Mid Term Assignment

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Question # 1

Explain the process of formation of electrical torques in synchronous generators? How these electrical torques stabilizes the operation of electrical power system.

Answer:

Rotor Angle Stability:-

The ability of interconnected synchronous machines to remain in synchronism under normal conditions and after being subjected to a disturbance is called rotor angle stability. It depends upon the ability to maintain/restore equilibrium between electromagnetic torque and mechanical torque of each synchronous machine in the system.

For Example:-

If the generators become unstable when perturbed, it is as a result of a run-away situation due to torque imbalance.

A fundamental factor is the manner in which power outputs of synchronous machines vary as their rotor angles swing. Instability that may result occurs in the form of increasing angular swings of some generators leading to loss of synchronism with other generators.

The relationship between interchange power and the angular positions of the rotor of synchronous machines is highly non-linear.

In order to illustrate this relationship, consider the system below shown in figure (1), where machine 1 is operated as synchronous generator and machine 2 is operated as a synchronous motor.

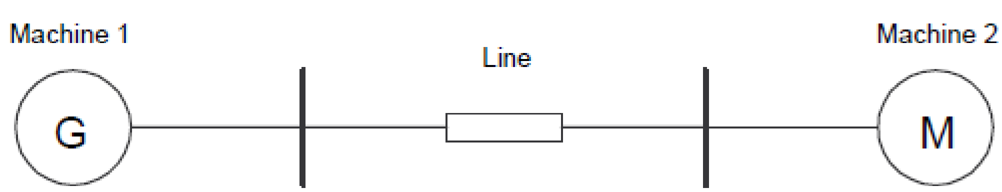

Figure (1)

It will be observed that the Power transferred from the generator to the motor is a function of the angular separation (δ) between the machines.

The angular separation is due to the following three components:

- The generator internal angle G.
- Angular difference between the terminals of the generator and the motor L.
- The motor internal angle M.

The figure (2) below shows a model of the system, where the machines are modeled as an internal voltage behind an effective reactance.

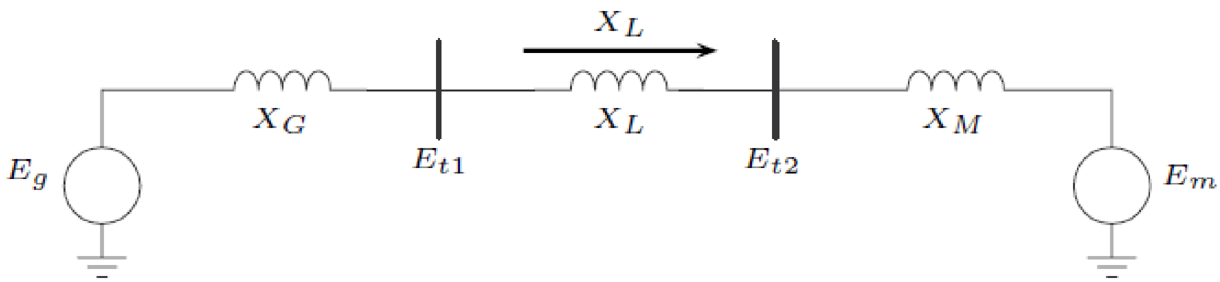

Figure (2)

The Phasor diagram shown in figure (3), the relationship between the generator and motor voltages, which shows that here is a maximum steady state power that can be transmitted between the two machines.

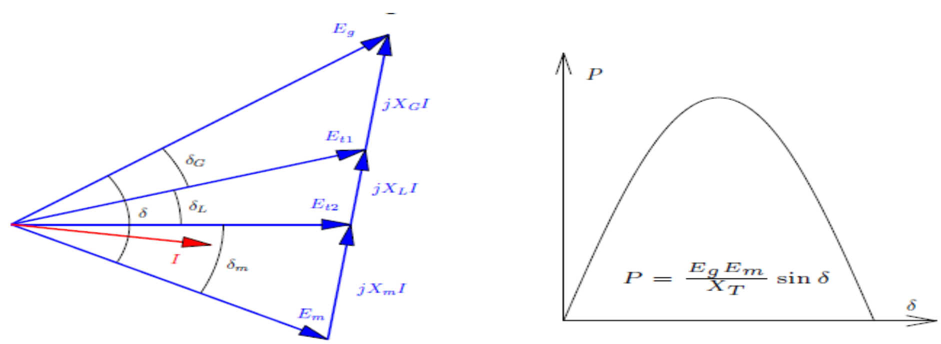

Figure (3)

Under steady-state conditions, there is equilibrium between electromagnetic and mechanical torques. But if the system is perturbed, this equilibrium is upset, causing acceleration or deceleration of the rotor synchronism is maintained through development of restoring forces.

Change in electrical torque can be resolved into two components.

$$\Delta T_e = (T_S \bullet \Delta\delta) + (T_D \bullet \Delta\omega)$$

Where

- T_S is the synchronizing torque coefficient.
- T_D is the damping torque coefficient.

The Power System Stability depends on the existence of both components of torque for each of the synchronous machines. Because:

–A lack of synchronizing torque (Ts) results in aperiodic instability.
–A lack of damping torque (T_D) results in oscillatory instability.

For convenience in analysis and for gaining inside into the nature of stability problems, it is usual to characterize the rotor angle stability phenomena in terms of two categories:

(a) Small signal(angle)stability
(b) Transient stability

(a) Small Signal (Angle) Stability:

Small-Signal (or Small Disturbance) Stability is the ability of a power system to maintain synchronism under small disturbances. Such type of disturbances occurs continually on the system due to small variations in loads and generation.

The disturbance is considered sufficiently small if linearization of system equations is permissible for analysis.

Instability that may result can be of the following two forms:

- A periodic increase in rotor angle due to lack of sufficient synchronizing torque.
- Rotor oscillations of increasing amplitude due to lack of sufficient damping torque.

The nature of the system response to small disturbances depends on number of factors such as:

- Initial operating conditions
- Strength of the transmission system
- Type of generator excitation (Manual, AVR)

(b) Transient Stability:

This term is used traditionally to denote large-disturbance angle stability and is the ability of a power system to maintain synchronism when subjected to a severe transient disturbance. The resulting system response involves large excursions of generator rotor angles and is influenced by the nonlinear power-angle relationship and the stability depends on the initial operating condition, severity of the disturbance, and strength of post-fault transmission network.

A wide variety of disturbances can occur on the system with varying degree of severity and probability of occurrence. The system is, however, designed and operated so as to be stable for a selected set of contingencies (usually, transmission faults: L-G, L-L-G, three phase).

Transient Stability Example:

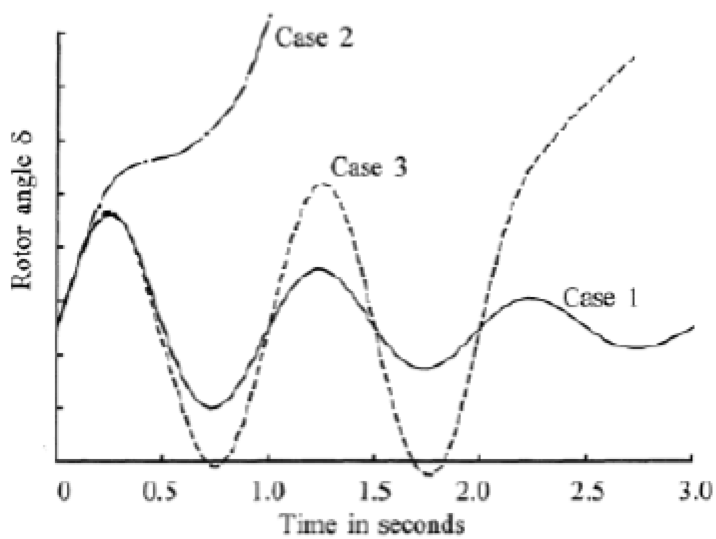

Figure (4)

Figure (4) shows a graph between rotor angle and time. It has been explained in the following three cases as follows.

Case 1, is a stable case where rotor angle increases to a maximum, then decreases and oscillates with decreasing amplitude.

•In Case 2, the rotor angle continues to increases steadily until synchronism is lost (first swing instability).

•In Case 3, the system is stable during the first swing but becomes unstable at a later point. This form of instability occurs when the post fault steady-state condition of the system is small-signal unstable.

Synchronous Machine during a Transient:

During a transient the system seen by synchronous machine causes the machine terminal voltage, rotor angle and the frequency to change. The impedance seen "look into" the network at the machine terminal also change. The field winding voltage will be affected by:

- Induced current in the damper windings due to sudden change in armature currents. The time constant for these currents are of the order of 0.1 seconds and often referred as "sub transient" effects.
- Induced currents in the field windings due to sudden change in armature currents. The time constant for these transients are of the order of seconds and often referred as "transient" effects.
- Change in the rotor voltage due to a change in the exciter voltage if activated by changes at the machine terminal. Both sub transient and transient effects are observed. Since the sub transient effects decay very rapidly, so they are neglected and only the transient effects are considered important.

Question # 2

What are the factors associated with synchronous machines that enhances the damping and synchronizing torques?

Answer:

Damping Torque:

A damping torque is produced by a damping or stopping force which acts on the moving system only when it is moving and always opposes its motion. Such a torque is necessary to bring the pointer to rest quickly. If there is no **damping torque**, then the pointer will keep moving to and fro about its final deflected position for some time before coming to rest, due to the inertia of the moving system.

This damping torque acts only when the pointer is in motion and always opposes the motion. The position of the pointer when stationary is, therefore, not affected by **damping torque**. The degree of damping decides the behavior of the moving system.

If the instrument is under-damped, the pointer will oscillate about the final position for some time before coming to rest. On the other hand, if the instrument is over damped, the pointer will become slow. However, if the degree of damping is adjusted to such a value that the pointer comes up to the correct reading quickly without oscillating about it, the instrument is said to be critically damped, which is shown in figure (1) bellow

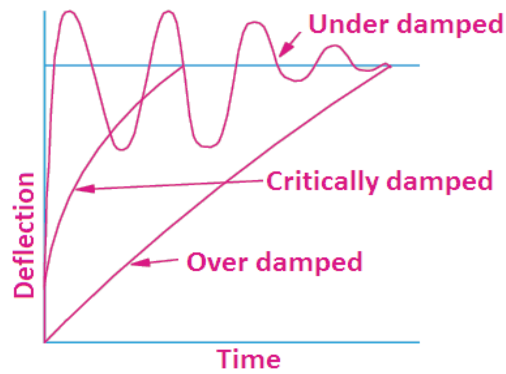

Figure (1)

Synchronizing Torque:

Synchronizing torque is a component of the electrical torque produced by a synchronous generator and is defined "as the most important component of the electrical torque. It is produced by the interaction of the stator windings with the fundamental component of the air
gap flux. It is dependent upon the machine terminal voltage, the rotor angle, the machine reactance's, and the so-called quadrature axis EMF."

The synchronizing torque has a significant role in determining the initial rotor speed behavior of conventional generators following an event on the network. The immediate impact of synchronizing torque can be observed in two ways: first the initial angular deviation and second the instantaneous rate of change of rotor speed (ROCORS) following a major event in the network e.g. loss of generation. The machine rotor speed is tightly linked to the frequency throughout the system. It is vital to determine the contribution of synchronizing torque to the rotor speed deviation.

Change in electrical torque can be resolved into two components

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Where

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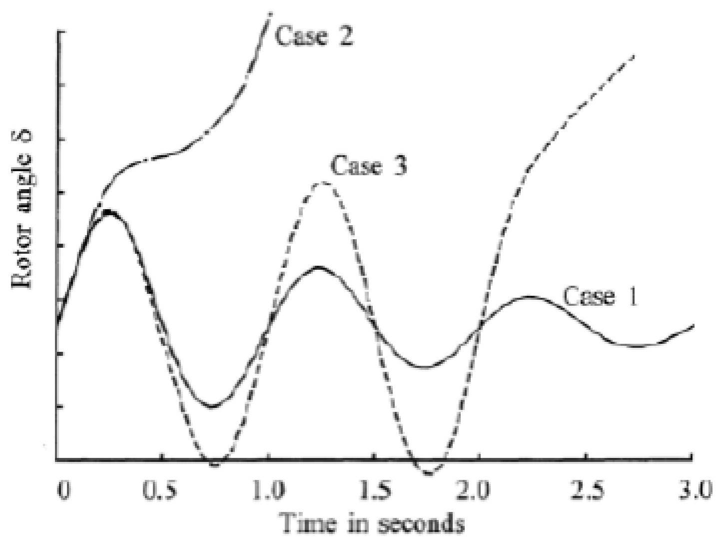
Transient Stability Example:



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Question # 3

Through examples differentiate the power system stability from power system security and power system reliability

Answer:

Relationship between the Concepts of Reliability, Security and Stability of a Power System

(a) Power System Stability:

Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact.

The definition applies to an interconnected power system as a whole. Often, however, the stability of a particular generator or group of generators is also of interest. A remote generator may lose stability (synchronism) without cascading instability of the main system. Similarly, stability of particular loads or load areas may be of interest; motors may lose stability (run down and stall) without cascading instability of the main system.

The power system is a highly nonlinear system that operates in a constantly changing environment; loads, generator outputs and key operating parameters change continually. When subjected to a disturbance, the stability of the system depends on the initial operating condition as well as the nature of the disturbance.

Stability of an electric power system is thus a property of the system motion around an equilibrium set, i.e., the initial operating condition. In an equilibrium set, the various opposing forces that exist in the system are equal instantaneously (as in the case of equilibrium points) or over a cycle (as in the case of slow cyclical variations due to continuous small fluctuations in loads or aperiodic attractors).

Power systems are subjected to a wide range of disturbances, small and large. Small disturbances in the form of load changes occur continually; the system must be able to adjust to the changing conditions and operate satisfactorily. It must also be able to survive numerous disturbances of a severe nature, such as a short circuit on a transmission line or loss of a large generator. A large disturbance may lead to structural changes due to the isolation of the faulted elements.

At an equilibrium set, a power system may be stable for a given (large) physical disturbance, and unstable for another. It is impractical and uneconomical to design power systems to be stable for every possible disturbance. The design contingencies are selected on the basis they have a reasonably high probability of occurrence. Hence, large-disturbance stability always refers to a specified disturbance scenario. A stable equilibrium set thus has a finite region of attraction; the larger the region, the more robust the system with respect to large disturbances. The region of attraction changes with the operating condition of the power system.

The response of the power system to a disturbance may involve much of the equipment. For instance, a fault on a critical element followed by its isolation by protective relays will cause variations in power flows, network bus voltages, and machine rotor speeds; the voltage variations will actuate both generator and transmission network voltage regulators; the generator speed variations will actuate prime mover governors; and the voltage and frequency variations will affect the system loads to varying degrees depending on their individual characteristics. Further, devices used to protect individual equipment may respond to variations in system variables and cause tripping of the equipment, thereby weakening the system and possibly leading to system instability.

If following a disturbance the power system is stable, it will reach a new equilibrium state with the system integrity preserved i.e., with practically all generators and loads connected through a single contiguous transmission system. Some generators and loads may be disconnected by the isolation of faulted elements or intentional tripping to preserve the continuity of operation of bulk of the system. Interconnected systems, for certain severe disturbances, may also be intentionally split into two or more “islands” to preserve as much of the generation and load as possible. The actions of automatic controls and possibly human operators will eventually restore the system to normal state. On the other hand, if the system is unstable, it will result in a run-away or run-down situation; for example, a progressive increase in angular separation of generator rotors, or a progressive decrease in bus voltages. An unstable system condition could lead to cascading outages and a shutdown of a major portion of the power system.

Power systems are continually experiencing fluctuations of small magnitudes. However, for assessing stability when subjected to a specified disturbance, it is usually valid to assume that the system is initially in a true steady-state operating condition.

Power system stability refers to the continuance of intact operation following a disturbance and it depends on the operating condition and the nature of the physical disturbance. a system may be stable following a contingency, yet insecure due to post-fault system conditions resulting in equipment overloads or voltage violations. Stability is a time-varying attribute which can be judged by studying the performance of the power system under a particular set of conditions

(b) Power System Security:

The degree of risk in the ability to survive imminent disturbances (contingencies) without interruption of customer service is known as power system security and it depends on the system operating condition as well as the contingent probability of disturbances. To be secure the system must be stable but must also be secure against other contingencies that would not be classified as stability problems, e.g. damage to equipment such as an explosive failure of a cable, fall of transmission towers due to ice loading or sabotage. System security may be further distinguished from stability in terms of the resulting consequences.
–For example, two systems may both be stable with equal stability margins, but one may be relatively more secure because the consequences of instability are less severe
Security is a time-varying attribute which can be judged by studying the performance of the power system under a particular set of conditions.

An overriding factor in the operation of a power system is the desire to maintain system security. System security involves practices designed to keep the system operating when components fail. For example, a generating unit may have to be taken off-line because of auxiliary equipment failure. By maintaining proper amounts of spinning reserve, the remaining units on the system can make up the deficit without too low a frequency drop or need to shed any load. Similarly, a transmission line may be damaged by a storm and taken out by automatic relaying. If, in committing and dispatching generation, proper regard for transmission flows is maintained, the remaining transmission lines can take the increased loading and still remain within limit.

Because the specific times at which initiating events that cause components to fail are unpredictable, the system must be operated at all times in such a way that the system will not be left in a dangerous condition should any credible initiating event occur. Since power system equipment is designed to be operated within certain limits, most pieces of equipment are protected by automatic devices that can cause equipment to be switched out of the system if these limits are violated. If any event occurs on a system that leaves it operating with limits violated, the event may be followed by a series of further actions that switch other equipment out of service. If this process of cascading failures continues, the entire system or large parts of it may completely collapse. This is usually referred to as a system blackout.

An example of the type of event sequence that can cause a blackout might start with a single line being opened due to an insulation failure; the remaining transmission circuits in the system will take up the flow that was flowing on the now-opened line. If one of the remaining lines is now too heavily loaded, it may open due to relay action, thereby causing even more load on the remaining lines. This type of process is often termed a cascading outage. Most power systems are operated such that any single initial failure event will not leave other components heavily overloaded, specifically to avoid cascading failures.

Most large power systems install equipment to allow operations personnel to monitor and operate the system in a reliable manner. We will lump these under the commonly used title system security. Systems security can be broken down into three major functions that are carried out in an operations control center:

1. System monitoring. 2. Contingency analysis. 3. Security-constrained optimal power flow.

System monitoring provides the operators of the power system with pertinent up-to-date information on the conditions on the power system. Generally speaking, it is the most important function of the three. From the time that utilities went beyond systems of one unit supplying a group of loads, effective operation of the system required that critical quantities be measured and the values of the measurements be transmitted to a central location. Such systems of measurement and data transmission, called telemetry systems, have evolved to schemes that can monitor voltages, currents, power flows, and the status of circuit breakers, and switches in every substation in a power system transmission network. In addition, other critical information such as frequency, generator unit outputs and transformer tap positions can also be telemetered. With so much information telemetered simultaneously, no human operator could hope to check all of it in a reasonable time frame. For this reason, digital computers are usually installed in operations control centers to gather the telemetered data, process them, and place them in a data base from which operators can display information on large display monitors. More importantly, the computer can check incoming information against prestored limits and alarm the operators in the event of an overload or out-of-limit voltage.

State estimation is often used in such systems to combine telemetered system data with system models to produce the best estimate (in a statistical sense) of the current power system conditions or “state.”. Such systems are usually combined with supervisory control systems that allow operators to control circuit breakers and disconnect switches and transformer taps remotely. Together, these systems are often referred to as SCADA systems, standing for supervisory control -- and data acquisition system. The SCADA system allows a few operators to monitor the generation and high-voltage transmission systems and to take action to correct overlords or out-of-limit voltages.

The second major security function is contingency analysis. The results of this type of analysis allow systems to be operated defensively. Many of the problems that occur on a power system can cause serious trouble within such a quick time period that the operator could not take action fast enough. This is often the case with cascading failures. Because of this aspect of systems operation, modern operations computers are equipped with contingency analysis programs that model possible systems troubles before they arise. These programs are based on a model of the power system and are used to study outage events and alarm the operators to any potential overlords or out-of-limit voltages. For example, the simplest form of contingency analysis can be put together with a standard power-flow program together with procedures to set up the power-flow data for each outage to be studied by the power-flow program. Several variations of this type of contingency analysis scheme involve fast solution methods, automatic contingency event selection, and automatic initializing of the contingency power flows using actual system data and state estimation procedures.

The third major security function is security-constrained optimal power flow. In this function, a contingency analysis is combined with an optimal power flow which seeks to make changes to the optimal dispatch of generation, as well as other adjustments, so that when a security analysis is run, no contingencies result in violations. To show how this can be done, we shall divide the power system into four operating states.

- **Optimal dispatch** this is the state that the power system is in prior to any contingency. It is optimal with respect to economic operation, but it may not be secure.
- **Post contingency**: is the state of the power system after a contingency has occurred. We shall assume here that this condition has a security violation (line or transformer beyond its flow limit, or a bus voltage outside the limit).
- **Secure dispatch:** is the state of the system with no contingency outages, but with corrections to the operating parameters to account for security violations.
- **Secure post-contingency**: is the state of the system when the contingency is applied to the base-operating condition-with corrections.

(c) Power System Reliability:

Power system reliability shows the probability of satisfactory operation over the long run and it denotes the ability to supply adequate electric service on a nearly continuous basis, with few interruptions over an extended time period Reliability is the overall objective in power system design and operation. To be reliable the power system must be secure most of the time. Reliability, on the other hand, is a function of the time-average performance of the power system. It can only be judged by consideration of the system's behavior over an appreciable period of time. For reliable service, a power system must remain intact and be capable of withstanding a wide variety of disturbances It is usually impractical to achieve stable operation for all possible disturbances or contingencies. The general practice is to design and operate the power system so that the more probable contingencies can be sustained without loss of system integrity.

- "Normal Design Contingencies"

Loss of any single element, either spontaneously or proceeded by a fault This is referred to as the "N-1 criterion" because it examines the behavior of an N-component grid following the loss of any one major components. Events that exceed the severity of normal design contingencies can in fact occur:

- "Extreme Contingencies"

Measures should be taken to minimize their occurrence and impact

The basic function of an electric power system is to satisfy the system load requirements as economically as possible and with a reasonable assurance of continuity and quality. In order to achieve the required degree of reliability, power system managers, designers, planners and operators have utilized a wide range of criteria in their respective areas of activity. Initially all of these criteria were deterministically based and many of these criteria and associated techniques are still in use today. The basic weakness of deterministic criteria is that they do not respond to nor do they reflect the probabilistic or stochastic nature of system behavior, of customer demands, or of component failures. These factors can be incorporated in a probabilistic approach to electric power system reliability assessment and a wide range of techniques and criteria are available.
Electrical power systems are very complex and highly integrated. Failure in any part of the system can cause interruptions of supply to end users. Power system reliability is increasingly a concern to the power industry and society at large. At present, power system operations are to be handled in a heterogeneous environment. Generally, reliability analysis is being carried out during planning stage of power system operations. In order to maintain the operational state of the power systems at the required levels and subsequently to meet the load demand satisfactorily, the power system operations such as state estimation, reliability analysis etc., are to be carried out at frequent intervals. Perhaps, the above operations have to be invoked dynamically whenever the power system resumes its operation back after had experienced sudden failure or outage. Reliability analysis has to be carried out at regular intervals during operating period of power systems in order to monitor the customer requirement satisfaction at desired levels. The reliability evaluation system should be dynamically adaptable to the current operating conditions of the power systems.

The primary function of a power system is to supply its customers with electrical energy as economically as possible with acceptable reliability and quality. Power system reliability is defined as the ability of the system to satisfy the customer demand. Demands for electric power with high reliability and quality have increased tremendously in the past few decades due to the digital revolution. It is expected that the requirements for high quality, reliable power supply will continue to increase in the immediate future. Customers such as commercial, industrial and residential users expect a highly reliable supply with relatively low rates. The electric power industry throughout the world is undergoing considerable changes in information systems, and Web enabled service oriented architectural models are emerging to support the integration of different power system applications. The evolving changes in power system planning and operation needs require a distributed control center that is decentralized, integrated, flexible, and open.

Proper application of equipment also can also help to increase overall reliability. For example, not overloading equipment and applying proper protection against surges. Equipment failures cause a number of interruptions if they appear on underground circuits. Keeping track of those failures (either by year of installation or installation type) and failures of accessory and then replacing equipment with reliability indexes can help to improve reliability. Monitoring and keeping information of circuit loadings can help to distinguish circuits that may fail from thermal stress.

Poor equipment can be identified before it gets into service by conducting quality acceptance tests. These tests are particularly important for underground cables. These tests can include evaluation of slices of cables to discover voids and drosses in samples. Bad cable batches can be discovered by a high-pot test. Workmanship plays a important role in quality of underground cable splices therefore keeping track of this information can also prevent future problems. For example, if a cable splice breaks down after 6 months and if it is known who made the splice, future problems can be eradicated or prevented whether it was due to workmanship or improper manufacturing quality

Electrical utilities use different inspection programs and methods to improve overall system reliability. For example in visual inspections the maintenance teams often find gross problems such as seriously degraded poles, damaged or broken conductor strands, and broken insulators. Particular electrical utilities conduct frequent and planned visual inspections but more commonly, maintenance teams inspect circuits during other activities. In some situation same teams conduct targeted, visual inspection based on circuit performance. The most efficient visual inspections are those focused on finding fault sources which may be subtle. Maintenance teams need to be educated to discover them. load shedding, system robustness against the fault occurrence are the examples. Reliability has to do more with the load end of the business and keeping all of the customers connected. The unreliability (and exposure to interruptions) of the system is mostly at the distribution end where trees, lightning, equipment failures, etc. can interrupt service to some of the customers.

Question # 4

During contingency analysis, why the power system stability is not judged for all possible fault events.

Answer:

Contingency analysis (CA) is critical in much routine power system and market analyzes to show potential problems with the system. Due to the tremendous and yet increasing amount of data computed by CA, effective visualizations are needed to present the CA results to assist the system operators and engineers to comprehend the static security status of the system in a quick and intuitive manner. The desirable functionalities of such visualizations include showing the overall system security status, showing the severity levels of the contingencies in terms of their associated limit violations, and showing the geographic connection between the violated elements and the contingent elements.

The major security function is contingency analysis. The results of this type of analysis allow systems to be operated defensively. Many of the problems that occur on a power system can cause serious trouble within such a quick time period that the operator could not take action fast enough. This is often the case with cascading failures. Because of this aspect of systems operation, modern operations computers are equipped with contingency analysis programs that model possible systems troubles before they arise. These programs are based on a model of the power system and are used to study outage events and alarm the operators to any potential overlords or out-of-limit voltages. For example, the simplest form of contingency analysis can be put together with a standard power-flow program together with procedures to set up the power-flow data for each outage to be studied by the power-flow program. Several variations of this type of contingency analysis scheme involve fast solution methods, automatic contingency event selection, and automatic initializing of the contingency power flows using actual system data and state estimation procedures. For reliable service, a power system must remain intact and be capable of withstanding a wide variety of disturbances It is usually impractical to achieve stable operation for all possible disturbances or contingencies. The general practice is to design and operate the power system so that the more probable contingencies can be sustained without loss of system integrity.

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Loss of any single element, either spontaneously or proceeded by a fault This is referred to as the "N-1 criterion" because it examines the behavior of an N-component grid following the loss of any one major components. Events that exceed the severity of normal design contingencies can in fact occur:

- "Extreme Contingencies"

Measures should be taken to minimize their occurrence and impact

The normal design contingencies include the following:

- Three-phase fault on any generator, transmission circuit, transformer or bus section, with normal fault clearing.
- Simultaneous phase-to-ground faults on different phase of each of two adjacent transmission circuits on a multiple-circuit tower, cleared in normal time.
- A permanent phase-to-ground fault on any transmission circuit, transformer or bus section with delayed clearing because of malfunction of circuit breakers, relay or signal channel.
- Loss of any element without a fault
- A permanent phase-to-ground fault on a circuit breaker, cleared in normal time.

The criteria require that the stability of the bulk power system is maintained during and after the most severe of the contingencies specified above.

Reliability is the overall objective in power system design and operation

- To be reliable the power system must be secure most of the time.
- To be secure the system must be stable but must also be secure against other contingencies that would not be classified as stability problems, e.g. damage to equipment such as an explosive failure of a cable, fall of transmission towers due to ice loading or sabotage. As well, a system may be stable following a contingency, yet insecure due to post-fault system conditions resulting in equipment overloads or voltage violations.

- **Operating States of Power System Control**:

The following figure (1) shows are the operating states of power system control.

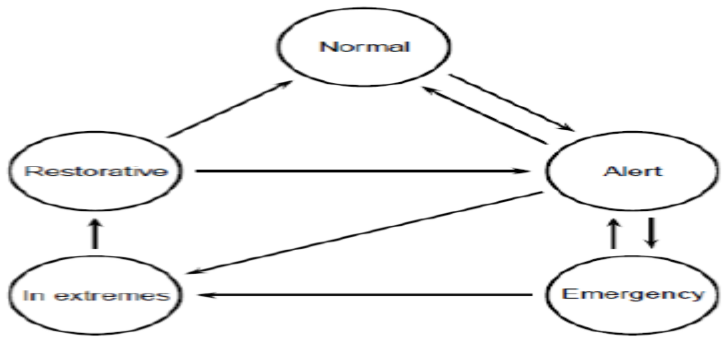

Figure (1) Operating states of power system control

- In the **normal state**, all system variables are with in normal range and no equipment is being over loaded
- In the **alert state**, this security has gone below certain limit of adequacy or if the possibility of a disturbance increases due to weather conditions .All system variables are though with in the acceptable range and all constrains are satisfied.
- In the **emergency state**, a sufficiently severe contingency has occurred while the system was in the alert state. The system may be restored to the alert state by initiating emergency control actions.
- The system is in **extreme state** is if the emergency control actions are not applied or they are not sufficient. The result is cascading outages and possibly a shut-down of a major portion of the power system.
- The **restorative state** represents a condition in which a control action is being taken to reconnect all the facilities and to restore system load.

Question # 5

Provide reasons for classification of power system stability.

Answer:

Classification of Power System Stability:

A typical modern power system is a high-order multivariable process whose dynamic response is influenced by a wide array of devices with different characteristics and response rates. Stability is a condition of equilibrium between opposing forces. Depending on the network topology, system operating condition and the form of disturbance, different sets of opposing forces may experience sustained imbalance leading to different forms of instability.

- **Need for Classification**

Power system stability is essentially a single problem; however, the various forms of instabilities that a power system may undergo cannot be properly understood and effectively dealt with by treating it as such. Because of high dimensionality and complexity of stability problems, it helps to make simplifying assumptions to analyze specific types of problems using an appropriate degree of detail of system representation and appropriate analytical techniques. Analysis of stability, including identifying key factors that contribute to instability and devising methods of improving stable operation, is greatly facilitated by classification of stability into appropriate categories Classification, therefore, is essential for meaningful practical analysis and resolution of power system stability problems.

- **Categories of Stability**

The classification of power system stability proposed here is based on the following considerations.

• The physical nature of the resulting mode of instability as indicated by the main system variable in which instability can be observed.
• The size of the disturbance considered which influences the method of calculation and prediction of stability.
• The devices, processes, and the time span that must be taken into consideration in order to assess stability.

Fig. 1 gives the overall picture of the power system stability problem, identifying its categories and subcategories.

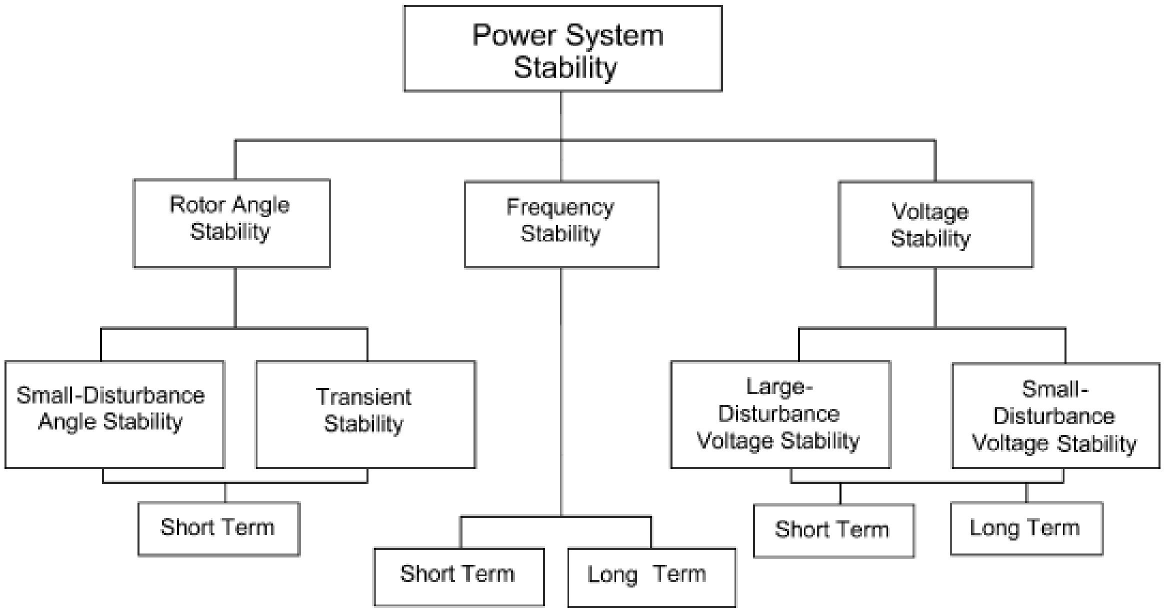

Figure (1) Classification of Power System Stability

The following are descriptions of the corresponding forms of stability phenomena.

(a) Rotor Angle Stability:

Rotor angle stability refers to the ability of synchronous machines of an interconnected power system to remain in synchronism after being subjected to a disturbance. It depends on the ability to maintain/restore equilibrium between electromagnetic torque and mechanical torque of each synchronous machine in the system. Instability that may result occurs in the form of increasing angular swings of some generators leading to their loss of synchronism with other generators. The rotor angle stability problem involves the study of the electromechanical oscillations inherent in power systems. A fundamental factor in this problem is the manner in which the power outputs of synchronous machines vary as their rotor angles change. Under steady-state conditions, there is equilibrium between the input mechanical torque and the output electromagnetic torque of each generator, and the speed remains constant. If the system is perturbed, this equilibrium is upset, resulting in acceleration or deceleration of the rotors of the machines according to the laws of motion of a rotating body. If one generator temporarily runs faster than another, the angular position of its rotor relative to that of the slower machine will advance. The resulting angular difference transfers part of the load from the slow machine to the fast machine, depending on the power-angle relationship. This tends to reduce the speed difference and hence the angular separation. The power-angle relationship is highly nonlinear. Beyond a certain limit, an increase in angular separation is accompanied by a decrease in power transfer such that the angular separation is increased further. Instability results if the system cannot absorb the kinetic energy corresponding to these rotor speed differences. For any given situation, the stability of the system depends on whether or not the deviations in angular positions of the rotors result in sufficient restoring torques. Loss of synchronism can occur between one machine and the rest of the system, or between groups of machines, with synchronism maintained within each group after separating from each other.

- **Small-disturbance (or small-signal) rotor angle stability**

It is concerned with the ability of the power system to maintain synchronism under small disturbances. The disturbances are considered to be sufficiently small that linearization of system equations is permissible for purposes of analysis. Small-disturbance stability depends on the initial operating state of the system. Instability that may result can be of two forms:

i) Increase in rotor angle through a non-oscillatory or aperiodic mode due to lack of synchronizing torque,

ii) Rotor oscillations of increasing amplitude due to lack of sufficient damping torque.

- **Large-disturbance rotor angle stability or transient stability**

It is commonly referred to and is concerned with the ability of the power system to maintain synchronism when subjected to a severe disturbance, such as a short circuit on a transmission line. The resulting system response involves large excursions of generator rotor angles and is influenced by the nonlinear power-angle relationship.

(b) Frequency Stability:

It refers to the ability of a power system to maintain steady frequency following a severe system upset resulting in a significant imbalance between generation and load. It depends on the ability to maintain/restore equilibrium between system generation and load, with minimum unintentional loss of load. Instability that may result occurs in the form of sustained frequency swings leading to tripping of generating units and/or loads.

During frequency excursions, the characteristic times of the processes and devices that are activated will range from fraction of seconds, corresponding to the response of devices such as under frequency load shedding and generator controls and protections, to several minutes, corresponding to the response of devices such as prime mover energy supply systems and load voltage regulators. Therefore, as identified in Fig. 1, frequency stability may be a *short-term* phenomenon or a *long-term* phenomenon.

An example of short-term frequency instability is the formation of an under generated island with insufficient under frequency load shedding such that frequency decays rapidly causing blackout of the island within a few seconds [28]. On the other hand, more complex situations in which frequency instability is caused by steam turbine overspeed controls [29] or boiler/reactor protection and controls are longer-term phenomena with the time frame of interest ranging from tens of seconds to several minutes.

During frequency excursions, voltage magnitudes may change significantly, especially for islanding conditions with under frequency load shedding that unloads the system. Voltage magnitude changes, which may be higher in percentage than frequency changes, affect the load-generation imbalance. High voltage may cause undesirable generator tripping by poorly designed or coordinated loss of excitation relays or volts/Hertz relays. In an overloaded system, low voltage may cause undesirable operation of impedance relays.

(c) Voltage Stability:

It refers to the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition. It depends on the ability to maintain/restore equilibrium between load demand and load supply from the power system. Instability that may result occurs in the form of a progressive fall or rise of voltages of some buses. A possible outcome of voltage instability is loss of load in an area, or tripping of transmission lines and other elements by their protective systems leading to cascading outages. Loss of synchronism of some generators may result from these outages or from operating conditions that violate field current limit.

As in the case of rotor angle stability, it is useful to classify voltage stability into the following subcategories:

• Large-disturbance voltage stability

It *refers* to the system's ability to maintain steady voltages following large disturbances such as system faults, loss of generation, or circuit contingencies. This ability is determined by the system and load characteristics, and the interactions of both continuous and discrete controls and protections. Determination of large-disturbance voltage stability requires the examination of the nonlinear response of the power system over a period of time sufficient to capture the performance and interactions of such devices as motors, under load transformer tap changers, and generator field-current limiters. The study period of interest may extend from a few seconds to tens of minutes.

• **Small-disturbance voltage stability**

It refers to the system's ability to maintain steady voltages when subjected to small perturbations such as incremental changes in system load. This form of stability is influenced by the characteristics of loads, continuous controls, and discrete controls at a given instant of time. This concept is useful in determining, at any instant, how the system voltages will respond to small system changes. With appropriate assumptions, system equations can be linearized for analysis thereby allowing computation of valuable sensitivity information useful in identifying factors influencing stability.

As noted above, the time frame of interest for voltage stability problems may vary from a few seconds to tens of minutes. Therefore, voltage stability may be either a short-term or a long-term phenomenon as identified in Figure 1.

• ***Short-term voltage stability*** involves dynamics of fast acting load components such as induction motors, electronically controlled loads, and HVDC converters. The study period of interest is in the order of several seconds, and analysis requires solution of appropriate system differential equations; this is similar to analysis of rotor angle stability. Dynamic modeling of loads is often essential. In contrast to angle stability, short circuits near loads are important. It is recommended that the term *transient voltage stability* not be used.

• ***Long-term voltage stability*** involves slower acting equipment such as tap-changing transformers, thermostatically controlled loads, and generator current limiters. The study period of interest may extend to several or many minutes, and long-term simulations are required for analysis of system dynamic performance. Stability is usually determined by the resulting outage of equipment, rather than the severity of the initial disturbance. Instability is due to the loss of long-term equilibrium e.g., when loads try to restore their power beyond the capability of the transmission network and connected generation.