Chapter 1
The Traditional Power Generation and Transmission System: Some Fundamentals to Overcome Challenges

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Abstract In present power system, the engineers face variety of challenges in planning, construction and operation. In some of the problems, the engineers need to use managerial talents. In system design or upgrading the entire system into automatic control instead of slow response of human operator, the engineers need to exercise more technical knowledge and experience. It is principally the engineer's ability to achieve the success in all respect and provide the reliable and uninterrupted service to the customers. This chapter covers some important areas of the traditional power system that helps engineers to overcome the challenges. It emphasizes the characteristics of the various components of a power system such as generation, transmission, distribution, protection and SCADA system. During normal operating conditions and disturbances, the acquired knowledge will provide the engineers the ability to analyse the performance of the complex system and execute future improvement.

1.1 Introduction

Electric power system is a network that consists of electrical machines, lines and mechanism to generate electricity and supply to the customers. For a small region, this generation and supply of electricity are simple but it cannot ensure the

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A. B. M. S. Ali (ed.), *Smart Grids*, Green Energy and Technology,
DOI: 10.1007/978-1-4471-5210-1_1, © Springer-Verlag London 2013

consistency of the supply and may cost much higher. In the modern world, the generators and small networks are interconnected and electrical energy can be transmitted to a long distance and finally supply to the industries, hospitals, commercial buildings and dwellings in different regions. This type of interconnected power network is known as grid. The grid is a very complex system, and the engineers face variety of challenges in planning, construction and operation of this system. The entire power system is divided into sections such as generation, transmission and distribution. This chapter discusses the important aspects in all the three sections of the traditional power system. Voltage, reactive power control and the protection system are important aspects and relate to the system stability and major interruptions. Supervisory control and data acquisition (SCADA) system has become an important area which plays critical role in day-to-day operations of power system. It also manages to perform the activities faster. This chapter emphasizes on these sections and illustrates to get good understanding for solving the future problems. It is expected that the subject matter in this chapter will upgrade the engineer's technical knowledge and enable to provide reliable and uninterrupted power supply to the consumers.

1.2 Power System

The interconnected power network is generally divided into three sectors such as Generation, Transmission and Distribution. Figure 1.1 represents a typical uncomplicated single line diagram of a power system. The sections of the power system are connected via transformers (Tx) which step up or step down the voltages.

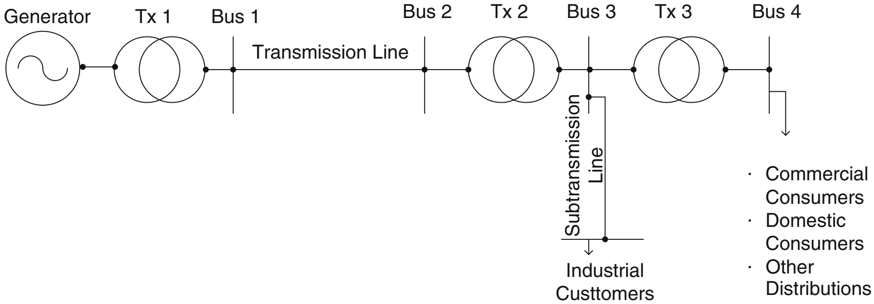

Fig. 1.1 Single line diagram of an uncomplicated power system with busbar (*Bus*) and transformer (Tx)

1.2.1 Generation

In generation section, the generators convert the energy from various sources to electric power at a particular voltage. Power generator has a prime mover and excitation system to control the output power as per the demand. For economic dispatch of power generation, control centre collects all the generator outputs and manages to control the output values based on the individual unit's generation costs. With system load variation, the generator outputs are controlled to have changes according to their individual generation cost to meet the system demand. Some instantly generating ability is always maintained by the individual generators for taking over sudden load for any unforeseen outage of generators or abrupt increase of the demand. Generation frequency is an indication of this sudden load changes. AC electric power is generated at frequencies 50 or 60 cycles per second (cs) which is also known as hertz (Hz). For example, Australia produces electric power at 50 Hz, and USA produces it at 60 Hz. This frequency remains constant at steady-state condition when the mechanical torque balances the electrical torque and the torque loss (T_{loss}) due to friction and windage. Mechanical torque (T_m) is produced by the prime mover for the applied force to its input from the energy source. Electrical torque (T_e) is generated as a result of the rotating electromagnetic field of the armature current. The torque equation at the generator output is given as

$$T_m - T_e = T_{loss}. \tag{1.1}$$

Since T_{loss} is very small in comparison with the other, it can be neglected. Hence, it can be stated that the generator operates at a constant speed in the steady state when the difference between the mechanical torque and electrical torque is zero. If sudden electrical load increases, the electrical torque also increases. At this stage, if the mechanical torque remains constant, the rotor mass decelerates causing a decrease in frequency, that is, the system frequency drops when $T_m < T_e$. Similarly, if the mechanical torque remains constant for sudden decrease in electrical load, the rotor mass accelerates resulting an increase in frequency, that is, the system frequency rises when $T_m > T_e$.

In order to maintain the constant system frequency, the mechanical torque needs to be increased or decreased with respect to the changes in electrical torque due to the electric load variation. This variation of mechanical torque is done by increasing or decreasing the input energy to the prime mover and is known as torque for acceleration (T_a). So, for negligible frictional loss, the torque equation of a generator can be written as in Eq. (1.2). As per the equation, T_a becomes zero when the generator attains its synchronous speed.

$$T_m - T_e = T_a. \tag{1.2}$$

Multiplying the angular speed (w) on both sides of the equation, the power balance equation is given as in Eq. (1.3).

$$P_m - P_e = P_a \tag{1.3}$$

where $P_m = wT_m$ is the mechanical power supplied by the prime mover, $P_e = wT_m$ the electromagnetic power of the generator, and $P_a = wT_a$ the increase in power input to the prime mover for acceleration. The mechanism that controls the inputs of the prime mover according to generator load variation to preserve the synchronous speed and frequency is known as governor of the power generating system. There are varieties of prime movers and governors. Mostly used conventional prime movers are as follows;

- steam turbine prime mover,
- hydraulic turbine prime mover,
- combustion turbine prime mover,
- combined cycle prime mover.

The modern complex power generation systems are making use of them according to their efficiency and applicability.

In addition to the prime mover and governor, the generator has exciter and voltage regulator to control the output voltage at the generator terminals as well as the reactive power and real power flow. Exciters are basically DC (direct current) generators which supply DC current to the field winding usually on the rotor. There are also various AC (alternate current) excitation systems that use solid rectifiers to supply DC current to the field windings.

1.2.2 Transmission

Electric power is transmitted to a long distance through high-voltage (HV) overhead lines or HV underground cables. The range of transmission line voltages are 33 to 500 kV. Some power consumers specially the industries are provided power supply from the 33 to 66 kV transmission lines. These power consumers have their own substations to step down the voltage level according to their requirements. Power transmission at these 33 to 66 kV voltage levels is known as sub-transmission system.

The enormous electrical power is transmitted using 132 to 500 kV transmission lines. The voltage levels are determined on the basis of the amount of power and the distance it has to be transmitted. Power transmission network is highly meshed, though few radial transmission and/or sub-transmission lines in many rural and developing areas are found for supplying power to small inhabitants [1]. The reason of the meshed network is to ensure the non-interrupted power supply due to loss of any section of the network.

In the meshed network system designed for secured electric supply, the lines and transformers are underutilized than their capacities. They are generally loaded around 50 % to allow continuation of supply after outage of the load sharing lines or transformers. This underutilization of the transmission system increases the power transmission cost. The other factors of limiting the maximum transmission capacity of the system are voltage magnitude limits, the real power generation of the power plant and appropriate reactive power support. In order to get the benefit of meshed system, sufficient generation need to be ensured to meet peak demands. There should have a balance of demand and supply, so that the schedule power curtailments are not required. However, besides the supply reliability, the meshed network provides some more benefits such as broad choices of generating plants and their locations, reduction in reserve capacity of generators, diversity of load demand and many others.

The power electronics contributes to the development of high-voltage direct current (HVDC) transmission system [2–4]. At the same time, it contributes for the development of flexible AC transmission system (FACTS) as detail in [5, 6]. HVDC transmission system needs some additional equipment which increases the initial investments, but it offers lower transmission loss and cost compared to AC system when used for large amount of energy transfer at long distances. In selecting the HVDC system, it is important to compare the total capital and operating costs with the high-voltage AC system (HVAC) system.

High-voltage DC power transmission started in 1984 with 300 kV and in 1985 with 600 kV at the Itaipu hydropower plant in Brazil (Rudervall et al. [7]). In those times, HVDC is chosen over an AC system for transmission of power more than 500 MW at distances greater than 500 km. With the advancement of technology and materials, in today's electricity industry, HVDC transmission systems are being in use at very low voltages compared to old installations. For example, in Australia, 80 kV DC cables are used to connect the Queensland and New South Wales electricity grids between Terranora and Mullumbimby in the year 2000 for the transmission of 180 MVA load over a distance of 65 km. There are reasons of choosing HVDC transmission system over an AC system. Some of the important reasons are given below:

- technically efficient for long distance power transfer,
- offer low environmental impact and better power quality,
- allow interconnection of two networks in an asynchronous manner,
- imply stability improvements.

1.2.3 Distribution

Distribution is the power supply lines between high-voltage substations and customers. Mostly the distribution voltage level is 11 kV, but in many circumstances, voltages are higher up to 66 kV. They are step down to 440 V (line to line voltage) through distribution transformers before supplying to the customers. Some commercial customers receive three-phase 440 V supply. The other commercial customers and domestic customers receive single-phase 250 V supply. Conventional 440 V supply lines in the distribution are radial. Higher-voltage distribution lines are also rarely interconnected unless there are essential services. So, in distribution

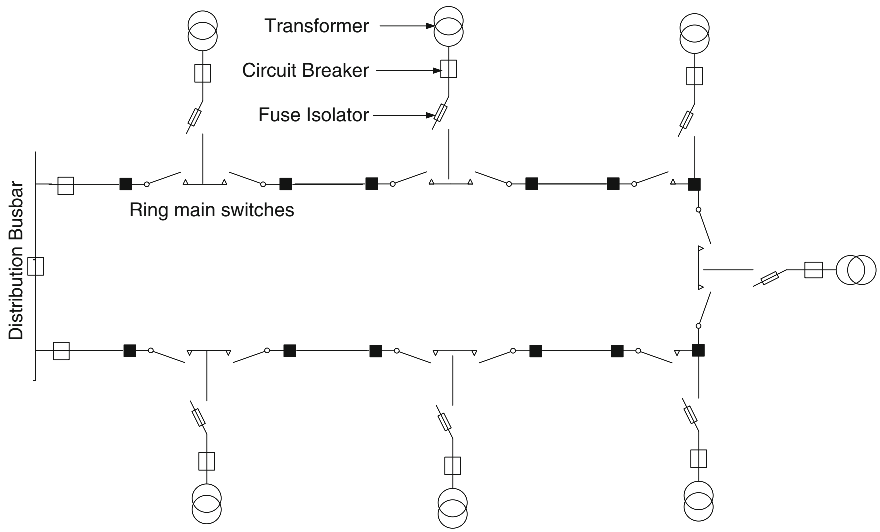

Fig. 1.2 Arrangement of ring-main feeder in distribution system

network in normal circumstances, a number of consumers may experience loss of supply for the failure of a section of the network.

In order to reduce the duration of the supply interruptions to the consumers, the auto-reclosers and sectionalizers are used in the radial lines/feeders. In business and densely populated areas, sometimes 11 kV supply network is arranged in ring-main feeders from the same switching station/substation with an open point preferably in the middle, so that for fault in one section, the consumers can be provided supply from other side. An example of ring-main feeders is shown in Fig. 1.2. This arrangement improves power restoration time, but the initial supply interruptions still take place. The reason of arranging the feeder rings from same substation is that the distribution feeders are not normally fitted with synchronizing equipment.

1.3 Power System Reliability and Quality

The reliability of power supply is the capability of delivering the uninterrupted power to consumers within accepted standards and in the amount. It relates more to complete loss of voltages rather than sags, swells, impulses or harmonics [8]. Reliability can be measured by frequency and duration of interruptions as well as magnitude of adverse effects on the electric supply.

Power quality may be defined as the measures, analysis and improvement of bus voltage to maintain that voltage to be sinusoidal at rated voltage and frequency, so that it is suitable for the operations of the consumers' devices [8, 9].

Modern sophisticated electronic equipments are sensitive to the events such as voltage sags, impulses, harmonics and phase imbalances. These events contaminate the sinusoidal wave of the voltage and hence become the power quality concern. Power quality events may arise from different causes such as switching or tripping of large inductive loads, lighting strikes and fault in the network. Some of the events such as harmonics may originate from customer's own installation due to the load temperament and impure the network.

Both power system reliability and power quality have a huge economic impact. There are huge production losses in consumer's industries. Process industry can be particularly vulnerable to problems with voltage sags and unbalance conditions because the equipments are interconnected with different controls, relays and adjustable speed drives where a trip of any component in the process can cause the whole plant to shut down [10]. The losses in process industries are also much higher because constituent materials may become irrecoverable scrap once the particular equipment or total industry trips during the production. Moreover, a process interruption for short duration (less than a minute) may cause a complete restart of the industry accruing to hours of production loss. Besides the total losses in industrial production, the equipment also experience damages and reduction in life expectancy [11].

Voltage sag may drop below the nominal voltage by 10 to 90 %, and its duration is 0.5 cycles to 1 min. Voltage drops below 90 % of nominal voltage for more than 1 min is known as under-voltage. Over-voltage occurs when nominal voltage rises above 110 % for more than 1 min. These over-voltage and under-voltage may occur and last for longer duration at the steady state of the system. These over-voltage and under-voltage at steady state are sometimes expressed as high steady-state voltage and low steady-state voltage. The major causes of steady-state voltage problems are overloading, inappropriate design, load switching and faulty regulating equipment. High steady-state voltages shrink the life of electronic devices and light bulbs. Alternatively, a low steady-state voltage reduces illumination levels, shirks the television pictures and causes slow heating of heating devices, motor starting problems and overheating in motors [12, 13].

1.4 Voltage Profile of Power System

1.4.1 Load Characteristics

Power system analysis involves relevant models of its components such as generation, transmission and distribution, and load devices. Knowledge of the load characteristics has a significant effect on loan modelling to analyse the load flow in the system. Consumer loads are categorized as follows.

Constant impedance load: Constant impedance load is a static load where the power varies with the square of the voltage magnitude. It can also be termed as constant admittance load.

Constant current load: Constant current load is a static load where the power varies directly with voltage magnitude.

Constant power load: Constant power load is a static load where the power does not vary with changes in voltage magnitude. It can also be termed as constant MVA load. Constant power load can be expressed as in Eq. (1.4).

$$P = P_0\left(\frac{V}{V_0}\right)^x, \ Q = Q_0\left(\frac{V}{V_0}\right)^y \tag{1.4}$$

where P_0 and Q_0 are the real and reactive powers at a reference voltage V_0. Similarly, P and Q are the real and reactive power at a reference V. The exponents x and y depend on the type of load, for example, for constant power load $x = y = 0$, for constant current load $x = y = 1$ and for constant impedance load $x = y = 2$.

Polynomial load: Polynomial load is a static load that represents the power–voltage relationship as a polynomial equation of voltage magnitude. It is made up of constant impedance, constant current and constant power loads. A polynomial power load can be shown as in Eqs. (1.5) and (1.6).

$$P = P_0\left[a_P\left(\frac{V}{V_0}\right)^2 + b_P\left(\frac{V}{V_0}\right) + c_P\right] \tag{1.5}$$

$$Q = Q_0\left[a_Q\left(\frac{V}{V_0}\right)^2 + b_Q\left(\frac{V}{V_0}\right) + c_Q\right] \tag{1.6}$$

where a_P b_P, c_P, a_Q b_Q, c_Q are fractional values such that $(a_P + b_P + c_P) = (a_Q + b_Q + c_Q) = 1$.

1.4.2 Power Transfer Through Radial Feeder

Transmission or feeder lines transferring the power have a voltage drop between sending end (source bus) and the receiving end (load bus) voltages. Determination of this voltage drop for a radial feeder, supplying power from a source point, is an easy solution, and it depends on phase angle, voltage dependency of static load and line parameters. If the V_S and V_L are the voltages of source and load buses their vector relations with voltage drop V_d and the load current I_L can be presented as in Fig. 1.3.

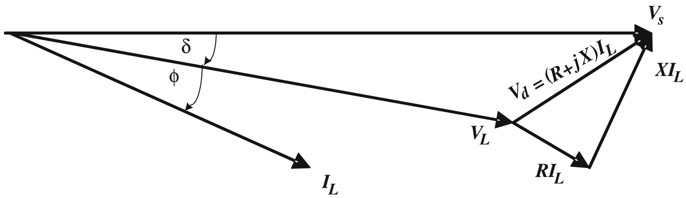

Fig. 1.3 Vector relations of the current and voltages in a radial feeder

where R and X are the equivalent resistance and reactance of the line, δ is the phase angle between V_S and V_L, and ϕ is the phase angle between voltage and current at load bus.

Consumer load phase angle ϕ may vary for the addition of load depending on its characteristic. For the increase of ϕ, the current will increase which reduces the V_L, and the decrease of ϕ will have opposite effects. In power system, Cos (ϕ) is known as the power factor (pf) of the load.

1.4.3 Power Transfer Between Active Sources

In a mesh transmission system, load flow is complicated. In that case, interconnecting buses can be the active source of synchronous system or generators. Power will flow from the bus which has the voltage that leads the voltage of the other bus. Figure 1.4 shows a simple diagram of the two synchronous buses where bus voltage V_1 leads the bus voltage V_2 by the power angle δ and V_2 presents the reference voltage. Considering the resistance of the transmission line is very low comparing to the reactance, it has been neglected to simplify the analysis. The phasor diagram of the voltages between bus 1 and bus 2 is presented in Fig. 1.5.

Voltage between bus 1 and bus 2 is

$$\mathrm{XI_2 sin}\phi + \mathrm{jXI_2}\cos\phi = V_1\angle\delta - V_2\angle 0. \tag{1.7}$$

Expressing all in phasor components

$$\mathrm{XI_2 sin}\phi + \mathrm{jXI_2}\cos\phi = V_1\cos\delta + \mathrm{j}V_1\sin\delta - V_2. \tag{1.8}$$

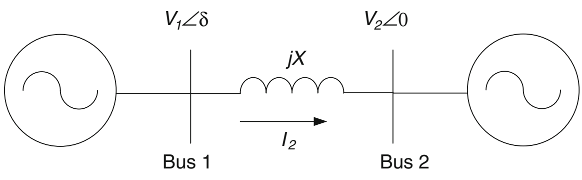

Fig. 1.4 Interconnection between two synchronous systems

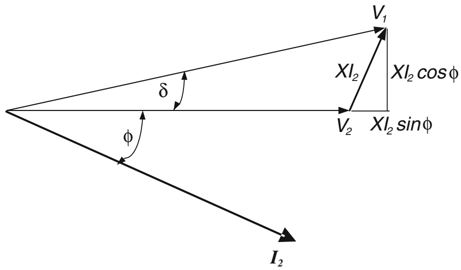

Fig. 1.5 Phasor diagram of the voltages between bus 1 and bus 2

Multiplying both sides by $-\mathrm{j}V_2/X$

$$V_2 I_2 \cos\phi - \mathrm{j}V_2 I_2 \sin\phi = \frac{V_2 V_1 \sin\delta - \mathrm{j}V_2(V_1\cos\delta - V_2)}{X}. \tag{1.9}$$

By equating the real and the reactive terms of Eq. (1.9), the real power P and reactive power Q can be expressed as

$$P = V_2 I_2 \cos\phi = \frac{V_2 V_1 \sin\delta}{X} \tag{1.10}$$

$$Q = V_2 I_2 \sin\phi = \frac{V_2(V_1\cos\delta - V_2)}{X}. \tag{1.11}$$

1.5 Power System Stability and Control

The modern society needs ever-increasing electric power to meet the industrial commercial and domestic demands. In order to meet this demand, the generation, transmission and distribution capacities are increasing very fast forming a gigantic, complex interconnected power system. The main issues of this vast system are the voltage regulation, stability, protection system to isolate the section under fault and hence ensure continuity of the supply system.

Power networks always experience random changes in load due to faults on the network, switching in or out a large load such as a steel mill or heavy industry, loss of lines or generating units. These changes can be considered as the shifts of the power system from one stable state condition to another. During the time of shifting between two stable states, the system undergoes dynamics of the transition during which generator may lose synchronism or oscillate and finally trips. There is also a possibility of tripping line circuit breaker causing a power loss. So, during any disturbance, the power, frequency and voltage changes need to be subsequently adjusted by the generators during and after the transition. For example, in case a generator trips, the other connected generators must be capable of sharing the load demand; or if a line is lost, the power it was carrying must be supplied through the alternate sources. Failure of balancing the power may lead to a catastrophe of cascade tripping of generators and sections of the lines resulting disintegration of power network. Many control devices response to adjust the voltage, frequency and load sharing by generators during transition time of power system disturbances. Distance relay used for the line protection in the transmission system has the power swing module that can pick up during the power swing between the generators and block the line tripping. In case generators are overloaded resulting in slowing down the speed, frequency relays using for load shedding can isolate some unimportant feeders and save the generators from cascade tripping. Generator exciters, voltage regulating mechanism and governor play the vital role in stabilizing the transition time problems.

1.5.1 Generator Excitation

Excitation of a generator controls the electromagnetic force (EMF) of the generator which sequentially controls output voltage, power factor and current magnitude. Figure 1.6 shows a synchronous generator with simple excitation system.

An initial excitation induces a generator internal voltage E_g and delivers a power P at load bus voltage V and current I at power factor (pf) cosϕ across a generator reactance X. The power for this excitation can be expressed as in Eqs. (1.12) and (1.13). When the excitation is increased while the input power/torque is kept the same by the governor and voltage (V) is maintained equal by other machines operating in parallel, the generator internal voltage, current, phase angle and power angle will be changed to new values as expressed in Eqs. (1.14) and (1.15).

$$P = \frac{E_g V \sin\delta}{X} \tag{1.12}$$

$$P = VI\cos\phi \tag{1.13}$$

$$P = \frac{E_{g1} V \sin\delta_1}{X} \tag{1.14}$$

$$P = VI_1\cos\phi_1. \tag{1.15}$$

The phasor diagram of the voltage, currents, phase and power angles for these two excitation conditions is shown in Fig. 1.7.

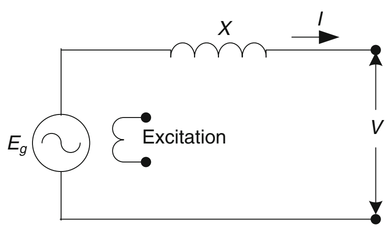

Fig. 1.6 Synchronous generators with simple excitation

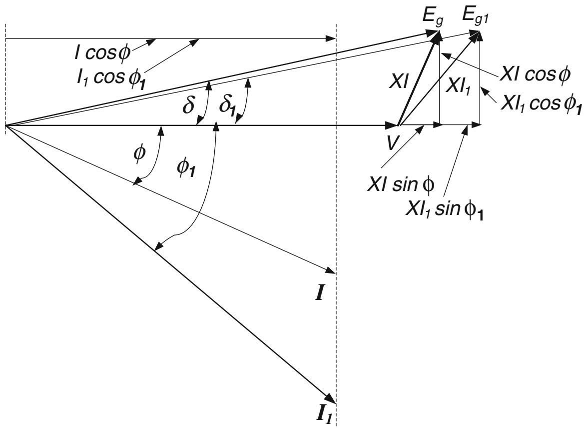

Fig. 1.7 Excitation for increasing voltage E_g with constant power and voltage

As observed in Fig. 1.7, due to the increase in excitation generator, internal voltage is increases to $E_{g1,}$ and power angle is decreased to δ_1 to maintain the constant power. Similarly, current is increase to I_1 and the phase angle is increased to ϕ_1 to maintain the constant power. The variations entirely satisfy the mathematical expressions in Eqs. (1.12) to (1.15). Since current and phase angle increase, the reactive power generation is also increases for the excitation rise as in (1.16).

$$VI_1 \sin\phi_1 > VI \sin\phi. \tag{1.16}$$

Similarly for constant power/torque by decreasing the excitation of the generator, reverse effects can be observed in the voltage, current, phase angle and the reactive power generation.

1.5.2 Excitation Control

The generator exciter can be a DC generator driven by the same shaft of the steam turbine that drives the main generator. There are other varieties of exciter consisting of rectifier or thyristor system receives power supply from the AC bus or alternator. Voltage regulating mechanism is used in generators to control the output of exciter to change the voltage and reactive power as per the requirement. This mechanism is known as voltage regulator. Figure 1.8 shows a block diagram of excitation system with voltage regulator.

The voltage regulator senses the generator output voltages (and sometimes the current) and then makes the move to correct excitation by changing the exciter control. Some excitation system has options for manual operation of voltage regulator. In that case, operator observes the terminal voltage and adjusts the regulator until the required output voltage is achieved. In modern technology,

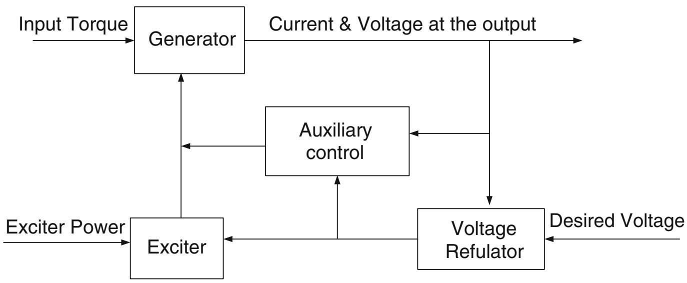

Fig. 1.8 Block diagram of generator excitation system with voltage regulator

manual system is not used unless necessary for any reason. The most important fact is that the speed of this voltage regulating system is of great interest for stability. Auxiliary control may have additional features as required for feedback of speed, frequency, acceleration, damping to prevent overshooting and many others [14]. Figure 1.9 shows two additional features: the damping transformer and the current compensator of the excitation system.

The damping transformer is an electrical dashpot device that damp out excessive action of the moving plunger. The current compensator controls the division of reactive power among generators when operate in parallel and utilize

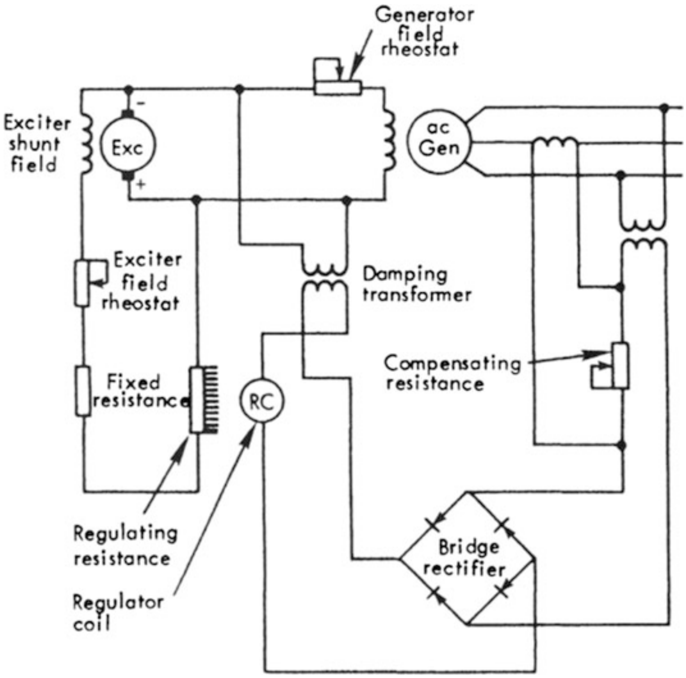

Fig. 1.9 Self-excited main exciter with Silverstat regulator (Engineers [15])

this kind of control. A voltage drop takes place in the potential circuit in relation to the line current for the current transformer and compensator resistance. The circuit connection is arranged in such a way that the voltage drop across the compensating resistance for lagging current adds to the voltage from the potential transformers. In this way, the regulator lowers the excitation voltage for the increase in lagging current (i.e. increase in reactive power output) and offers drooping characteristics so that the parallel operating generators equally share the reactive power load. There are more sophisticated excitation systems available in (Engineers [15], Chambers et al. [16], Barnes et al. [17], Report [18]) using in the growing large interconnected generators operating in parallel in the power system.

1.5.3 Governor System

Among the various prime movers, steam turbine prime mover is commonly used as maximum cases the energy is received in the form of heat that produce steam for generating massive electric power. Governor controls the amount of steam to be injected into the turbine for producing the requisite mechanical torque to the prime mover shaft. There are various types of governors. As an example, a flyball governor is shown Fig. 1.10. Two forces are acting on the flyball arms due to the shaft rotation: a centrifugal force on the masses and a downward force on the spring. The downward spring force is actually used to adjust prime mover speed by controlling the steam flow through a mechanical linkage that changes a shaft or collar position with the change of shaft speed.

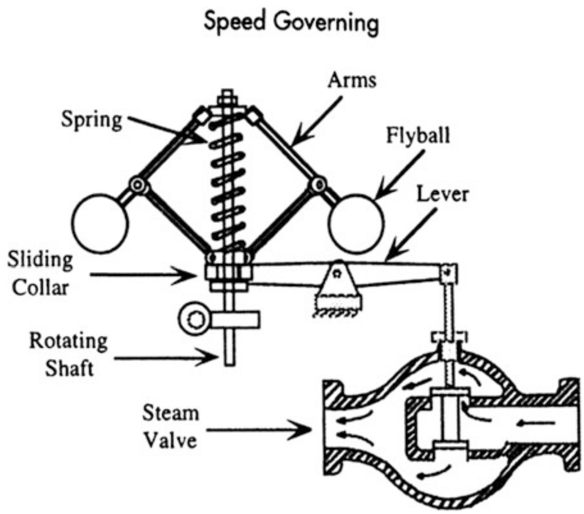

Fig. 1.10 Flyball governor

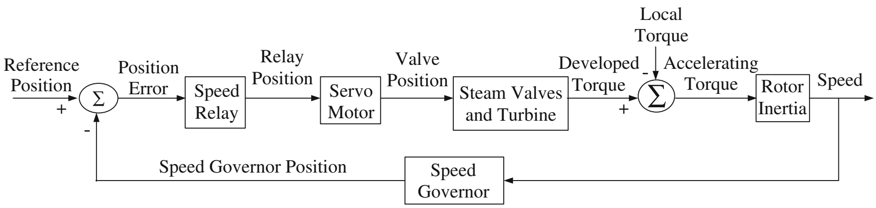

Fig. 1.11 Block diagram of steam turbine control system (Eggenberger [25])

Some steam turbine governing systems are made more efficient by using speed transducer, amplifiers comparators and force-stroke amplifiers. A block diagram of such a steam turbine control system is shown in Fig. 1.11.

The speed governor is a speed transducer which may be a mechanical, hydraulic or electrical device. It measures shaft speed and supply an output signal in any form such as position, pressure or voltage for comparison against the reference. The output of the transducer shown in the Fig. 1.11 is characteristically the position (stroke) of a rod that is proportional to the speed. The position error obtained from the comparison stroke and the preset reference position is proportional to speed. Speed relay and servomotor are used to amplify the position error and the force that controls the position error to regulate the steam and hence the torque.

By regulating the steam, the governor system on the whole changes the power at the generator output. Once the prime mover input as mechanical torque to the generator is increased, the real power (MW) at the generator output is increased. This results in the increase in the resistive component of the line current. The increased prime mover mechanical torque also increases the bus voltage and for constant power load, and this will results in decrease in the reactive power component as well as reactive component of line current and hence improve the power factor.

1.6 Protection System

Protective relays and devices are used in power system to protect electrical generators, transformers, lines and equipments against faults that may occur during normal system operation. The purpose is to quick isolation of the faulty part from the system so that remaining part can maintain the continuity of power supply. In that case, the relay operation should be selective and faster to trip the related circuit breaker. Appropriate design and operation of protection system prevent personnel injuries and damage to the equipments. It also minimizes power interruptions, effects of faults and fault-related disturbances on the system.

The following short circuit faults may occur in the system during operations causing abnormal current flow:

- phase to phase,
- three phase,
- phase to ground,
- phase to phase to ground,
- three phase to ground.

The magnitude of current depends on the impedance at the fault. If there is zero impedance at the fault, the current will be high, and for high impedance at the fault, the current will be small. The faulty section of the system is detected and isolated by the protection system. Fuses and miniature circuit breakers are used for lower voltage and small power supply in the distribution. In transmission and distribution, carrying bulk power (usually more than 1 MVA) relays are used to sense the abnormal current and initiate the circuit interrupting equipment such as circuit breaker through external control circuits or mechanically coupled mechanisms.

In distribution feeders, mostly over current and earth fault relays are used in protection system. These protections have instantaneous or time-delay characteristics. Time-delay relays can be co-ordinated with the downstream relays for correct isolation of the faulty section. For parallel feeders, directional over current and earth fault relays are used to correctly isolate the faulty feeder. Like feeder protection distribution transformers have similar over current and earth fault protection. Multiple transformers operating in parallel have reverse power relays to prevent power flow in reverse direction. Besides these over current and earth fault relays, transformers also have differential and restricted earth fault relays for selective and fast operation to isolate the faulty transformers. Differential and restricted earth fault protections are known as current balance protection which covers the zone between measuring points (HV side and LV side of transformers) of the currents that pass through the relays. These protections are sensitive for internal faults and stable for through faults (faults at outside the zone) as well as provide the high-speed operation to isolate the faulty section. Differential and time delays over current relays are also used for generator and busbar protections.

Transmission and sub-transmission lines and distribution feeders protections at voltages from 33 kV up to the highest transmission voltages are mostly made of distance relays which are operated based on the impedance of the line and the fault (if any).

The following are the main characteristics of distance relays:

- high speed (for zone 1),
- directional,
- discriminates through measuring impedance,
- time graded (zones 2 and above),
- self-contained.

The distance relay has the facility to measure the angle and the magnitude of the impedance to the fault by which it acquires the directional characteristics. The various directional impedance characteristics of the distance relays are given as follows:

- mho,
- quadrilateral,
- elliptical,
- offset mho,
- reactance.

These directional impedance characteristics are important in choosing relays for different transmission line and distribution feeder protections.

Distance relay protection scheme uses communication facility between two ends of the transmission lines for intertrip and protection signalling with various distance schemes such as trip acceleration, permissive under reach, permissive overreach, blocking scheme. This communication facility with the various distance schemes provides accurate and high-speed isolation of the faulty lines from the transmission network.

There is always some possibility of protection failure due to operation of the primary relays. Therefore, it is essential to add on backup protection besides the primary protection to ensure clearance of the fault from the system. In distribution system, the consequences of maloperation or failure to operate are less serious than in transmission systems. Hence, backup protection in distribution system can be simple and is often inherent in the main protection or watched over by the immediate upstream time graded primary relays. In transmission system (132 kV and above), where the interconnection is more complex, duplicate distance relays are used as backup protection to improve reliability. The backup and main protections should have different operating principle, so that abnormal events causing failure of the one have different influence on the other.

There are other relays which are used for special purposes such as loss of excitation for generators, under-voltage relay, over-voltage relay, power factor relay. More details about the protective relays and application are found in Blackburn [19], GeneralElectricCompany [20], Elmore [21].

1.7 SCADA System

Supervisory control and data acquisition (SCADA) system is an important infrastructure of electricity grids. Its main role in power system is to provide monitoring, control and automation functions that improve operational reliability supervisory control and data acquisition. In addition, the SCADA system is very useful for acquiring valuable knowledge and capabilities essential for the business function of utility companies in delivering power in a reliable and safe manner.

SCADA system has three essential components as given below:

- remote telemetry units (RTU),
- communications,
- human–machine interface (HMI).

The role of RTU is to collect information at a site. Communications transport that information from regional RTU sites to a central location and intermittently return commands to the RTU. The function of HMI is to display the information in graphics form, archive the receiving data, transmit alarms and allow operator control as necessary.

Communications within a plant are done by any of the following networking media:

- Ethernet cables (Cat5, Cat5e, Cat6, Cat6a),
- coaxial cable,
- token ring cables (Cat4),
- telecommunications cable (Cat2/telephone cord),
- optical fibre cable.

But radio is the most common use for communications in regional systems. The HMI is basically a PC system that runs powerful graphic and alarm software programs. Figure 1.12 shows a local area network (LAN) of substation, and Fig. 1.13 shows a SCADA system with interconnected LAN.

In this stage of technology, general-purpose computers (PC) have the capability for parallel computing and can run potential softwares that speed up problem solutions. Therefore, they can be used in computerized control system for the high-voltage and medium-voltage transformer substations. The LAN configuration shown in Fig. 1.6 can easily be housed in a substation control room.

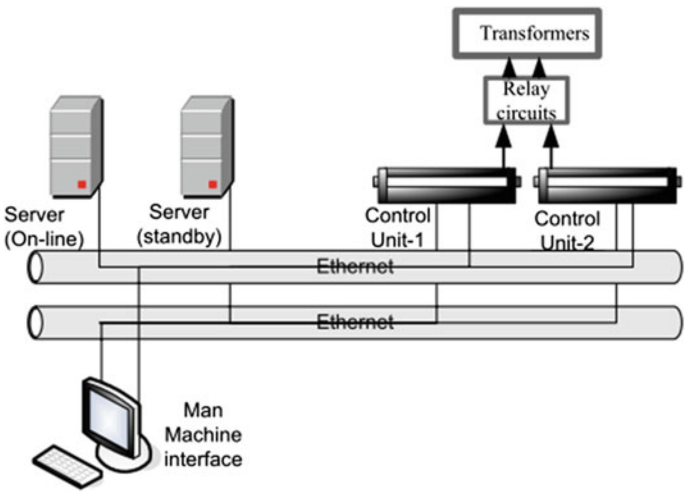

Fig. 1.12 Local area network in an electrical substation (Islam and Kamruzzaman [26])

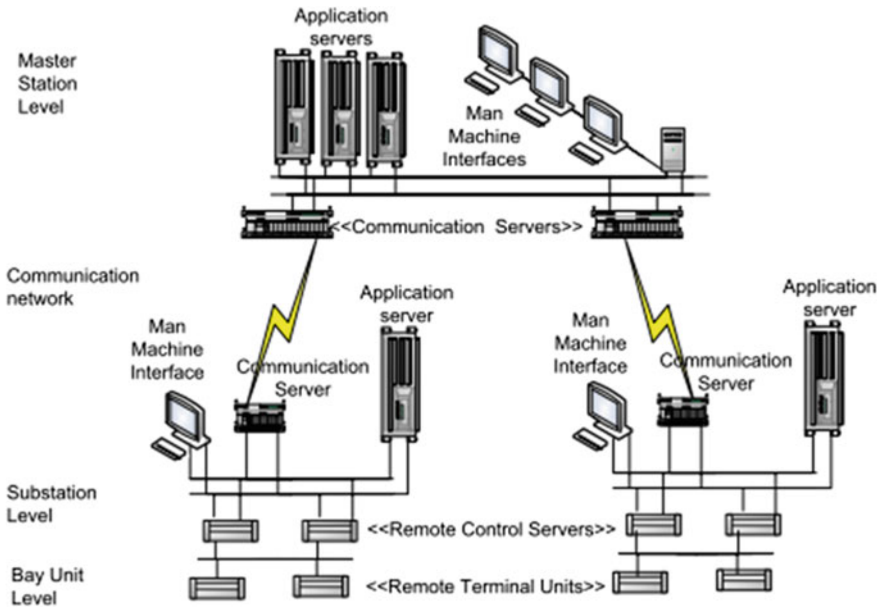

Fig. 1.13 SCADA systems with interconnected local area network (Islam and Kamruzzaman [26])

In the figures, servers (PC) that run controlling software modules are duplicated to secure the reliability of function. In the systems, one server is assigned for operating in online mode as the main control, while the other is kept in the fully operational mode for immediate take over (standby mode) as a backup control. The servers are similarly equipped with the breakdown monitoring and switchover control process. For multitask operating system, they are capable to function through Ethernet, RS485 communication interface and suitable communication protocol. SCADA system is built up with a number of servers such as application servers, communication servers and remote control servers [22–24]. The central or master station hardware architecture is built up to function at real time with the RTUs and servers distributed in different substations.

1.8 Conclusions

This chapter discussed the characteristics of the various components of a power system those are useful during normal operating conditions and during disturbances. The power system generation, transmission and distribution become very complex due to increase in the area of distribution as well as increase in power demand for rising population. Engineers have to solve enormous problem to maintain the quality and reliability of the power supply. SCADA system is the backbone of modern power system. This chapter therefore described the SCADA system along with the areas that manages the voltage, reactive power and frequency of the system during the disturbances. It will provide the engineers the ability to analyse the performance of the complex system. Their knowledge will help in operation, planning and design for future development more efficiently.

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