Power Network Analysis

Dr. Abheejeet Mohapatra

Department of Electrical Engineering

IIT Kanpur

Week-12

Lecture-59

Lecture 59: Stability analysis- multi-machine transient rotor angle stability

Hello everyone, welcome to Lecture 4 of Week 12 of the course Power Network Analysis. This is the second last lecture of this entire series of lectures that we have had and we were discussing the last module transient row triangle stability analysis and in today's discussion We will look at certain practical aspects involved in analyzing transient rotor angle stability for multi machine systems, power networks which have several synchronous generators and machines connected, not just one single machine infinite bus case or two coherent or two known coherent generators considered together. So, we will look at those measures or the issues involved in applying the assumptions of classical rotor angle stability analysis on multi-machine systems, what the demerits or pitfalls are if we use the conventional classical assumptions in analyzing multi-machine stability, and then what countermeasures or corrective actions can be taken in order to create a more practical or reasonable scenario. The last lecture we had at length discussed two solved examples that emphasized the aspects of equal area criteria, applying numeric integration techniques to solve the swing equation under different operating scenarios, and also the importance of synchronizing the power coefficient in terms of minor disturbances if they occur in a power network. Specifically, with respect to a synchronous machine. Then, in terms of the natural frequency that might occur in the rotor angle or the overall frequency, we also understood and discussed how it is dependent on the synchronizing power coefficient.

To start this discussion today, I will essentially provide a background on how multi-machine stability analysis can be done. So what we have observed or discussed is the physical phenomena involved in understanding transient root triangle stability for SMIB, single machine infinite bus systems. or two coherent or non-coherent synchronous generators. The same concepts or notions are also applicable to multi-machine systems.

The only get around or way around for doing such an analysis is to make use of numeric integration techniques because the number of swing equations involved would be very high and it is not always necessary that the transient triangle stability analysis will always be done for a dead short circuit fault. There might be cases where, in the post-disturbance situation, power may still flow out of the synchronous machine from an electrical perspective. So essentially the number of equations involved for multi machine systems they tend to go up essentially we have one individual swing equation for every machine. and all these swing equations they have to be solved together to get the swing curves or rotor angle curves for all these machines together. In case the difference between these swing curves tends to remain within a finite limit, then the system can be assumed to be stable; else, if the differences increase with respect to rotor angle differences, then the machine, as part of the multi-machine system, would essentially go into an unstable state.

And equal area criteria, as I mentioned, this is a direct approach to analyzing the transindo triangle stability, cannot be applied for multi-machine systems because, as I mentioned, the power angle equation need not always refer to a dead short circuit fault. With multiple machine equations involved, the swing equation numbers are also more complex. Remember, the equal area concept or idea was applicable for one swing equation, either for a single machine infinite reverse system or two coherent or non-coherent machines. which can be represented again by a single swing equation. So, that was the limitation of the equal area criteria for a multi-machine system; we have to use numeric integration techniques in order to get these corresponding swing curves or swing points at different points in time.

Before going into the classical transindo triangle stability analysis for multi-machine systems, I will first discuss the assumptions that were involved, just for refreshment or as a sort of summary of what we discussed. So, the typical assumptions involved the aspect that the mechanical input of power the mechanical input power of the synchronous generator it was always constant the dynamics of automatic generation control and AVR automatic voltage regulator they are also neglected because the transient time period is much smaller than the inertia time constant or the corresponding inertia constants of the Respective feedback closed loops. Dampings of the system were neglected, and all system resistances were sort of ignored. Each synchronous machine was represented by a constant internal EMF magnitude, with the rotor angle being the same as the load angle, and this EMF was in series with the direct access transient reactance, flux decay, air gap saturation, and armature reaction; all those aspects were not considered. All loads are assumed to be constant impedance loads, and they are connected as shunt elements, or shunt admittances, or impedances between the bus and the ground.

The bus, being the point where the loads are connected, has its dynamics all ignored, and this is done in a way to sort of avoid doing power flow analysis to the extent possible; the values of the corresponding impedances of the loads are obtained from some base case power flow study. The network is completely reduced using water reduction. To machine nodes where these machine nodes pertain to the internal EMF voltages to avoid doing exclusive power flow analysis during fault, pre-fault, and post-fault conditions to the extent possible. So the different steps if we would do transient triangle stability classical perspective for multi machine system the different steps that would be involved would all start with any for the matter any stability problem analysis would start with identifying a initial operating point or initial equilibrium point where the system was in steady state condition. So the same would be done in the context of multi-machine triangular triangle stability analysis.

We would need a pre-disturbance power flow solution which determines what is the steady state operating condition from which we compute what is the real power which is being generated by individual synchronous machine. Assuming the system's internal losses or machines' internal loss are neglected, we can get an estimate of the input mechanical power, which is going to remain constant as per classical transient triangle stability analysis for the entire period of study. Using this electrical power output, we can also get the corresponding current injection. We have seen this step in the previous lecture while solving one of those solved examples. Once we know the current injection, we can find the internal emf of the machine by using the KVL equation for a synchronous machine.

$$E_i\angle\delta_i = V_i\angle\theta_i \pm jX_s I_i$$

Remember, the positive term here, sign here, would refer to a synchronous generator, whereas the negative term here would refer to the synchronous motor. And correspondingly, for a synchronous generator, the delta value would be a positive angle, whereas for a synchronous motor, delta would be a negative number; that is the aspect which we also discussed in the last lecture. All system loads are represented as constant impedance loads. So we evaluate based on the corresponding base power flow solution and the power ratings or capacities of the respective loads. We evaluate the corresponding impedances and use all these impedances, considering the machine's transient reactance as well.

$$Z_{Li} = \frac{|V_i|^2}{S_{Li}^*}$$

In steady state, we use the steady-state reactance, whereas for transient or triangular stability, we would be considering the machine's transient direct-axis reactance. We convert all the information on a common system base if it is not done already and evaluate the bus admittance matrix as it is done in load flow or as it is done in the context of water reduction. Wherein only the machine internal EMF nodes are retained and all other buses they are reduced, they are neglected or they are sort of hidden in context of considering that the loads are just voltage insensitive or frequency insensitive entities they are referring to just like impedances. So this sort of a retainment it is done for during the disturbance condition as well as for the post disturbance condition depending on what changes being observed in the power network because of which the corresponding bus admittance matrix might change. Based on the different bus impedance matrices that we would obtain, we would then evaluate the expression of electrical power output for every synchronous machine under three distinct conditions.

One being the pre-fault condition, the other being during fault condition or during disturbance condition and the last one is the post disturbance or the post fault condition. So, O, D and P are those subscripts or superscripts which present over here indicate the different expressions of electrical power output under different operating conditions.

$$P_{ei}^{odp} = \sum_{k=1}^{m} |E_i||E_k||Y_{ik}^{odp}| \cos\left(\delta_k - \delta_i + \theta_{ik}^{odp}\right), \forall i \in \text{machine nodes}$$

In fact, we have also seen this sort of evaluation in the previous lecture while we were discussing the second numeric example. So once we get to know the different electrical power outputs under different conditions and with assumption that the electric mechanical power input of every synchronous machine is constant, we get to know what is the form of swing equation that is there for every synchronous machine and then we tend to solve this equation using a numeric integration technique as per the convenience from some initial operating condition where we know that at t is equal to 0 which refers to the point of or inception of disturbance where the machine was in steady state and hence the relative rotor angle speed with respect to synchronous speed was 0 and delta I naught value is being obtained from some base case power flow analysis as has been shown in this particular equation here. So, using this as our initial condition, we apply a numeric integration technique and try to get the values of rotor angles at distinct points in time.

If these different rotor angles tend to have the same pattern or the difference between these rotor angles of different machines tends to be finite at steady state, then the system would remain stable; otherwise, the system would go into an unstable condition from a transient rotor angle stability perspective. The problems of such an analysis for a multi-machine system are that the practical power network generally doesn't abide by the assumptions that we discussed. Some of those assumptions being that system damping is always neglected. It is not there. Whereas, on the other hand, practical power networks have a lot of system resistances, including the machine itself.

So, basically, loads are not always insensitive; they are also sensitive. So, the issue is that practical power systems are complex systems with a lot of assumptions that are not applicable. So, the question is should we first of all understand the application of the classical transient row triangle stability model for multi machine systems, yes it is beneficial, but it also has its own limitation that it will be able to give an estimate of the first swing that was going to happen in the rotor angle in terms of few periods of seconds. So what is meant by this first swing? Let me just give you an example. Suppose I have a SMIB system and the synchronous machines rotor angle has been obtained through some numeric integration technique with respect to the infinite bus and if I plot this different values of rotor angle using some numeric integration technique or by criteria then probably at let us say t is equal to 0 when the disturbance occurred the system is in steady state.

So, the rotor angle is having some bounded variation during the disturbance when the fault occurred the rotor angle had some it might increase, it might decrease and then depending on the severity of the disturbance and till what point the rotor angle was till what point the disturbance was persisting in the sense when the fault was cleared or not cleared. The corresponding rotor angle may have some variation if things are going to remain stable. So, basically, this might refer to a stable operating point. So, what could refer to an unstable point? Suppose I draw another case where the system, or SME system, was in a stable condition and the fault or disturbance persisted beyond the critical period of time. So, it may happen that the swing in the rotor angle may go up, and being unstable, it may further go up.

Being unstable, it may further go up. So basically, what I am trying to do is, with not much damping present, we might experience a change in the rotor angle not only until the first increase; there might be increases in the rotor angles or deviations beyond the first increase. By "first swing," I specifically mean the aspect that is happening or being captured here. The classical ultra angle stability analysis it can at best give a measure of what is the first maximum deviation that is going to happen both for stable or unstable conditions in case of SMIB or multi machine systems. Classical transient ultra angle stability analysis in case the system is going to be in the unstable mode cannot give us an estimate of these swings that might happen, and the system may become further disastrous.

So, beyond this period of classical ultra and rotor angle stability analysis, because of the assumptions involved, the classical model cannot aid in giving accurate rotor angle values beyond a particular period, and it might be necessary, or it might become essential, that the system stability needs to be assessed beyond the first swing. So, because of these limitations, practical trans-neutral triangle stability analysis does need to have dynamic models of all respective assumptions that we have considered in the classical case. So, let us see what those few steps, methods, or incorporations are that can be done in the practical transient rotor angle stability analysis of a multi-machine system. The first assumption that is handled here is that system damping was neglected. So, in practice, system damping will always be present, and there can be different ways of modeling system damping.

One simpler way of considering or incorporating the effect of system damping is through a linear damping characteristic in the form of d omega, where omega is basically the rotor angle relative to rotor speed, and D is the damping coefficient, which is incorporated into the swing equation in this particular form. So this swing equation does not remain a homogeneous second-order differential equation.

$$\frac{2H_i}{w_s}\frac{dw_i}{dt} + Dw_i = P_{mi} - P_{ei}$$

The damping value it varies depending on what is the system damping load coefficient, what are the system turbine characteristic, generator characteristic, winding characteristic and the different network and load characteristics. Typically, and ideally in a power network, the value of D for classical transient triangle stability analysis varies in terms of 1 to 5 per unit. So, by considering this damping effect, the rotor angle swings would experience or incorporate the effect of this damping; the corresponding swing equation itself would change, and in case the system is not going into a stable mode despite having damping, the corresponding character measures may be taken by incorporating corresponding damping here, or by correspondingly increasing the inertia constant, or by playing around with the mechanical input and the electrical power output.

The second assumption that is thrown out of the window here is that loads are all passive. They are not passive at all. They are highly active. And they are voltage-dependent and frequency-dependent; dynamic load behavior has a significant effect on system stability. Composite models that we discussed in the load flow analysis context, where we only considered the effect of voltage dependency, indicate that in practice our loads are also frequency-dependent.

So, when frequency changes, system loads also tend to change, specifically the heating or cooling loads in inductive motor loads. And hence, the assumption of only having voltage dependency in composite load models does not work. We also have to consider frequency-dependent load models. Few typical characteristics of resistive motor load AC loads are given here.

$$P_d = P_{d0}\left(\frac{|V|}{|V_0|}\right)^a\left(\frac{f}{f_0}\right)^b;$$

$$Q_d = Q_{d0}\left(\frac{|V|}{|V_0|}\right)^c\left(\frac{f}{f_0}\right)^d$$

Resisitive loads – $a = 2, b = c = d = 0$

Motor loads – $a = 0.1, b = 2.5, c = 0.6, d = -0.5$

AC loads – $a = 0.5, b = 0.6, c = 2.5, d = -2.7$

So, in the composite load model that we discussed in load flow analysis, the portion on the right-hand side of this particular ordered line, that aspect was not there.

In fact, the model that we considered here in the encircled part represented the exponential load model. In practice, loads are also frequency-sensitive. So this aspect of considering frequency also needs to be considered. By doing so, our loads would also respond to disturbances and the corresponding rotor angle equations might also change. And hence, the corresponding load dynamics also need to be considered appropriately. Loads being passive, that assumption is not applicable at all. The third aspect that practical trans-rotor angle stability analysis considers is that, in practice, apart from the usual disturbances that might happen, there might also be inter-area oscillations, or there might be numerous natural frequencies of oscillations over and above the 50 Hz or 60 Hz natural frequency. These inter-area oscillations are a result of the interactions of power flow between two machines, two areas, or two large graphical areas. And it is quite possible that in the event of presence of these numerous natural frequencies the worst case swing need not always happen in the first instant itself it might happen that if at all instability has to come in the worst case swing might come in the second or third or any other possible peak that might be encountered in the corresponding swing curve or outer angle curve, similar to the effect in the case of resonance, where during resonance, platoon marching in coherency over a bridge leads to a risk of the bridge collapsing if the platoon marching frequency or oscillation natural frequency matches the natural frequency of the bridge. So same sort of event might also be possible for practical transient ultra angle stability of multi machine systems where because of inherent presence of these inter area oscillations, these oscillations might become resonant or coherent at a one particular second or third peak and the corresponding classical analysis might not be even be able to even guess or understand what these peaks are.

So it is possible that the oscillations may retain even after the first swing is out, and hence the corresponding practical triangle stability should analyze the system beyond the first swing. The assumption that the automatic generation control loop and automatic voltage regulator loop, with their time constants being larger than in the transient neutrality analysis, is that their dynamics are not to be considered, which is actually an impractical condition. Dynamics of slow acting AGC should also be considered, fast acting AVR should also, must be considered because both frequency and voltage, they have an impact on the real power output of the machine. Specifically, in terms of real power output. So, detailed modeling of AGC and AVR also needs to be considered in transino-tranquil stability analysis, which can be done through relevant additional differential equations, because of which the number of differential equations involved in such analysis would go up, and as a result.

Constant mechanical power input and neglecting AVR considerations are not practical. In fact, not considering constant mechanical power input to the synchronous machine helps

improve the transino-triangle stability perspective. How does it happen? The aspect comes in the last consideration that the transient ultra-angle stability analysis time period may be larger than the or may be comparable to the time constant of the field winding because of which the machine which is represented by a constant internal EMF and fixed rate axis transient reactance, this model itself may not be applicable. A detailed dynamic model of AGCE, AVER, as well as the synchronous machine along with its turbine characteristics, air gap saturation, and field current limit effects needs to be considered, because of which the number of differential equations would tend to go up, and field flux dynamics also need to be considered because they significantly affect the voltage magnitude, which in turn directly affects the electrical power output of the synchronous machine. And hence, the number of equations and differential equations involved might increase.
One typical model that can be used is a more complicated two-axis dynamic model. In the classical model, we focus only on the direct axis impact. Quadrature axis equations may also need to be considered, because of which this two-axis dynamic model refers to equations in the DQ domain. So that is all for this discussion; the next lecture, which is the last lecture of this course, will conclude with certain challenges that arise with the integration of renewable energy resources and, in a way, what sort of corrective actions can be in place because Renewable energy resources definitely we cannot just ignore them they have to be there because they are green resources but with these integrations coming in what corresponding counteraction should be in place so that transient to triangle stability analysis specifically is not a instable analysis and what all efforts need to be done or to be taken care of.

There's a well-documented report. There are a lot of studies that have been conducted. In fact, there are a lot of blackouts which have happened because of these renewable integrations. So we'll discuss those aspects at length. And we'll sort of end the course with an overall summary of the various topics that we have discussed so far.

Thank you.