{|V_3|} + |V_4|\frac{\partial Q_i}{\partial |V_4|}\frac{\Delta|V_4|}{|V_4|} \tag{3.43}$$

Each non-slack bus of the system has two equations like those for $\Delta P_i$and $\Delta Q_i$. Collecting all the mismatch equations into vector-matrix form yields

It is included mismatches for the slack bus since $\Delta P_i$ and $\Delta Q_i$ are undefined when $P_1$ and $Q_1$ are not scheduled. It is also omitted all terms involving $\Delta\delta_1$and $\Delta|V_1|$ from the equation because those corrections are both zero at the slack bus. The partitioned form of equation (3.45) emphasizes the four different types of partial derivatives which enter into the jacobian J.

$$\underbrace{\begin{bmatrix} \frac{\partial P_2}{\partial \delta_2} & \cdots & \frac{\partial P_2}{\partial \delta_4} & |V_2|\frac{\partial P_2}{\partial |V_2|} & \cdots & |V_4|\frac{\partial P_2}{\partial |V_4|} \\ \vdots & J_{11} & \vdots & \vdots & J_{12} & \vdots \\ \frac{\partial P_4}{\partial \delta_2} & \cdots & \frac{\partial P_4}{\partial \delta_4} & |V_2|\frac{\partial P_4}{\partial |V_2|} & \cdots & |V_4|\frac{\partial P_4}{\partial |V_4|} \\ \frac{\partial Q_2}{\partial \delta_2} & \cdots & \frac{\partial Q_2}{\partial \delta_4} & |V_2|\frac{\partial Q_2}{\partial |V_2|} & \cdots & |V_4|\frac{\partial Q_2}{\partial |V_4|} \\ \vdots & J_{21} & \vdots & \vdots & J_{22} & \vdots \\ \frac{\partial Q_4}{\partial \delta_2} & \cdots & \frac{\partial Q_4}{\partial \delta_4} & |V_2|\frac{\partial Q_4}{\partial |V_2|} & \cdots & |V_4|\frac{\partial Q_4}{\partial |V_4|} \end{bmatrix}}_{Jacobian} \underbrace{\begin{bmatrix} \Delta\delta_2 \\ \vdots \\ \Delta\delta_4 \\ \frac{\Delta|V_2|}{|V_2|} \\ \vdots \\ \frac{\Delta|V_4|}{|V_4|} \end{bmatrix}}_{Corrections} = \underbrace{\begin{bmatrix} \Delta P_2 \\ \vdots \\ \Delta P_4 \\ \Delta Q_2 \\ \vdots \\ \Delta Q_4 \end{bmatrix}}_{Mismatches} \tag{3.45}$$

The elements of $J_{12}$ and $J_{22}$ have voltage-magnitude multiplies because a simpler and more symmetrical jacobian results. In choosing this format, it is identified

$$\underbrace{|V_j|\frac{\partial P_i}{\partial |V_j|}}_{Element of J_{12}} \times \underbrace{\frac{\Delta|V_j|}{|V_j|}}_{Correction} = \frac{\partial P_i}{\partial |V_j|} \times \Delta|V_2| \tag{3.46}$$

And the correction become $\Delta\,|V_j|/|V_j|$as shown rather than $\Delta|V_j|$.

The solution of equation (3.45) is found by iteration as follows

- Estimate values $\delta_i^{(0)}$ and $|V_i|^{(0)}$ for the sate variables.
- Use the estimates to calculate $P_{i,calc}^{(0)}$and $Q_{i,calc}^{(0)}$ from equation (3.38) and (3.39), mismatches $\Delta P_i^{(0)}$ and $\Delta Q_i^{(0)}$from equation (3.40) and (3.41), and the partial derivative elements of the jacobian J.
- Solve equation (3.45) for the initial estimates to obtain

$$\delta_i^{(1)} = \delta_i^{(0)} + \Delta\delta_i^{(0)} \tag{3.47}$$

$$|V_i|^{(1)} = |V_i|^{(0)} + \Delta|V_i|^{(0)} = |V_i|^{(0)}\left(1 + \frac{\Delta|V_i|^{(0)}}{|V_i|^{(0)}}\right) \tag{3.48}$$

- Use the new values $\delta_i^{(1)}$ and $|V_i|^{(1)}$ as starting values for iteration 2 and continue.

In more general terms, the update formulas for the starting values of the state variable are

$$\delta_i^{(k+1)} = \delta_i^{(k)} + \Delta\delta_i^{(k)} \tag{3.49}$$

$$|V_i|^{(k+1)} = |V_i|^{(k)} + \Delta|V_i|^{(k)} = |V_i|^{(k)}\left(1 + \frac{\Delta|V_i|^{(k)}}{|V_i|^{(k)}}\right) \tag{3.50}$$

For the four-bus system sub-matrix $J_{11}$has the form

$$J_{11} = \begin{bmatrix} \frac{\partial P_2}{\partial \delta_2} & \frac{\partial P_2}{\partial \delta_3} & \frac{\partial P_2}{\partial \delta_4} \\ \frac{\partial P_3}{\partial \delta_2} & \frac{\partial P_3}{\partial \delta_3} & \frac{\partial P_3}{\partial \delta_4} \\ \frac{\partial P_4}{\partial \delta_2} & \frac{\partial P_4}{\partial \delta_3} & \frac{\partial P_4}{\partial \delta_4} \end{bmatrix} \tag{3.51}$$

Expressions for the elements of this equation are easily found by differentiating the appropriate number of terms in equation (3.38). When the variable $n$ equals the particular value $j$, only one of the cosine terms in the summation of equation (3.38) contains $\delta_i$, it is obtain the typical off-diagonal element of $J_{11}$,

$$\frac{\partial P_i}{\partial \delta_j} = -|V_i V_j Y_{ij}| \sin(\theta_{ij} + \delta_j - \delta_i) \tag{3.52}$$

On the other hand, every terms in the summation of equation (3.38) contains $\delta_i$, and os the typical diagonal; element of $J_{11}$ is

$$\frac{\partial P_i}{\partial \delta_i} = \sum_{\substack{n=1 \\ n\neq i}}^{N} |Y_{in} V_i V_n| \sin(\theta_{in} + \delta_n - \delta_i) = -\sum_{\substack{n=1 \\ n\neq i}}^{N} \frac{\partial P_i}{\partial \delta_n} \tag{3.53}$$

By comparing this expression and that for $Q_i$in equation (3.39), it can be written

$$\frac{\partial P_i}{\partial \delta_i} = -Q_i - |V_i|^2 B_{ii} \tag{3.54}$$

In a quite similar manner, it can be obtained formulas for the elements of sub-matrix $J_{21}$ as follows

$$\frac{\partial Q_i}{\partial \delta_j} = -|V_i V_j Y_{ij}| \cos(\theta_{ij} + \delta_j - \delta_i) \tag{3.55}$$

$$\frac{\partial Q_i}{\partial \delta_i} = \sum_{\substack{n=1 \\ n \neq i}}^{N} |Y_{in} V_i V_n| \cos(\theta_{in} + \delta_n - \delta_i) = -\sum_{\substack{n=1 \\ n \neq i}}^{N} \frac{\partial Q_i}{\partial \delta_n} \tag{3.56}$$

Comparing this equation for $\partial Q_i / \partial \delta_i$, with equation (3.38) for $P_i$, it can be shown that

$$\frac{\partial Q_i}{\partial \delta_i} = -P_i - |V_i|^2 G_{ii} \tag{3.57}$$

The elements of sub-matrix $J_{12}$ are easily found by first finding the expression for the derivative $\partial P_i / \partial |V_j|$ and then multiplying by $|V_j|$ to obtain

$$|V_j| \frac{\partial P_i}{\partial |V_j|} = |V_j Y_{ij}| |V_i| \cos(\theta_{ij} + \delta_j - \delta_i) \tag{3.58}$$

Comparing with equation yields

$$|V_j| \frac{\partial P_i}{\partial |V_j|} = -\frac{\partial Q_i}{\partial \delta_i} \tag{3.59}$$

This is a most useful result, for it reduces the computation involved in forming the jacobian since the off-diagonal elements of $J_{12}$ are now simply the negatives of the corresponding elements in $J_{21}$. This fact would not have become apparent when $\partial P_i / \partial |V_j|$ is multiplied by the magnitude $|V_j|$ in equation (3.43). In as analogues manner, the diagonal elements of $J_{12}$ are found to be

$$|V_i| \frac{\partial P_i}{\partial |V_i|} = |V_i| + \left[ 2|V_i| G_{ii} + \sum_{\substack{n=1 \\ n \neq i}}^{N} |V_n Y_{in}| \cos(\theta_{in} + \delta_n - \delta_i) \right] \tag{3.60}$$

And comparing this result with equation (3.56) and (3.57), it is arrived at the formula

$$|V_j| \frac{\partial P_i}{\partial |V_j|} = \frac{\partial Q_i}{\partial \delta_i} + 2|V_i|^2 G_{ii} = P_i + |V_i|^2 G_{ii} \tag{3.61}$$

Finally, the off-diagonal and diagonal elements of sub-matrix $J_{22}$ of the jacobian are determined to be

$$|V_j| \frac{\partial Q_i}{\partial |V_j|} = -|V_i V_j Y_{ij}| \sin(\theta_{ij} + \delta_j - \delta_i) = \frac{\partial P_j}{\partial \delta_j} \tag{3.62}$$

$$|V_i| \frac{\partial P_i}{\partial |V_i|} = -\frac{\partial P_i}{\partial \delta_i} - 2|V_i|^2 B_{ii} = Q_i - |V_i|^2 B_{ii} \tag{3.63}$$

Let us now bring together the result developed above in the following definitions

Off-diagonal elements, $i \neq j$

$$M_{ij} \triangleq \frac{\partial P_j}{\partial \delta_j} = |V_j| \frac{\partial Q_i}{\partial |V_j|} \tag{3.64}$$

$$N_{ij} \triangleq \frac{\partial Q_i}{\partial \delta_j} = -|V_j| \frac{\partial P_i}{\partial |V_j|} \tag{3.65}$$

Diagonal elements, $i = j$

$$M_{ii} \triangleq \frac{\partial P_i}{\partial \delta_i} \qquad |V_i| \frac{\partial Q_i}{\partial |V_i|} = -M_{ii} - 2|V_i|^2 B_{ii} \tag{3.66}$$

$$N_{ii} \triangleq \frac{\partial Q_i}{\partial \delta_i} \qquad |V_i| \frac{\partial P_i}{\partial |V_i|} = -N_{ii} - 2|V_i|^2 G_{ii} \tag{3.67}$$

Internationalships among the elements in the four sub-matrices of the jacobian are more clearly seen if the definition is used to rewrite equation (3.45) in the following form:

$$\begin{bmatrix} M_{22} & M_{23} & M_{24} & N_{22} + 2|V_2|^2 G_{22} & -N_{23} & -N_{24} \\ M_{32} & M_{33} & M_{34} & -N_{32} & N_{33} + 2|V_3|^2 G_{33} & -N_{34} \\ M_{42} & M_{43} & M_{44} & -N_{42} & -N_{43} & N_{44} + 2|V_4|^2 G_{44} \\ N_{22} & N_{23} & N_{24} & -M_{22} - 2|V_2|^2 B_{22} & M_{23} & M_{24} \\ N_{32} & N_{33} & N_{34} & M_{32} & -M_{33} - 2|V_3|^2 B_{33} & M_{34} \\ N_{42} & N_{43} & N_{44} & M_{42} & M_{43} & -M_{44} - 2|V_4|^2 B_{44} \end{bmatrix} \times$$

$$\begin{bmatrix} \Delta\delta_2 \\ \Delta\delta_3 \\ \Delta\delta_4 \\ \Delta|V_2|/|V_2| \\ \Delta|V_3|/|V_3| \\ \Delta|V_4|/|V_4| \end{bmatrix} = \begin{bmatrix} \Delta P_2 \\ \Delta P_3 \\ \Delta P_4 \\ \Delta Q_2 \\ \Delta Q_3 \\ \Delta Q_4 \end{bmatrix} \tag{3.68}$$

So far it is regarded all non-slack buses as load buses. Now for voltage –controlled buses it can be defined also.

Voltage-controlled buses: in the polar form of the power-flow equations voltage-controlled buses are easily taken into account. For example, when bus (4) of the four-bus system is voltage controlled, and then $|V_2|$ has a specifiec constant value and the voltage correction $\Delta|V_4|/|V_4|$ must always be zero. Consequently, the sixth column of the jacobian of equation (3.68) is always multiplied by zero, and so it may be removed. Furthermore, since $\Delta Q_4$ is not specified the mismatch $\Delta Q_4$ cannot be defined, and so it must be omitted the sixth row of equation (3.68) corresponding to $Q_4$. Of course, $Q_4$ can be calculated after the power-flow solution becomes available.

## 3.4 Power Flow Analysis for System Design and Operation

Generally power analysis is common part of power system which comprises of generation, transmission and distribution. To design a standard power system, it is necessary to consider the real and reactive power of the connected bus and generation. The magnitude of voltage and current are directly related to the real power and reactive power of the bus. The system frequency is also related to the produced voltage from the generator and connected load of the system. The variation of the system load causes change in power (both real and reactive) as well as frequency which may cause problem in system stability [10]. In a well designed power system some considerations need to be considered which are, the generation must be supplied the demand (load) plus the losses, bus voltage magnitudes must remain close to rated values, generators must be operated within the

specified real and reactive power limits, transmission lines and transformers should not be overloaded for long periods. Therefore it is important for power flow analysis of an electrical system in order to get overall information about the system parameters which is essential for system operation and stability under various loading and operating conditions. In case of designing a new power system, the power flow analysis helps in determining the nature of the system in advance for proper installation of the system. So that power flow analysis is used extensively in the planning, design and operation of electrical systems.

## 3.5 Modern Techniques for Power Flow Analysis

Due to the complexity of the modern power system, conventional methods of power flow are replaced by power system analysis softwares. Power systems analysis and simulation softwares are widely used now. Initially, these softwares are used for quickly solving the non-linear load flow problem and calculate short circuit currents, but their use are now extended in many other areas such as power system stability, protection and coordination, contingency and reliability, economic modeling and others.

Some commonly simulation softwares which are used for power system are mentioned below:

1. PowerWorld Simulator: It solves the power flow and economic dispatch problems. It is an interactive power system simulation package designed to simulate high voltage power system operation on a time frame ranging from several minutes to several days. Powerful visualization techniques are used on an interactive basis, resulting in an extremely intuitive and easy to use graphical user interface (GUI). The GUI includes animated one-line diagrams with support for panning, zooming and conditional display of objects. The software runs under Microsoft Windows 95/98/NT [25].

2. Voltage Stability Toolbox: The Voltage Stability Toolbox (VST), developed at the Center for Electric Power Engineering, Drexel University, combines proven computational and analytical capabilities of bifurcation theory and symbolic implementation and graphical representation capabilities of MATLAB and its Toolboxes [25]. It can be used to analyze voltage stability problem and provide intuitive information for power system planning, operation, and control. For using VST, MATLAB and its toolbox and windows based operating system are needed.

3. PSAT, Power System Analysis Toolbox: The main features of PSAT are Power flow, Continuation power flow, Optimal power flow, Small signal stability analysis, Time domain simulation, Phasor Measurement Unit (PMU) placement, Complete graphical user

interface, CAD for network design (Simulink library), User defined models,Conversion of data files from several formats, Export results to EPS, plain text, MS Excel and LaTeX files, Interfaces to GAMS and UWPFLOW programs, Command line usage, GNU/Octave compatibility [25].

4. CAPSA Software: Supplementary Software from "Computer Aided Power System Analysis, 2nd ed." by Dr. G. Kusic. The software is free to all. Programs include droop and dynamic response of generation by AGC, abc to/from symmetrical components, dc power flow, line parameters from geometric factors, short circuit calculations from user constructed bus impedance matrices, network power flow with FACTS devices, economic dispatch, unit commitment, network reduction to obtain loss coefficients and state estimation from corruptible data snapshots. All programs run as stand-alone or from a PowerPoint interface [25].There are also some DOS base software is used to analysis power system. The computer based powerflow analysis has been promoted more extra concern about power system design and operation. Whereas accuracy level of manual calculation method was very low.

## 3.6 Proposed Method

### Theory

Figure 3.3 shows that simple circuit with an AC voltage source, a resistor, an inductor and load. The corresponding phasor diagram of voltage & current of the circuit is shown in figure 3.4.

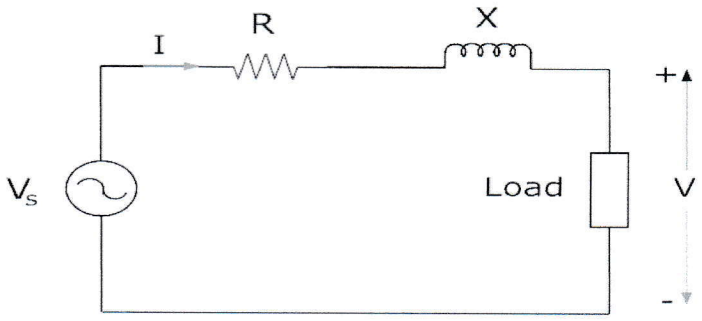



Figure 3.3: A simple AC circuit

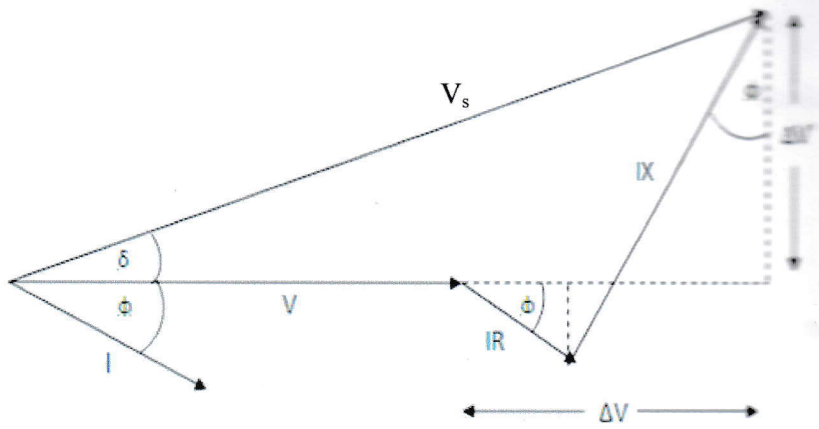



Figure 3.4: Phasor diagram of the simple AC circuit

From figure 3.4

$$V_s^2 = (V + \Delta V)^2 + \Delta V'^2 \tag{3.69}$$

$$\text{Where } \Delta V = IR\cos\varphi + IX\sin\varphi = \frac{RP}{V} + \frac{XQ}{V}$$

$$\Delta V' = IX\cos\varphi - IX\sin\varphi = \frac{XP}{V} - \frac{RQ}{V}$$

Practically, $V + \Delta V \gg \Delta V'$ so neglecting $\Delta V'$, equation (3.69) can be written as

$$V_s = V + \Delta V = V + \frac{RP}{V} + \frac{XQ}{V}$$

Hence the reactive power is given by

$$Q = \frac{V_s V - V^2 - PR}{X} \tag{3.70}$$

Differentiating equation (3.70) with respect to V, we get

$$\frac{\delta Q}{\delta V} = \frac{V_s - 2V}{X} \tag{3.71}$$

For a three phase short circuit at the receiving end $(V = 0)$

$$\frac{\delta Q}{\delta V} = \frac{V_s}{X} = I_{sc} \tag{3.72}$$

The rate of change of reactive power with respect to voltage at a node is equal to the short circuit current.

However in a system with many buses the short circuit current at any bus K is obtained neglecting pre-fault current as follows

$$I_{sc,K} = \frac{V_{f,K}}{Z_{KK}} \tag{3.73}$$

Where $V_{f,K}$= Pre-fault voltage of bus K which is usually considered as 1per unit

$Z_{KK}$ = Diagonal element corresponding to bus K in the system bus impedance matrix $\mathbf{Z}_{bus}$

So equation (3.72) can be extended to any bus K in large system as follows.

$$\frac{\delta Q}{\delta V} = I_{sc} = \frac{1}{Z_{KK}} \tag{3.74}$$

So VAR required at a bus in respect to the change in its voltage ΔV can always be obtained as

$$\Delta Q_K = \frac{1}{Z_{KK}} \Delta V_K \tag{3.75}$$

i.e $$Q_{K,reqd} - Q_{K,existing} = \frac{1}{Z_{KK}} (V_{K,reqd} - V_{K,existing}) \tag{3.76}$$

## 3.7Algorithm and Flow Chart of Proposed Method

1. Form $\mathbf{Y_{bus}}$ matrix of the network.
2. Find $\mathbf{Z_{bus}}$matrix of the network inverting the $\mathbf{Y_{bus}}$ matrix.

   $\mathbf{Z_{bus}} = \mathbf{Y_{bus}}^{-1}$
3. Perform base case load flow by the given network data.
4. Identify K buses suffering from low voltages having voltages under 0.95 p.u.
5. Select a candidate bus K and find the desired voltage raise, $\Delta V_k$.

   $\Delta V_K = V_{K,reqd} - V_K$
6. Find the required VAR size.

   $$\Delta Q_K = \frac{1}{Z_{KK}} \Delta V_K$$

   Where, $Z_{KK}$ = Corresponding diagonal element of $\mathbf{Z_{bus}}$ for the candidate bus K.

   $$\Delta Q_K = Q_{K,reqd} - Q_{K,existing}$$
7. Run a test load-flow using a capacitor bank, $\Delta Q_K$ MVAR at the bus K and find new$V_K$.
8. Repeat steps 5, 6 and 7 for other buses mentioned in step 4.

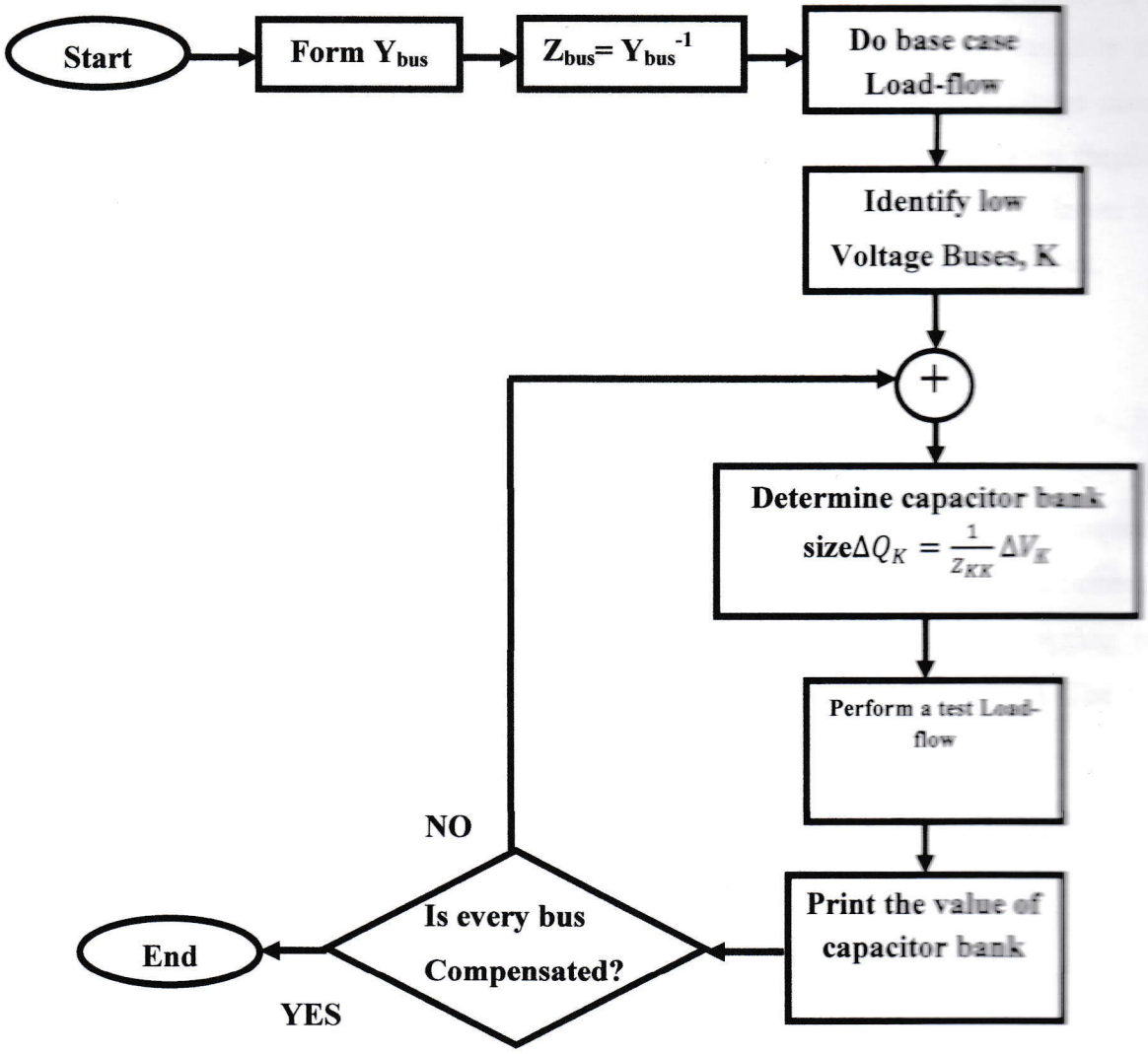



Figure 2.6: Flow chart of proposed method

A simplified cross section of a Triac is shown in figure 4.13. A positive voltage applied to the anode with respect to the cathode forward-biases J1, while reverse biasing J2; J4, and J3 are shorted by the metal contacts. When J2 is biased to breakdown, a lateral current is flown in the p2 region. This lateral flow forward-biases the edge of J3, causing carrier injection. The result is that the device switches into its thyristor mode and latches [14]. Applying a reverse voltage causes the opposite behavior at each junction, but with the same result. Figure 4.13 also shows the plot for a Triac. The addition of a gate connection allows the break over to be controlled at a lower forward voltage. And the number of resistors, capacitors, inductors is used in compensator circuit.

## 4.5 Calculation of Design of Capacitor and Inductor Bank

Figure 4.14 shows that an inductive load takes a lagging current $I$ at a power factor $\cos\varphi_2$. In order to improve the power factor of this circuit, it is necessary to connect a device in parallel with the load which takes a leading reactive current and partly cancels the lagging reactive current of the load [3]. Figure 4.14(i) shows a capacitor is connected across the load which takes a current $I_c$ that leads the supply voltage $V$ by 90 degree. The current $I_c$ partly cancels the lagging reactive component of the load current as shown in the phasor diagram in figure 4.14(ii). The resultant circuit current becomes $I'$ and its lagging angle is$\varphi_2$.

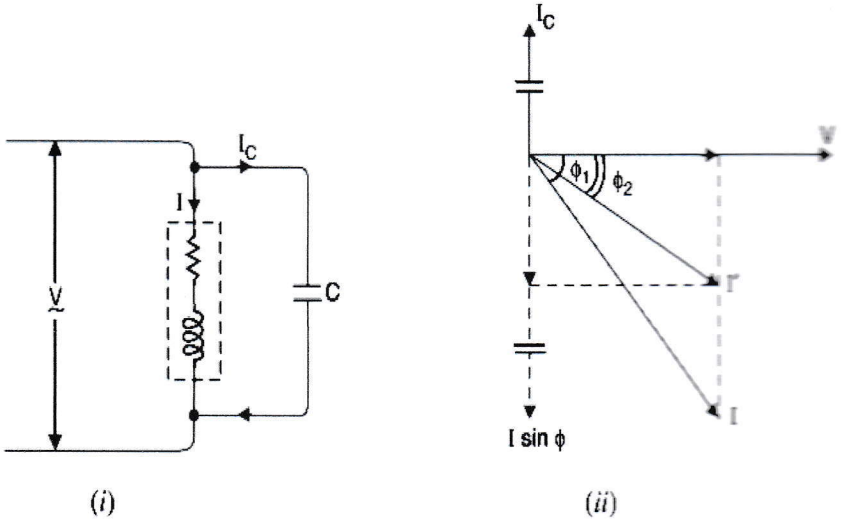



Figure 4.14: Reactive power compensation of lagging current (i) Circuit diagram and (ii) Phasordiagram

From the phasor diagram, it is clear that after p.f (power factor) correction, the lagging component of the load is reduced to$I' \sin\varphi_2$.

$$I' \sin\varphi_2 = I \sin\varphi_1 - I_C$$

$$I_C = I' \sin\varphi_1 - I' \sin\varphi_2 \qquad (4.1)$$

The capacitance of capacitor to improve p.f. or to compensate reactive power from $\cos\varphi_1$ and $\cos\varphi_2$

$$X_C = \frac{V}{I_C} = \frac{1}{\omega c}$$

Or $$C = \frac{I_c}{\omega V} \qquad (4.2)$$

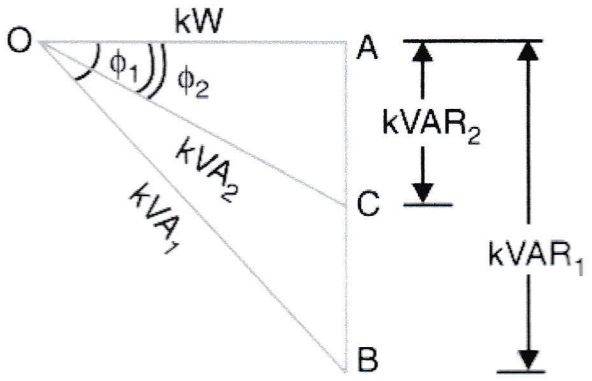



Figure 4.15: Power triangle reactive power compensation

Figure 4.15 shows that power triangle of reactive power compensation or power factor improvement. The power triangle of OAB is for the power factor $\cos\varphi_1$, whereas power triangle OAC is for the improved power factor $\cos\varphi_2$. It can be seen that active power (OA) does not change with power factor improvement. However, the lagging k of the load is reduced by the p.f. correction equipment correction equipment, thus improving the p.f. to $\cos\varphi_2$.

$$= BC = AB - AC$$

$$= kVAR_1 - kVAR_2$$

$$= OA(\tan\varphi_1 - \tan\varphi_2)$$

$$= kW(\tan\varphi_1 - \tan\varphi_2)$$

The leading kVAR is supplied by the p.f. correction equipment for obtaining the desired result

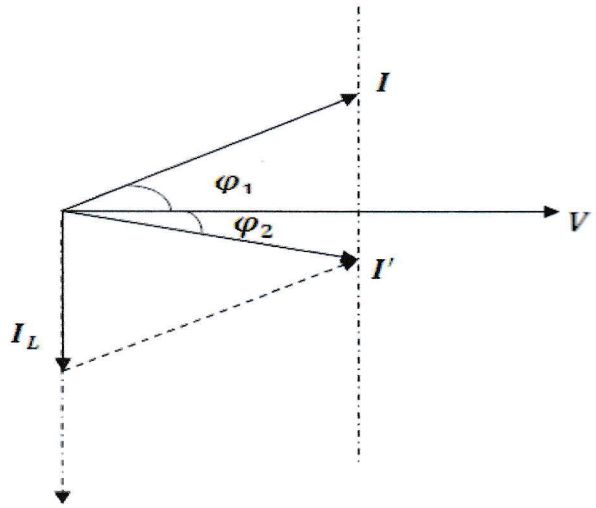



Figure 4.16: Reactive power compensation for leading current

Similarly for leading current,

$$I' \sin \varphi_2 = I_L - I \sin \varphi_1$$

Or $$I_L = I' \sin \varphi_2 - I \sin \varphi_1 \quad (4.3)$$

The inductance of inductor diminish the leading current from $\cos \varphi_1$ to $\cos \varphi_2$

$$V = I_L X_L = I_L \omega L$$

And $$L = \frac{V}{\omega I_L} \quad (4.4)$$

The size of the capacitor and inductor bank can be calculated by equation (4.2) and (4.4) respectively. Moreover the size of the reactive banks also depends on the current, power factor and expected power factor of that transmission line.

# Chapter 4: Test and Results

The proposed method is applied for 4-bus and 7-bus power system, the comparison of the traditional and proposed method shows that the proposed method quite more efficient than the traditional method. The fast decoupled method is used for analyzing the power flow of 42 buses of the transmission network of Bangladesh. The MATLAB coding is used for finding the faulty buses which have low voltage problem among those 43 buses. The transient of the SVS system is free from any harmonics distortion and the switching action of Triac is faster than the mechanical switching. In the traditional fast decoupled method, Capacitor size of Elm bus is 0.98 p.u.(Per Unit) where in the proposed method, the capacitor size of Elm bus is 0.9868 p.u. By using MATLAB of fast decoupled method, some low voltage buses are found of Sutkhira 33kV of voltage 0.7792 p.u. and angle is -42.2266 degree, Madaripur 33kV of voltage 0.7069 p.u. and -49.1578 degree. When the voltage is decreased due to the lagging current, the voltage is improved by the capacitor in the transmission line. Similarly when the voltage is increased due to the leading current, the voltage is improved by the inductor in the transmission line which is discussed in this chapter.

## 4.1 Results of Power Flow analysis

### For 4-bus Power System

The network used here is a very simple four bus network consisting two source and two load buses with no transformer connected to any of the buses. Figure 5.1 shows the four bus power system where the bus no 1 (Birch) is considered as the slack-bus.

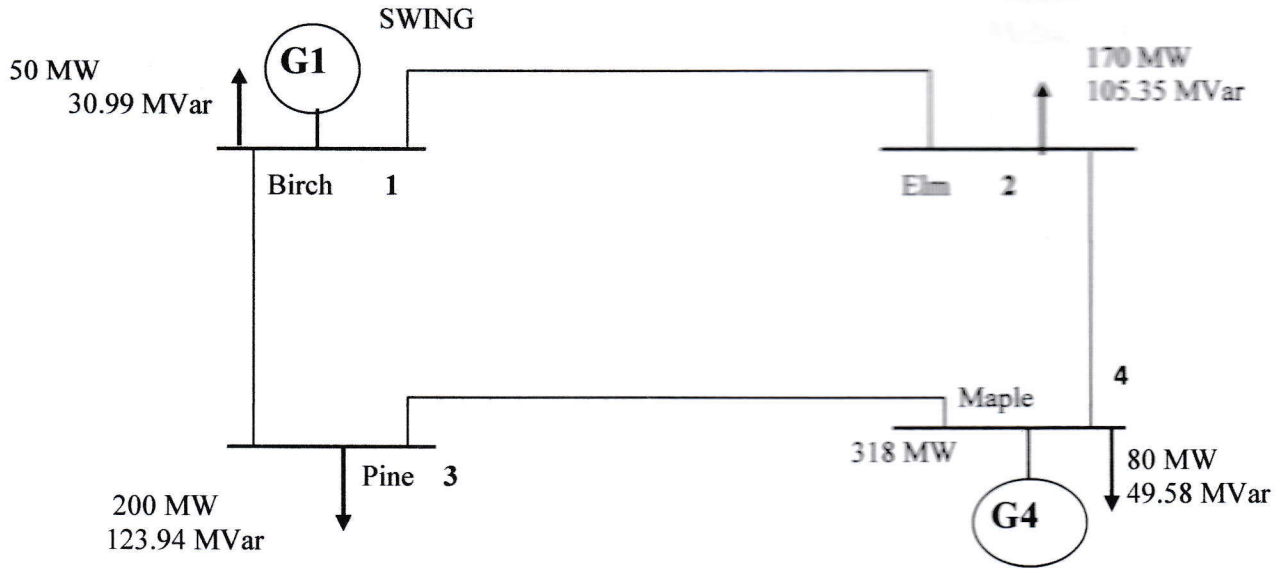



Figure 4.1: Four bus system network

All the four buses supplies some loads of different levels. The voltage, power, phase angle and other related data for the four bus network by using fast decoupled load-flow analysis are given in appendix B.

Table 4.1: Base Case Load-Flow Results of 4-bus Network

| Bus No. | Bus Name | Voltage | Angle |
|---|---|---|---|
| 1 | Birch | 1.0 | 0 |
| 2 | Elm | .9785 | -0.9399 |
| 3 | Pine | .9642 | -1.8308 |
| 4 | Maple | 1.02 | 1.5243 |

For each load-bus (bus 2 and 3), the desired voltage rise, $\Delta V$ is calculated from subtracting the base case voltage from the target voltage. The capacitor bank size is then determined by the proposed method. A test load-flow is run to find the new voltage level after installing the calculated capacitor bank. Then in traditional way, load-flow analysis is run several times to find the actual capacitor bank size. Comparison between the results obtained from these two methods is shown in table 5.2.

Table 4.2: Comparison results between proposed and traditional method for raising the voltage level

| A | B | C | D | E | F | G | H | I | J | K |
|---|---|---|---|---|---|---|---|---|---|---|
| **Bus No** | **Bus Name** | **Base voltage in p.u.** | **Voltage difference in p.u.** | **Capacitor Size in p.u.** | | | Voltage after installing Capacitor Bank in p.u. | | | Remarks: No of times of Iteration Required in Traditional Method |
| | | | | **Traditional Method** | **Proposed Method** | % of Error | Traditional Method | Proposed Method | % of Error | |
| **2** | Elm | .9785 | .0215 | .98 | 0.9868 | .693 | 1.0 | 1.0002 | **0.02** | 8 |
| **3** | Pine | .9642 | .0358 | 1.48 | 1.498 | **1.22** | 1.0 | 1.0005 | **0.05** | 11 |

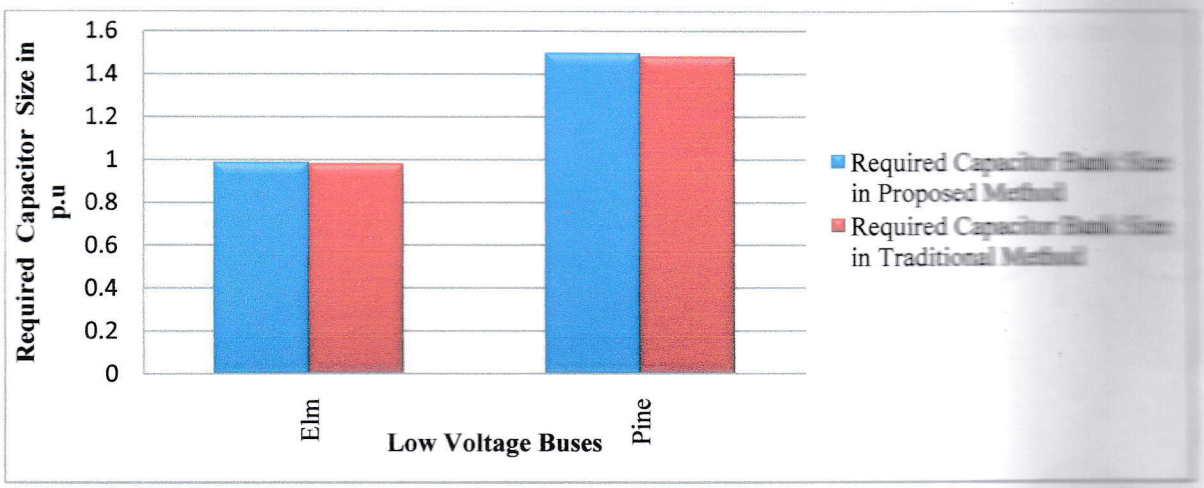



Figure 4.2: Relative comparison between traditional and proposed method for determining the capacitor bank size

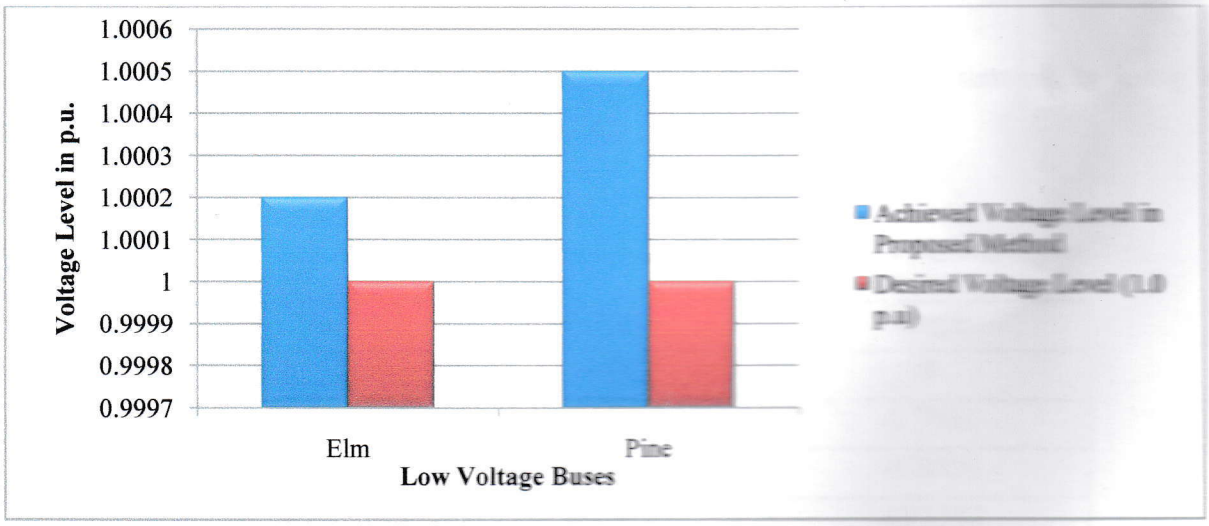



Figure 4.3: Comparison between desired (1.0 p.u.) and achieved voltage level by proposed method

So it is observed that the proposed method works quite successfully for the four-bus system. Probably, the method works perfectly for the simplicity of the network which consists of two source and load buses. The generators of source buses meet the reactive power demand of the load buses which causes slight distortion of system voltage. As voltage level deteriorates a little for the four bus system, a more complex network needs to be analyzed to verify the validity of the proposed method.

**7-bus Power System**

The network used here is also a very simple network consisting of three source and four load buses with transformer connected to all of the three generator buses. Figure 5.4 shows the 7 bus power

system network where bus no 1 is the slack-bus. All the seven buses supplies some loads of different levels except the slack-bus.

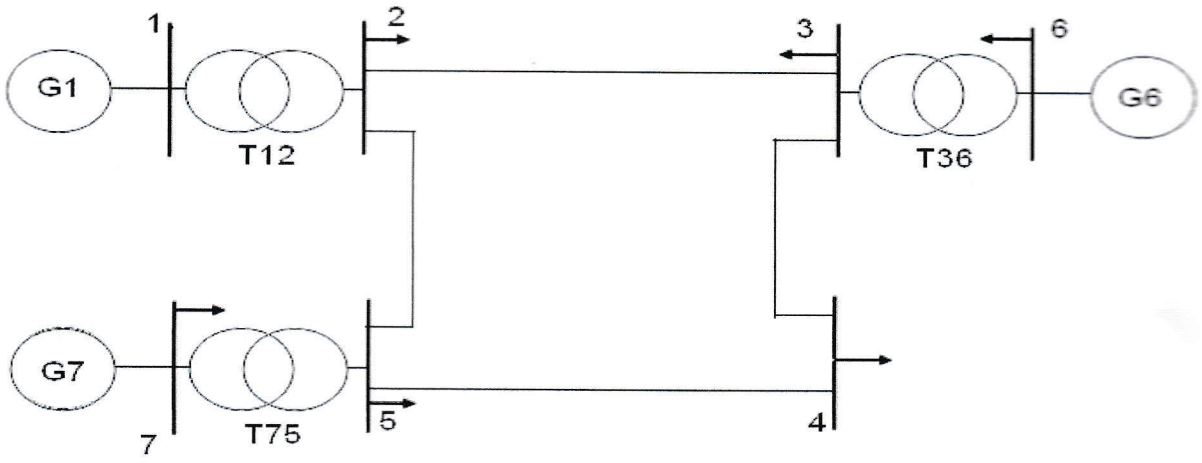



Figure 5.4: 7-Bus System Network

The voltage, power, phase angle and other related data for the four bus network by using fast decoupled load-flow analysis are given in appendix B.

Table4.3: Base Case Load-Flow Results of 7-bus Network

| Bus No. | Voltage | Angle |
|---|---|---|
| 1 | 1.0000 | 0 |
| 2 | 0.9905 | -1.7861 |
| 3 | 1.0105 | -9.8008 |
| **4** | **0.9785** | -49.1582 |
| **5** | **0.9642** | -46.1465 |
| 6 | 1.0200 | -9.2566 |
| 7 | 1.0200 | -45.7662 |

Table 4.4: Comparison results between proposed and traditional method for raising the voltage level

| A | B | C | D | E | F | G | H | I | J |
|---|---|---|---|---|---|---|---|---|---|
| Bus No | Base voltage In p.u. | Voltage difference in p.u. | Capacitor Size in p.u. | | | Voltage after installing Capacitor Bank in p.u | | | Remarks: No of times of Iteration Required in Traditional Method |
| | | | Traditional Method | Proposed Method | % of Error | Traditional Method | Proposed Method | % of Error | |
| 4 | .9785 | .0215 | **0.827** | **0.852** | 3.023 | 1.0 | 1.0755 | **7.55** | 7 |
| 5 | .9642 | .0358 | **1.542** | **1.619** | 4.99 | 1.0 | 1.0145 | **1.45** | 9 |

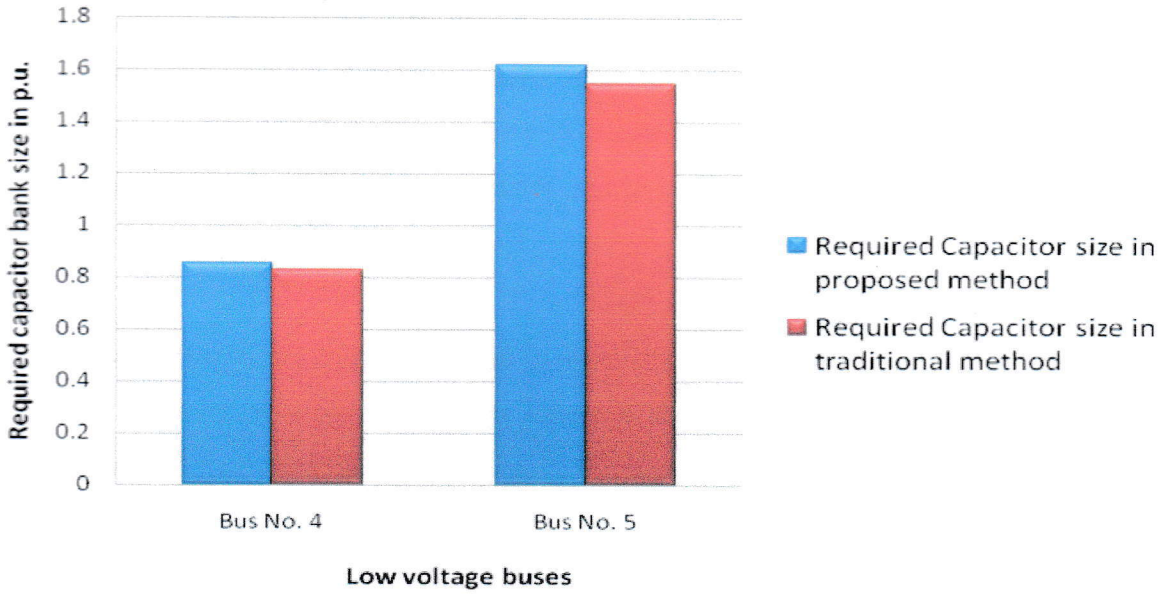



Figure 4.5: Comparison between capacitor sizes by traditional and proposed method for 1.0 p.u voltage in 7-bus network

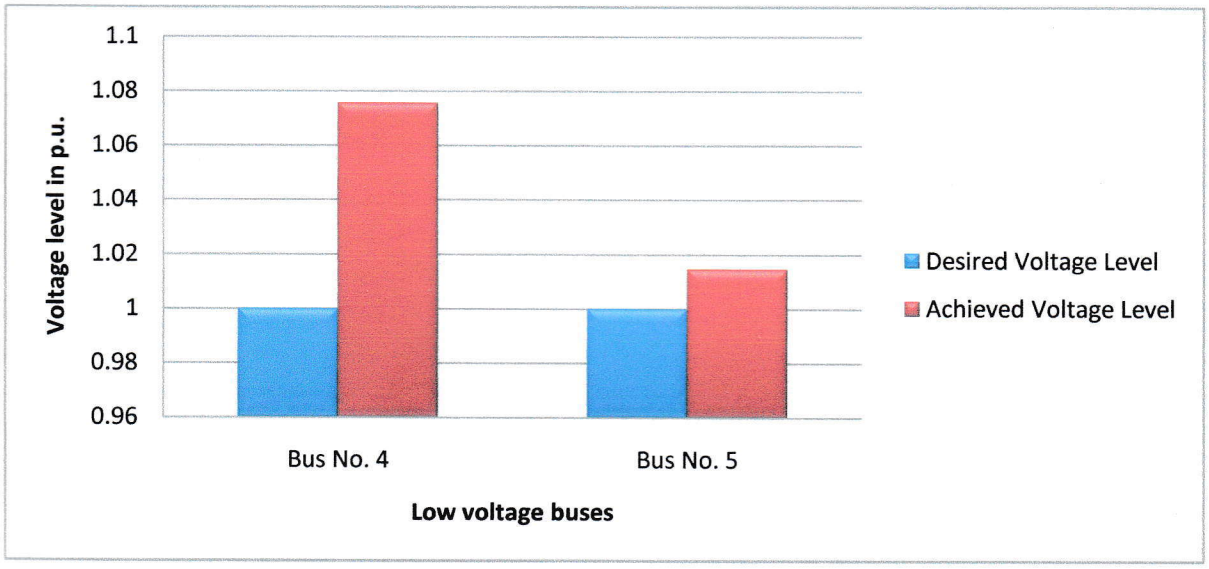



Figure 4.6: Comparison between desired (1.0 p.u.) and achieved voltage level by proposed method in 7-bus network

Here also the proposed method works successfully for the seven-bus system. So now it can be said that the proposed method works perfectly for any simple network. In the case studies shown above, the proposed method is used for reactive power compensation of the Bangladesh Power system.

## 4.2 Analysis and Determination of Faulty Buses

Bangladesh power system is a subtle system with peak demand of about 4500MW and peak generation of about 4000MW[23]. The entire power system is divided into two parts, east zone and west zone. Bangladesh power system consists of 200 buses. Among them 21 buses are source buses and others are load buses.

Using the network data and parameters given in appendix B and with the help of a MATLAB code, the load-flow analysis of total Bangladesh power system network is performed. Here fast de-coupled method of load-flow analysis is used as it works faster than Gauss-Siedel or Newton-Raphson method. Considering an arbitrary load- generation scheme, first a base case load flow is performed. As the ultimate target of this effort is to find a fast method for reactive power compensation to upgrade the voltage profile, the buses suffering from low voltage ( below .85 p.u. ) are identified first from the whole system load-flow result which is given in appendix B. The base case result for only the identified low voltage buses are given in table 3.5.

Table 3.5: Base case load-flow result for the identified low voltage buses

| Bus No | Bus Name | Voltage in p.u. | Angle |
|---|---|---|---|
| 140 | Satkhira 33 | 0.7792 | -42.2266 |
| 141 | Khulna C r 33 | 0.7917 | -41.7527 |
| 142 | Noapara 33 | 0.7772 | -42.1156 |
| 143 | Jessore 33 | 0.7676 | -43.1015 |
| 144 | Jhenidah 33 | 0.7693 | -42.3545 |
| 145 | Kushtia 33 | 0.806 | -39.544 |
| 146 | G.K 33 | 0.7962 | -37.2581 |
| 147 | Faridpur 33 | 0.7183 | -45.7453 |
| 148 | Madaripur 33 | 0.7069 | -49.1578 |
| 149 | Gopalgonj 33 | 0.6997 | -49.6241 |
| 150 | Patuakhali 33 | 0.7218 | -51.1849 |
| 151 | Bhandaria 33 | 0.7393 | -47.8677 |
| 152 | Bagherhat 33 | 0.7462 | -46.7403 |
| 153 | Mongla 33 | 0.7379 | -47.0881 |
| 154 | Ishurdi 33 | 0.808 | -35.6519 |
| 155 | Pabna 33 | 0.8353 | -36.1892 |
| 156 | Shahjadpur 33 | 0.8466 | -33.0306 |
| 157 | Serajganj 33 | 0.8408 | -33.3038 |
| 164 | Naogaon 33 | 0.8045 | -36.4802 |
| 165 | Natore 33 | 0.804 | -36.5924 |
| 166 | Rajshahi 33 | 0.7816 | -38.734 |
| 167 | Ch.nawabganj 33 | 0.762 | -40.1075 |
| 168 | Goal para 33 | 0.7977 | -40.9016 |
| 169 | Barishal 33 | 0.7418 | -49.7142 |

Now for every low voltage bus (K), the desired voltage variation $\Delta V_K$ is calculated from subtracting the respective bus voltage to the base voltage (0.95 or 1.0 p.u.). The VAR required is then determined from dividing $\Delta V_K$ by the corresponding diagonal element of bus impedance matrix for each of the two cases. After then in the traditional way, several load-flow analyses is run to find the actual value of VAR needed. The result includes the no of trials needed to find the required value of capacitor bank to improve the voltage level to the desired value by the traditional method.

# Conclusion

The low-voltage is a very common phenomenon in Bangladesh especially in the west zone of Bangladesh. So maintaining the system reliability it is necessary to compensate the reactive power and thereby the selection of reactor (capacitor or inductor) bank is required. In this thesis work, fast decoupled method is used for power flow analysis of the Bangladesh Power system and later conventional method is used for reactive power compensation and selection of reactor bank. A relative comparison of the two methods (fast decoupled method and conventional method) is done for analyzing the power flow of 42 buses (21 buses of 33kV and 21 buses of 132kV) of Bangladesh Power System which are suffering severe low voltage problem..TheMicrocontroller based thyristor is used for switching capacitor or inductor bank according to the requirement of the system voltage with the variation of load in the transmission line. This thesis work is solely devoted to develop a fast and simple algorithm for the computation of capacitor and inductor bank size for reactive power compensation and switching technique for connecting that bank according to the system requirement. In this work the achievements and new modifications are:

- By using MATLAB of fast decoupled method, some low voltage buses are found of Satkhira 33kV of voltage 0.7792 p.u. and angle is -42.2266 degree, Madaripur 33kV of voltage 0.7069 p.u. and -49.1578 degree.
- The proposed method increases the bus voltage of 1.0005 per unit where the desired bus voltage is 1 per unit for selected buses.
- Microcontroller based switching of reactor bank according to the system requirement is more efficient than the conventional method.
- Transient free switching action is obtained.
- The compensator circuit design can be used for 3-phase transmission line by synchronizing the gate pulses of the Triacs.

In traditional method several trials and errors are to be done each of which comprises several iterations which make this method complicated and time consuming, whereas the proposed method needs a trivial computation which is less time consuming and simple. It is very tough to implement the time consuming and complicated traditional method for online capacitor or inductor bank computing purpose. On the other hand, being extremely fast, the proposed method has high opportunities to be used for online capacitor or inductor bank computation purpose. In case of addition of new buses or some modification of the system, the $Z_{bus}$ can be modified easily using certain procedures. In case of reactive power compensation of two or more buses at a time with the proposed method, the method is to be applied on the buses one by one. After applying the method once in one of the buses, a test load-flow is to be run to observe the effect on the voltages. These new voltages are to be taken in account while applying the method on the next bus.The$Z_{bus}$ of a network during faults differs from the $Z_{bus}$ in steady state as sub transient reactance of generators is included. For simplicity, it is avoided during the development of the proposed method. Further work needs to be done to modify the proposed method (fast decoupled method) by analyzing the system taking transient and sub-transient reactance in account. While developing the theory, the load current of the circuit is ignored, this can cause some effect on the desired result. The proposed method in this thesis is a simple and uncomplicated method for analyzing the power flow and reactive power compensation of complicated power system network having many buses.

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# Appendix A

**MATLAB code for Load-Flow of Bngladesh Power System Network.**

```
clear all
clc
clf


% No of maximum iteration
iteration=30;


% Tolerance
check=.0001;

%  Initial assumption for all bus voltages and angle
n=200;
x=195;
y=n-x;
vl=ones(1,x);
vc=1.02*ones(1,y);
v=[vl';vc']';
d=zeros(1,n);

% Loading Scheduled P Q from power subroutine
[ps,qs,qa]=power();

% Loading Ybus from Ybus subroutine
[g,b]=ybus();
bm=-b;
[ar,y]=cart2pol(g,b);
y1=inv(bm(2:n,2:n));
y2=inv(bm(2:x,2:x));

% Calculation
for ii=1:iteration

% Real Power Calculation
p=zeros(1,n);
fori=1:n
for j=1:n
      p(i)=p(i)+(y(i,j)*v(i)*v(j))*cos(ar(i,j)+d(j)-d(i));
end
end


% Miss match P
delp=ps(2:n)'-p(2:n);
delp=delp./v(2:n);
```

```
% Correction of Angle
deld=y1*delp';
d(2:n)=d(2:n)+deld';

% Reactive Power Calculation
q=zeros(1,n);
fori=1:n
for j=1:n
      q(i)=q(i)-(y(i,j)*v(i)*v(j))*sin(ar(i,j)+d(j)-d(i));
end
end

% Miss Match Q
delq=qs(2:x)'+(qa(2:x).*v(2:x)'.^2)'-q(2:x);
delq=delq./v(2:x);

% Correction V
delv=y2*delq';
v(2:x)=v(2:x)+delv';

% Checking for stopping iterations
a=[deld;delv];
c=max(abs(a));
if c<check
break;
end
end
```

**MATLAB code for Loading the Given Power Data from Excel Sheet**

```
% Defining the returning variables of power subroutine
function [ps,qs,qa]=power();
clear all;
clc;

% Loading power data
ps= -.9*load ('power.dat')/100;
qs=.62*ps;


% Loading Existing Capacitor Bank Data
qa=load ('cap.dat')/100;


% Maximum Supplied VAR of the generators.
qs(180:200)=[1.2 0.55 0.3 1.11 0.2 0.9 0.38 0.6 ...
   0.23 0.6 0.2 0.64 0.9 1.3 0.47 1.4 1.86 ...
   3.05 3.15 4.6 7];
```

**MATLAB code for $Y_{bus}$ Building by the Given Network Data.**

```
% Defining the returning variables of Ybus subroutine
function [g,b,zz]=ybus();
clear all;
clc;

% Loading Line to Line Impedance Data
load bus2bus.dat
H = spconvert(bus2bus);
f=full(H);
n=length(f);

ff=f;
for ii=1:n
for j=1:n
if ii<j
ff(j,ii)=ff(ii,j);
end
end
end

% Loading Transformer Impedance Data
load xformer.dat
G = spconvert(xformer);
f=full(G);

for ii=1:n
for j=1:n
if ii<j
f(j,ii)=f(ii,j);
end
end
end

z=f+ff;

for ii=1:n
for j=1:n
if z(ii,j)~=0
y(ii,j)=1/z(ii,j);
end
end
end


% Loading Parallel Susceptance Data of line
load sus.dat
S = spconvert(sus);
f=full(S);
```

```
for ii=1:n
for j=1:n
if ii<j
f(j,ii)=f(ii,j);
end
end
end

for ii=1:n
y(ii,ii)=-sum(f(ii,:));
end
for ii=1:n
suss(ii)=abs(y(ii,ii));
end

% forming Ybus
yy=zeros(n);
for iii=1:n
for j=1:n
if iii==j
for ii=1:n
yy(iii,j)=yy(iii,j)+y(iii,ii);
end
else
yy(iii,j)=-y(iii,j);
end
end
end
zz=inv(yy);
g=real(yy);
b=imag(yy);
```

**Microcontroller *ATmega8***

High-performance, low-power AVR 8-bit microcontroller.

Advanced RISC architecture:

130 powerful instructions – most single-clock cycle execution

32 x 8 general purpose working registers

fully static operation

Up to 16 MIPS throughput at 16 MHz

On-chip 2-cycle multiplier

High endurance non-volatile memory segments:

- 8K bytes of in-system self-programmable flash program memory
- 512 bytes EEPROM
- 1K byte internal SRAM

- Write/Erase cycles: 10,000 flash/100,000 EEPROM
- Data retention: 20 years at 85°C/100 years at 25°C
- Optional boot code section with independent lock bits
- In-system programming by on-chip boot program

1. True read-while-write operation-Programming lock for software security
2. Peripheral features:
   - Two 8-bit Timer/Counters with separate Prescaler, one compare mode
   - One 16-bit Timer/Counter with separate Prescaler, compare mode, and capture Mode
   - Real time counter with separate oscillator
   - Three PWM channels
   - 8-channel ADC in TQFP and QFN/MLF package
   - Eight channels 10-bit accuracy
   - 6-channel ADC in PDIP package
   - Six channels 10-bit accuracy
   - Programmable serial USART
   - Master/Slave SPI serial interface
   - Programmable Watchdog Timer with separate on-chip oscillator
   - On-chip analog comparator
3. Special Microcontroller features:
   - Power-on Reset and programmable Brown-out Detection
   - Internal calibrated RC oscillator
   - External and internal interrupt sources
   - Five sleep modes: Idle, ADC noise reduction, Power-save, Power-down, and Standby
4. I/O and Packages:
   - 23 programmable I/O lines
   - 28-lead PDIP, 32-lead TQFP, and 32-pad QFN/MLF
5. Operating Voltages:
   - 2.7 - 5.5V (ATmega8L)
   - 4.5 - 5.5V (ATmega8)
6. Speed Grades:
   - 0 - 8 MHz (ATmega8L)
   - 0 - 16 MHz (ATmega8)
7. Power consumption at 4 Mhz, 3V, 25°C

8. Active: 3.6 mA
9. Idle mode: 1.0 mA
10. Power-down mode: 0.5 µA

**The Code of Microcontroller**

```
/*****************************************************
This program was produced by the
CodeWizardAVR V2.05.0 Professional
Automatic Program Generator
© Copyright 1998-2010 Pavel Haiduc, HP InfoTech s.r.l.
http://www.hpinfotech.com

Project :
Version :
Date    : 06-Jan-2012
Author  :NeVaDa
Company :
Comments:


Chip type           : ATmega8L
Program type        : Application
AVR Core Clock frequency: 8.000000 MHz
Memory model        : Small
External RAM size   : 0
Data Stack size     : 256
*****************************************************/

#include <mega8.h>
#include <stdio.h>
#include <delay.h>
unsignedintadc=0;
#define ADC_VREF_TYPE 0x20

// Read the 8 most significant bits
// of the AD conversion result
unsigned char read_adc(unsigned char adc_input)
```

```
{
ADMUX=adc_input | (ADC_VREF_TYPE & 0xff);
// Delay needed for the stabilization of the ADC input voltage
delay_us(10);
// Start the AD conversion
ADCSRA|=0x40;
// Wait for the AD conversion to complete
while ((ADCSRA & 0x10)==0);
ADCSRA|=0x10;
return ADCH;
}

// Declare your global variables here

void main(void)
{
// Declare your local variables here
int m=0;
// Input/Output Ports initialization
// Port B initialization
// Func7=Out Func6=Out Func5=Out Func4=Out Func3=Out Func2=Out Func1=Out Func0=Out
// State7=0 State6=0 State5=0 State4=0 State3=0 State2=0 State1=0 State0=0
PORTB=0x00;
DDRB=0xFF;

// Port C initialization
// Func6=In Func5=In Func4=In Func3=In Func2=In Func1=In Func0=In
// State6=T State5=T State4=T State3=T State2=T State1=T State0=T
PORTC=0x00;
DDRC=0x00;

// Port D initialization
// Func7=In Func6=In Func5=In Func4=In Func3=In Func2=In Func1=In Func0=In
// State7=T State6=T State5=T State4=T State3=T State2=T State1=T State0=T
PORTD=0x00;
DDRD=0x00;
```

```
// Timer/Counter 0 initialization
// Clock source: System Clock
// Clock value: Timer 0 Stopped
TCCR0=0x00;
TCNT0=0x00;

// Timer/Counter 1 initialization
// Clock source: System Clock
// Clock value: Timer1 Stopped
// Mode: Normal top=0xFFFF
// OC1A output: Discon.
// OC1B output: Discon.
// Noise Canceler: Off
// Input Capture on Falling Edge
// Timer1 Overflow Interrupt: Off
// Input Capture Interrupt: Off
// Compare A Match Interrupt: Off
// Compare B Match Interrupt: Off
TCCR1A=0x00;
TCCR1B=0x00;
TCNT1H=0x00;
TCNT1L=0x00;
ICR1H=0x00;
ICR1L=0x00;
OCR1AH=0x00;
OCR1AL=0x00;
OCR1BH=0x00;
OCR1BL=0x00;

// Timer/Counter 2 initialization
// Clock source: System Clock
// Clock value: Timer2 Stopped
// Mode: Normal top=0xFF
// OC2 output: Disconnected
ASSR=0x00;
TCCR2=0x00;
TCNT2=0x00;
```

```
OCR2=0x00;

// External Interrupt(s) initialization
// INT0: Off
// INT1: Off
MCUCR=0x00;

// Timer(s)/Counter(s) Interrupt(s) initialization
TIMSK=0x00;

// USART initialization
// USART disabled
UCSRB=0x00;

// Analog Comparator initialization
// Analog Comparator: Off
// Analog Comparator Input Capture by Timer/Counter 1: Off
ACSR=0x80;
SFIOR=0x00;

// ADC initialization
// ADC Clock frequency: 125.000 kHz
// ADC Voltage Reference: AREF pin
// Only the 8 most significant bits of
// the AD conversion result are used
ADMUX=ADC_VREF_TYPE & 0xff;
ADCSRA=0x86;

// SPI initialization
// SPI disabled
SPCR=0x00;

// TWI initialization
// TWI disabled
TWCR=0x00;

while (1)
```

```
    {
    // Place your code here

//if(read_adc(0)<read_adc(1)){PORTB.0=1;delay_ms(100);PORTB.1=1;delay_ms(100);PORTB.2=0;PORT
B.3=0;};

//if(read_adc(0)>read_adc(1)){PORTB.2=1;delay_ms(100);PORTB.3=1;delay_ms(100);PORTB.0=0;PORT
B.1=0;};
adc=read_adc(0);
    if(adc<read_adc(1)&&m==0){PORTB.0=1;PORTB.1=0;PORTB.2=0;PORTB.3=0;};
    if(adc>read_adc(1)&&m==0){PORTB.1=1;delay_ms(100);PORTB.1=0;m=1;};
    if(adc>read_adc(1)&&m==1){PORTB.2=1;PORTB.3=0;PORTB.1=0;PORTB.0=0;};
    if(adc<read_adc(1)&&m==1){PORTB.3=1;delay_ms(100);PORTB.3=0;m=0;};

    }

}
```

# Appendix B

## B.1 Network Data of the 4-Bus Network

**Line Data of the 4-Bus Network**

| Line Bus to Bus | Series Impedance Z | | Shunt Y |
|---|---|---|---|
| | Resistance R in p.u | Reactance X in p.u | Y/2 in p.u. |
| 1-2 | 0.01008 | 0.0504 | 0.05125 |
| 1-3 | 0.00744 | 0.0372 | 0.03875 |
| 2-4 | 0.00744 | 0.0372 | 0.03875 |
| 3-4 | 0.01272 | 0.0636 | 0.06175 |

**Load-Generation schedule of 4-Bus Network**

| Bus No. | Bus Name | Generation | | Load | |
|---|---|---|---|---|---|
| | | P in MW | Q in MVar | P in MW | Q in MVar |
| 1 | Birch | - | - | 50 | 30.99 |
| 2 | Elm | 0 | 0 | 170 | 105.33 |
| 3 | Pine | 0 | 0 | 200 | 123.94 |
| 4 | Maple | 318 | - | 80 | 49.58 |

**Base Case Load-Flow Results of 4-Bus Network**

| Bus No. | Bus Name | Voltage | Angle |
|---|---|---|---|
| 1 | Birch | **1.0** | **0** |
| 2 | Elm | **.9785** | **-0.9399** |
| 3 | Pine | **.9642** | **-1.8308** |
| 4 | Maple | **1.02** | **1.5243** |

## B.2 Network Data of the 7-Bus Network

### Line and Transformer Data of 7-Bus Network

| Line Bus to Bus | Series Impedance Z | | Shunt Y |
|---|---|---|---|
| | Resistance R in p.u | Reactance X in p.u | Y/2 in p.u. |
| 1-2 | 0.00149 | 0.0187 | - |
| 2-3 | 0.07488 | 0.44919 | .01766 |
| 2-5 | 0.11472 | 0.6886 | .02709 |
| 3-4 | 0.11472 | 0.6886 | .02709 |
| 3-6 | 0.000997 | 0.01196 | - |
| 4-5 | 0.07488 | 0.44919 | .01766 |
| 5-7 | 0.00389 | 0.04729 | - |

### Load-Generation Data of 7-Bus Network

| Bus No. | Generation | | Load | |
|---|---|---|---|---|
| | P in MW | Q in MVar | P in MW | Q in MVar |
| 1 | - | - | 0 | 0 |
| 2 | 0 | 0 | 40 | 6 |
| 3 | 0 | 0 | 40 | 4 |
| 4 | 0 | 0 | 80 | 20 |
| 5 | 0 | 0 | 100 | 100 |
| 6 | 148 | 74 | 60 | 8 |
| 7 | 80 | 203 | 50 | 5 |

### Load-Flow Results in Terms of Voltage Level and Angle at Buses of 7-Bus Network

| Bus No. | Voltage | Angle |
|---|---|---|
| 1 | 1.0000 | 0 |
| 2 | 0.9905 | -1.7861 |
| 3 | 1.0105 | -9.8008 |
| **4** | **0.9785** | -49.1582 |
| **5** | **0.9642** | -46.1465 |
| 6 | 1.0200 | -9.2566 |
| 7 | 1.0200 | -45.7662 |

## Bus Names in the Bangladesh Power System Network

| BUS No | BUS NAME | BUS No | BUS NAME |
|---|---|---|---|
| 1 | Ghorasal | 32 | Tongi 230 |
| 2 | Cox's bazar | 33 | Uttara |
| 3 | dohazari | 34 | Mirpur |
| 4 | Sikalbaha | 35 | Aminbazar |
| 5 | Shahmirpur | 36 | Aminbazar 230 |
| 6 | Julda | 37 | Kalyanpur |
| 7 | Halishahar | 38 | Kamrangirchar |
| 8 | Bakulia | 39 | Hasnabad |
| 9 | Kulshi | 40 | Hasnabad 230 |
| 10 | Baraulia | 41 | Shyampur |
| 11 | Madunaghat | 42 | Sitalakhya |
| 12 | Chandraghona | 43 | Madanganj |
| 13 | Hathazari | 44 | Haripur 230 |
| 14 | Hathazari 230 | 45 | Bhulta |
| 15 | Feni | 46 | Siddhirganj |
| 16 | Chowmohani | 47 | Matuail |
| 17 | Chandpur | 48 | Maniknagar |
| 18 | Comilla N | 49 | Narinda |
| 19 | Comilla N 230 | 50 | Bangabhaban |
| 20 | Comilla S | 51 | Ullon |
| 21 | Sreemongol | 52 | Dhanmondi |
| 22 | Fenchuganj | 53 | Moghbazar |
| 23 | Chatak | 54 | Rampura |
| 24 | Netrokona | 55 | Rampura 230 |
| 25 | Mymenshing | 56 | Gulshan |
| 26 | Jamalpur | 57 | Bashundhara |
| 27 | Kishorgonj | 58 | Satkhira |
| 28 | Joydevpur | 59 | Khunla C |
| 29 | Kabirpur | 60 | Khulna S 230 |
| 30 | Tangail | 61 | Khulna C r |
| 31 | Manikganj | 62 | Noapara |

| BUS No | BUS NAME | BUS No | BUS NAME |
|---|---|---|---|
| 143 | Jessore 33 | 172 | Haripur 33 |
| 144 | Jhenidah 33 | 173 | Ghorashal 33 |
| 145 | Kushtia 33 | 174 | Ashugong 33 |
| 146 | G.K 33 | 175 | Sylhet 33 |
| 147 | Faridpur 33 | 176 | Shahjibazar 33 |
| 148 | Madaripur 33 | 177 | Kaptai 33 |
| 149 | Gopalgonj 33 | 178 | Saidpur 33 |
| 150 | Patuakhali 33 | 179 | Bogra 33 |
| 151 | Bhandaria 33 | 180 | Goal para |
| 152 | Bagherhat 33 | 181 | Barishal |
| 153 | Mongla 33 | 182 | Bheramara |
| 154 | Ishurdi 33 | 183 | Baghabari |
| 155 | Pabna 33 | 184 | Bogra |
| 156 | Shajidpur 33 | 185 | Tongi |
| 157 | Serajganj 33 | 186 | Haripur |
| 158 | Barapukuria 33 | 187 | Ghorashal |
| 159 | Thakurgaon 33 | 188 | Ashugong |
| 160 | Purbasadipur 33 | 189 | Fenchugongps |
| 161 | Rangpur 33 | 190 | Sylhet |
| 162 | Lalmonirhat 33 | 191 | Shahjibazar |
| 163 | Palashbari 33 | 192 | Kaptai |
| 164 | Naogaon 33 | 193 | Shiddir gong 230 |
| 165 | Natore 33 | 194 | Said pur |
| 166 | Rajshahi 33 | 195 | Mymensing PS |
| 167 | Ch.nawabganj 33 | 196 | Barapukuria 230 |
| 168 | Goal para 33 | 197 | AES haripur 230 |
| 169 | Barishal 33 | 198 | Meghnaghat 230 |
| 170 | Bogura 33 | 199 | Raojan |
| 171 | Tongi 33 | 200 | Ashugong 230 |

* Here the bus names having prefices 230 and 33 represent 230kV and 33kV buses respectively. All the other buses are 132 kV buses.

## Transmission Line Parameters in Bangladesh Power System Network

| To BUS | From BUS | Resistance in p.u | Reactance in p.u | Charging |
|---|---|---|---|---|
| 12 | 192 | 0.00464 | 0.01768 | 0.002068 |
| 13 | 192 | 0.01102 | 0.04199 | 0.019646 |
| 11 | 192 | 0.02204 | 0.08398 | 0.009823 |
| 11 | 12 | 0.017864 | 0.068068 | 0.0079618 |
| 11 | 13 | 0.00261 | 0.009945 | 0.004653 |
| 10 | 13 | 0.00348 | 0.01326 | 0.006204 |
| 13 | 15 | 0.02581 | 0.098345 | 0.046013 |
| 4 | 11 | 0.004669 | 0.018998 | 0.0078246 |
| 9 | 11 | 0.003683 | 0.014986 | 0.0061722 |
| 3 | 4 | 0.004508 | 0.036386 | 0.0166474 |
| 5 | 6 | 0.00098 | 0.00791 | 0.003619 |
| 4 | 8 | 0.00098 | 0.00791 | 0.003619 |
| 4 | 6 | 0.0014 | 0.0113 | 0.0012925 |
| 6 | 7 | 0.00224 | 0.01808 | 0.002068 |
| 2 | 3 | 0.010808 | 0.087236 | 0.0399124 |
| 7 | 9 | 0.00783 | 0.03186 | 0.0032805 |
| 9 | 10 | 0.003741 | 0.0142545 | 0.0066693 |
| 8 | 9 | 0.00116 | 0.00472 | 0.001944 |
| 15 | 16 | 0.00928 | 0.03536 | 0.016544 |
| 15 | 18 | 0.018415 | 0.0701675 | 0.0328295 |
| 16 | 17 | 0.01305 | 0.049725 | 0.023265 |
| 18 | 20 | 0.009222 | 0.035139 | 0.00411015 |
| 17 | 20 | 0.03538 | 0.13481 | 0.0157685 |
| 17 | 18 | 0.02233 | 0.085085 | 0.039809 |
| 18 | 186 | 0.020996 | 0.080002 | 0.0374308 |
| 46 | 186 | 0.00087 | 0.003315 | 0.00038775 |
| 48 | 186 | 0.007018 | 0.026741 | 0.00312785 |
| 51 | 186 | 0.005133 | 0.0195585 | 0.0091509 |
| 41 | 186 | 0.018618 | 0.070941 | 0.00829785 |
| 43 | 186 | 0.007482 | 0.028509 | 0.00333465 |
| 186 | 187 | 0.025578 | 0.09702 | 0.0115101 |
| 45 | 186 | 0.01392 | 0.0528 | 0.006264 |
| 47 | 186 | 0.0058 | 0.0221 | 0.002585 |
| 47 | 48 | 0.00928 | 0.03536 | 0.004136 |
| 46 | 48 | 0.00638 | 0.02431 | 0.0028435 |
| 46 | 51 | 0.00928 | 0.03536 | 0.004136 |
| 48 | 49 | 0.00015 | 0.000855 | 0.006138 |
| 48 | 51 | 0.00348 | 0.01326 | 0.001551 |

| BUS No | BUS NAME | BUS No | BUS NAME |
|---|---|---|---|
| 63 | Jessore | 103 | Chandraghona 33 |
| 64 | Jhenidah | 104 | Hathazari 33 |
| 65 | Kushtia | 105 | Feni 33 |
| 66 | G.K | 106 | Chowmohani 33 |
| 67 | Faridpur | 107 | Chandpur 33 |
| 68 | Madaripur | 108 | Comilla N 33 |
| 69 | Gopalgonj | 109 | Comilla S 33 |
| 70 | Patuakhali | 110 | Sreemongol 33 |
| 71 | Bhandaria | 111 | Fenchuganj 33 |
| 72 | Bagherhat | 112 | Chatak 33 |
| 73 | Mongla | 113 | Netrokona 33 |
| 74 | Ishurdi | 114 | Mymenshing 33 |
| 75 | Ishurdi 230 | 115 | Jamalpur 33 |
| 76 | Baghabari 230 | 116 | Kishorgonj 33 |
| 77 | Pabna | 117 | Joydevpur 33 |
| 78 | Shajidpur | 118 | Kabirpur 33 |
| 79 | Serajganj | 119 | Tangail 33 |
| 80 | Bogra | 120 | Manikganj 33 |
| 81 | Bogra new 230 | 121 | Uttara 33 |
| 82 | Serajganj 230 | 122 | Mirpur 33 |
| 83 | Barapukuria | 123 | Kalyanpur 33 |
| 84 | Thakurgaon | 124 | Kamrangirchar 33 |
| 85 | Purbasadipur | 125 | Hasnabad 33 |
| 86 | Rangpur | 126 | Shyampur 33 |
| 87 | Lalmonirhat | 127 | Sitalakhya 33 |
| 88 | Palashbari | 128 | Madanganj 33 |
| 89 | Naogaon | 129 | Bhulta 33 |
| 90 | Natore | 130 | Siddhirganj 33 |
| 91 | Rajshahi | 131 | Matuail 33 |
| 92 | Ch.nawabganj | 132 | Maniknagar 33 |
| 93 | Cox's bazaar 33 | 133 | Narinda 33 |
| 94 | dohazari 33 | 134 | Bangabhaban 33 |
| 95 | Sikalbaha 33 | 135 | Ullon 33 |
| 96 | Shahmirpur 33 | 136 | Dhanmondi 33 |
| 97 | Julda 33 | 137 | Moghbazar 33 |
| 98 | Halishahar 33 | 138 | Gulshan 33 |
| 99 | Bakulia 33 | 139 | Bashundhara 33 |
| 100 | Kulshi 33 | 140 | Satkhira 33 |
| 101 | Baraulia 33 | 141 | Khulna C r 33 |
| 102 | Madunaghat 33 | 142 | Noapara 33 |

| To BUS | From BUS | Resistance in p.u | Reactance in p.u | Charging |
|---|---|---|---|---|
| 51 | 52 | 0.001595 | 0.0060775 | 0.0028435 |
| 51 | 54 | 0.00116 | 0.00442 | 0.002068 |
| 53 | 54 | 0.001305 | 0.0049725 | 0.0023265 |
| 54 | 57 | 0.003219 | 0.0122655 | 0.0057387 |
| 54 | 56 | 0.000957 | 0.0036465 | 0.0017061 |
| 39 | 41 | 0.011136 | 0.042432 | 0.0049632 |
| 39 | 42 | 0.00696 | 0.02652 | 0.003102 |
| 42 | 43 | 0.00348 | 0.01326 | 0.001551 |
| 39 | 43 | 0.009048 | 0.034476 | 0.0040326 |
| 37 | 39 | 0.01044 | 0.03978 | 0.004653 |
| 57 | 185 | 0.00232 | 0.00884 | 0.004136 |
| 34 | 185 | 0.00841 | 0.032045 | 0.00374825 |
| 33 | 185 | 0.00522 | 0.01989 | 0.0023265 |
| 51 | 53 | 0.00116 | 0.00442 | 0.000517 |
| 33 | 34 | 0.00754 | 0.02873 | 0.0033605 |
| 29 | 185 | 0.00609 | 0.023205 | 0.010857 |
| 29 | 31 | 0.00754 | 0.02873 | 0.013442 |
| 29 | 30 | 0.0145 | 0.05525 | 0.02585 |
| 28 | 187 | 0.00754 | 0.02873 | 0.013442 |
| 187 | 188 | 0.012586 | 0.047957 | 0.0224378 |
| 28 | 29 | 0.00725 | 0.027625 | 0.012925 |
| 25 | 28 | 0.02465 | 0.093925 | 0.043945 |
| 45 | 187 | 0.0116 | 0.044 | 0.00522 |
| 34 | 35 | 0.0029 | 0.01105 | 0.00517 |
| 35 | 37 | 0.00087 | 0.003315 | 0.001551 |
| 27 | 188 | 0.015022 | 0.057239 | 0.0267806 |
| 188 | 191 | 0.01508 | 0.0572 | 0.027144 |
| 25 | 27 | 0.017081 | 0.0650845 | 0.0304513 |
| 25 | 26 | 0.015921 | 0.0606645 | 0.0283833 |
| 24 | 25 | 0.00986 | 0.03757 | 0.017578 |
| 21 | 191 | 0.010556 | 0.04004 | 0.0190008 |
| 21 | 22 | 0.028536 | 0.10824 | 0.0128412 |
| 21 | 189 | 0.030508 | 0.11572 | 0.0137286 |
| 22 | 189 | 0.00203 | 0.0077 | 0.0009135 |
| 189 | 190 | 0.00841 | 0.0319 | 0.015138 |
| 23 | 190 | 0.009338 | 0.03542 | 0.0168084 |
| 61 | 180 | 0.00029 | 0.0011 | 0.00052 |
| 72 | 180 | 0.012124 | 0.097858 | 0.01119305 |
| 59 | 61 | 0.00036 | 0.002475 | 0.01899 |
| 61 | 62 | 0.0083545 | 0.0244125 | 0.0112189 |

| To BUS | From BUS | Resistance in p.u | Reactance in p.u | Charging |
|---|---|---|---|---|
| 62 | 63 | 0.0035 | 0.02825 | 0.012925 |
| 63 | 64 | 0.0063 | 0.05085 | 0.023265 |
| 64 | 65 | 0.006076 | 0.049042 | 0.0224378 |
| 65 | 182 | 0.00315 | 0.025425 | 0.0116325 |
| 74 | 182 | 0.0014 | 0.0113 | 0.00517 |
| 67 | 182 | 0.04004 | 0.11492 | 0.053768 |
| 67 | 68 | 0.024794 | 0.071162 | 0.0332948 |
| 68 | 69 | 0.0084 | 0.0678 | 0.03102 |
| 68 | 181 | 0.0216755 | 0.0622115 | 0.0291071 |
| 70 | 181 | 0.0261 | 0.09945 | 0.0116325 |
| 71 | 181 | 0.029 | 0.1105 | 0.012925 |
| 71 | 72 | 0.01694 | 0.0495 | 0.005687 |
| 72 | 73 | 0.024178 | 0.069394 | 0.0081169 |
| 58 | 59 | 0.00812 | 0.06554 | 0.029986 |
| 74 | 90 | 0.0087 | 0.03315 | 0.01551 |
| 74 | 91 | 0.01305 | 0.049725 | 0.023265 |
| 74 | 77 | 0.00928 | 0.03536 | 0.004136 |
| 74 | 183 | 0.029 | 0.1105 | 0.012925 |
| 90 | 91 | 0.0308 | 0.0884 | 0.01034 |
| 90 | 184 | 0.01885 | 0.071825 | 0.033605 |
| 91 | 92 | 0.01363 | 0.051935 | 0.024299 |
| 77 | 78 | 0.0232 | 0.0884 | 0.01034 |
| 78 | 183 | 0.00406 | 0.01547 | 0.0018095 |
| 78 | 79 | 0.01972 | 0.07514 | 0.008789 |
| 79 | 183 | 0.0116 | 0.0442 | 0.02068 |
| 79 | 184 | 0.01914 | 0.07293 | 0.034122 |
| 89 | 184 | 0.01305 | 0.049725 | 0.023265 |
| 88 | 184 | 0.014558 | 0.055471 | 0.0259534 |
| 86 | 88 | 0.015196 | 0.057902 | 0.0270908 |
| 86 | 87 | 0.022156 | 0.084422 | 0.0098747 |
| 86 | 194 | 0.01189 | 0.045305 | 0.021197 |
| 85 | 194 | 0.006061 | 0.0230945 | 0.0108053 |
| 84 | 85 | 0.012586 | 0.047957 | 0.0224378 |
| 83 | 86 | 0.01305 | 0.049725 | 0.023265 |
| 83 | 194 | 0.01044 | 0.03978 | 0.018612 |
| 14 | 199 | 0.002732438 | 0.018785511 | 0.015637134 |
| 14 | 19 | 0.025047348 | 0.173054408 | 0.075591834 |
| 19 | 200 | 0.013191604 | 0.091141988 | 0.039811699 |
| 19 | 198 | 0.007286501 | 0.050094697 | 0.041699025 |
| 1 | 200 | 0.010018939 | 0.051430556 | 0.021564917 |

| To BUS | From BUS | Resistance in p.u | Reactance in p.u | Charging |
|---|---|---|---|---|
| 1 | 32 | 0.006147986 | 0.031559659 | 0.013233017 |
| 1 | 55 | 0.010474346 | 0.053768308 | 0.022545141 |
| 1 | 75 | 0.040531164 | 0.208059975 | 0.087239893 |
| 44 | 198 | 0.001408724 | 0.009684975 | 0.008061811 |
| 40 | 198 | 0.003157484 | 0.021707702 | 0.018069577 |
| 44 | 197 | 0.000166982 | 0.001153696 | 0.000503946 |
| 44 | 55 | 0.003157484 | 0.021707702 | 0.018069577 |
| 32 | 36 | 0.003036042 | 0.02087279 | 0.017374594 |
| 36 | 40 | 0.002671717 | 0.018368056 | 0.015289642 |
| 82 | 200 | 0.017001837 | 0.116887626 | 0.097297724 |
| 66 | 182 | 0.00435 | 0.016575 | 0.00193875 |
| 44 | 193 | 0.00068311 | 0.003506629 | 0.000367584 |
| 25 | 195 | 0.00058 | 0.00221 | 0.001034 |
| 48 | 50 | 0.00145 | 0.005525 | 0.002585 |
| 37 | 38 | 0.00522 | 0.01989 | 0.0023265 |
| 38 | 39 | 0.00522 | 0.01989 | 0.0023265 |
| 81 | 196 | 0.036432507 | 0.187020202 | 0.078417881 |
| 81 | 82 | 0.022770317 | 0.116887626 | 0.049011176 |
| 80 | 184 | 0.00116 | 0.00442 | 0.002068 |
| 75 | 76 | 0.018216253 | 0.093510101 | 0.039208941 |
| 60 | 75 | 0.022770317 | 0.116887626 | 0.049011176 |

*Here Buses are presented by their corresponding numbers other than their names

## Parameters of Existing Transformers in Bangladesh Power System Network

| To BUS | From BUS | Resistance of | Reactance of |
|---|---|---|---|
| 83 | 196 | 0.00009525 | 0.009525 |
| 80 | 81 | 0.00009525 | 0.009525 |
| 74 | 75 | 0.000074 | 0.0074 |
| 59 | 60 | 0.00009525 | 0.009525 |
| 76 | 183 | 0.000222 | 0.0222 |
| 32 | 185 | 0.0000665 | 0.00665 |
| 1 | 187 | 0.0002 | 0.02 |
| 188 | 200 | 0.0001665 | 0.01665 |
| 35 | 36 | 0.0000665 | 0.00665 |
| 54 | 55 | 0.0000665 | 0.00665 |
| 39 | 40 | 0.0000665 | 0.00665 |
| 44 | 186 | 0.0000665 | 0.00665 |
| 18 | 19 | 0.000222 | 0.0222 |
| 13 | 14 | 0.000111 | 0.0111 |
| 2 | 93 | 0.00025 | 0.025 |
| 3 | 94 | 0.00025 | 0.025 |
| 4 | 95 | 0.00025 | 0.025 |
| 5 | 96 | 0.00025 | 0.025 |
| 6 | 97 | 0.00025 | 0.025 |
| 7 | 98 | 0.000166667 | 0.016666667 |
| 8 | 99 | 0.00025 | 0.025 |
| 9 | 100 | 0.000166667 | 0.016666667 |
| 10 | 101 | 0.00025 | 0.025 |
| 11 | 102 | 0.00025 | 0.025 |
| 12 | 103 | 0.00025 | 0.025 |
| 13 | 104 | 0.00025 | 0.025 |
| 15 | 105 | 0.00025 | 0.025 |
| 16 | 106 | 0.000166667 | 0.016666667 |
| 17 | 107 | 0.00025 | 0.025 |
| 18 | 108 | 0.00025 | 0.025 |
| 20 | 109 | 0.000125 | 0.0125 |
| 21 | 110 | 0.00025 | 0.025 |
| 22 | 111 | 0.00025 | 0.025 |
| 23 | 112 | 0.000166667 | 0.016666667 |
| 24 | 113 | 0.00025 | 0.025 |
| 25 | 114 | 0.000166667 | 0.016666667 |
| 26 | 115 | 0.000166667 | 0.016666667 |
| 27 | 116 | 0.000166667 | 0.016666667 |

| To BUS | From BUS | Resistance in p.u | Reactance in p.u |
|---|---|---|---|
| 28 | 117 | 0.000166667 | 0.016666667 |
| 29 | 118 | 0.000166667 | 0.016666667 |
| 30 | 119 | 0.00025 | 0.025 |
| 31 | 120 | 0.00025 | 0.025 |
| 33 | 121 | 0.00025 | 0.025 |
| 34 | 122 | 0.000166667 | 0.016666667 |
| 37 | 123 | 0.000166667 | 0.016666667 |
| 38 | 124 | 0.00025 | 0.025 |
| 39 | 125 | 0.000125 | 0.0125 |
| 41 | 126 | 0.000166667 | 0.016666667 |
| 42 | 127 | 0.00025 | 0.025 |
| 43 | 128 | 0.00025 | 0.025 |
| 45 | 129 | 0.00025 | 0.025 |
| 46 | 130 | 0.00025 | 0.025 |
| 47 | 131 | 0.00025 | 0.025 |
| 48 | 132 | 0.0005 | 0.05 |
| 49 | 133 | 0.00025 | 0.025 |
| 50 | 134 | 0.00025 | 0.025 |
| 51 | 135 | 0.000166667 | 0.016666667 |
| 52 | 136 | 0.000166667 | 0.016666667 |
| 53 | 137 | 0.00025 | 0.025 |
| 56 | 138 | 0.00025 | 0.025 |
| 57 | 139 | 0.000166667 | 0.016666667 |
| 58 | 140 | 0.00025 | 0.025 |
| 61 | 141 | 0.000166667 | 0.016666667 |
| 62 | 142 | 0.00025 | 0.025 |
| 63 | 143 | 0.000166667 | 0.016666667 |
| 64 | 144 | 0.00025 | 0.025 |
| 65 | 145 | 0.00025 | 0.025 |
| 66 | 146 | 0.000166667 | 0.016666667 |
| 67 | 147 | 0.00025 | 0.025 |
| 68 | 148 | 0.00025 | 0.025 |
| 69 | 149 | 0.00025 | 0.025 |
| 70 | 150 | 0.000166667 | 0.016666667 |
| 71 | 151 | 0.00025 | 0.025 |
| 72 | 152 | 0.00025 | 0.025 |
| 73 | 153 | 0.00025 | 0.025 |
| 74 | 154 | 0.000166667 | 0.016666667 |
| 77 | 155 | 0.00025 | 0.025 |
| 78 | 156 | 0.000125 | 0.0125 |

| To BUS | From BUS | Resistance in p.u | Reactance in p.u |
|---|---|---|---|
| 79 | 157 | 0.000166667 | 0.016666667 |
| 83 | 158 | 0.00025 | 0.025 |
| 84 | 159 | 0.00025 | 0.025 |
| 85 | 160 | 0.000166667 | 0.016666667 |
| 86 | 161 | 0.00025 | 0.025 |
| 87 | 162 | 0.00025 | 0.025 |
| 88 | 163 | 0.00025 | 0.025 |
| 89 | 164 | 0.000166667 | 0.016666667 |
| 90 | 165 | 0.00025 | 0.025 |
| 91 | 166 | 0.000166667 | 0.016666667 |
| 92 | 167 | 0.000125 | 0.0125 |
| 168 | 180 | 0.00025 | 0.025 |
| 169 | 181 | 0.00025 | 0.025 |
| 170 | 184 | 0.000125 | 0.0125 |
| 171 | 185 | 0.000166667 | 0.016666667 |
| 172 | 186 | 0.00025 | 0.025 |
| 173 | 187 | 0.00025 | 0.025 |
| 174 | 188 | 0.000125 | 0.0125 |
| 175 | 190 | 0.000166667 | 0.016666667 |
| 176 | 191 | 0.00025 | 0.025 |
| 177 | 192 | 0.0005 | 0.05 |
| 178 | 194 | 0.00025 | 0.025 |
| 80 | 179 | 0.0005 | 0.05 |

## Generation Data in Bangladesh Power System Network

| Bus No. | Bus Name | Generation in MW | Max. Var Limit at Buses in |
|---|---|---|---|
| 180 | Goal para | 135 | 120 |
| 181 | Barishal | 24 | 40 |
| 182 | Bheramara | 56 | 30 |
| 183 | Baghabari | 170 | 111 |
| 184 | Bogra | 20 | 20 |
| 185 | Tongi | 65 | 40 |
| 186 | Haripur | 30 | 38 |
| 187 | Ghorashal | 80 | 60 |
| 188 | Ashugong | 40 | 23 |
| 189 | Fenchugongps | 88 | 60 |
| 190 | Sylhet | 20 | 12 |
| 191 | Shahjibazar | 180 | 64 |
| 192 | Kaptai | 117 | 90 |
| 193 | Shiddir gong 230 | 125 | 130 |
| 194 | Said pur | 18 | 12 |
| 195 | Mymensing PS | 132 | 140 |
| 196 | Barapukuria 230 | 177 | 186 |
| 197 | AES haripur 230 | 355 | 305 |
| 198 | Meghnaghat 230 | 450 | 315 |
| 199 | Raojan | 310 | 460 |
| 200 | Ashugong 230 | 494 | 700 |

## Loads at Load Buses for an Arbitrary Case inBangladesh Power System Network

| Bus No. | Bus Name | Real Loads,P in MW | Reactive Load,Q in Mvar |
|---|---|---|---|
| 93 | Cox's bazaar 33 | 24 | 14.88 |
| 94 | Dohazari 33 | 20 | 12.4 |
| 96 | Shahmirpur 33 | 10 | 6.2 |
| 97 | Julda 33 | 6 | 3.72 |
| 98 | Halishahar 33 | 77 | 47.74 |
| 99 | Bakulia 33 | 51 | 31.62 |
| 100 | Kulshi 33 | 82 | 50.84 |
| 101 | Baraulia 33 | 28 | 17.36 |
| 102 | Madunaghat 33 | 21 | 13.02 |
| 103 | Chandraghona | 10.6 | 6.572 |
| 104 | Hathazari 33 | 36 | 22.32 |
| 105 | Feni 33 | 37 | 22.94 |
| 106 | Chowmohani 33 | 4 | 2.48 |
| 107 | Chandpur 33 | 26 | 16.12 |
| 108 | Comilla N 33 | 51 | 31.62 |
| 109 | Comilla S 33 | 66 | 40.92 |
| 110 | Sreemongol 33 | 23 | 14.26 |
| 111 | Fenchuganj 33 | 19 | 11.78 |
| 112 | Chatak 33 | 21 | 13.02 |
| 113 | Netrokona 33 | 26 | 16.12 |
| 114 | Mymenshing 33 | 66 | 40.92 |
| 115 | Jamalpur 33 | 56 | 34.72 |
| 116 | Kishorgonj 33 | 32 | 19.84 |
| 117 | Joydevpur 33 | 50 | 31 |
| 118 | Kabirpur 33 | 48 | 29.76 |
| 119 | Tangail 33 | 65 | 40.3 |
| 120 | Manikganj 33 | 34 | 21.08 |
| 121 | Uttara 33 | 50.6 | 31.372 |
| 122 | Mirpur 33 | 99.5 | 61.69 |
| 123 | Kalyanpur 33 | 119 | 73.78 |
| 124 | Kamrangirchar | 48.2 | 29.884 |
| 125 | Hasnabad 33 | 47 | 29.14 |
| 126 | Shyampur 33 | 59 | 36.58 |
| 127 | Sitalakhya 33 | 54 | 33.48 |
| 128 | Madanganj 33 | 35 | 21.7 |
| 129 | Bhulta 33 | 38 | 23.56 |
| 130 | Siddhirganj 33 | 66 | 40.92 |
| 131 | Matuail 33 | 11.4 | 7.068 |

| Bus No. | Bus Name | Real Loads,P in MW | Reactive Load,Q in Mvar |
|---|---|---|---|
| 132 | Maniknagar 33 | 46 | 28.52 |
| 133 | Narinda 33 | 70 | 43.4 |
| 134 | Bangabhaban 33 | 20 | 12.4 |
| 135 | Ullon 33 | 72 | 44.64 |
| 136 | Dhanmondi 33 | 75 | 46.5 |
| 137 | Moghbazar 33 | 87 | 53.94 |
| 138 | Gulshan 33 | 41.6 | 25.792 |
| 139 | Bashundhara 33 | 27 | 16.74 |
| 140 | Satkhira 33 | 19.7 | 12.214 |
| 141 | Khulna C r 33 | 60 | 37.2 |
| 142 | Noapara 33 | 20 | 12.4 |
| 143 | Jessore 33 | 52 | 32.24 |
| 144 | Jhenidah 33 | 44 | 27.28 |
| 145 | Kushtia 33 | 34 | 21.08 |
| 146 | G.K 33 | 18.6 | 11.532 |
| 147 | Faridpur 33 | 36 | 22.32 |
| 148 | Madaripur 33 | 28 | 17.36 |
| 149 | Gopalgonj 33 | 13.2 | 8.184 |
| 150 | Patuakhali 33 | 15.5 | 9.61 |
| 151 | Bhandaria 33 | 12 | 7.44 |
| 152 | Bagherhat 33 | 23 | 14.26 |
| 153 | Mongla 33 | 12 | 7.44 |
| 154 | Ishurdi 33 | 16 | 9.92 |
| 155 | Pabna 33 | 35 | 21.7 |
| 156 | Shajidpur 33 | 18 | 11.16 |
| 157 | Serajganj 33 | 27.5 | 17.05 |
| 158 | Barapukuria 33 | 14 | 8.68 |
| 159 | Thakurgaon 33 | 43 | 26.66 |
| 160 | Purbasadipur 33 | 29 | 17.98 |
| 161 | Rangpur 33 | 48 | 29.76 |
| 162 | Lalmonirhat 33 | 22.4 | 13.888 |
| 163 | Palashbari 33 | 23 | 14.26 |
| 164 | Naogaon 33 | 73 | 45.26 |
| 165 | Natore 33 | 38 | 23.56 |
| 166 | Rajshahi 33 | 57 | 35.34 |
| 167 | Ch.nawabganj 33 | 43 | 26.66 |
| 169 | Barishal 33 | 34 | 21.08 |
| 174 | Ashugong 33 | 40 | 24.8 |
| 175 | Sylhet 33 | 50 | 31 |
| 178 | Saidpur 33 | 38 | 23.56 |
| 179 | Bogra 33 | 82.5 | 51.15 |
| | **Total** | 3175.3 | 1968.686 |

## Size of Capacitor Banks Existing in Bangladesh Power System Network

| Bus No. | Bus Name | Capacitor Bank in Mvar |
|---|---|---|
| 93 | Cox's bazaar 33 | 35 |
| 94 | dohazari 33 | 30 |
| 98 | Halishahar 33 | 20 |
| 99 | Bakulia 33 | 35 |
| 100 | Kulshi 33 | 15 |
| 101 | Baraulia 33 | 35 |
| 102 | Madunaghat 33 | 15 |
| 104 | Hathazari 33 | 35 |
| 118 | Kabirpur 33 | 15 |
| 122 | Mirpur 33 | 30 |
| 125 | Hasnabad 33 | 20 |
| 135 | Ullon 33 | 25 |
| 141 | Khulna C r 33 | 20 |
| 143 | Jessore 33 | 15 |
| 144 | Jhenidah 33 | 10 |
| 145 | Kushtia 33 | 75 |
| 147 | Faridpur 33 | 10 |
| 154 | Ishurdi 33 | 20 |
| 155 | Pabna 33 | 75 |
| 159 | Thakurgaon 33 | 35 |
| 161 | Rangpur 33 | 30 |
| 164 | Naogaon 33 | 15 |
| 165 | Natore 33 | 20 |
| 166 | Rajshahi 33 | 40 |
| 167 | Ch.nawabganj 33 | 15 |
| 179 | Bogra 33 | 10 |

## BUS VOLTAGE & ANGLE OF TOTAL BANGLADESH POWER SYSTEM NETWORK

| BUS No | BUS NAME | Voltage | Angle | BUS No | BUS NAME | Voltage | Angle |
|---|---|---|---|---|---|---|---|
| 1 | Ghorasal | 1 | 0 | 42 | Sitalakhya | 0.9751 | -1.7062 |
| 2 | Cox's bazar | 1.0288 | -3.2735 | 43 | Madanganj | 0.9794 | -1.4661 |
| 3 | dohazari | 1.0146 | -2.1227 | 44 | Haripur 230 | 1.0166 | 1.0627 |
| 4 | Sikalbaha | 1.0047 | -1.2275 | 45 | Bhulta | 0.9922 | -0.3909 |
| 5 | Shahmirpur | 1.0006 | -1.5228 | 46 | Siddhirganj | 0.9934 | -0.69 |
| 6 | Julda | 1.0012 | -1.4855 | 47 | Matuail | 0.9907 | -0.8291 |
| 7 | Halishahar | 0.9977 | -1.7646 | 48 | Maniknagar | 0.9834 | -1.2494 |
| 8 | Bakulia | 1.004 | -1.209 | 49 | Narinda | 0.9829 | -1.2777 |
| 9 | Kulshi | 1.0039 | -1.0682 | 50 | Bangabhaban | 0.9824 | -1.2985 |
| 10 | Baraulia | 1.0087 | -0.4619 | 51 | Ullon | 0.9835 | -1.3187 |
| 11 | Madunaghat | 1.0096 | -0.3831 | 52 | Dhanmondi | 0.9797 | -1.5216 |
| 12 | Chandraghona | 1.0263 | 0.5477 | 53 | Moghbazar | 0.9823 | -1.3783 |
| 13 | Hathazari | 1.0117 | 0.322 | 54 | Rampura | 0.9847 | -1.2541 |
| 14 | Hathazari 230 | 1.01 | 1.9595 | 55 | Rampura 230 | 0.9914 | -0.5971 |
| 15 | Feni | 0.9638 | -1.1611 | 56 | Gulshan | 0.9834 | -1.3214 |
| 16 | Chowmohani | 0.9577 | -1.3487 | 57 | Bashundhara | 0.9805 | -1.59 |
| 17 | Chandpur | 0.9526 | -1.5514 | 58 | Satkhira | 0.7828 | - |
| 18 | Comilla N | 0.9703 | -0.803 | 59 | Khunla C | 0.7956 | - |
| 19 | Comilla N 230 | 0.9877 | 0.7274 | 60 | Khulna S 230 | 0.7945 | - |
| 20 | Comilla S | 0.9504 | -1.8089 | 61 | Khulna C r | 0.7963 | - |
| 21 | Sreemongol | 1.0988 | 7.0296 | 62 | Noapara | 0.7808 | - |
| 22 | Fenchuganj | 1.122 | 7.1098 | 63 | Jessore | 0.7721 | - |
| 23 | Chatak | 1.1159 | 6.2438 | 64 | Jhenidah | 0.7756 | - |
| 24 | Netrokona | 0.9997 | -0.6311 | 65 | Kushtia | 0.7969 | - |
| 25 | Mymenshing | 1.0082 | -0.2236 | 66 | G.K | 0.7984 | - |
| 26 | Jamalpur | 0.9782 | -1.6803 | 67 | Faridpur | 0.7236 | - |
| 27 | Kishorgonj | 1.008 | 1.2851 | 68 | Madaripur | 0.7125 | - |
| 28 | Joydevpur | 0.9798 | -1.1222 | 69 | Gopalgonj | 0.7024 | - |
| 29 | Kabirpur | 0.9641 | -2.3038 | 70 | Patuakhali | 0.7238 | - |
| 30 | Tangail | 0.9308 | -3.9987 | 71 | Bhandaria | 0.7416 | - |
| 31 | Manikganj | 0.9554 | -2.7543 | 72 | Bagherhat | 0.7506 | - |
| 32 | Tongi 230 | 0.9806 | -1.4748 | 73 | Mongla | 0.7402 | - |
| 33 | Uttara | 0.97 | -2.2728 | 74 | Ishurdi | 0.8072 | - |
| 34 | Mirpur | 0.9687 | -2.407 | 75 | Ishurdi 230 | 0.8059 | - |
| 35 | Aminbazar | 0.9706 | -2.1457 | 76 | Baghabari 230 | 0.8467 | - |
| 36 | Aminbazar | 0.9747 | -1.7349 | 77 | Pabna | 0.8256 | -35.529 |
| 37 | Kalyanpur | 0.9683 | -2.2439 | 78 | Shajidpur | 0.8481 | - |
| 38 | Kamrangirchar | 0.9694 | -2.1097 | 79 | Serajganj | 0.8439 | - |
| 39 | Hasnabad | 0.9787 | -1.5443 | 80 | Bogra | 0.8436 | - |
| 40 | Hasnabad 230 | 0.9842 | -0.9374 | 81 | Bogra new 230 | 0.8466 | - |
| 41 | Shyampur | 0.9723 | -1.8322 | 82 | Serajganj 230 | 0.8903 | - |

| BUS | BUS NAME | Voltage | Angle | BUS | BUS NAME | Voltage | Angle |
|---|---|---|---|---|---|---|---|
| 83 | Barapukuria | 1.0078 | - | 126 | Shyampur 33 | 0.9665 | -2.3684 |
| 84 | Thakurgaon | 0.9772 | - | 127 | Sitalakhya 33 | 0.9671 | -2.4398 |
| 85 | Purbasadipur | 0.9789 | - | 128 | Madanganj 33 | 0.9742 | -1.9361 |
| 86 | Rangpur | 0.9595 | - | 129 | Bhulta 33 | 0.9867 | -0.8882 |
| 87 | Lalmonirhat | 0.9425 | - | 130 | Siddhirganj 33 | 0.9838 | -1.5553 |
| 88 | Palashbari | 0.8926 | - | 131 | Matuail 33 | 0.9891 | -0.9781 |
| 89 | Naogaon | 0.8111 | - | 132 | Maniknagar 33 | 0.9697 | -2.4856 |
| 90 | Natore | 0.8068 | -35.84 | 133 | Narinda 33 | 0.9726 | -2.2159 |
| 91 | Rajshahi | 0.7834 | - | 134 | Bangabhaban | 0.9795 | -1.5648 |
| 92 | Ch.nawabganj | 0.7646 | - | 135 | Ullon 33 | 0.9806 | -1.9587 |
| 93 | Cox's bazaar | 1.0345 | -3.5675 | 136 | Dhanmondi 33 | 0.9723 | -2.1941 |
| 94 | dohazari 33 | 1.0195 | -2.3748 | 137 | Moghbazar 33 | 0.9694 | -2.5489 |
| 95 | Sikalbaha 33 | 1.0047 | -1.2275 | 138 | Gulshan 33 | 0.9773 | -1.8759 |
| 96 | Shahmirpur 33 | 0.9992 | -1.651 | 139 | Bashundhara 33 | 0.9779 | -1.8306 |
| 97 | Julda 33 | 1.0003 | -1.5622 | 140 | Satkhira 33 | 0.7792 | - |
| 98 | Halishahar 33 | 0.9937 | -2.4299 | 141 | Khulna C r 33 | 0.7917 | - |
| 99 | Bakulia 33 | 1.0056 | -1.8612 | 142 | Noapara 33 | 0.7772 | - |
| 100 | Kulshi 33 | 0.9986 | -1.7682 | 143 | Jessore 33 | 0.7676 | - |
| 101 | Baraulia 33 | 1.0137 | -0.8178 | 144 | Jhenidah 33 | 0.7693 | - |
| 102 | Madunaghat | 1.0104 | -0.649 | 145 | Kushtia 33 | 0.806 | -39.544 |
| 103 | Chandraghona | 1.0248 | 0.4186 | 146 | G.K 33 | 0.7962 | - |
| 104 | Hathazari 33 | 1.0156 | -0.1319 | 147 | Faridpur 33 | 0.7183 | - |
| 105 | Feni 33 | 0.9583 | -1.6744 | 148 | Madaripur 33 | 0.7069 | - |
| 106 | Chowmohani | 0.9573 | -1.386 | 149 | Gopalgonj 33 | 0.6997 | - |
| 107 | Chandpur 33 | 0.9487 | -1.92 | 150 | Patuakhali 33 | 0.7218 | - |
| 108 | Comilla N 33 | 0.9627 | -1.5024 | 151 | Bhandaria 33 | 0.7393 | - |
| 109 | Comilla S 33 | 0.9454 | -2.2794 | 152 | Bagherhat 33 | 0.7462 | - |
| 110 | Sreemongol | 1.0959 | 6.7849 | 153 | Mongla 33 | 0.7379 | - |
| 111 | Fenchuganj 33 | 1.1196 | 6.916 | 154 | Ishurdi 33 | 0.808 | - |
| 112 | Chatak 33 | 1.1141 | 6.0995 | 155 | Pabna 33 | 0.8353 | - |
| 113 | Netrokona 33 | 0.996 | -0.9657 | 156 | Shajidpur 33 | 0.8466 | - |
| 114 | Mymenshing | 1.0019 | -0.7816 | 157 | Serajganj 33 | 0.8408 | - |
| 115 | Jamalpur 33 | 0.9728 | -2.1829 | 158 | Barapukuria 33 | 1.0058 | - |
| 116 | Kishorgonj 33 | 1.005 | 1.0153 | 159 | Thakurgaon 33 | 0.9795 | - |
| 117 | Joydevpur 33 | 0.9749 | -1.5693 | 160 | Purbasadipur | 0.9761 | - |
| 118 | Kabirpur 33 | 0.9617 | -2.7474 | 161 | Rangpur 33 | 0.9585 | - |
| 119 | Tangail 33 | 0.9207 | -4.9705 | 162 | Lalmonirhat 33 | 0.9941 | - |
| 120 | Manikganj 33 | 0.9503 | -3.2341 | 163 | Palashbari 33 | 0.8889 | - |
| 121 | Uttara 33 | 0.9625 | -2.9672 | 164 | Naogaon 33 | 0.8045 | - |
| 122 | Mirpur 33 | 0.9636 | -3.3204 | 165 | Natore 33 | 0.804 | - |
| 123 | Kalyanpur 33 | 0.9564 | -3.3415 | 166 | Rajshahi 33 | 0.7806 | -38.734 |
| 124 | Kamrangirchar | 0.9623 | -2.7717 | 167 | Ch.nawabganj | 0.762 | - |
| 125 | Hasnabad 33 | 0.9778 | -1.8603 | 168 | Goal para 33 | 0.7977 | - |