Power Network Analysis

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Week-11

Lecture-52

Lecture 52: Stability analysis- Basics and classification of power system stability

Hello everyone, welcome to lecture 2 of week 11 of the course Power Network Analysis. In this discussion, we will start with our last module of the course, which is on stability analysis. To be specific, as I mentioned in the previous discussion, we will be talking about or focusing mostly on transient rotor angle analysis. Stability analysis of the rotor angle here pertains to the synchronous generators. And before we go deep into what this transient rotor angle stability analysis is, what are the ways of analyzing it, and first of all, what is stability? What are the ways of analyzing this stability or instability? We will first briefly talk in this discussion about the basics and various forms of power system stability or instability problems as devised and dictated by the IEEE task force. So till the previous lecture we had finished up all our main modules the last one being fault analysis which was a study primarily focusing on the sub transient period following a disturbance and the intent was to find the worst case fault current that the system or the power network can encounter different during different types of faults and based on these worst case fault currents or the sub transient period analysis the settings of relays and associated circuit breakers are designed and that is how the power network tends to protect itself through these protective devices against Intentional or unintentional faults.

It is also to be observed that a fault event is not a healthy event in a power network. The reason is that in a fault, the normal load current or the normal flow of current to the load is perturbed, and hence we need to protect the system. On the other hand, the previous module was power flow analysis, which mostly aimed at finding the steady-state bus voltages. By bus voltages, I mean bus voltage magnitudes and phase angles in polar coordinates or real and imaginary parts of bus voltage in rectangular coordinates in the phasor domain.

for different changes in system conditions. So basically, Power Flow is a steady-state study, and it is mostly used for security analysis or contingency analysis, which is a study that involves aiding the operator in letting them know that in case some contingency or change in system condition happens, then what the impact of those changes on the overall system and the network would be in terms of bus voltages. And once we know these bus voltages, then the corresponding other flows, injections, and currents can all be evaluated. Coming to the stability problem, in general, power system stability, like any other network or system, the notion of stability remains the same in a power network as well. Stability is the ability of a power network for a given initial condition; this is an important aspect, stability is always measured with respect to a given initial condition and if the network can remain stable or remain in equilibrium condition after being subjected to several such disturbances, contingencies, faults, etc., etc., wherein after the disturbance, if the system remains stable, then all system variables which could refer to bus voltages, currents, voltage phase angles, frequency, they all remain bounded and the The entire network still remains intact; it is still able to satisfy the loads both immediately after the disturbance and in steady state. So essentially, stability is all about analyzing how the system can remain in an equilibrium state for a given initial operating condition when a disturbance occurs, and when this disturbance occurs, several opposing forces come into the picture which, if they don't equalize each other, then probably the system tends to be in an unstable mode. Let's say from the synchronous generator's perspective, if more mechanical power is fed into the generator and the same quantum of electrical power output is not being generated because of some fault in the stator winding or some issue in the rotor, then essentially the machine would start gaining kinetic energy and eventually it would go into a runaway condition, which would eventually become an unstable operating mode.

So equilibrium, as I mentioned, is all about trying to understand whether different opposing forces can balance out each other when the system encounters a disturbance, and this equilibrium is always measured with respect to an initial steady-state operating point. So, coming to the disturbance aspect, what exactly is the disturbance? It is any change in the system parameters of the operating conditions that can be classified as small or large disturbances. A small disturbance specifically for the case of examples to be given, a small disturbance or a change in system condition might refer to a change in system load or change in tap position of a transformer. or change in capacitor steps or taps of a capacitive bank. And these small disturbances keep happening continually.

For example, the load is not a stagnant quantity. It keeps varying. If we have a power network that has renewable energy resources connected to it, then depending on the weather conditions, the renewable energy resource generation would also keep changing. So small disturbances are all those sets of disturbances. Which continuously happens in the network, and the good part about these small disturbances, if the system remains stable, is that the power network is expected to adjust itself so that it remains in a stable operating condition for overall satisfactory operation.

The next category could be if small disturbances can be defined and the next category is definitely large disturbances where some transmission line or some generator or a transformer because of intentional or unintentional purposes is stripped off. For intentional purposes, it is mostly due to a maintenance perspective, or unintentional reasons; this could be due to the occurrence of a fault. or any large load change some new load coming up or the large load change going down might come into the notion of large disturbances. So, for example, the 9-minute sort of load shedding that was declared during the time of COVID. So, the entire nation experienced around 9 PM on a particular day, a huge drop in the system load in the quantum of few gigawatts and the planners sitting at Northern Load NLDC, Northern Load Dispatch Center or the LDCs, they had to plan for this load change so that the system can remain stable.

So, overall it might appear that small and large they could refer to certain quantitative measures, but actually it is purely qualitative and it has to do more with the type of analysis which is involved in understanding the stability problem when the power network experiences small or large disturbances. As I mentioned earlier, stability all depends on the initial steady-state operating condition where the system is already in equilibrium. Please remember that the stability analysis we are going to discuss assumes that the system is in a stable condition, similar to the assumption we had for the fault analysis of the system being in a balanced condition. If the system is inherently in an unstable mode at the given initial operating condition, then additional steps need to be taken, and the same conventional analysis probably won't hold true. So stability depends on the initial operating conditions and also on the type of disturbance.

If the system becomes stable after the disturbance, then the equilibrium point achieved after the disturbance may or may not be the same as the initial operating condition or the pre-disturbance equilibrium. There is a classification involved about how small or large can be defined based on whether the post disturbance equilibrium matches the pre disturbance equilibrium or whether it does not match the pre disturbance equilibrium or the initial operating condition. If the system tends to become unstable, then eventually the loads would start tripping, generators would start tripping first, loads would tend to get cleared off or cut off, and eventually the system or the power network may run into a cascaded event that can lead to several small pockets of islands being created. If these islands can't sustain their own loads in terms of the generation available, then the system tends to be in a blackout condition. Which is what happened in July 2018 or 2019, if I remember correctly, in the month of July.

So this paper here is very good; it is a very recent paper, although different variants of this paper have already been published. It talks about the different classes and definitions of the power system stability problem, and it is written by a group of well-known researchers and renowned authors. who happen to be part of the IEEE task group that looks into this power system stability problem. So, in terms of that paper devised by the

IEEE SIGRE joint task force, they have classified power system stability into five problems. These five problems pertain to which particular variable is getting perturbed following a disturbance, so based on that, resonance stability, converter stability, rotor stability, voltage stability, and frequency stability are the five broad domains.

The previous version of the paper, it focused only on these three stability problems with increase in inverter resources and the corresponding torsional and subtorsional effects that come, that are growing up in the power network over the years because of IBR based, inverter based renewable resources. The task force also felt that these two classes should be added in addition to the existing three stability problems. They have also further classified these stability problems into the time span and the size of the disturbance that can affect these different variables. So in today's discussion, I will briefly explain or talk about rotor angle stability, basic definitions, voltage stability, and frequency stability. And eventually, in this particular module, we will be focusing on the transient rotor angle stability problem at length.

The other stability problems due to a limited number of lectures and the time that we have will be avoided, but for those of you who are interested, if you understand the transient rotor angle stability analysis problem or the discussion, a similar approach may also be applied to large disturbance voltage stability or large disturbance frequency stability problems. The small disturbance problems tend to be the different types of analysis that we will eventually see. So let's go deep into what this rotor angle stability problem is. Rotor angle as we all know from the discussion of synchronous generators module as well as from the fault analysis discussion that rotor angle happens to be a attribute of synchronous generators or synchronous machines to be general. And if this stability has to be ensured, then it essentially boils down to the fact that all synchronous machines which are connected to the power network, they remain synchronized even after a disturbance.

What is meant by synchronization or synchronism? Four specific conditions have to be met when the system remains synchronized with respect to a particular synchronous generator. Its voltage magnitude should match the terminal voltage of the grid. Its voltage phase angle difference should be zero at the time of synchronization. So basically, the angles should correspondingly reciprocate to changes in system load from the grid perspective. The frequency should match, and the phase sequence ABC or RYB of the generator should match the incoming terminals of the grid to which the generator is being connected.

So if the system tends to remain rotor angle stable, then the four conditions that I mentioned, obviously phase sequence can't change immediately, but frequency, rotor angle, and the voltage magnitude, they should remain equal to the rest of the network in the bus for a synchronized operation. So essentially, if this synchronism from an angle perspective is to be maintained, it is more to do with the balance that exists between input mechanical power or torque and the output electromagnetic torque or power generated by the synchronous generator, which I was trying to explain a few slides ago. Any instability that might occur from rotor angle perspective is will lead to increase in the rotor angle and basically the rotor angles the differences between each generators rotor angles they would increase and they would come a point where this angle is so large this angle difference is so large that the machine would tend to lose its synchronism with respect to rest of the generators or the network. essentially it involves analyzing the rotor angle stability problem, it essentially involves analyzing the power outputs of synchronous machines with respect to rotor angles in the post disturbance state and at steady state as we all know for a synchronous machine the synchronous speed is the synchronous machine speed and both input mechanical power and output electrical power electromagnetic torque they tend to Match each other. In case any difference comes in between these powers what would happen intuitively the machine would tend to accelerate rotor machine of the machine basically would tend to accelerate or deaccelerate in a way either leading to increase in kinetic energy or reduction in kinetic energy which would manifest as a swing in the rotor phase angle if nothing is done and if this imbalance is maintained.

So when the system is perturbed, the equilibrium is upset; as I mentioned, it might lead to acceleration or deceleration of the machine rotors as per Newton's second law of motion, and eventually, if nothing is done, it may happen that one synchronous machine may run faster due to a gain in kinetic energy. Eventually, the rotor angle position of that particular machine tends to increase with respect to the remaining slower ones. Beyond a particular rotor angle difference, the machine loses its synchronism, and instability might occur. The aspect which is mentioned over here it is just for information although it involves detailed analysis. For the sake of discussion it is imperative that the output electrical power or electromagnetic torque for the sake of analysis it can be resolved into two distinct powers or torques One power which is important for rotor angle stability, transient rotor angle stability is the synchronizing torque which we will see maybe in the next few lectures to come in which usually happens to be in phase with the rotor angle deviation that is happening and the next torque is the damping torque which is important from The small disturbance or small signal rotor angle stability analysis, which is usually in phase with the speed deviation.

There is an elaborate discussion behind why these phases of coherency happen, again because of this limited period of time. To keep our discussion simple, I will avoid those details. But those of you who are interested may explore more about these topics to have a better understanding of this particular fact. So the lack of synchronizing torque, which happens to be in phase with rotor angle deviation, essentially determines how much the machine can gain or lose kinetic energy. If there is not sufficient synchronizing torque, then the rotor angle would swing, and it would experience a periodic or non-oscillatory instability.

So, if I were to sort of plot the rotor angle deviation or rotor angle of a particular synchronous machine with respect to time and assuming that everything was stable or everything was in equilibrium in the steady state condition before some time t is equal to t star that means the rotor angle was having some swings, but it was all controlled and limited and if at t is equal to t star some disturbance happens and The machine does not have sufficient synchronizing torque in the case of unstable operation; it might happen that the rotor angle would either continue to grow or increase, or it may continue to go down or decrease with respect to time. This is what is known as periodic or non-oscillatory instability, which is due to a lack of synchronizing torque. In case the machine does not have sufficient damping torque, then the swings would happen, but because of insufficient damping, the swings might go up or increase, or they might tend to go down, which is again part of the discussion on small single outer angle stability, which we will not be discussing at length in this particular module. So now comes the definition or the quantification or qualification of small disturbances or large disturbances. For small disturbances the machine can remain in a synchronizing mode following a small disturbance and by this small disturbance I mean the machine has experienced a disturbance around its initial existing equilibrium point.

But the disturbance is small enough that linearized system equations can be used to analyze the impact of that small disturbance; that is point number one. Point number two: it is likely that following a small disturbance, the post-disturbance equilibrium point will be the same as the pre-disturbance or the initial operating equilibrium point condition. And those disturbances which tend to satisfy these two conditions: that the post-disturbance equilibrium will be the same as the pre-disturbance equilibrium, and that the system analysis can be done in a linearized mode while avoiding non-linear differential equations. Only those disturbances would be analyzed as small signals or small disturbances. Disturbances that don't satisfy those conditions would be categorized as last disturbances or transient rotor angle stability, in which the analysis involves nonlinear system equations and time-dependent dynamic equations for the sake of analysis.

Now you may wonder why we have dynamic equations coming in; we never had dynamic equations in fault analysis or, for that matter, in power flow analysis. The reason was that in fault analysis, we were trying to find one particular worst-case value of fault current in the worst-case condition. We were not looking at the dynamics involved in achieving that particular worst case fault current that is the all about fault analysis in power flow we are aiming to find the steady state voltages or currents again there is no dynamics involved for stability problems for specifically for large or small disturbances the variation from worst case condition to steady state condition how it is happening that definitely involves some dynamics some differential equation in fact if i if you remember i was mentioning about the acceleration and deacceleration aspect In the previous slide.

To measure the acceleration or deceleration according to Newton's second law, which involves a differential equation to understand large disturbances, we will have to use certain dynamic or differential equations; that is the reason. These same differential equations with the disturbances small can be linearized for the sake of analysis, and the overall analysis becomes simpler.

So it's not that dynamics are not involved for small disturbances. Dynamics are involved, but these dynamics are so small that they can be analyzed or evaluated using a simple linearized equation or through some typical eigenvalue analysis; that is the idea. So small signal outer angle stability is. The system dynamics as I was mentioned is governed by non-linear differential equations for small disturbances these differential equations they can be linearized for the sake of analysis around the steady state equilibrium condition and often we tend to make use of eigenvalue analysis for the sake of small signal to triangle stability. Different examples that likely fall into small disturbances include excitation control of the generator, change in transformer tap, shunt position, etc. and AGC actions, etc. So, depending on the initial operating condition, instability that may occur will be due to an increase in the triangle stability caused by the non-oscillatory modes or oscillations in the rotor speed. Rotor angle instability, as I mentioned, is mostly due to a lack of sufficient damping. A periodic instability that is due to a lack of sufficient synchronizing torque is largely eliminated in small signals to triangle stability due to the closed-loop feedback available from the automatic voltage regulator and excitation control. And if the system is stable from a small disturbance perspective, the pre-disturbance point and the post-disturbance equilibrium point remain the same. So essentially, after a disturbance, the pre-disturbance equilibrium point is regained in the steady state for small disturbance analysis.

The time period of interest is on the order of a few seconds after a disturbance, which falls well within the domain of the transient period of synchronous machine behavior after a disturbance. We would avoid further details for the sake of simplicity. Coming to transient outer angle stability, as I mentioned, it is about large disturbance analysis in which non-linear dynamic equations and static equations have to be solved for the sake of analysis because linearization won't help in capturing the right picture or right value of the outer angle variations. Examples include the occurrence of faults, sudden load changes, and it is not necessary that in Transcendental Triangle Stability the post-disturbance equilibrium point should be the same as the pre-disturbance equilibrium point. It may happen that the post-disturbance equilibrium point is different from the pre-disturbance equilibrium point, which again is a new equilibrium point in itself.

So, transient ultra-angle stability essentially tends to find the trajectory along which the post-disturbance, sorry, the pre-disturbance equilibrium point has been perturbed to reach the post-disturbance equilibrium point, and this trajectory with respect to time is all about obtaining it through the corresponding dynamic equations. And that's the reason why we would often need the help of integrating techniques or numeric integration techniques. The time period of interest is smaller than the small signal stability, which still falls within the domain of the transient period. And any instability that might occur as I mentioned is due to lack of insufficient synchronizing torque manifested as the first swing instability wherein I was mentioning that the rotor angle is in steady state at t is equal to t star and t star some disturbance happens then the rotor angle would either tend to increase or either tend to decrease around the initial steady state operating condition. So, basically the first swing instability refers to the first change that has occurred in the rotor angle following a large disturbance and these differential equations they would help assess these first angle instabilities.

We are coming to our last two aspects: voltage stability and frequency stability. Voltage stability, as the term refers to voltage, is all about maintaining steady-state bus voltages following a disturbance from an initial operating condition. It mostly has to do with the imbalance that exists between power demand and power supply. Any instability that occurs either leads to progressive rise or fall in the bus voltage magnitudes which essentially leads to loss of load, line tripping and eventually possibility of loss of synchronism from the load perspective. If nothing is done and the voltage instability has to happen, eventually we would enter a point of no return, which is called voltage collapse, in which the sequence of events accompanying voltage instability leads to a complete blackout or abnormally low voltages in a significant part of the network where the load cannot be satisfied at all.

The driving force, as I mentioned, is mostly due to loads. Voltage stability can be ensured through proper reactive voltage setting devices or reactive power devices, which essentially involve transformer taps, capacitors, synchronous condensers, or through the proper controlled action of loads being on or off. It is mostly associated with the voltage drop that occurs due to high reactive power flows in inductive transmission lines because of which there is a large voltage drop absorbed at the load end and with no proper reactive power compensation at the load end it might lead to large drop in the voltage because of which the load might not even consume a sufficient amount of reactive power. Instability may also occur at lower loads when the synchronous generators tend to saturate their generation limit or excitation control, basically leading to saturated excitation operation or AVR operation. Frequency stability, as the term suggests, is all about maintaining a steady frequency across the power network, and this is mostly due to the imbalance between generation and load from a given initial operating point.

It depends on the ability to maintain or restore equilibrium between demand and supply with minimal loss of load. Any instability that might occur from a frequency perspective would lead to sustained frequency swings, either a progressive decrease or increase in system frequency. And the processes that are usually considered for the frequency stability problem involve the dynamics of the boiler, the mechanical source of power for synchronous generators. Voltage by frequency protection philosophy is located at the generation or the load ends. Automatic generation control or automatic load frequency control tends to regulate the generator's frequency.

To conclude, it might appear that, okay, we have discussed three classes of voltage stability, frequency stability, and rotor angle stability problems, but they are all correlated; they are not independent. The distinction or classification is just for the purpose of figuring out different ways of analyzing these stability problems. But it might happen, or it is likely to happen, that one disturbance may impact all the stability problems at the same time. The distinction is all about specifying which set of opposing forces is experienced in the network. That leads to imbalance and what primary variable is being looked at from the stability or instability perspective.

Any form of instability equally affects all the rotor angle, voltage stability, frequency stability, and resonance stability problems together. It is not to be expected that, if I'm only focusing on a disturbance from a transient outer angle stability perspective and that particular disturbance happens to be a stable event, the same event might lead to a voltage stability problem or a frequency stability problem in a different time domain with different initial operating conditions. So that's the bottom line, discussion, conclusion, or takeaway from this. This correlation or dependency has nothing to do with the fact that voltage phase angles are strongly coupled with real power flow in the network and voltage magnitudes are strongly coupled with the reactive power flow in the network. This is often only from the perspective of power flow analysis where we have often made use of this fact where we tend to sort of discuss the fast decoupled or decoupled power flow tool which was based on this coupling.

Please don't correlate this coupling with the dependency of the fact that any disturbance might equally affect all three or all five stability problems together. So, that is all for this discussion. The next lecture, we will take up our main lecture on transient outer angle stability analysis, which will involve understanding a differential equation called the swing equation. which is nothing but the analogous Newton's second law of motion for a synchronous machine that is being fed by a mechanical source of power and generating some electrical power. So how a balance between mechanical input and electrical power output is maintained, the corresponding acceleration and deceleration are dictated by this swing machine.

That is what we will discuss in the next lecture.

Thank you.