Chapter 1

INTRODUCTION- TRANSIENTS AND INSTABILITY

1.1 Systems and components

According to Dasgupta [99], a system is a collection of interacting objects or sub-systems, whose main purpose is to convert a quantitative input into a quantitative output according to some specific rule. The system may be mechanical, electrical, hydraulic, electronic or a combination of them. At present, a system is understood as a coordinated whole of individual units aimed at performing a specific function. It produces an output in response to an input which is generally guided by a set of differential/difference equations.

The present day systems are highly complex. Their close control is not manually possible. Therefore, systems or part of the systems are automatically controlled. All automatic control systems, directly or indirectly, employ feedback and/or feedforward for effecting automation [100]. A control system is a combination of elements and subsystems in which a quantity or a set of quantities are either kept constant or kept within close limits or made to vary according to a specified rule while inputs to the system may vary and the system may be swept by disturbances. The components of a system are tied up by the control laws so that it behaves as a coordinated and cohesive whole [101].

There are some control systems which are not fully automated. They are called semi-automatic. Again in some automated schemes, a human element may be a part of the system for man-machine interfacing.Automatic control systems are distinctly different from stabilizers which tend to keep a system stable under varying input or under disturbances. With reference to power system, the automatic voltage regulator (AVR) is an example of automatic control. The power system stabilizer, used to damp out swings, is an example of stabilizer [104].

1.2 Power system

An electric power system is a network of electrical components used to supply, transmit and use electric power. An example is the network that supplies a region's domestic and industrial consumers with power - this power system is known as the grid and can be broadly divided into the generators that supply the power, the transmission system that carries the power from the generating centers to the load centers and the distribution system that feeds the power to nearby homes and industries. Smaller power systems are also found in industry, hospitals, commercial buildings and homes. The majority of these systems rely upon three-phase AC power - the standard for large-scale power transmission and distribution across the modern world.

Application of 6-phase systems is there in rectifiers for getting smoother d.c. Specialised power systems, which uses single-phase, are found in aircraft, electric rail, ocean liners and automobiles [104].

1.3 Components of power system

The present day power system is a gigantic complex. It has many sub-systems and components viz. A brief outline of the sub-systems and components are outlined below:

1.3.1 Power stations

Bulk electric power is generated in power stations from which they are evacuated to consumer points by the transmission and distribution network interposed by transformers to regulate the operating voltage. The power stations are classified as: a) thermal b) hydel c) nuclear and d) non-conventional.

Fossil fuels are burnt for production of power in thermal power stations- coal or oil. Oil is used only in oil-rich country. Coal, mostly of low grade, is used at other places. The heat generated in the coal-fired furnace produces high parameter steam in a water-tube boiler. The stored energy of high pressure steam runs the steam turbine to produce mechanical power which is then converted to the electrical form by a synchronous generator of the cylindrical pole type [105].

The potential energy of water trapped at a relatively higher altitude, either from rainfall or from glacier drain, is utilized in a hydel power station to produce mechanical power by using water-turbines. The speed of such a turbine depends on the height and quantity of water in the catchment area. The type of turbine to be used also depend on the hydraulic variables (Pelton wheel for high, Francis turbine for medium and Kaplan/bulb for low). A salient pole synchronous generator is coupled to the turbine to produce electric power [106,107].

Nuclear power stations differ from thermal only in the type of mechanism to produce heat. In an NPP (Nuclear power Plant), heat is produced by controlled combustion of pre-processed nuclear fuel in the reactor. Normal Uranium (U_{238}) is used in our country along with pressurized heavy water for moderation except for the oldest station at Trombay, where enriched Uranium has to be used. Unit system is not generally used- the steam is produced in a single boiler run by a single reactor which is divided between the steam turbines. The control, instrumentation and protection schemes within an NPP are of paramount importance so that the reactor in the NPP may not turn super-critical and create potential hazards [105].

Both thermal and nuclear power stations are highly pollutant. Proper measures are to be taken to keep the pollution level within statutory limits. The hydel power stations are relatively environment-friendly [105].

The non-conventional energy sources include solar, wind, bio-mass and bio-gas, river current, ocean power, tidal power, fuel cells, MHD etc. They take relatively small share in the production of electricity in this country, chiefly due to their high installation cost and high per capita cost of generation, in spite of the fact that they are environment-friendly. However, they are coming up gradually to take a major role in the production of power as the fossil fuels are getting depleted. At present, particular interest has been focused on solar and wind power and power from bio-mass. Non-conventional sources produce variable power which poses difficulty in utilizing them properly. However, they can be connected to the grid system by properly controlling them to obviate this difficulty [108].

1.3.2 The generators

Isolated generators are not used now-a-days. Generally a no. of generators operates in parallel in any power station. Most of the generators used are of the synchronous type, either having cylindrical or salient pole construction. They are paralleled to each other by the process of synchronization.

The steam turbines tend to run at a very high speed. Even after power stage cascading (high pressure, intermediate pressure and low pressure stages), the speed can be kept at 3000 r.p.m., so as to produce electric power at commercial frequency of 50 Hz. with 2-pole generators. At this high speed, cylindrical pole generators are suitable and they are made use of in thermal power stations. The same type of generator is used in a nuclear power station [105].

The speed of a hydro-generator is much lower than 3000 r.p.m, whatever be the type. Hence, a multi-polar rotor is required to produce power at 50 Hz. Salient pole construction is suitable for this type of turbine. The generators used for tidal power, ocean power etc. are also of the salient pole type [106].

Induction type generators are often used for wind turbines. They may also be used as small power unit, provided their reactive power demand can be met from the grid or they are made self-excited by using capacitor banks [108].

The steady state behavior and the transients in an electric power system heavily depend on the mechanical features of the turbine and the type of generator used [104]. One of the pioneers who used digital computer for the solution of transients in the power system was H.W. Domell [78]

1.3.3 Transformers

Transformers are frequently interposed in a power system to step up or step down the voltage. For transmitting power over long distance economically, the operating voltage has to be stepped up. The most economic voltage depends on the bulk of power to be transmitted and the distance through which the power is to flow. At the receiving end the voltage has to be stepped down, generally in two stages, for making it convenient for use (for feeder lines at a higher voltage like 11Kv/6.6 Kv and for domestic at a lower voltage, 400/230V) [104,109,127].

Transformers are modeled as series impedance [11]. They affect the steady state load flow and transient phenomena in the power system due to their impedance. Transient phenomena are also associated with them while they are switched on or off. They run in parallel between the generator and the transformer bus, provided the generators have the same rated voltage.

Tap-changing transformers are used for adjusting the voltage. On-load tap-changers and phase-shifters are part of H.V. transmission system. Phase-shifters (also induction regulators) are used to bring about changes in the turns ratio and the phase angle both, so that scheduled power exchange can take place through the tie-lines [110]. Tie-lines are lines connecting different areas for scheduled exchange.

Auto-transformers are frequently used in power system to link two parts of the system the voltages of which do not differ much e.g. between 132 Kv and 220 Kv. at Kolaghat, between 220 KV and 400 Kv at Farakka etc. [138] An autotransformer is relatively cheap and has lower leakage reactance. Hence its voltage regulation is better [109].

1.3.4 Transmission lines operating at high and extra high voltage

Transmission systems are classified as overhead and underground. Overhead transmission is cheaper and is commonly used if there be no physical constraints in their erection and commissioning [104]. All a.c. transmission systems are of 3-phase, the no. of circuits being one or more. 6-phase transmission-systems have been proposed by some authors, for greater economy but such systems have not come up for their complexity.

The O/H transmission lines are again classified as: short, medium and long. The distinction is not very sharp. There are four parameters in a transmission line- the resistance and the inductance in series and the capacitance and the leakance in shunt. If the shunt parameters are small and negligible, the line can be approximated as a series-impedance only. This renders the solution quite easy and is possible only with short lines. The parameters are distributed by nature. If there be no appreciable error in lumping them either at the center or at the terminals (nominal-T or nominal-π approach), the transmission line is called medium. For long lines, the lumped parameter approximation is not tenable. The I/O relations are framed taking distribution effect into consideration, which yields equations containing hypergeometric functions. To ease out the calculations, the line is represented by equivalent-T or equivalent-π.

In long transmission lines, the VAR absorbed by the series inductance is generally less than the VAR generated by the shunt capacitance. So there is a net generation of VAR. This is beneficial during peak hours but may pose difficulty during the lean hours due to VAR-IN phenomena, giving rise to Ferranti effect.

The VAR generation and Ferranti effect is much greater in cable transmission as cables are much more capacitive than transmission lines. But at places, cables have to be used, e.g. for crossing the English channel (between U.K. and France), for crossing the Pawk strait (between India and Srilanka). In such cases, high voltage d.c. transmission is preferred, to avoid high receiving end voltage due to Ferranti effect [76,98].

The operating voltages of transmission lines in India are: 132 Kv, 220 Kv, 400 Kv and 800Kv. There are also some lines operating at 66 KV (in North Bengal). As yet, 800 Kv lines have not appeared in this part of the country, but there is extensive networking between 400Kv, 220 Kv and 132 Kv sub-systems in the eastern regional grid [138].

1.3.5 The grid system and the regions

The Indian power system is divided into five regions- the Northern, Western, Southern, Eastern and the North-Eastern. The Western region caters the largest bulk of power, the northern, southern and the eastern also handles bulk power, but the power handles by the north-eastern is relatively less as this part of the country is economically and technically less developed. A national power grid covering all the region is in the offing. At present, some of the regions are synchronously coupled to increase the total inertia and enhance the reliability. There are also asynchronous (HVDC) links between the regions for scheduled transfer of power [98].

The eastern regional power grid, to which West Bengal belongs, developed gradually with increasing interconnections between its statutory members like BSEB (now BSEB & JSEB), WBSEB & OSEB (now restructured for economic reasons), DVC, DPL, NTPC & NHPC etc. and CESC, deemed to be a member. These utilities are individually controlled by their individual load dispatch centers and collectively by the regional load dispatch center (RLDC), housed at Golf green of Kolkata. The WBSETCL & WBSEDCL, restructured components of WBSEB looking after transmission and distribution, are controlled by the state load dispatch center (SLDC) housed near *Botanical Garden* of Howrah and another at Siliguri, for the North Bengal part. DVC has its LDC at Maithon and CESC at Victoria House. NTPC and NHPC are not utilities themselves- they only cater bulk power to the utilities under EREB, in accordance with the predefined share of each member [138].

1.3.6 Electric utility

An electric utility is a company, mostly public utility, that engages itself in the generation, transmission, and distribution of electricity for sale generally in a regulated market. These are major provider of energy in most countries. It is indispensable to factories, commercial and residential establishments, even to recreational facilities. Lack of electricity causes not only inconvenience, but also economic loss due to reduced industrial production.Therefore, reliable and flawless operation of electric utilities is required for national prosperity.

Electric utilities include investor owned, publicly owned, cooperatives, and nationalized entities. They may be engaged in all or only some aspects of the industry. Electricity marketsare also considered electric utilities--these entities buy and sell electricity, acting as brokers, but usually do not own or operate generation, transmission, or distribution facilities. Utilities are regulated by local and national authorities.

Utility service territories are typically geographically distinct from one another. These territories may be set by regulation or by economics as the capital cost of reproducing infrastructure is usually prohibitive. Each territory is composed of different types of consumers, usually broadly described as commercial, residential or industrial.

WBSEDCL, CESC Ltd. etc. are public utilities- they cater power to everyone in the locality through which its distribution lines run. There are some utilities which cater power to selected consumers e.g. DVC, Dishergarh Power Supply Co (to industrialists only, not domestic consumers) [138].

1.3.7 Distribution lines to feed the bulk and retail consumers

Distribution of electric energy is generally made in two stages- by feeders and distributors. The feeders operate at a relatively high voltage (11 Kv being quite common, 33 Kv at some places) and cater to the bulk consumers e.g. to Kesoram Cotton Mills from BTPS. The feeders may be O/H or U/G. U/G cables are used at densely populated urban places. The rating of the feeder is chosen with a look to the maximum demand and futuristic trends.

The distributors run through the roads and streets and supply power to the retail consumers- domestic, shops and establishments, and small and micro-industries. The commonly used voltage is 400/230 V a.c. The process of stepping down the voltage from 11Kv is made by distribution transformers placed at H-pole substations or specially constructed platforms. Cable distribution has to be used in urban places. It is not only expensive but may create problem due to capacitive effect at lean hours.

The distribution may be radial or in mesh. Mesh-type is more reliable but it is expensive. Hence, the use of radial distribution is quite common.

1.4 VAR-Compensators- active or passive

Flow of active power over long distance does not pose any substantive problem to the operators but the flow of reactive power has to be restrained due to the following reasons:

a) The flow of inductive reactive power causes much larger voltage drop than that of active power and tends to increase the voltage regulation.

b) The flow of inductive reactive power causes reactive power losses (I^2X_L), which has to be generated either by the alternators or by capacitance, internal or external.
c) The flow of capacitive reactive power causes voltage rise at the receiving end, particularly while the load is small. The voltage may become dangerously high for the load end equipment.
d) The flow of reactive power increases the total current and hence the active power losses, reducing the efficiency of transmission.

Therefore, reactive power flow over transmission lines has to be dynamically regulated.

The regulation is made by the use of VAR-compensators. The VAR-compensators may be inductive or capacitive, active or passive [74].

1.5 Instrumentation panels

All modern power stations are equipped with control and instrumentation schemes. The instrumentation schemes have gone through ages of evolution, gradually leading to more and more automation.

Instrumentation is a branch of engineering that deals with measurement and control. According to ISA (Instrument Society of America), the official definition of Instrumentation - is a collection of Instruments and their application for the purpose of observation, measurement and control.

An instrument is a device that measures or manipulates variables such as flow, temperature, level, or pressure. Instruments include many varied contrivances which can be as simple as valves and transmitters, and as complex as analyzers. Instruments often comprise control systems of varied processes. The control of processes is one of the main branches of applied instrumentation.

Control instrumentation includes devices such as solenoids, valves, circuit breakers, and relays. These devices are able to change a field parameter, and provide remote or automated control capabilities. Transducers are used to produce electrical signals proportional to non-electrical signals. They occupy key role in instrumentation practice and are used to control other instruments directly, or they can be sent to a PLC, DCS, SCADA system, or other type of computerized controller. They are interpreted into readable values and are used to control other devices and processes in the system. Instrumentation plays a significant role in both gathering information from the field and changing the field parameters, and as such are a key part of control loops.

Instrumentation engineering specially focuses on automated systems in electrical, mechanical, thermal, pneumatic domains etc. They are used in industries with automated processes, such as chemical or manufacturing or power producing plants, with the goal of improving system productivity, reliability, safety, optimization and stability. To control the parameters, in a process or in a particular system, microprocessors, micro-controllers, and programmable logic controllers (PLCs) etc. are used, but their ultimate aim is to control the parameters of a system.

1.6 Control system

A control system is a device or set of devices to manage, command, direct or regulate the behavior of other devices or systems [100,101].There are two common classes of control systems- logic or sequential controls, and feedback controls. There is also fuzzy logic, which attempts to combine some of the design simplicity of logic with the utility of linear control. Some devices or systems are inherently not controllable.

1.6.1 Overview of control system

A control system may be manual or automatic control. Manual control is inaccurate, slow and sluggish and depends heavily on the attention of the operator. On the other hand, automatic control systems are fast-acting reliable and needs little human attention. The operation of an automatic control system depends on the principle of negative feedback. The feedback systems may be linear or non-linear, continuous or discrete, SISO OR MIMO. In any case the stability of the system is to be checked carefully and the performance should be optimized. Power systems are non-linear MIMO systems [104].

Another class of control has recently emerged viz. the intelligent control. It includes neural network, fuzzy control, genetic algorithm etc or a synergy of them. They become highly effective for specific cases. The various tools and techniques of intelligent control are finding application in power systems. Other types of control in common use are the logic control and the on–off control [99,100].

There are three control loops in a thermal power plant- the boiler-firing control, the turbine-governor control and the AVR-excitation control. In addition, power system stabilisers (PSS) are used to damp out system oscillations [32]. The control loop may use feedback, feedforward or a combination of them using a minor loop. The signals may be proportional, derivative, integral or a combination of them (PID).

1.6.2 Physical implementation

Physical implementation was done in the earlier days by using discrete elements-electrical, electronic, mechanical and hydraulic. Such elements are used still now, but generally the complex control task is carried out by a microprocessor or microcontroller [103]. Since modern small microcontrollers are so cheap, it's very common to implement control systems, including feedback loops, with computers, often in an embedded system. The feedback controls are simulated by having the computer make periodic measurements and then calculating from this stream of measurements.

Computers emulate logic devices by making measurements of switch inputs, calculating a logic function from these measurements and then sending the results out to electronically-controlled switches. Logic systems and feedback controllers are usually implemented with programmable logic controllers which are devices available from electrical supply houses. They include a little computer and a simplified system for programming. Most often they are programmed with personal computers. Logic controllers have also been constructed from relays, hydraulic and pneumatic devices, and electronic devices like transistors [102].

1.6.3 Optimal, adaptive and robust control

For optimizing the control, various methods are adopted. Much work has been done in this area by eminent mathematicians and engineers. Optimal control theory, a modern extension of the calculus of variations, is a mathematical optimization method for deriving control policies. The method is largely due to the work of Lev Pontryagin and his collaborators in the Soviet Union and Richard Bellman in the United States. There are many other classes of control systems in common use. Adaptive control is one amongst them. It is used for such applications where the variables of the system undergo random variations. Robust control is another. It is used where some of the parameters may undergo rapid and unprecedented changes. An expert system is a class of computer programs developed on the basis of artificial intelligence. They are programs made up of a set of rules that analyze information (usually supplied by the user of the system) about a specific class of problems, as well as provide analysis of the problem(s), and, depending upon their design, recommend a course of user action in order to implement corrections. These modern schemes are gradually coming up in power system control [100,101].

The control and instrumentation schemes are clubbed together with protection. The related equipments are housed in the control room. Unit systems are used in a power house for greater flexibility and reliability. There is a control room for each turbo-generator unit. Telemetering systems are used to receive the signals. Now-a-days more advanced SCADA-systems are being used almost everywhere[102]. These are potentially good means of power system control.

1.7 Protection schemes

The protection schemes adopted for a power system is of paramount importance. Often, it is clubbed together with the control and instrumentation schemes. The scheme deals with the protection of electrical power systems from faults by isolating the faulted parts from the rest of the electrical network. The objective is to keep the power system in healthy condition by isolating only the faulty parts, keeping rest of the network in operation. The protection schemes must respond very quickly, clear the fault within a few cycles to pass and be very reliable. For important applications, back up protection must be provided [119].

1.7.1 Components

Protection systems usually comprise of these components:

- Current and voltage transformers to step down the high voltages and currents to convenient levels for the relays to deal with.
- Protective relays to sense the fault and initiate a trip, or disconnection.
- Circuit breakers to open/close the system based on relay and auto-recloser commands
- Batteries to provide power in case of power disconnection in the system
- Communication channels for sensing current and voltage at remote terminals of a line and to allow remote tripping of equipment
- Buses and bus-couplers
- Isolators
- Lightning/surge arresters

1.7.2 Classes of protective devices

For a distribution system, HRC fuses may be enough for sensing and disconnecting the faults.Now-a-days the use of MCB has become quite common. A disconnection may be initiated due to insulation failure, fallen or broken transmission lines, incorrect operation of circuit breakers, short circuits and open circuits. The protective devices are installed for protection of the costly equipment and to ensure continued supply of energy. The three classes of protective devices are:

- Protective relaycontrol for tripping the circuit breakers on occurrence of a fault in the network
- Automatic operation, such as auto-reclosing or system restart
- Monitoring equipment which collects data on the system for post event analysis

While the operating quality of these devices, and especially of the protective relays, is always critical, different strategies are considered for protecting the different parts of the system. Very important equipment may have completely redundant and independent protective systems, while a minor branch distribution line may have very simple low-cost protection.

1.7.3 Types of protection

a) *Generator-transformer sets* – This protection is intended to prevent damage to alternators or the transformers in case of any abnormality either due to internal failures, or a failure in insulation or any kind of malfunctions. Such failures do not usually occur, so the protective relays have to operate rarely. If a protective relay fails to detect a fault, the damage to the alternator or to the transformer incurs financial losses due to repair or replacement of equipment and due to reduction in sale of energy units.

b) *High voltage transmission network* – Protection on the transmission and distribution serves two functions: Protection of plant and protection of the public (including employees). At a basic level protection looks to disconnect equipment which experience an overload or a connection to earth. Some items in substations such as transformers may require additional protection based on temperature or gassing among others.

c) *Overload* – Overload protection requires a current transformer which simply measures the current in a circuit. If this current exceeds a pre-determined level, a circuit breaker or fuse should operate.

d) *Earth fault* – Earth fault protection again requires current transformers and senses an imbalance in a three-phase circuit. Normally a three-phase circuit is in balance, so if a single (or multiple) phases are connected to earth an imbalance in current is detected. If this imbalance exceeds a pre-determined value a circuit breaker should operate.

e) *Distance* – Distance protection detects both voltage and current. A fault on a circuit will generally create a sag in the voltage level. If this voltage falls below a pre-determined level and the current is above a certain level the circuit breaker should operate. This is useful on long lines where if a fault was experienced at the end of the line the impedance of the line itself may inhibit the rise in current. Since avoltage sag is required to trigger the protection the current level can actually be set below the normal load on the line.

f) *Back-up* – At all times the objective of protection is to remove only the affected portion of plant and nothing else. Sometimes this does not occur for various reasons which can include:

- Mechanical failure of a circuit breaker to operate
- Incorrect protection setting
- Relay failures

A failure of primary protection will usually result in the operation of back-up protection which will generally remove both the affected and unaffected items of plant to remove the fault [119,88].

g) *Low-voltage networks* – The low voltage network generally relies upon fuses or low-voltage circuit breakers to remove both overload and earth faults [21].

1.7.4 SCADA protection

SCADA stands for Supervisory Control and Data Acquisition- it is used extensively in power systems to control and monitor the process of power production. SCADA is a complex system which spreads out over large areas - the system automatically performs by remote terminal units RTUs or PLCs programmable logic controllers. The state load dispatch center and regional load dispatch centers of West Bengal are SCADA-controlled [138].

1.7.5 Coordination

Protective device coordination is the process of determining the "best fit" timing of current interruption when abnormal electrical conditions occur. The goal is to minimize an outage to the greatest extent possible. Historically, protective device coordination was done on translucent log-log paper. Modern methods normally include detailed computer based analysis and reporting [119,88].

1.7.6 Disturbance monitoring equipment (DME)

Disturbance monitoring equipment (DME) monitors and records system data pertaining to afault. DME accomplish three main purposes [119]:

1) Model validation

2) Disturbance investigation, and

3) Assessment of system protection performance.

DME devices include:

- Sequence of event recorders, which record equipment response to the event
- Fault recorders, which record actual waveform data of the system primary voltages and currents.
- Dynamic Disturbance Recorders (DDRs), which record incidents that portray power system behavior during dynamic events such as low frequency (0.1 Hz – 3 Hz) oscillations and abnormal frequency or voltage excursions

1.8 Steady state and transient

The behavior of a system under slow changes, as is characteristic of a system, is called steady state. Steady state does not mean constancy. It is a state of gradual changes. On the contrary, the transient phenomena are associated with abrupt or sudden changes. The transients become dominant in presence of energy-storing elements. They persist for a long time if the time constants are large.

If the transients die down with time, and the system restores its steady state, the system is called stable. If the transients gradually grow in amplitude and eventually pulls down the generator from synchronously operating condition, the system is called unstable [5].

A system may be linear or non-linear. About all power system problems are non-linear. Only under small perturbations, the deviation from the quiescent point is small and the system may be linearized about this point.

1.9 Linear and non-linear system

A system is called linear,if it obeys the principle of superposition. Mathematically, a linear system obeys the following relations:

$$f(kx) = kf(x)\,; \qquad f(x_1 + x_2) = f(x_1) + f(x_2) \qquad 1.1$$

Linear systems have two basic properties viz[99].

i) *homogeneity*- the inputs multiplied by *k*, yield outputs multiplied by *k*

ii) *additivity*- the output in response to a no. of inputs equals the sum of outputs due to those inputs applied individually.

A departure from these conditions gives rise to non-linearity. The power system transients are basically non-linear by nature. Non-linearity arises in transients due to the presence of product terms and trigonometric relations in the describing equations e.g. in the swing equation. The transient stability and the voltage stability problems are non-linear

If the degree of non-linearity as well as the deviation from the operating point is small, the system may be approximated as linear. This approximation is advantageous as the powerful tools of linear system analysis can be applied to it. This technique is applied in small signal stability analysis, also known as dynamic stability.

There are two general approaches to linear control system representation viz. the transfer function approach and the state variable approach. The analysis can be made either in the time domain or in the frequency domain.

The power system transients are non-linear by nature.There is no general method to solve them. The describing equations of the transient are solved using various numerical methods. Some graphical methods are also used e.g. the equal area criterion or the phase plane method. The equal area criterion was used in the earlier days. The phase plane method can be conveniently used only if the no of states is limited to two.

1.10 Power system transients

The system load varies with hours of the day between evening peak and night lean. This variation is gradual and comes under the purview of steady state analysis. A sudden loading or a sudden loss of load, a sudden loss of generation, tripping of CB and its reclosure on clearance of fault etc. comes under the purview of transient phenomena [44,104].

The transients may be electromechanical or electromagnetic. The electro mechanical transients are created by the mismatch of power between mechanical and electrical ports. The power differential created by a sudden change causes either acceleration ($P_m > P_e$) or deceleration ($P_m < P_e$), thereby creating a swing in speed and power angle under the influence of synchronizing force. This phenomenon is guided by constancy of speed before and after a sudden change due to inertia. The nature of electromagnetic transients is guided by constancy of magnetic flux before and after a sudden change (constant flux-linkage theorem of Doherty). An example is the transient current of a synchronous generator or a transformer on sudden short-circuit [104, 132].

These are not isolated phenomena- a sudden short-circuit followed by CB-operation also creates electro mechanical transients. In addition, there are slower transients in power system e.g. thermal transients in a boiler which do not appreciably affect the electric transients. Therefore they are separately treated.

1.11 The concept of stability

The term stability means the ability of synchronous machines operating in parallel to retain synchronism between each other [32,33]. The stability problem is categorised as:

a) Steady state stability problem.
b) Transient stability problem.

Steady state stability can again be divided into static stability and dynamic stability. While changes are very slow and in absence of control actions, the stability is called static. The dynamic stability problem is, in essence, the performance of a turbine-generator connected to grid system under small impacts, in presence of fast acting control systems. viz. the AVR-excitation control. The small impact may be a small change in load, or in voltage or in network parameters.

The transient stability limit is lower than the steady state stability limit. The loading and the power factor have to be controlled to keep the operating point well within the capability curve of the generator such that there is a good stability margin (angle margin). The transient stability limit can be enhanced by the action of automatic voltage regulator and the excitation control schemes. The excitation control pulls back the generator to stable zone even from a power angle as high as $(130\text{-}135)^0$. This is highly beneficial from the point of view of transient stability but the fast-acting excitation control may give rise to growing oscillations which may eventually cause dynamic instability. Therefore, the parameters of the excitation control must be properly tuned [32,33,132]. Assessment of stability is made by matrix analysis on the basis of mathematical modeling of the power system elements [112,113].

Another kind of instability occurs due to mismatch in reactive power flow- this is voltage instability. If uncontrolled, this phenomenon may also be detrimental for the power system. It may cause severe voltage swings eventually leading to voltage collapse and cascaded failure [63,64].

1.12 Transient over-voltages

Switching phenomena or lightning stroke creates transient overvoltage in utilities by capacitor or other. Some of the power electronic devices also generate significant amount of transients when they are switched on or off. The frequency is high during load switching and lightning. Such switching phenomena create high frequency oscillation in system voltage. The frequency of oscillation is medium or low while capacitors are energized. The frequency depends on the inductive counterpart [115,116].

1.12.1 Capacitor switching

Capacitor switching is very common in utilities. Capacitors are used for various reasons in a power system viz. to improve the power factor by partly cancelling out the reactive VAR drawn by the load, to reduce the line current and hence the line loss and to improve the voltage regulation. They are also used for series compensation of a long line with a look to enhance the power handling capability. These devices are economical and trouble-free. The use of rotating machines and switchable static VAR compensators, is a costlier alternative having higher maintenance cost. Hence, the use of capacitors in power systems is quite common [84].

The only drawback of capacitors is the oscillatory transients due to switching. This problem is posed by switchable bank switch takes care of the variation in load, not the fixed banks. The switching control is exercised by sensing time, temperature, voltage, current, or reactive power. Commonly a no of these variables are combined together for higher efficacy.

The power quality problems related to capacitor switching overvoltage occur at nearly the same time each day. In feeder distribution (to cater industrial loads), capacitors are frequently switched at a particular time in anticipation of a load increment (during the approach of peak hours). It may force adjustable-speed-drives to trip and/or cause malfunctioning of other electronically controlled load equipment.

The insulation across the contacts of the switch tends to break down while the voltage across the capacitor is zero and as such the voltage across the switch is at its maximum value. The capacitor is a storage element. The voltage across it cannot change instantaneously- it falls to zero during discharging and rebuilds during charging. As the source is basically inductive, there is an overshoot in the capacitor voltage which rings at natural frequency of the system. The overshoot generates a transient between 1.0 and 2.0 p.u. depending on system damping[104,89].

If there be capacitors in the secondary, the voltage may get magnified on the load side and give rise to brief transients up to 2.0 pu. These are not generally very harmful to the system insulation, but may cause malfunctioning of electronic power converters. The high voltage may be interpreted as a sign of impending danger and the load disconnected for safety. The transient may also interfere with the gating of SCRs.

1.13 Power system quality

The term power system quality is of recent origin but the idea is of long past. Even in earlier days of electric power distribution, the utilities were compelled to follow the statutory regulations in respect of supply voltage and supply frequency. The new generation of loads with μ-P control and power electronic devices like SCRs and IGBTs are highly sensitive to the quality of power. The level of harmonics is also increasing day-by-day due to increased use of adjustable-speed drives and capacitors for p.f. improvement. The consumers are also very much aware of the quality of power and are pressurizing the utilities to improve the quality of power. Moreover, the processes are integrated with one another- failure of a component results in low productivity and poor economic efficiency [117,118].

Deregulation has made the utilities more cost-competitive. Consequently this has given rise to power quality problem. Also distributed generation (i.e. generation throughout the entire system) has given rise to a no of power quality problems. For all these reasons benchmarks have been developed for power quality assessment all over the world. India is also not an exception to this.

Power quality is a consumer-related issue. Any deviation in voltage, current or frequency that causes failure or malfunctioning of sophisticated equipment is a power quality problem [118].

1.14Power system reliability

The reliability of power system is an important issue in this age of rapid industrial progress and urbanization. Electrical energy is the only form of energy that is most suited for catering the power need of consumers- bulk or retail. The ever-increasing power need of the people has given rise to large scale expansion of power industry and transmission network. This gigantic complex must act reliably to sustain the modern civilization [133].

A system is 100% reliable if no failure occurs. But failures are unavoidable. The frequency of failure is an index of reliability. The failures may be: a) early failure b) wear out or fatigue failure or c) chance failure. Early failures occur due to the use of sub-standard components or improper design. This was the case in the early years of Santaldihi TPS. Later on it could be made reliable to some extent by changing the components and modifying the design. The procedure to avoid early failure is by trial runs, known as debugging, before the actual operation starts. Fatigue failure can be reduced by periodic maintenance schedule- both preventive and curative. Chance failures are of stochastic nature, they occur after debugging and before the wear out takes place. Reliability engineering deals with this type of failures. Though failures cannot be accurately predicted, the probability of their occurrence can be found out. The frequency of failure is least during the useful period. It is more during the trial run and after wear out.

The generators switch over to down state from the up state due to fault and subsequent operation of the breakers. They re-enter into the up state after removal of the fault, possibly after some repair work. The mean time between two such failures (MTBF), denoted as m, is an index of reliability. It indicates the expected trouble-free operating period between two failures. The reciprocal of m, is the mean failure rate, given as:

$$\lambda = \frac{No\ of\ failures}{Sum\ of\ operating\ periods} \qquad 1.2$$

The mean down time is given as

$$r = \frac{Total\ down - time}{Total\ no\ of\ down - states} \qquad 1.3$$

The reciprocal of ‘r’ is μ= the mean repair rate.

The reliability of a unit is the probability of its remaining in the up-state and is given as:

$$R = p_{up} = \frac{m}{m+r} = \frac{m}{T}$$, where T = mean period of the cycle. 1.4

The unreliability is obviously given as:

$$Q = p_{down} = \frac{r}{m+r} = \frac{r}{T}$$ 1.5

In terms of the reciprocals these are given as:

$$R = \frac{\mu}{\lambda + \mu}; Q = 1 - R$$ 1.6

These quantities can be found out by making a large no of observations followed by statistical analysis. The probability of failure of a unit at a certain time is found out from the following expression:

$$p_{down}(t) = \frac{\lambda}{\lambda + \mu} e^{-(\lambda+\mu)t}$$ 1.7

These general expressions for reliability can be extended for systems with multiple units by combining the probability functions.

If there be sufficient generating capacity such that the entire demand can be fully met in spite of outages, then outages are of no concern for the utilities. But, in reality, this is not the case. There is always a gap between the demand and the supply of electricity, such that there is no reserve. Load-shedding has to be made during the peak hours even if all peaking units are available for generation.

Also, the demand for electricity is steadily rising with the growth in industrialization and urbanization. At the same time the machines are undergoing derating with passing of time and continuous usage of the machines. This is widening the gap between generation and demand every year. A power-surplus state in one decade may become a power-deficit state in the next decade if no capacity augmentation is made. The older machines are also less reliable. Therefore, there is a probability of outage. The probability of outage of units gives rise to the probability of further load-shedding or loss of load. The LOLP is computed for planning the operation of a power system, such that the loss of load is minimum possible.

This is an optimality problem that can be dealt with by the methods described in references [107].

1.15Scope and outline of the thesis

The thesis covers the following areas viz.

a) Computer-based analysis of steady state and transient conditions in a high voltage unit or in a system comprising of several units. The transients are both electromechanical and electromagnetic by nature.
b) Optimal design of high voltage (HV) systems e.g. medium and long transmission line, VAR-compensators- capacitive and inductive etc.
c) Analysis of dynamic instability and performance of a system under sudden loss of excitation.
d) Analysis of asynchronous conditions arising out of sudden field failure
e) Voltage instability under reactive power mismatch
f) Performance analysis of HVDC-links.

Specially constructed programs, as well as MATLAB-tools have been used for the analysis. The analysis of short transmission line is simple. These are represented as series impedances, neglecting the small capacitive effects. Normally, the generators connected to grid through short lines are approximated as one machine on infinite bus. This part of the analysis has been clubbed together with that for dynamic stability. The steady state and transient analysis of medium and long transmission lines have been taken up in part-I.

1.16 Contents of the chapters

The thesis is divided into ten chapters followed by conclusion, annexure, reference and bibliography. The contents of the chapters are given below:

Chapter-1

This chapter gives an introduction to the work and highlights the thrust areas. It gives the theories and concepts behind subsequent chapters. Starting with an introduction to systems and components, vivid description on various elements and aspects of power system have been given covering power stations, generators, transformers, EHV transmission lines and grid systems, utilities, distribution lines, VAR-compensators, protection, control and instrument panels. Then the stability phenomena in interconnected power systems have been discussed followed by a brief review of power system quality and reliability. At the end of the chapter the contents of the chapter have been given.

Chapter-2

This chapter deals with high voltage transient analysis. Starting from the definitions and analysis of basic circuits, it has gradually emerged into MATLAB simulations for various types of circuits, linear and non-linear, with a look to find out the transient response. Initially, it has dealt with transient restriking and recovery voltage of linear systems. In the next stage, transient analysis of non-linear circuits has been made, in which a saturable reactor is the source of non-linearity. The data generated and graphical plots have been given. Then FFT analysis of the non-linear circuit has been made which has been extended to cover the snubber circuits. With a brief introduction to surge protection, analysis of non-linear circuits using surge protection has been taken up. Starting from the basic dynamical equations of the long transmission lines, analysis has been made for transient recovery voltage for HV circuit-breakers. Then analysis of the system using series compensation (to increase power transfer capability) has been taken up. Finally transient analysis of a 2-bus system with embedded non-linearity has been made using software ETAP.

Chapter-3

Performance analysis of medium and long transmission lines have been taken up in the first part of this chapter. With a brief introduction to transmission lines for bulk power transfer, distinction has been made between short, medium and long transmission lines. The mathematical models for such lines and the common analytical tools have been discussed in details. The concepts of nominal π/T and equivalent π/T (for the long line) have been highlighted. Then case-studies have been taken up on medium and long transmission lines have been taken up. The case studies relate to real world systems and the analysis has been made by specially constructed computer programs. The phenomena of VAR-generation and Ferranti effect are evident from the results.

In the second part, detailed discussions have been made on reactive compensation of medium and long transmission lines. Both capacitive and inductive compensation have been taken up and the principle of shunt and series compensation has been established. Discussion has been made on the synchronous compensators of the earlier regime and the Static VAR Compensators of the modern age. Mathematical modeling has been made for distributed compensation so as to keep almost a flat voltage profile in a long line (by the application of: i) shunt and ii) series compensation). A case-study has been made in this area, for a hypothetical system.

Chapter-4

The chapter deals with design approach to high voltage transmission lines. Starting with introduction and general description of high voltage transmission lines, detailed discussion has been made on the design procedure, specification and the formulae used. Then the design algorithm has been presented. A special program has been constructed to make the design which also deals withthe performance analysis. Case-studies have been made on the design of a 20 MVA, 66Kv, 30 Km long medium transmission line and a 125 MVA, 220 Kv, 100Km long transmission line have been taken up. Performance analysis has been made for both the cases by the analytical tools for medium and long transmission lines. As yet, the design is analytic/synthetic but it can be extended towards optimization.

Chapter-5

The chapter deals with the design and design analysis of high voltage high rating alternators. Computer programs have been developed for both analysis and design. In the analysis part, studies have been conducted on a 210 Mw set manufactured by BHEL India Ltd. The analytical studies have explored the usual values for the design variables for a large turboalternator. From the knowledge acquired from analysis, in the next stage a 120 Mw turboalternator has been designed and its performance analysis has been made. Optimization has been reached by adjusting the variables. Then the design of the corresponding generator-transformer has been taken up. A 3-winding Y-Y-D transformer has been designed. The tertiary winding has been connected in delta to suppress the triplen harmonics and the zero sequence components. The optimal solution has been reached by exhaustive search in order to avoid local minimals.

Chapter-6

The chapter is devoted to the design of capacitive and inductive compensation. It starts with finding out appropriate value of capacitance required for power factor improvement at the load end of a feeder and for shunt capacitive compensation of transmission lines. The principle of capacitive compensation for feeder lines has been taken up at first and the design procedure has been given. A self-made program has been used to find out the rating of the capacitors required at the load end for power factor improvement and for the design. The algorithm has been given. The path to economic optimization has been indicated.

In recent times inductive compensation has also become necessary for long EHV lines which are highly capacitive by nature. Normally, the VAR-loss of the lines under loaded condition is less than the VAR-generation. This phenomenon causes Ferranti effect, voltage rise and reduces the power angle stability margin. For this reason inductors of appropriate rating are installed at the terminals of long lines, sometimes also at the center or at different points to get the effect of distributed compensation. These phenomena have been dealt with and the way to find out the rating of the power inductor and to design it cost-optimally have been indicated. The performance equations with inductive compensation have also been given. The power inductor has been designed for the 400Kv line from Farakka to Jeerut. Performance analysis with and without compensation has also been made.

Chapter-7

High voltage power systems of modern days have extensive synchronous coupling. The large grid power increases the total inertia and reduces the chances of transient instability. But the large scale interconnection reduces the system damping and makes the system prone to dynamic instability. Dynamic instability is a phenomenon arising out of small perturbations. It has been found that systems which can withstand large impacts may fall victim to instability due to growing oscillations. The chapter highlights on this phenomenon. The modeling approach and the procedure to find out the initial conditions have been given, followed by linearization technique for the state space models. The simplified linear model in terms of the constants of Concordia and De-Mello inclusive of solid state excitation has been developed. The role of Power System stabilizer (PSS) in damping out oscillations has also been highlighted. Three case-studies have been made on different operating conditions on an idealized one-machine to infinite bus.The analysis has been made by self-made programs, which can be extended to multi-machine systems.

Chapter-8

The chapter deals with voltage profile under sudden loss of excitation. Loss of excitation is a common fault in power plants. It is taken care of by LOE- relaying using offset-type mho-relays with appropriate time-setting. Recent studies have revealed that sustained operation under LOE can be allowed for 15-20 minutes for a turbo generator, provided the voltage profile is not unacceptably poor. But it cannot be allowed for a hydro generator between 3-5 minutes due to large reactive power drawn from the system and due to voltage and power pulsations.

Mathematical modeling of an alternator connected to infinite bus through a series impedance has been made and equations have been framed for steady state operation under LOE. Newton-Raphson method has been used to find out the steady state slip and the asynchronous active and reactive power. The effect including discharge resistance in the field circuit and series impedance between the machine terminals and the infinite bus has been taken into consideration. The pulsating power and torque have been evaluated. The mechanical transients following LOE, taking turbine lags into consideration, and the slip cycles have been computed. Case-studies on a turbo generator and a hydro generator set have been taken up and the comparative view has been given in the concluding part of the chapter.

Chapter-9

This chapter starts with detailed discussions on the phenomenon of voltage instability which may lead to cascaded failure of a power system. It is a major source of power system insecurity. Proper attention should be given to it.

Reactive power mismatch has been identified as the major cause of voltage instability. It has also been mentioned that the heavily loaded systems are more prone to this type of instability. Distinction has been made between short term and long term voltage instability and the mechanism of its building up has been discussed. Then the tools and techniques for voltage stability analysis e.g. P-V curve method, V-Q curve method etc. have been highlighted. Preceded by a brief note on static voltage instability, discussions have been made on some recent works on voltage instability and cascaded failure of systems.

Then a fictitious network has been taken up and load flow studies have been conducted on it after implementing reactive power mismatch in it. Three conditions with gradually increasing reactive power mismatch have been taken up as case-studies- the bad, worse and worst. It reveals from the study that the voltage profile is unacceptably poor for even the bad system and it becomes poorer and poorest for the worse and the worst system, respectively. It was noted that the load flow study did not converge for any further reactive loading, indicating a voltage collapse of the system.

Chapter-10

This chapter is devoted to computer-based analysis of HVDC links. At the first part of the chapter, the context and historical background behind the development of high voltage d.c. transmission lines, their application, advantages and disadvantages have been highlighted followed by a description of the electronic devices and various types of HVDC configurations in common use. At the end of the chapter the steps for mathematical analysis of HVDC-links along with a few case-studies have been given.

The conclusion, novelty of the work and future possibilities have been given in the next chapter. This has been followed by the annexure which gives the different algorithms and the numerical methods used, and finally the reference and bibliography.

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