Power Network Analysis

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Week-12

Lecture-60

Lecture 60: Stability analysis- Challenges with RE integration

Hello everyone, welcome to Lecture 5 of Week 12 of the course Power Network Analysis, which is also the last lecture of this entire course series. We will continue with the discussion on the last module, which is Transient Rotor Angle Stability Analysis, in simpler words simply known as stability analysis. Although there are different aspects and facets of stability analysis, we have focused only on transient rotor angle stability. And in this discussion today, we will specifically be discussing a few aspects of the challenges involved with integrating more and more renewable energy resources, RE here standing for renewable energy. So, what are the issues that come up? with the integration of these green non-conventional resources in terms of system stability that is what we will discuss. The last lecture we discussed a few classical as well as practical aspects involved in the transient rotor angle stability analysis of a multi-machine power network in which there could be more than one synchronous machine. And it is not necessary for this entire SM multi-machine system to always be represented as an SMIB single-machine infinite bus system or the two synchronous generator cases, which could be coherent or non-coherent; it is not always necessary. And as a result, the equal area criteria concept, which is a direct approach to analyzing the transgenital triangle stability, is applicable. Cannot be directly applied to multi-machine systems, the reasons being. In a multi-machine system, the number of equations involved, specifically swing equations, would be more than one for sure because every synchronous machine would have its own corresponding swing equation in place for understanding the transient stability.

The second important reason is that the multi-machine system need not always experience three-phase bolted faults at the terminals of the synchronous generators or elsewhere in the network, during which the electrical power output need not always be 0; it could be a non-zero quantity, and in such a case, often the right-hand side of the swing equation will not be a constant quantity, and as a result, solving the swing equation through conventional integration techniques. may not always give a closed-form solution for the rotor angle curve or the swing curve, and that is where numeric integration comes into the picture. So, today's discussion before we go into the challenges involved with

renewable energy integration on triangle stability analysis starts with a few methods or steps that can be thought of as bringing into the power network, which may help in improving the transient row triangle stability perspective. So, what are those steps before I sort of go into those methods? I will probably rewrite the typical swing equation that we have seen for a given synchronous machine, which is 2H by omega s d omega r by dt equal to Pm minus Pe, and furthermore, omega r is d delta by dt.

$$\frac{2H}{\omega_s}\frac{d\omega_r}{dt} = P_m - P_e$$

$$\omega_r = \frac{d\delta}{dt}$$

Where h is the inertia constant of the machine, omega s is the rated synchronous speed of the machine at which the rotor should rotate in steady state.

Omega r is the relative rotor speed with respect to the synchronous speed. P is the time variable, Pm is the input mechanical power to the machine, Pe is the electrical power output of the machine, and delta is the corresponding rotor angle, which is what we are measuring or trying to look at. And in the classical transient neutral angle stability perspective, this angle happens to be the angle of the internal EMF measured with respect to some voltage phasor. In essence, the entire stability analysis is dictated by these two first-order equations, which can also be rewritten as a second-order differential equation if we set omega r as d delta by dt over here. So in order to ensure that transino triangle stability always occurs and instability problems are addressed.

Each of these terms, be it the inertia constant, the mechanical power, the electrical power, or the rotor relative speed itself. All these terms have their own rules. So, the methods that we would discuss would essentially be talking about the roles of these different terms or, in fact, we can also define P A acceleration power as P M minus P E. So, P A will also have a role because it is dependent on P M and P E. The first method which To help improve transient rotor angle stability, it is essential to ensure a higher value of H, which is the inertia constant.

So, the associated swings or oscillations encountered during a disturbance or a fault are minimized. How? We have probably also discussed this aspect in the previous lectures. Where a disturbance is likely to impact the acceleration power, and if this acceleration power happens to be large in quantum, the corresponding equation dictates that this term should be equal to P a under all dynamic conditions. So, if in a case where a synchronous generator or by some measure the H value is higher for the same value of PA, the corresponding rotor acceleration would be lesser compared to a case where the H value is smaller, the corresponding rotor acceleration would be higher, which may ensure that the rotor would have a large possibility of either gaining a lot of kinetic energy or reducing a

lot of kinetic energy. In order to compensate for the value of acceleration power, if h is also high, the corresponding rotor acceleration can be limited and minimized in terms of quantum.

And the problem becomes even more concerning with the increased integration of renewable energy resources, which do not support the inertia constant, specifically solar PV, battery energy storage, or all those devices that are integrated through a power electronic converter. So the possible ways of improving system stability in the presence of renewable energy resources are to bring in proper control actions in the power electronic inverter or converter, which is integrating or acting as an interface between the renewable energy resource and the power network. Certain techniques which help improve this control action are known in the literature as virtual synchronous generators. or synchro converter or regulating the DC link capacitor voltage of the interface in between so that, by proper control action, the inertia quantum H value at the interface bus can be emulated even if it is not present. So the term VSG, or virtual synchronous generator, essentially refers to the aspect that, by proper control action of the control philosophy in the pilot running converter, which basically consists of switches and some signals or pulse width modulation signals, regulates the closure or opening of these switches.

By proper switching and with proper control gain and proper control feedback, the inertia value can be increased or decreased at the interface level of the converter. By regulating the real and reactive power output of the converter, that is essentially what all these devices do, be it a virtual synchronous generator, which has a lot of dependency in terms of the electrical power output of the converter. A synchronous converter basically regulates or tries to play around with the level of frequency at which the converter is operating, the switching frequency, and the resealing voltage capacitor; it helps regulate the voltage level on the DC side so that the corresponding P and Q on the AC side are regulated. By properly regulating or emulating the electrical power output at the interface level, inertia emulation can be achieved. The next possibility is: Why should mechanical power input be constant? We discussed that in the practical aspect of trans-node triangle stability earlier.

Why should we ensure that mechanical input power is always a constant quantity? Why can't AGC dynamics come into the picture so that in the event of a disturbance when the electrical power is experiencing variations, on similar lines, if the AGC can also reciprocate to the electrical power output change, which in a way would also bring about a similar change in the mechanical power input, then essentially what we are trying to say is that by having fast AGC action, it can follow the electrical power output better. So that the electrical mechanical power input is also regulated, overall the acceleration power during disturbances would be small, and as a result, the effective rotor acceleration or de-acceleration would also be minimized, no matter what the inertia constant is. The third

measure could be to provide sufficient damping in terms of dynamic arrestors or resistive entities or through the damper findings of the synchronous machine. So that no matter what disturbance comes in, with sufficient damping, the transients or over-transients would be minimized and limited, and possibly the chances of instability would decrease. The only pitfall with the use of dynamic arresters is that they would lead to higher losses even during transient conditions, and often it's an infeasible solution.

I forgot to mention the aspect of the inertia increase. There is a term or statement written here that says it is not feasible in the operational stage. What is meant by this aspect? We cannot expect a converter, the Pilotronics-based converter, to change its control philosophy once it is already in commission mode. Once it is already implemented and in the field, it is not possible to go and change the pilotronic converter control scheme in real time. If one has to sort of emulate the inertia perspective from the proper control action of a pilotronic converter, proper design is required.

Proper planning is required, and hence we also have to identify which of these converters at which of these locations in the power network can help improve the transient triangle stability. That is the reason why I mentioned that it is not feasible in the operational stage while the system is operating. Proper planning and design need to go in order to have this inertia emulation. The fourth aspect is that we usually try to understand what we encounter during disturbances; those disturbances are detrimental, and as a result, the electrical power output of the machine usually goes down even if the mechanical power input is not changing. With the electrical power output going down, the acceleration power would go up, so the other possibility is that.

Can there be ways to increase or ensure the same power output level even during disturbances that are detrimental to synchronous generators by having a high automatic voltage regulator gain, through proper voltage compensation, or by using certain FACTS devices? All this is okay and possible to do. A lot of research is already in place. A lot of researchers are already working on how to have these methods in place. The only word of caution that, unfortunately, we cannot discuss as part of this lecture is that ensuring high automatic voltage regulator gain, although it helps improve transient ultra-angle stability because electrical power output tends to go up, also needs to have a trade-off regarding how high this gain can be. With a lot of high value of the gain, there might be a chance of a disturbance, which, if it occurs, may bring in small signal instability, which we have not discussed.

So, one individual factor, the high AVR gain value, can enhance transgenital triangle stability, but at the same time can also bring in high chances of small signal ultra-angle instability. So, a word of caution is that electrical power output should be improved and enhanced; the impact of disturbances should be minimized, but proper care must be taken to ensure that while trying to improve one aspect of stability, another instability problem does not arise. And specifically with respect to voltage compensation devices, voltage

stability or instability can also occur, which unfortunately we have not been able to discuss in this particular lecture. The last few measures could be why the generator or sources should always bother about maintaining transient triangle stability. Why should the load also not respond? Why should it not have demand response behavior? So that the load also reciprocates and helps ensure maintaining system stability because essentially the load is being served during these transient conditions.

So proper load shedding measures, corrective measures, and curtailment measures can also help minimize the need for increasing high mechanical power during disturbances. And the last aspect is from the protection perspective, where we make our relays highly sensitive and highly fast-acting in time. So that the fault clearing is done as early as possible and the duration of disturbance is as low as possible, it is kept to a minimum. There again goes a word of caution that if we start making our relays and circuit breakers fast-acting in nature, with everything becoming fast, there also comes a significantly increased chance of loss of reliability. A relay with a fast operating time or a breaker with a fast operating time may also tend to maloperate even during a non-fault condition.

 For example, a load switching event has occurred where the load has gone down, and as a result, the generation quantum has still not changed. It can also replicate or behave as a single-line-to-ground fault. With a load increase pattern, and in such cases, if the relays start sensing these very sensitive currents with fast-acting devices, then yes, from a stability perspective, they are beneficial, but there should not be demerits in terms of system protection. So, with that, let's go into a bit of a summarized version of what I am trying to focus on in this particular lecture. Stability, as we have discussed, is primarily dependent on the initial operating condition of the network and the type of disturbance encountered in the network; as a result, stability problems, according to the recent IEEE Secret Task Force paper, can be categorized into five categories, which we discussed in the first lecture of the stability discussion. And, as mentioned, the disturbance can have various components. It can impact different parameters, ranging from system frequency to voltage levels to the quality of power distribution, as well as the rotor angles of synchronous generators. So, in terms of renewable energy integration, since inertia is an important factor or a constant in some equations, conventional synchronous generators or machines inherently have this intrinsic inertia, which helps in counteracting the initial power imbalances between mechanical power and electrical power during disturbances. And this inertia value, as I had discussed earlier, $2h \cdot \omega_s \cdot \frac{d\omega_r}{dt} = P_a$, depends significantly on the value of P_a and h, as the corresponding rotor acceleration does. This rotor acceleration is also a measure of the rate of change of frequency known as rock-off.

So, these two quantities go hand in hand, although they are analogous. If we get an estimate of d omega r by dt, we can also get an estimate of the rate of change of

frequency. For systems that have a high inertia value experiencing the same quantum of acceleration power, it is expected that this quantum of d omega r by dt will be smaller, and as a result, the rate of change of frequency would also be minimized. A typical plot of different control actions from a synthetic inertia perspective to different control loops of automatic generation control—the primary, secondary, and tertiary control, which we have not discussed in this particular course discussion. Advanced courses on system stability and control can cover these topics in detail.

With high inertia emulation or high synthetic inertia in place. For the same quantum of acceleration power, the dip in the steady-state frequency can be minimized, and the frequency nadir, which is basically the point at which the frequency has gone down to its lowest possible value, can be brought up. The lower the frequency deviation is in the network, the lesser the chance of rotor angle instability, and the lesser the chance of frequency instability. This report is a very well-documented report done as part of collaborative work between Power Grid Corporation of India and IIT Bombay, which is basically an Indian assessment. So basically, the title is "Assessment of Inertia in Indian Power Systems with a lot of renewables in place. What sort of impact does the system inertia have that can affect the Transient Triangle Stability? It is very well-documented in this particular report. Since inertia is a concern, let's talk about the inertia aspect that we have briefly discussed in the previous lectures as well. Unlike synchronous machines, renewable energy resources are integrated through a palatronic-based interface that acts as a decoupler between the mechanical power and the input electrical power from the synchronous generator perspective. Unfortunately, renewable energy resources in the conventional perspective cannot provide this inertia-inertial response, and if we talk about the H constant, which is the inertia constant, it is essentially the ratio of the stored kinetic energy in megajoules at synchronous speed in a given machine divided by the rated power of the corresponding machine.

$$H = \frac{\text{stored KE in } MJ \text{ at syn. speed}}{\text{machine rating in } MVA} \text{ (seconds)}$$

So with the integration of, basically, the H whose unit is in constant seconds is a ratio of energy to power. The H constant is essentially a measure of the availability of stored kinetic energy in the system, which the synchronous generator can dissipate or gain during rotor deceleration or acceleration, respectively, and that's the essence or reason behind why H is measured in seconds. So basically, a system or a network that has a higher value of H will be able to handle a disturbance or a disastrous disturbance from the electrical perspective because the same H value also represents how much kinetic energy is stored in the network inherently, which can still be used. Minimize the generation load imbalance while trying to work on minimizing the impact of the disturbance or while trying to curtail the impact of this disturbance. So, a system having a high value of H in

terms of seconds indicates that the corresponding strength of the system to handle a disturbance for a longer period of time tends to go up. Thanks to a lot of kinetic energy that is available in the network.

So that's the reason why, with more integration of rotating mass, the H value also tends to go up because kinetic energy tends to increase with increasing rotating mass, as well as the machine or generation capacity tends to rise. So in a way, with rotating mass, the value of H doesn't change much. But now, if we have renewable energy integration resources that cannot emulate or directly provide this inertia value because there is no rotating mass involved at all. So the energy quantum doesn't change much; only the generation capacity has gone down, and as a result, the value of H tends to go down, meaning that during a disturbance, there is not sufficient stored kinetic energy, although there is sufficient generation capacity. Steady state generation load imbalance occurs, but not during the transient period, and that's the essence we have discussed earlier as well.

Also, there is a trend of having more and more HPDC links replacing the high-voltage AHV transmission lines, which in a way is also acting to the fact that with decreasing overall system inertia, the system operation and control are becoming more and more challenging. This is a plot that is obtained or given in the same report that I mentioned a couple of slides back, which shows that with an increase in the penetration of renewable energy resources, the corresponding inertia constant that the authors in the report have calculated. They are showing that the value of H is also tending to decrease. So it's likely that a trade-off needs to be made between the amount of renewable energy that can be integrated and the type of system flexibility that can be provided so that system stability is not at stake. What can be done, or what issues can we expect or encounter with the growing integration of renewable energy resources? The overall system inertia is tending to decrease.

The renewable energy resources also have high intermittency in terms of their power output, as a result of which this variability does pose challenges in terms of system stability, specifically during significant disturbances. The countermeasures or effective ways of handling these sorts of instability problems from an inertia perspective for renewables are to make use of certain energy storage devices like flywheel governor mechanisms, battery energy storage systems, or electric vehicles specifically from a vehicle-to-grid mechanism perspective, which is usually conventionally in India still in grid-to-vehicle mode. Vehicles are still charging themselves from the grid, but V2G mechanisms, where vehicles can support, exist because electric vehicles are basically lithium-ion-based storage devices. They can discharge and provide additional kinetic energy support in the V2G mechanism, which is the vehicle-to-grid mechanism, and help improve system inertia or the possibility of having higher energy rotor angle stability. All these mechanisms in terms of energy storage need proper control action.

From the perspective of the power electronic interface converter that is connecting these devices to the electrical power network. So the control action perspective is important here while maintaining or fetching energy storage as the demand for power has increased. I'll explain and discuss two typical case studies relevant to system frequency and system instability perspectives. So the Southern Australia blackout that happened in September 2016 was due to extreme weather conditions that led to the disconnection of three critical transmission lines in the Southern Australian power network, as a result of which this disconnection occurred. A lot of other devices, like wind power generation, had almost 25% capacity shut down because of inherent protective measures in place at the wind power generation sites.

And as a result, there was a lot of isolation or islanding that occurred, which caused the entire southern Australia to be somewhat isolated from the broader Australian power network due to the overflow protective mechanism of a particular interconnector. The result was that because of a cascading event which started with bad weather conditions and the subsequent international and national line tripping, the corresponding power generation was curtailed, resulting in the system frequency collapsing and causing a significant power outage, almost a blackout condition, leading to an imbalance between the remaining generation capacity and electricity demand. These two links, in fact this link here, provide a detailed study of how these events were. The summary or takeaway from this case study is that the system frequency was a troublesome factor here. So, if the system had sufficient inertia emulation devices in place even during the outage of a lot of wind power generation and with sufficient reserves in place, this blackout event could have been avoided to the extent possible.

Obviously, there would have been detrimental impacts on the power network, but those impacts would have been limited; the unhealthy parts would have remained isolated from the network with the inherent protective devices in place, and the rest of the power network would have still remained healthy, provided there were sufficient inertia emulation capacity devices and sufficient reserves in place, which need to be encountered or activated. Properly when the power demand went up. The next case study is the case of the United Kingdom. The blackout happened in August 2019. It had a substantial impact on several consumers.

Almost 1 gigawatt of power disruption occurred, which was nearly 5% of the country's overall consumption. The total generation loss, it surpassed the available backup reserves prompting the implementation immediate demand response measures to bring in back the system stability and frequency. The plot here shows the sequence of events that typically happen. The plot or the x-axis of this plot is in the order of seconds. And the y-axis here is a measure of system frequency in hertz.

The UK system has a nominal frequency of 50 hertz. Pardon me for the faint color of this plot. But the events do bring in the importance of frequency. How the actions happened. So, a critical fault occurred because of this incident of the blackout; it happened at 4:52 PM on a particular day in August 2029, and in a fraction of a few seconds— not even a second, in fact— in a fraction of 39 to 40 seconds, the system frequency dipped from 50 hertz to 49.2 hertz, and this dip occurred. The demand started responding for a certain period of time, but still, the power demand was so high that the frequency went all the way down to 48.8 hertz, as shown here. You can see or compare the timelines; the entire grid was responding within a minute, and 50 hertz dropped to 48.8 hertz. There is a substantial dip within a minute, and as a result, the existing generators also started tripping because of under-voltage or under-frequency protective operation; effectively, the ESO or the corresponding operator had to activate almost 1 gigawatt of backup reserve, and gradually, from 4:53 PM onwards until 4:57 PM, it took almost 4 minutes to bring back the system frequency from 48.8 Hz to 50 Hz, thanks to the corresponding backup reserves that were in place, although they were slow-acting reserves; with proper balancing of their activation, the system frequency was somewhat brought back. So reserves also play a very critical role in terms of system stability. In terms of short-circuit levels, which is basically an extension of what we discussed in the fault analysis module, short-circuit levels sort of determine the system's capacity to supply power in the event of a failure. With high short-circuit levels, conventional protection schemes tend to work well with renewable energy resources, which also have the demerit of limited fault current capacity because of the pilotronic interface converter. The fault identification or protection work itself becomes a challenge.

So what are the ways to address these different fault levels? Try to bring in certain paratronic-based control philosophies that can emulate the synchronous machine characteristics during a fault. Specifically bring the fault right through the capability feature into the power turning converter. So that the corresponding transient overratings during the fault event can be minimized or maintained, or proper support action can be given from the protection perspective. So that's all for the discussion I have. I'll just take a few minutes to summarize the course we discussed.

 It's been a series of 60 lectures since we started our first lecture. It started with an introduction to power networks, how power networks came into existence, what the first DC network was, the lower management area, Nikola Tesla and Edison and their competition, how AC machines came to be, and how the AC network came into existence. So that was our first lecture. Then we moved on to basic circuit principles in which we talked about power, impedance diagrams, triangle diagrams, and the essence of KVL and KCL.

Then we moved to transformers and period analyses. Where we talked about three-phase transformers and the importance of understanding per unit analysis, and how it helps in

resolving many aspects, specifically from transformers with different turn ratios. Then we talked about the module on synchronous generators, where we discussed salient pole machines, cylindrical pole machines, their steady-state models, as well as the economics involved in operating several such synchronous generators while feeding in a corresponding forecasted load. Then we moved our focus to transmission lines, where we understood how the resistance, inductance, and capacitance of the transmission lines come into play. And then, from a steady-state perspective, from a modeling perspective, and from a performance perspective, how do we connect these different line parameters that we incorporated into our line models: short line, medium line, and long line models? And then based on these different discussions that we had, the models, the synchronous generator behavior. We move to our next module, which was power flow analysis, essentially a steady-state tool, an offline tool that helps in understanding the impact of different contingencies or disturbances from a long-term perspective.

The next module was fault analysis, which was a sub-transient period in which we got an idea of what could be the worst-case fault currents encountered in the power network under different operating conditions, and based on which the corresponding relay settings and circuit breaker settings are decided. Then we discussed one typical transient analysis study, or transient period study, which was transient no-triangle stability analysis. Although stability analysis in itself is a very detailed module, we focused only on this particular aspect. So in a way, we sort of covered different steady state, sub-transient, and transient analysis periods of study for the power network, starting with the basics of permanent analysis, transmission line parameters, and transmission line modules.

So, with that, I sincerely thank all my viewers. I sincerely thank IIT Kanpur. I sincerely thank the NPTEL team at IIT Kanpur, who have facilitated and helped me in recording these lectures for quite some time now. I also thank my family; I also thank my students, specifically Sunil, Nivedita, and Abhishek, who have been a great support in the preparation of these lectures, the corresponding assignments, assessments, and so on. Thank you so much.