1

Introduction

1.1 INTRODUCTION

A great demand of electricity is a notable feature of modern civilisation. Most of the energy is required for lighting, heating, domestic appliances, industrial electrical machinery and electrical traction. This importance of electric supply has constructed such circumstances that we must secure the power system from large faults and provide protection to the machineries and devices used and to ensure maximum continuity of the power supply. For this purpose, machines such as generators and motors are needed to be switched on and off many times. Means provided to achieve this are called 'switch gears'.

"The appratus used for switching, controlling and protecting electrical circuits and equipments is known as switchgear."

The term **switchgear,** used in association with the electric power system, or grid, refers to the combination of electrical disconnects, fuses and/or circuit breakers used to isolate electrical equipment. Switchgear is used both to de-energize equipment to allow work to be done and to clear faults downstream. *Switchgear* is a non-count noun, much like the software term "code," and is never used as "switchgears."

Hence, in an electric power system, switchgear is the combination of electrical disconnect switches, fuses or circuit breakers which are used to control, protect and isolate electrical equipment. Switchgear is used both to de-energize equipment to allow work to be done and to clear faults downstream. This type of equipment is directly linked to the reliability of the electricity supply. In general term, Switchgear is used for covering a wide range of equipment concerned with switching and protection. It includes all the switching devices associated with mainly power system protection. It also includes the devices associated with control, metering and regulating of electrical power system. Assembly of such devices in a logical manner forms a switchgear. This is very basic definition of switchgear. In this chapter, we shall present the elementary introduction to switchgear. We shall know the simplest form of switchgear which is used to control and protect lights.

1.2 SIGNIFICANCE OF SWITCHGEAR

Electrical energy management system ensures supply of energy to every consumer at all times at rated voltage, rated frequency and specified wave form, at lowest cost and with minimum environmental degradation. The switchgear, protection and network automation are integral part of the modern energy management system and national economy. The modern 3 phase, 50 Hz, AC interconnected power system has several conventional and non-conventional power plants, EHV AC and HVDC transmission systems, back-to-back HVDC coupling stations, HV transmission network, substations, MV and LV distribution systems, and connected electrical loads. The energy in electrical form is supplied to various consumers located in a vast geographical area, instantly, automatically and safely with required quality at *all times*. The service continuity and high-quality of power supply have become very important.

Generation planning, transmission planning, system expansion, installation, operation control and maintenance of electrical energy systems, fault calculations, network calculations, load flow studies have become very essential functions of modern power engineers. switchgear and controlgear are also essential with every power consuming devices at utilization level.

1.2.1. Features of Switchgear

(1) *Complete Reliability:* With continued trend of inter-connection and the increasing capacity of generating stations, the need for a reliable switchgear has become of paramount importance. This is not surprising because switchgear is added to the power system to improve the reliability. When fault occurs on any part of the system, the switchgear must operate to isolate the faulty section from the remainder circuit.

(2) *Absolutely Certain Discrimination:* When fault occurs on any section of the power system, the switchgear must be able to discriminate between the faulty section and healthy section. It should isolate the faulty section from the system without affecting the healthy part. This will ensure the continuity of supply of power.

(3) *Quick Operation:* When fault occurs on any section of the power system, the switchgear must operate quickly so that no damage is done to generators, transformers and other equipment by the short circuit currents. If fault is not cleared by the switchgear quickly, it is likely to spread into healthy parts, thus endangering complete shutdown of the system.

(4) *Provision for Manual Control:* A switchgear must have provision for manual control. In case the electrical (or electronic) controls fail, the necessary operation can be carried out through manual control.

(5) *Provision for Instruments:* There must be provisions for instruments which may be required. These may be in the form of ammeter or voltmeter on the unit itself, or necessary current and voltage transformers for connecting to the main switch board or a separate instrument panel.

1.3 SWITCHGEAR AND PROTECTION

We all familiar with low voltage switches and re-wirable fuses in our home. The switch is used to open and close the electrical circuit in our home manually and electrical fuse is used to protect our household electrical circuit from over current and short circuit faults. In the same way every electrical circuit including high voltage electrical power system needs switching and protective devices. But in high voltage and extra high voltage system, these switching and protective scheme becomes complicated one for high fault current interruption in safe and secure way. In addition to that from commercial point of view every electrical power system needs measuring, control and regulating arrangement. Collectively the whole system is called switchgear and protection of power system. The electrical switchgear have been developing in various forms.

Switchgear and protection/control-panels are installed at each *voltage* levels at each switching point for

(1) normal routine switching, control and monitoring and

(2) automatic switching during abnormal and faulty operating conditions such as short circuits, undervoltage, overloads.

The computer controlled network automation by load control centre, power station control rooms and substation control rooms and communication channels together ensures the control of national and regional grids and control of voltage, frequency, power and waveform under prevailing and ever changing load conditions.

The primary purpose of switchgear and protection is to ensure safe operation of power systems. Switchgear protection plays a vital role in modern power system network, right from generation through transmission to distribution end. The current interruption device or switching device is called circuit breaker in switchgear protection system. The circuit breaker can be operated manually as when required and it is also operated during over current and short circuit or any other faults in the system by sensing the abnormality of system. The circuit breaker senses the faulty condition of system through protection relay and this relay is again actuated by faulty signal normally comes from current transformer or voltage transformer.

1.4 FUNCTIONS OF SWITCHGEAR

A circuit-breaker is a switching and current-interrupting device in a switchgear. The circuit-breaker serves two basic purposes.

(1) Switching during normal operating conditions for the purpose of operation and maintenance.

(2) Switching during abnormal conditions such as short circuits and interrupting the fault currents.

The first function mentioned above is relatively simple as it involves normal currents which are easy to interrupt. The second function is complex as the fault currents are relatively high and they should be interrupted automatically within a short time of the order of a few cycles. One cycle in 50 Hz system takes 1/50 second.

One of the basic functions of switchgear is protection, which is interruption of short-circuit and overload fault currents while maintaining service to unaffected circuits. Some of the basic functions of switchgear are:

- Switchgear provides isolation of circuits from power supplies.
- It involves normal currents which are easy to interrupt.
- Switchgear is used to enhance system availability by allowing more than one source to feed a load.

- A switchgear has to perform the function of carrying, making and breaking the normal load current like a switch and it has to perform the function of clearing the fault in addition to that it also has provision of metering and regulating the various parameters of electrical power system.

Thus the switchgear includes circuit breaker, current transformer, voltage transformer, protection relay, measuring instrument, electrical switch, electrical fuse, miniature circuit breaker, lightning arrestor or surge arrestor, electrical isolator and other associated equipment. Electric switchgear is necessary at every switching point in the electrical power system. There are various voltage levels and hence various fault levels between the generating stations and load centers. Therefore various types of switchgear assembly are required depending upon different voltage levels of the system.

Switchgear is an essential part of a power system and also that of any electric circuit. In addition to circuit-breaker and protective relays, the associated equipment for controlling, regulating and measuring can also be considered as switchgear devices. Switchgear includes switches, fuses, circuits-breakers, isolators, relays, control panels, lightning arresters, current transformers and various associated equipments.

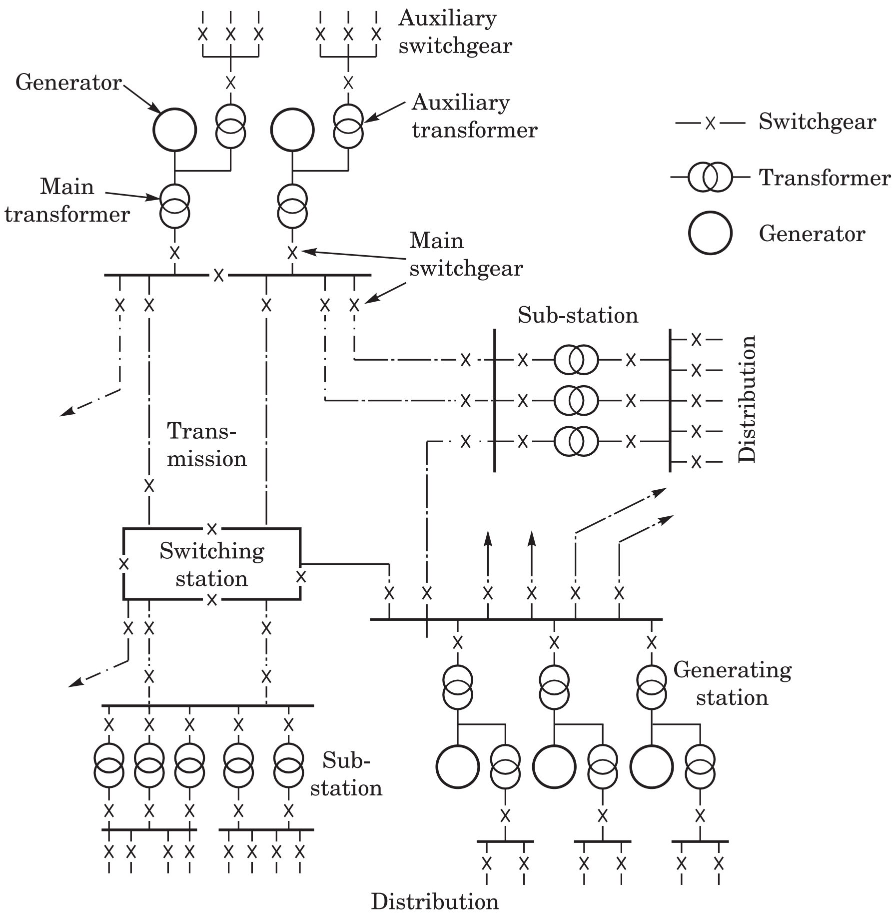


Fig. 1.1. Location of switchgear in typical power system (single line, simplified diagram).

Switchgear are necessary at every switching point in AC power system. Between the generating station and final load point, there are several voltage levels and fault levels.

Hence, in the various applications, the requirements of switchgear vary depending upon the location, ratings and switching duty. Besides the supply network, switchgear is necessary in industrial works, industrial projects, domestic and commercial buildings. A *controlgear* is used for switching and controlling power-consuming devices.

1.5 SUB-STATION EQUIPMENT

The power system is a constituent of power generation, transmission and distribution systems. For all the power system operations, substations are required for their course of action. Substations are congregation of electrical equipment through which consumers get supply of electrical power from generating stations. By varying the voltage levels or frequency or any other aspects, the required electrical quantity can be altered in substations to provide quality power to consumers.

Based on the application of substations, they are classified into different types: Generation substation, indoor substation, outdoor substation, pole mounted substation, switching substation, transmission substation, converter substation and distribution substation. In rare cases like wind farm power generation system, multiple hydroelectric and thermal power plants one can observe the collector substation which is used for transferring power from multiple turbines into one transmission unit.

The substation is an assembly of the following major electrical equipment:

- Electrical power transformers
- Instrument transformers
- Conductors and Insulators
- Isolators
- Bus bars
- Lightning arresters
- Circuit breakers
- Relays
- Capacitor banks and miscellaneous equipment.

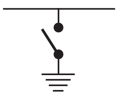
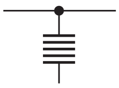
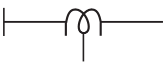
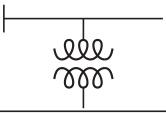
In every electrical sub-station, there are generally various indoor and outdoor switchgear equipment. Each equipment has a certain functional requirement (Ref. Table 1.1). The equipment are *either indoor or outdoor*, depending upon the voltage rating and local conditions. Generally indoor equipment is preferred for voltages upto 33 kV. For voltage of 33 kV and above, *outdoor switchgear* is generally preferred. However, in heavily polluted areas indoor equipment may be preferred even for higher voltages. SF_6 Gas Insulated Substations (GIS) are preferred in large cities for voltages above 33 kV.

The *outdoor equipment* is installed under the open sky. The indoor switchgear is generally in form of metal enclosed factory assembled units called metal-clad switchgear.

Circuit-breakers are the switching and current interrupting devices. Basically a circuit-breaker comprises a set of fixed and movable contacts. The contacts can be separated by means of an operating mechanism. The separation of current carrying contacts produces an arc. The arc is extinguished by a suitable medium such as dielectric oil, air, vacuum, SF_6 gas. The circuit-breakers are necessary at every switching point in AC sub-station (Ref. Fig. 1.1)

Isolators are disconnecting switches which can be used for disconnecting a circuit under no current condition. They are generally installed along with the circuit breaker. An *isolator*, can be opened after the circuit breaker. After opening the isolator, the *earthing switch* can be closed to discharge the trapped electrical charges to the ground. The *current transformers* and *potential transformers* are used for transforming the current and voltage to a lower value for the purpose of measurement, protection and control. *Lightning arresters* (surge arresters) divert the over-voltages to earth and protect the sub-station equipment from over-voltages. The further details about the sub-station equipment are given in Section I of this book.

TABLE 1.1: AC Sub-station equipment*

S. No.	*Symbol*	*Equipment*	*Function*
1.		Circuit-breaker	Switching during normal and abnormal conditions, interrupt the fault currents.
2.		Isolator (Disconnecting switch)	Disconnecting a part of the system from live parts under no load condition.
3.		Earthing-switch	Discharge the voltage on the lines to earth after disconnecting them.
4.		Surge arrester	Diverting the high voltage surges to earth and maintaining continuity during normal voltage.
5.		Current transformer	Stepping down the current for measurement protection and control.
6.		Potential transformer (Voltage transformer)	Stepping down the voltage for the purpose of protection, measurement and control.

1.6 FAULTS AND ABNORMAL CONDITIONS

There are several types of faults and abnormal conditions. The fault currents can damage the equipment and the supply installation if allowed to flow for a longer duration. In order to avoid such a damage every part of the power system is provided with a protective relaying system and an associated switching device. The protective relays are automatic devices which can sense the fault and send instructions to the associated circuit-breaker to open. The circuit breaker opens and clears the fault. All equipment associated with the fault clearing process are converted by the term 'Switchgear'.

A fault in an electrical equipment is defined as a defect in its electrical circuit due to which the current is diverted from the intended path. Faults are generally caused by breaking of conductors or failure of insulation. The other causes of faults include mechanical failure, accidents, excessive internal and external stresses, etc. The fault impedance being low, the fault currents are relatively high. During the faults, the voltages of the three phases become unbalanced. The fault currents being excessive, they can damage the faulty equipment and the supply installation. During the faults, the power flow is diverted towards the fault and the supply to the neighbouring zone is affected. Voltage becomes unbalanced.

* For 400 kV, and above series capacitors are used for increasing power transfer ability. Shunt reactors are used for compensation of reactive power.

The faults can be minimised by improving the system, design, quality of the equipment and maintenance. However, the faults cannot be eliminated completely.

For the purpose of analysis, AC faults can be classified as:

(*i*) single line to ground fault
(*ii*) line to line fault
(*iii*) double line to ground fault
(*iv*) simultaneous fault
(*v*) three phase fault
(*vi*) open circuit, etc.

The other abnormal conditions in AC system include:

(*i*) voltage and current unbalance
(*ii*) overvoltages
(*iii*) under frequency
(*iv*) reversal of power
(*v*) temperature rise
(*vi*) power swings
(*vii*) instability, etc.

Some of the abnormal conditions are not serious enough to call for tripping of the circuit-breaker. In such cases the protective relaying is arranged for giving an alarm. In more serious cases, the continuation of the abnormal condition (such as a fault) can be harmful. In such cases, the faulty part should be disconnected the system without any delay. This function is performed by protective relaying and switchgear.

As a fault occurs in a power system, the current increases to several times the normal current because of the low fault impedance. The value of the fault current depends on the voltage at the faulty point and the total impedance upto the fault. The voltage at the fault location changes from its normal value. Fault MVA is reactive MVAr.

During the fault, the current and voltage undergo a continuous change and the phenomena observed are called *'transient phenomena'*. The word 'transient' refers to a 'temporary happening' which lasts for a short duration of time. The fault current varies with time. During the first one to three cycles, the fault current is very high but decreases very rapidly. This zone in which the current is very high, but decreases very rapidly is called the *Sub-transient State*. After the first few cycles, the decrease in current in less rapid. This region of slow decreases in the short-circuit current is called the *Transient State.* The transient state lasts for several cycles. After the transient state, *Steady State* is reached. During the steady state the r.m.s. value of the short-circuit current remains almost constant.

The circuit-breakers operate during the transient state.

1.7 FAULT CALCULATIONS

Collecting the information from different parameters of the system is known as fault calculation. It is a calculation of fault current in any electrical power system.

The knowledge of the fault currents is necessary for selecting the circuit-breakers of adequate rating designing the sub-station equipment, determining the relay settings, etc. The fault calculations provide the information about the fault currents and the voltages at various points of the power system under different fault conditions.

The per-unit system is normally used for fault calculations. The symmetrical faults such as three phase faults are analyzed on per phase basis. For calculations on unsymmetrical faults, the method of *Symmetrical Components is adopted.* The network analyzer and digital computers are used for fault calculations of larger systems. (Ref. Sec. II).

1.8 THE FAULT CLEARING PROCESS

The protective relays are connected in the secondary circuits or current transformers and/or potential transformers. The relays sense the abnormal conditions and close the trip circuit of the associated circuit-breaker. The circuit-breaker opens its contacts. An arc is drawn between the contacts as they separate. The arc is extinguished at a natural current zero of the AC wave by suitable medium and technique. The stresses occurring on the circuit breaker while interrupting the arc, can be analysed by studying the following transient phenomena:

- transient variation of the short-circuit currents
- transient variation of the voltage after final arc interruption (transient recovery voltage)
- the arc extinguishing phenomenon.

After final arc extinction and final current zero, a high voltage wave appears across the circuit-breaker contacts tending to re-establish the arc. This transient voltage wave is called Transient Recovery Voltage (TRV). The TRV comprises a high frequency transient component superimposed on a power-frequency recovery voltage.

These phenomena have a profound influence on the behaviour of the circuit-breakers and the associated equipment (Ref. Ch. 3, 4).

1.9 PROTECTIVE RELAYING

AC power system is covered by several protective zones. Each protective zone covers one or two components of the system. The neighbouring protective zones overlap so that no part of the system is left unprotected. Each component of the power system is protected by a protective system comprising protective transformers, protective relays, all-or-nothing relays, auxiliaries, trip-circuit, trip coil etc. During the abnormal condition, the protective relaying senses the condition and closes the trip circuit of the circuit-breaker. Thereby the circuit-breaker opens and the faulty part of the system is disconnected from the remaining system.

The various power, system elements include generators, transformers, bus-bars, transmission lines, motors, etc. The protective relaying requirements of the various elements differ. Various types of protective systems have been developed to satisfy these requirements. For example, the over-current protection responds to increased currents. The differential protection responds to the vector difference between two or more similar electrical quantities.

The protective schemes for large electrical equipment comprise several types of protective systems. For low voltage equipment of relatively small ratings, fuses and thermal relays are generally adequate. The protective schemes of large power system-equipment are generally designed with due regards to power swings, power system stability and associated problems. (Ref. Sec. III and IV).

1.10 NEUTRAL GROUNDING (EARTHING) AND EQUIPMENT GROUNDING

The term 'Grounding or Earthing' refers to the connecting of a conductor to earth. The neutral points of generator and transformer are deliberately connected to the earth. In 3 phase a.c. systems the earthing is provided at each voltage level. If a neutral point is not available, a special earthing transformer is installed to obtain the neutral point for the purpose of earthing. Neutral points of star connected VTs and CTs are earthed. The neutral earthing has several advantages such as :

(*i*) Freedom from persistent arcing grounds. The capacitance between the line and earth gets charged from supply voltage. During the flash-over the capacitance get discharged to the earth. The supply voltage charges it again. Such alternate charging and discharging produces repeated arcs called *Arcing Grounds*. The neutral grounding eliminates the problem of 'arcing grounds'.

(*ii*) The neutral grounding stabilises the neutral point. The voltages of healthy phases with respect to neutral are stabilised by neutral earthing.

(*iii*) The neutral earthing is useful in discharging over-voltages due to lightning to the earth.

(*iv*) Simplified design of earth fault protection.

(*v*) The grounded systems require relatively lower insulation levels as compared with ungrounded systems.

The modern power systems are 3 phase a.c. systems with grounded neutrals.

The **Equipment Grounding** refers to the grounding of non-current carrying metal parts to earth. It is used for safety of personnel. If a metal part is grounded, its voltage with respect to earth does not rise to a dangerously high value and the danger of a severe shock to personnel is avoided (Ref. Ch. 18).

1.11 OVER-VOLTAGES AND INSULATION CO-ORDINATION

The over-voltage surges in power systems are caused by various causes such as : lightning, switching resonance etc. The power system elements should withstand the over-voltages without insulation failure. The insulation level of a power system element refers to its values of power frequency and impulse voltage withstand. The insulation levels of various power system elements are graded in such a way that the damage caused by the over-voltages is minimum and the design of insulation of the equipment is economical. The protective measures against over-voltages due to lightning include:

(*i*) use of overhead ground wires (*ii*) low tower footing resistance

(*iii*) use of lightning arresters (surge arresters)

Over-voltages are also caused during switching operations. The magnitude and wave shape of the switching over-voltages depend upon the values of equivalent inductance, capacitance and resistance in the system, the magnitude of the current to be interrupted and other local conditions. Over-voltages are produced during opening of a circuit-breaker. The amplitude of such over-voltages can be reduced by incorporating opening resistors across the circuit-breaker interrupters. Over-voltages are also produced during the closing operation of circuit-breaker especially while closing on unloaded transmission lines. Such over-voltage can be minimized by incorporating pre-closing resistors across the interrupters of the circuit-breakers.

The surge arresters offer low resistance to over-voltages and divert and over-voltages to earth.

1.12 STANDARD SPECIFICATIONS

The various standards institutions in the world publish the standards specifications of high voltage circuit breakers, isolators and other substation equipment. Standards have been published on various types of protections and protective relaying schemes for various electrical equipment. These standards protective the guideline to the manufacturers and users regarding the following:

(*i*) terms and definitions (vocabulary) (*ii*) ratings

(*iii*) conditions of service (*iv*) constructional details

(*v*) tests to be performed, standard test procedures, methods of evaluation of the test results.

(*vi*) guidelines for selection, erection and maintenance.

The standards are generally drafted for a wider application and they generally do not cover specific cases. IEC (International Elector-Technical Commission) recommendations are generally accepted all over the world and the IS (Indian Standards) specifications published by Bureau of Indian Standards (BIS) are generally based on IEC recommendations.

Quality Standards

The following standards organisations are associated with the standards on quality:

(*i*) International Standards Organisation (ISO), Headquarters: Geneva, Switzerland
(*ii*) Bureau of Indian Standards, New Delhi (BIS)
(*iii*) Bureau Veritas Quality International (BVQI)

The ISO and IS Standards on Quality are:

ISO	*IS*	*Title*
ISO: 9000	IS: 14000	Quality Management and Quality Assurance Standard. Selection and Use: 20 System Elements
ISO: 9001	IS: 14001	Level 1: Design/development production, testing in factory, installation and servicing
ISO: 9002	IS: 14002	Level 2: Production and installation all elements, some less stringent
ISO: 9003	IS: 14003	Level 3: Final Inspection and Tests-half the elements, low stringency
ISO: 9004	IS: 14004	Guidelines: Maximising benefits and minimising costs.

The *ISO 9000 Certificate* is given to manufacturers and Organisations as a recognition of the Quality. ISO Certification is essential for Switchgear and Controlgear Manufacturers for effective marketing and customers satisfaction.

Switchgear and protection are vital equipment in the electrical installations. It should have *Perfect Quality.*

1.13 RELAYS

Relays are an electrical switch that use an electromagnet to move the switch from the off to on position instead of a person moving the switch. They take a relatively small amount of power to turn on a relay but the relay can control something that draws much more power. It is usually an electromechanical device that is actuated by an electrical current. The current flowing in one circuit causes the opening or closing of another circuit. Relays are like remote control switches and are used in many applications because of their relative simplicity, long life, and proven high reliability. They are used in a wide variety of applications throughout industry, such as in telephone exchanges, digital computers and automation systems. Highly sophisticated relays are utilized to protect electric power systems against trouble and power blackouts as well as to regulate and control the generation and distribution of power. In the home, relays are used in refrigerators, washing machines and dishwashers, and heating and air-conditioning controls. Although relays are generally associated with electrical circuitry, there are many other types, such as pneumatic and hydraulic. Input may be electrical and output directly mechanical, or vice versa.

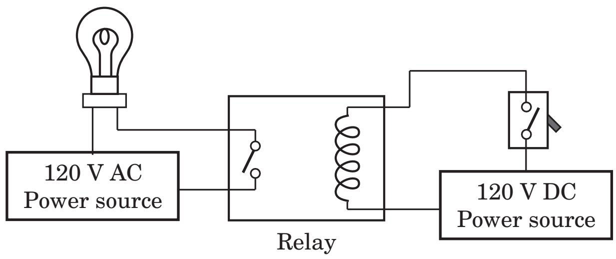


Fig. 1.2

For example, A relay is used to control the air conditioner in your home. The AC unit probably runs off of 220 V AC at around 30 A. That's 6600 Watts The coil that controls the relay may only need a few watts to pull the contacts together.

All relays contain a sensing unit, the electric coil, which is powered by AC or DC current. When the applied current or voltage exceeds a threshold value, the coil activates the armature, which operates either to close the open contacts or to open the closed contacts. When a power is supplied to the coil, it generates a magnetic force that actuates the switch mechanism. The magnetic force is, in effect, relaying the action from one circuit to another. The first circuit is called the control circuit; the second is called the load circuit.

1.13.1 ELECTRO-MECHANICAL RELAYS AND STATIC RELAYS

There are two basic classifications of relays: electromechanical and solid state. electromechanical relays have moving parts, whereas solid state relays have no moving parts. Advantages of electromechanical relays include lower cost, no heat sink is required, multiple poles are available, and they can switch AC or DC with equal ease.

In static relays the sensing, comparison and measurement are made by static (electronic) circuits having no moving parts. Static relays were developed during 1960's and have been accepted all over the world for almost all protective relaying, control and automation purposes.

- Static relays have versatile characteristics, offer low burden, and incorporate several protective/control/monitoring functions in one compact unit. Recently (1980's) programmable static relays incorporating microprocessor have been introduced. Microprocessor based relays have several superior features such as:
- Indication or operating values on demand and thereby no need of separate indicating instruments on panel.
- A single relay can perform 10 or more different protective functions thereby reducing number of separate relays and increasing reliability.
- Internal monitoring of own relays circuit.
- Memory function *e.g.*, a relay which has tripped on fault can remember and flash on the display, the magnitude of current and instant of time at the time of tripping.
- Better properties and extended range of application for generation, transmission, distribution and industrial application.

The range of static relays in rapidly spreading. Details about static relays are covered in section IV.

1.14 APPLICATIONS OF ON-LINE DIGITAL COMPUTERS MICROPROCESSORS AND STATIC PROTECTIVE/CONTROL DEVICES IN POWER SYSTEM

Complex tasks associated with data logging, monitoring, measurements, protection, control and automation are now being performed with the aid of new type of on-line programmable devices including on-line digital computers, microprocessors, static protective and control devices, data transmission and processing devices etc. These tasks include.

- Checking fault levels periodically
- Loading of plants for economical and reliable operation
- Protection analysis, setting of trip levels to suit network configuration and loading status.
- Back-up protection.
- Real-time energy management from National Load Control Centre, Regional Load Control Centre.

The task of power system protection control and automation are performed by SCADA systems*.

* Supervisory Control And Data Acquisition Systems (Ref. Ch. 50).

The equipment for automatic control of power system are either fixed wire or programmable type. These include:

(*i*) Data collection and processing equipment

(*ii*) Data transmission (telemetry)

(*iii*) Data monitoring equipment (*iv*) Man-machine interface.

The Data includes current, power, voltage, status etc. Load control centre receives the following:

(*i*) Data regarding generating stations (*ii*) Data regarding major sub-stations

(*iii*) Data regarding receiving stations.

The variables are scanned periodically and conveyed to load control centres as required.

The data is collected at sources by transducers, it is processed in data loggers. It is transmitted to load control centres through one or more of following channels:

(*i*) Power line carrier communication channels

(*ii*) Pilot wire communication

(*iii*) Microwave communication

(*iv*) Satellite communication

Now fibre-optics is being used for short lengths of upto 50 km for data transmission. Data is converted into digital form in A/D convertors.

Applications of digital computers and microprocessors in power system protection are described in Section V.

1.15 INTERCONNECTED POWER SYSTEM

Modern electrical power systems are large interconnected AC Networks. The total network is divided a few regional zones (Areas). Each Area controls its own loud, frequency and generation. Adjacent independently controlled areas are interconnected to from a regional/national grid.

For example, the Power Map of India is covered by the following five regional zones:

(*i*) Central zone (*ii*) Western zone

(*iii*) Southern zone (*iv*) Northern zone

(*v*) North-eastern zone

Some zones are already interconnected to form the Regional Grids. Each zone has its load control centre. National load control centre is in Delhi. However the total national grid is under development.

In an Interconnected network, the National Load Control Centre determines the exchange between regional zones. Regional load control centres control generation in the respective zone to match the prevailing load so as to maintain the regional frequency within target limits (49-51 Hz). During the low frequency/high load; the region imports power from adjacent surplus region. During low load/high frequency, the region exports power.

Advantages of Interconnections

(*i*) During the period of need, a region (Area) imports power from adjacent region and maintains stability and frequency.

(*ii*) The transient stability limit of each region is increased without increasing the installed capacity as the rotating reserve of adjacent region is used by interconnection.

(*iii*) Optimum economic loading of hydro/thermal/nuclear generating stations depending upon energy reserves. Economic loading of power plants.

(*iv*) Bulk transfer of energy as per agreed schedule.

Peak loads of each region may occur at different hours during the day. During this period, the region imports the power.

HVDC Back-to-Back HVDC Interconnections

After 1975, the back-to-back HVDC Coupling stations have become extremely successful for interconnections between adjacent AC grids. The rating of HVDC coupling stations are in the range of 500 MW, 1000 MW. By means of an HVDC coupling station, power exchange between two AC systems can be controlled rapidly, precisely and with minimum transmission losses. The transient stability of both the AC regional grids is improved. The Regional-Grids in India are getting interconnected by Back-to-Back HVDC Stations.

Multiterminal HVDC Interconnections has been introduced in Canada-USA during 1986. By means of an multi-terminal HVDC Interconnections, power, exchange between three or more AC systems can be controlled rapidly, precisely and with minimum transmission losses. The transient stability of entire national grid is improved. The MTDC Interconnection is not yet planned in India (1995). It may be introduced during 2000-2010.

Economic Load Despatch. The economic operation of large AC grid can be controlled from a centralized 'load control centre' or 'load despatch centre'.

The load control centre determines the allocation of generation by various plants on the basis of economic load distribution considering incremental operating costs λ and penalty factors for transmission losses (Ln) for each plant. The load control centre sends command to power stations-control rooms periodically by telemetric data transmission. The automatic load-frequency control in the control system of Generator-Turbine-Governor basically aims at maintaining constant frequency/speed as a primary control. But the setting of governor to turbines (secondary load frequency control) is changed according to the instructions of the load control centre. Thus the input to turbines of generators gets automatically adjusted by primary load-frequency control and the frequency is maintained. And the governor setting is determined by economy load dispatch instructions.

The total load frequency control is achieved jointly by:

(*a*) Load control centre

(*b*) Telemetry and telecontrol equipment and

(*c*) Power station control room.

Automatic Economic load despatch is illustrated in Chapter 46-B.

1.16 LOAD-FREQUENCY CONTROL, LOAD SHEDDING

Load-frequency control of AC grid is achieved by continuous matching of generation (production) of electrical power with prevailing load conditions by joint action of control rooms in generating stations. Voltage control is achieved by appropriate tap-changing and shunt compensation in respective sub-stations.

The regulations of power supply insist that the supply frequency variation should remain within 2% about the declared frequency of 50 Hz.

The frequency of a generator and generating station is controlled partly by the action of the mechanical governors controlling the turbine speed and partly by changes in load conditions. The plants output is increased by increasing input. How much load the plant should share is decided by grid control loading engineer?

Load Shedding. When the load increases beyond limits of generation, the system frequency starts dropping. Drop in frequency below 49 Hz is not permitted. To control the further drop of frequency, load is shed (disconnected) at distribution level. Load shedding may cause voltage rise. Tap changing should be arranged to prevent voltage rise beyond safe limits.

Reduced frequency causes vibrations and failures of stream turbine blades, overfluxing of transformer cores, drop in synchronous speed, error in clock time etc. Excellent power system operates within targetted frequency continuously.

Network Segregation (Islanding). In case of major fault or outage, the network has a tendency of cascade tripping and large blackout. It is difficult to resynchronise. To avoid such happening, the network is quickly segregated in smaller zones. Drop in frequency and rate of drop (df/dt) is used in frequency relay for segregation action.

1.17 VOLTAGE LEVELS IN NETWORK AND SUB-STATIONS

The network has various voltage levels for generation, transmission distribution, utilization, control and protection.

(*i*) Generation is at voltages upto 30 kV AC r.m.s. (phase to phase). This is due to design limitations of AC generators.

(*ii*) Long distance high power transmission is by EHV AC lines rated 220 kV, 400 kV, 760 kV AC. For longer distance and higher powers, higher voltages are economical and essential. In special cases, HVDC transmission is preferred. The rated voltages of long distance HVDC transmission are ± 400 kV, ± 500 kV, ± 600 kV.

(*iii*) Backbone transmission network is by EHV AC transmission lines (400 kV AC).

(*iv*) Distribution is at lower AC voltages between 132 kV AC and 3.3 kV AC.

(*v*) Utilisation is at low voltage (upto 1 kV) and medium voltages upto 33 kV.

(*vi*) The factory sub-stations receive power at distribution voltage upto 33 kV and step it down to 440 volts AC. Larger factories receive power at 132 kV and have internal distribution at 3.3 kV, to 440 volts AC.

TABLE 1.2: Reference Values of Nominal Voltages in A.C. and HVDC Sub-stations

		A.C. *Sub-stations*		
400 kV	220 kV	132 kV	110 kV	
66 kV	33 kV	22 kV	11 kV	6.6 kV
3.3 kV	400 V a.c. rms. phase to phase.			
		H.V.D.C. *Sub-stations*		
± 250 kV,				
± 400 kV, ± 500 kV, ± 600 kV				
		Station Auxiliaries		
Auxiliary A.C. supply :		11 kV, 6.6 kV, 3.3 kV		
400 V, 3 ph, phase to phase				
230 V a.c. single phase				
Auxiliary L.V.D.C. : 220 V, 110 V, 48 V.D.C.				

1.18 VOLTAGE CONTROL OF AC NETWORK

Voltages of various sub-stations buses should be held within specified limits, the variation allowed ± 10% (Refer Table 1.3).

Whereas the active power flow (P) determines directly the frequency (f), it does not affect the voltages significantly.

Voltages are affected significantly by the flow of reactive power Q.

$$|\Delta V| = \frac{QX}{|V_R|}$$

where $|V_R|$ = Receiving end voltage of the line, magnitude
Q = Reactive power flow through the line
X = Series reactance of line
$|\Delta V|$ = Voltage drop in line, $[V_S] - [V_R]$, magnitude

Voltages are controlled by supplying reactive power (Q). This is called compensation.

Basic Methods of Voltages Control

(*i*) Voltages regulators and excitation control of synchronous generators.

(*ii*) Tap-changing transformers at various sub-stations. Off-load tap changers are used for seasonal voltage variations. On-load tap changers are used for daily load variation. By changing the turns ratio of the transformer N_1/N_2 the voltages ratio V_1/V_2 is changed.

(*iii*) Series compensation (series capacitors) used for long lines. The inductive reactance drop in the line (IX_L) is compensated by the drop in series capacitors (IX_C). Series capacitors are generally used for long extra high voltage transmission lines.

(*iv*) Shunt capacitors are used for voltage control in transmission and distribution networks. They are connected near the load terminals, factory sub-stations, distribution substations. Capacitors supply reactive power and improve power factor, they are switched in during heavy loads.

(*v*) Shunt capacitors should be switched-in during low voltage and switched-off during high voltage.

TABLE 1.3: Reference Values of Voltage Limits in AC Network

Class	*System Voltage Nominal*	*Highest Voltage*	*Permissible Lowest System Voltage*
	ph. to ph. R.M.S.	*ph. to ph. R.M.S.*	*ph. to ph. R.M.S.*
LV(1 ph)	240 V	264 V	216 V
MV	415 V	457 V	347 V
M.H.V.	3.3 kV	3.6 kV	3 kV
M.H.V.	6.6 kV	7.2 kV	6 kV
M.H.V.	11 kV	12 kV	10 kV
M.H.V.	22 kV	24 kV	20 kV
M.H.V.	33 kV	36 kV	30 kV
H.V.	66 kV	72.5 kV	60 kV
H.V.	132 kV	145 kV	120 kV
E.H.V.	220 kV	245 kV	200 kV
E.H.V.	400 kV	420 kV	380 kV
U.H.V.	760 kV	800 kV	750 kV

where, L.V. = Low voltage
M.V. = Medium voltage,
M.H.V. = Medium high voltage
H.V. = High voltage,
E.H.V. = Extra high voltage
U.H.V. = Ultra high voltage

Permissible variation is approximately ± 10% Nominal value.

(*vi*) Shunt reactors are used with EHV AC lines for compensation of reactive power during low loads.

Compensation of Long Lines

During low loads and High receiving voltage	Switch-off shunt capacitors. Shunt-reactors-unswitched
During high loads and Low receiving voltage	Switch-in shunt capacitors at load end shunt-reactors-unswitched
Varying load	Static VAr Source (SVS)

The voltage control of each sub-station bus is achieved by appropriate action in that sub-station.

1.19 STATIC VAR SOURCES (SVS)

Static VAr sources are installed in receiving sub-stations, load sub-stations for fast, stepless control of reactive power compensation for voltage control. In conventional switched schemes the capacitors/reactors are switched in/out by circuit-breakers. In SVS, the capacitors/reactors are controlled by controlling the delay angle of thyristor triggering. The duration and magnitude of current flowing through reactor/capacitor is controlled. Thereby amount of compensation is controlled. Fast static compensation schemes are used for controlling voltage of AC buses in EHV AC sub-stations. Formerly synchronous compensators were used for similar purpose.

Voltage control techniques are described in Chapter 45 B.

1.20 POWER SYSTEM STABILITY

Synchronous generators connected to AC network have a tendency in synchronism with the network. The tendency to remain in synchron called *Stability*. The tendency to fall out-of step is called *unstable condition*.

Steady state stability limit denotes the maximum power transfer possible with very small disturbing forces. This occurs at load angle of 90° electrical. The load angle δ of a synchronous machine is the angle between the emf vector (corresponding to axis of rotating magnetic field) and the voltage vector (V). The power transfer is given by equation.

$$P = \frac{|V|.|E|}{X} \sin \delta$$

where $|V|$ = Terminal voltage, magnitude; $|E|$ = Induced emf, magnitude

δ = angle between V and E vectors; X = Synchronous reactance.

Steady state stability limit occur at $\delta = 90°$ and is equal to

$$P_{SS} = \frac{|V|.|E|}{X} \sin 90° = \frac{|V|.|E|}{X}$$

However, if a sudden disturbance occurs, the angle delta overshoots beyond 90° and the stability may be lost. Hence the limit of loading permitted (P_{ts}) for given amount of disturbance ΔP is defined. It is called Transient Stability Limit (P_{ts}). A synchronous generator can be loaded safely upto its transient stability limit. The transient stability limit (P_{ts}) is much lesser than steady state stability limit. Assuming safe load angle of 30° electrical:

$$P_{ts} = \frac{|V|.|E|}{X} \sin 30° = \frac{|V|.|E|}{X} \cdot \frac{1}{2}$$

i.e., $P_{ts} = 1/2\ P_{ss}$. .... for critical $\delta = 30°$

Transient state stability limit is half of steady state limit.

A similar analysis is applied to power transfer through an AC interconnecting transmission line

$$P_{st} = \frac{|V_1|.|V_2|}{X} \sin \delta$$

where $|V_1|$, $|V_2|$ = Sending and receiving voltage magnitudes

X = Series reactance of line ; δ = Angle between vectors V_1, V_2

Transient stability limit can be improved by several methods associated with switchgear and protection. These include the following:

- Use of faster and superior protection system.
- Use of faster circuit-breakers.
- Use of rapid auto-reclosing of circuit-breakers.

By improving transient stability limit, the installed generating stations can be loaded to higher levels resulting in major economy.

Details about transient stability limit are covered in Chapter 44.

1.21 HVDC OBTION

400 kV a.c. transmission links and sub-stations were established in India during 1970s. Three HVDC projects have been executed, (1992). By the year 2000, about five HVDC projects are likely to be commissioned in India. HVDC transmission systems are selected as an alternative to EHV and UHV a.c. transmission system for any one of the following reasons only for specific projects:

(*i*) Long distance high power transmission lines (say above 1000 MW and 800 km) for economic advantage. HVDC links are economical for long distance high power transmission lines when the saving in line cost is more than the additional cost of conversion sub-station. For backbone AC network, generation transmission and distribution AC is definitely superior and continues.

(*ii*) Asynchronous interconnection (Tie) between two a.c. systems having their own load-frequency control systems.

(*iii*) Back-to-back asynchronous tie sub-stations between two a.c. systems without tie-line.

(*iv*) Underground/submarine cables at voltages above 66 kV and length more than 25 km for technical reasons.

(*v*) Multi-terminal HVDC systems.

The HVDC obtion introduced in electrical network during early 1970's provides.

(*i*) faster and accurate control of real power (e.g., 30 MW/minute).

(*ii*) higher power system stability-limit for transmission of power without limit of sin δ, and improved stability of the connected AC networks.

(*iii*) HVDC line has no reactive power flow and therefore no need of intermediate compensating substations. The line losses are reduced. HVDC line losses are about 5% of power transfer as against 25% line losses for equivalent AC power transmission.

Three Phase, 50 Hz AC systems will continued universally for power system generation, transmission and distribution networks as it has natural tendency for load-frequency stability and several economical AC voltages levels through transformers.

Modern power system is a combination of Interconnected AC systems with a few HVDC coupling stations ; a few long distance 2 terminal bipolar HVDC links and possibly a high power multi terminal 2-Pole HVDC Interconnecting system.

Switchgear; protection and control of HVDC transmission systems and their interaction with AC system have been illustrated in Ch. 47.

1.22 POWER SYSTEM ANALYSIS

Power system analysis deals with various network phenomena, interaction between the network and the machines, stresses on equipment. The system studies evaluate the present and future power system operating performance/reliability/availability and to provide data and guidelines for satisfactory operation and control. The scope includes the following topics which have been covered in separate chapters of this book:

(*i*) Load flow calculations
(*ii*) Load frequency control
(*iii*) Short circuit calculations
(*iv*) Transient overvoltage studies.
(*v*) Insulation-coordination, neutral grounding.
(*vi*) Stability studies
(*vii*) Reliability studies
(*viii*) Voltage control and reactive power flow control
(*ix*) HVDC and EHV-AC transmission systems, interaction with network.
(*x*) Economic operation of the power system
(*xi*) Computer aided power system studies.

1.23 POWER SYSTEM NETWORK CALCULATIONS AND LOAD FLOW

The numerical problems in power system analysis deal with the power system variables V, I, P, Q, S, f, δ and network constants Z, Y, R. A network has several and buses and interconnecting branches. Basic Kirchoff's laws, network theorems, fundamentals electrical equations and mathematical tools are applied to solve numerical problems in power systems. The network calculations are simplified by writing the Kirchoff's current law in terms of nodal voltage equations.

$$I = Y \text{ bus } V$$

I and V are current and voltage matrices. Y bus is the bus-admittance matrix for the given network.

The methods of network calculations have been explained clearly Ch. 19 to 24 and in Ch. 57 with the help of several *solved numerical problems.*

Load flow calculations

Load flow studies deal with calculation of the following variables for the various busses and branches of the given network (power system) under given steady state operating conditions of generation and load.

Variables associated with a load flow study are:

Vk Bus voltage magnitude
P_k Real power entering/leaving bus-k
δk Phase angle of voltage
Q_k Reactive power entering leaving bus
Complex power = $P + j\,Q$
P_{mn} Real power flow in branch mn
I_{mn} Branch current
Q_{mn} Imaginary power flow in branch

These variables influence each other and their co-relation is expressed in terms of the load flow equations. Load flow studies are the used for evaluating the steady state performance and provide valuable data to power system engineers for operation, control and system planning and design. The Gauss siedel interactive method and newton raphson interactive method of load flow studies have been clearly explained in Ch. 58 with the help of solved numerical problems.

1.24 SOME TERMS IN THE TEST

Controlgear. Controlgear is a general term covering switching devices and their combination with associated control, measuring and protective equipment intended for *control of power consuming devices.* (Ch. 15)

Circuit-breaker. A device capable of making, breaking an electric circuit under normal and abnormal conditions such as short circuits.

Isolator (Disconnecting Switch). A switching device which can be opened or closed only under no current condition. It provides isolation of a circuit for the purpose of maintenance.

Earthing Switch. It is a switch which connects a conductor to the earth so as to discharge the charges on the conductor to the earth. Earthing switches are generally installed on the frames of the isolators.

Relay. An automatic device which closes its contacts when the actuating quantity/quantities reach a certain predetermined magnitude/phase.

Current Transformer (CT). The current ratio of current transformers is generally high (*e.g.* 500 A/5 A) and volt-ampere capacity is relatively low (*e.g.,* 50 VA) as compared with that of the power transformers.

Potential Transformer (PT), Voltage Transformer (VT). The volt-ampere capacity of a potential transformer is low (*e.g.* 100 VA) and the voltage ratio is relatively high (*e.g.,* 132 kV/100 V). The protective relays are connected in the secondary circuits of CTs and PTs.

Lightning Arrester (Surge Arresters). The equipment connected between the conductor and ground, to discharge the excessive voltages to earth.

Fault Clearing Time. The time elapsed between the instant of the occurrence of a fault and the instant of final arc extinction in the circuit-breaker. The fault clearing time is usually expressed in cycles. One cycle of 50 Hz system is equal to 1/50 second. The fault clearing time is the sum of the relay time and the circuit breaker time.

Auto-reclosure

Automatic closing of the circuit breaker after its opening. Auto-reclosure is provided to restore the service continuity after interrupting a transient fault. High voltage circuit-breakers used for controlling overhead transmission lines are provided with such a feature.

Contactor. Contactor is a switching device capable of making carrying and breaking electric current under normal and overload conditions.

HRC Fuse. High rupturing capacity cartridge fuse is used for over-current protection of low voltage and high voltages circuits.

Protective Scheme. A selected set of protective systems which protect one or two components of the power system against abnormal conditions, *e.g.*, generator protection scheme, transformer protection scheme, etc.

1.25 OBJECTIVE AND TASKS

Every electricity supply company aims at the following:

(*i*) Supply of required electrical power to all the consumers continuously at all times.
(*ii*) Maximum possible coverage of the supply network.
(*iii*) Energy conservation and use of renewable energy sources.
(*iv*) Maximum security of supply.
(*v*) Shortest possible fault-duration.
(*vi*) Optimum efficiency of plants and the network.
(*vii*) Supply of electrical power at specified frequency and waveform.
(*viii*) Supply of electrical power within specified voltage limits.
(*ix*) Supply of electrical energy to the consumers at the lowest cost.

The work of a power engineer is to cover a wide range of activities such as:

(*i*) design and development of the products, systems stations for systems stations, products.
(*ii*) research and development.
(*iii*) manufacturing, testing, quality control
(*iv*) project planning, monitoring, execution
(*v*) purchase sale of equipment, specifications
(*vi*) Erection, testing and commissioning, safety
(*vi*) Operation and maintenance, energy conservation
(*vii*) Power system control, operation, automation.

This book covers the basic aspects. For gaining expertise in the activities further study and experience is necessary.