Power Network Analysis

Dr. Abheejeet Mohapatra

Department of Electrical Engineering

IIT Kanpur

Week-09

Lecture-43

Lecture 43: Fault analysis-Synchronous machine parameter's variation time constants

Hello everyone, welcome to Lecture 3 of Week 9 of the course Power Network Analysis. In this lecture, we will start with our second-to-last module, which is fault analysis, and specifically, we will understand why this analysis is necessary not only in this lecture but also in the next lecture, and the discussion that we are going to have is how. What is the impact of a fault? So, what exactly is a fault, first of all, and what is the specificity behind the behavior of a typical conventional synchronous generator during a fault, regarding which we would understand more in today's discussion? So, this lecture is going to be more about the variation in the synchronous machine parameters, specifically the synchronous reactance of the synchronous generator, which we have indicated by x, and the associated time constants. We will spend more time discussing the time constants, preferably in the next lecture. In today's discussion, we will talk more about what a fault is and, if a fault occurs, how the synchronous machine, which is the major source of electrical power, responds. How does that machine behave particularly during a fault? So, until the previous lecture, we had finished with different techniques involved in the steady-state analysis of a given AC network, both for transmission as well as distribution systems, and we talked about different techniques starting from the Gauss-Riedel method.

Till next, we discussed the Newton-Raphson method; then we covered the fast decoupled method, followed by the DC model, and finally, we talked about the backward-forward technique for distribution networks, which is a very specific technique for simplifying the solution of complex equations in distribution networks. The first four methods are primarily used for the high voltage transmission network. Before I go further, I have probably not clearly explained something about the DC model. So if you recollect the DC power flow lecture discussion, there in our lecture, voltage phase angles and bus voltage phase angles theta were expressed in terms of the X matrix, which was again multiplied by the power injections at all buses except the slack bus.

So, this vector equation was not applicable for the slag bus because the phase angle reference for the slag bus is already known or defined. And this X matrix that we discussed, this X matrix was actually the inverse of the B dash matrix, where B dash is the matrix that was also used in the first half of the fast decoupled power flow method. So, this X matrix is actually the inverse of the B dash matrix, which is part of the fibers obtained or used in the first half of fast decoupled power flow. This X matrix should not be confused with the matrix that is based on the actual line reactances. So, let us say we have two buses that are connected by a transmission line of reactants XMN, the buses being M and N; the line reactants are XMN.

This XMN is part of the B' matrix and has nothing to do with the capital X matrix used in DC power flow. That was one point. The second point is that after obtaining all these phase angles, we also saw that the power flow from bus M to N on the line connecting them. It is nothing but theta m minus theta n divided by small xmn, where xmn is the actual line reactance. This xmn should not be confused with the m, nth element of the x matrix; this inference should not be made, as this is absolutely incorrect. xmn here is actually the actual line reactance, so I just wanted to emphasize these two points before we go further. So, coming to our module of interest, which is fault analysis, how do we define a fault? A fault is any disturbance in the power network that interrupts the flow of normal current. This normal current is flowing from the sources to the loads, so we would also refer to this normal current as the load current. So any such event, perturbation, or disturbance that hampers a particular load from getting its corresponding current from the source would be called a fault. And why does this fault occur? The power network is a man-made network that consists of several elements and components, starting from the source, transformers, transmission lines, distribution lines both underground and overhead, and then including step-down transformers, substations, circuit breakers, etc.

So there are a lot of components involved behind setting up this power network. So any such element or component, when it fails due to manual intervention, probably due to maintenance, aging effects, or continuous operation, would have its own lifespan. So, any of those activities, either prolonged use of a particular element or maintenance scheduling perspective, if the system element is no longer operational, might interrupt the normal flow of load current, and that is what we would call a particular fault. So, in general, the category or basket of faults is going to be large. In fact, there is another inference behind defining a fault.

The other inference is that typically, when a fault occurs in a power network, The bus voltages tend to go down; that is a typical signature of any particular fault. The bus voltages tend to go down from their actual values, whereas the current, typically the current in the line or the current injection at a particular bus, tends to go up. This is a very typical signature behind any fault that occurs in a power network. Any activity or event that does not follow this particular signature we would not classify as a fault, and regarding why this signature occurs, please have patience; we will address this particular signature of voltage going down and current going up as we delve deeper into the individual faults that we would consider. So at the outset, having said that a fault is any disturbance that interrupts the flow of normal load current, the fault can again be categorized into two classes: one being symmetric faults and the other being asymmetric faults.

Since our power network is a three-phase network, if we have a transmission line where the three lines correspond to phase A, phase B, and phase C, and if a fault has occurred that equally affects all three lines, then it is imperative that the normal flow of current through these transmission lines to some far-off load will not reach the load, and all three currents will be equally affected. So symmetric faults are those cases where all three phases, from the perspective of current or voltage, have a similar pattern, diminishing behavior, or increased behavior. Asymmetric faults are those cases where three phases of the line exist, but instead of equally affecting all three phases, either only one phase gets affected or two phases get affected together. Affected the third phase; at least one of the three phases is not being equally affected, and that would be called unsymmetric faults. So there can be different categories of unsymmetric faults; as I mentioned, if two phases are affected, we would call them a two-phase fault.

If one phase is affected, then we would call it a phase-to-ground fault, and there can be several other combinations of unsymmetrical faults. So, we will not go deep into that category; yet, we will take it up probably in the third or the fourth lecture of this particular fault analysis module. What we would be more interested in is having understood that a fault would have this particular signature. Let's understand, okay, what the impact of this particular signature is when, during a fault, the current tends to go up.

So let's see. So in our previous discussions, previous modules, like the power flow analysis module, we have discussed the steady state behavior of the power network at length. During the synchronous generator module, we also discussed the synchronous generator steady state model at length. And during that discussion, we understood that for a cylindrical rotor machine, the machine equivalent model or equivalent circuit representation will have a constant EMF, electromagnetic force, or internal EMF behind a synchronous reactance Xs. And this synchronous reactance is a component of the armature MMF reactance, which is the linkage with the stator flux. as well as the air gap flux and the rotor MMA flux.

So, asynchronous reactance arises from all those aspects considered together: the leakage component, the linking between stator flux and rotor flux, and so on. For a non-cylindrical pole machine or for a salient pole machine, we also understand that since the air gap is not uniform in a salient pole rotor, the air gap is minimum along the direct axis and maximum along the quadrature axis. So a salient pole machine, instead of having one unique synchronous reactance, tends to have two unique reactances, which we call XD and XQ, XD being higher than XQ. Usually, in fact, in practical cases, XD is much larger than XQ because the air gap along the right axis is minimal, so more linkage happens around the right axis. The air gap being maximum along the quadrature axis, the corresponding linkage is also minimum.

All these discussions that we had about the steady state operation won't be true in the event of a fault or, for that matter, during a disturbance occurring just at the terminal of a synchronous generator. If we understand why this steady-state behavior is no longer applicable for a disturbance or a fault, for a synchronous generator case, we can also extend this discussion to a fault or disturbance happening elsewhere in the power network. So we'll focus more on the synchronous generator behavior specifically, and then we'll extend this as and when required for faults at any point in the power network. So usually in this statement, we have just emphatically mentioned to mean the event of a short circuit or fault. So basically, a short circuit is also a type of fault in which the normal flow of load current is interrupted.

The short circuit refers to the current taking another path of least resistance; currents tend to always flow in the path of least impedance or resistance. So during a short circuit event, the current tries to flow through another path that has the least impedance or resistance and not through the usual transmission lines that the loads use to get their corresponding power. So, by short circuit, I specifically mean that during a fault or even during steady-state conditions, what we have seen is that typically, for a well-designed synchronous generator, the resistance or winding resistance can be neglected. The overall state of current tends to lag the corresponding internal EMF or the terminal voltage by almost 90 degrees; because the overall synchronous generator circuit, if the resistance is neglected, becomes purely reactive. Inductive circuit and for a pure inductor, the currents tend to lag the corresponding applied voltage by 90 degrees.

So it is not just during the fault, but in usual operation during steady state, also the state of the current of the synchronous generator tends to lag the corresponding applied or terminal voltage by 90 degrees, and for salient pole machines, since the direct axis reactance is larger, and as I mentioned here, the value is much larger than the quadrature axis reactance. So in terms of armature reaction, the armature reaction MMF produced due to stator excitation would mostly lie along the direct axis; the least part of it would lie along the quadrature axis because of the large distance. Not much of armature reaction would link to the corresponding rotor windings or rotor currents. It would mostly be impacted along the direct axis because the direct axis gap is minimal. So any armature reaction effect that arises because of the current is linked to the rotor along the direct axis, and that is the reason why I have mentioned that it is centered almost on the direct axis during typical steady-state or transient operation.

The catch behind all this discussion is that right after a disturbance or a fault at the terminal of a synchronous generator or a machine, the machine reactance, which we call Xs for a cylindrical pole machine, or if we talk about the dominant reactance, For a salient pole machine, the value of x, either xs or xd, does not remain constant; it varies with time as the machine experiences a fault or a disturbance. We will understand why this variation happens; please have patience, we will get into that aspect. I am just trying to emphatically state the reason for the discussion that we are going to have. So, because this machine's reactance is varying, the generators' response, or for that matter, the power network's response after a fault can be categorized into three distinct periods. The first one that appears is the subtransient period, which is just after a fault or a disturbance at the terminal of a synchronous generator.

Followed by a transient period that is a little bit larger compared to the subtransient period, the subtransient period typically lasts for 1 to 5 cycles, whereas the transient period would last for a few hundred cycles. Followed by the last steady state period in which the RMS values of voltage and current do not tend to change, during the subtransient and transient periods, the currents and voltages have time variations because the machine reactance is also varying with time. And overall, during the steady state analysis which we have discussed earlier, we have emphatically discussed the steady state period only. We have not previously discussed the sub-transient and transient periods. Now, why would these periods exist? It again goes back to this philosophy that the machine reactance is not constant.

So, in terms of the current envelope, this is basically the short-circuit current. Basically, it is the stator current that is typically plotted for a synchronous generator that has experienced a fault at time t equals zero. And this is a typical signature, a current signature that appears to indicate that the current would tend to go up compared to its previous steady state value, which is noted by this dotted line. The current magnitude would tend to go up and reach its maximum peak during the subtransient period, which we call the subtransient envelope, and gradually this peak current tends to decay in the transient envelope; the decay is still not 0. So, finally, after the decay has happened at t equal to infinity, the steady state period would begin, which typically happens after a few hundred cycles.

So, depending on the machine parameter, which is essentially the value of inductance L that the machine is exhibiting, and the associated resistance value, are the sub-transient, transient, and steady-state periods. The steady state period does not get affected much, but the sub-transient and transient states would have a strong dependency on how inductive the machine is and how lossy or lossless the corresponding synchronous machine is. So, we will again understand why this current behavior happens just after a fault at t is equal to 0 in the terminal of the synchronous generator. Please have patience, and please bear with me. Before I explain why this variation happens, first of all, let us understand the premise of how this variation is occurring.

There is a theorem known as the constant flux linkage theorem, which can be useful in understanding this behavior in machines' reactants. So, what I have not explained until slide six is why this current becomes peaky and then tends to decay, assuming that the synchronous machine stator current per phase is the armature current. has this behavior assuming that we can apply this constant flux linkage theorem and then understand in a reverse engineering fashion that why the synchronous machine parameter has variations at all. What it states is that in an inductive circuit, the flux linkage along any closed circuit with finite resistance and reactance cannot change instantaneously if there is an EMF source present. If there is no active source in the corresponding closed circuit, there is no question of flux linkage appearing at all, but if the circuit has an EMF, the flux linkage in a closed circuit of finite resistance and reactance cannot change instantaneously.

The reason is that the corresponding reactance or the inductive effect will always have a finite permeability, and permeability sort of resists the change in the corresponding magnetic flux linkage, which also appears because of the variation in the corresponding synchronous machine parameter. And for our discussion to sort of apply this to salient pole machines, we will assume that Xd is the dominant reactance, so we will correspondingly ignore the value of Xq and look at it from the perspective of how Xd varies. For a salient pole machine, it is all about Xd, whereas for a cylindrical pole machine, it is all about the synchronous reactance Xs. So in the case of a three-phase fault at the generator's terminal, by three-phase fault I mean all three phases of the generator terminal are equally getting shorted through some fault, and the corresponding synchronous generator current is not able to flow to the corresponding load; rather, this current is bypassing through this particular terminal to the ground.

any other short circuit path. And since I have given the assumption that the armature current is used significantly, assuming that the armature current tends to follow this particular envelope on slide 6, I will try to understand why the machine reactance tends to have this variation by understanding the constant flux linkage theorem. So, as per the constant flux linkage theorem, we can numerically associate or state that the flux linkage psi is a function of L and I, and if during the sub-transient period the value of I is at its maximum, it is imperative that, by the constant flux linkage theorem, the flux linkage cannot change instantaneously. The associated L, if the current is at its maximum, would be at its minimum during the sub-transient period. Then, during the transient period, as the current tends to go down, the corresponding L value would tend to go up, and finally, in steady state. The current is at its minimum, and the corresponding L would then again appear at its maximum, so that the product of IL-L during the transient, sub-transient, and steady-state periods does not change much and does not change instantaneously.

Physically, what happens, what leads to this lowest value of L or reactance in the sub-transient period, is that during the sub-transient period, when the stator fault has occurred, the stator flux lines,($\psi = Li$) being in a highly inductive circuit, do not link to the field winding or rotor winding at all. They are locally concentrated; they only just pass out of the rotor core, pass through the air gap, and link more with the damper windings rather than linking much with the rotor winding because damper windings are short-circuit windings, so they don't have initial current and therefore don't offer much impedance or resistance to this change in constant flux linkage. During the sub-transient period, the linking between the stator and rotor windings starts increasing, so more of the stator flux begins to link with the field windings and the remaining damper windings, which leads to more demagnetization and more reactance, and hence the corresponding reactance tends to go up. As compared to the sub-transient period, it is still not that high compared to the steady-state period because of the demagnetization that has started happening. So, the value of L here is at its minimum because there is not much linkage to the rotor winding; most of the air gap, and most of the flux, is linking only to the air gap and some of the damper windings.

In the transient period, the linkage effects have gone up. So, the value of L tends to go up because L is basically a linking effect between the rotor and the stator. And finally, in steady state, almost all the flux links to the rotor winding and field winding, and the corresponding value tends to reach its maximum possible value. So that is the overall essence or basic reason behind why synchronous machine reactance does vary. We still have not understood, thought about, or discussed why the current would have this particular behavior, as shown in slide 6.

So we'll take that up probably in the next lecture just to sort of conclude or summarize. With neglect of armature resistance for a well-defined machine, the machine impedance is mostly reactive or inductive in nature. This is true under normal and short circuit conditions, and that's the reason why the armature current would almost always lag the internal EMF for terminal voltage by almost 90 degrees. IQ is not very significant. So, we are considering most of the impact of Xd, which is the subtransient reactance for a salient pole machine; hence, Xd is of importance.

So, in general, if we have to represent or state that the Xd dash, which is the sub-transient reactance, Xd single dash is the transient reactance, and Xd is the steady-state reactance. The corresponding values of reactances are due to the constant flux linkage theorem, assuming that the current tends to go up in subtransient, goes down in transient, and finally reaches a steady state value. This is the typical signature, behavior, or performance of a synchronous machine in terms of its reactances. We will take up this simple example to better understand the application or implication of these different reactances. So what we have here is a three-phase 60 hertz synchronous generator or machine that is running at a constant synchronous speed.

The armature windings are initially open circuit, so there is no question of armature reaction appearing at all, and the field voltage is adjusted as the terminal voltage at the synchronous generator is equal to 1 per unit; the actual voltage rating is not given. But the machine reactance is under different subtransient periods; transient periods and short circuit periods are given. In case a short circuit fault occurs at the terminal of the machine, we have to find the corresponding steady-state, transient, and sub-transient short circuit currents. Since the machine is open-circuited, the armature current does not exist before the fault. The fault event is the only event that is happening in this synchronous machine.

So the corresponding values of XD double dash, XD dash, and XD, if you see, tend to follow this particular inequality relationship as per the discussion that we had. And if we have to find the corresponding steady-state current, then it is imperative to find the steady-state current again in per unit; which type of reactant should we consider? Should we consider the subtransient reactants to find steady-state current? Should we consider the transient reactants to find the steady-state current, or should we take the steady-state value of x to find the steady-state current? So essentially, that is what is shown in this particular expression here: Id is dependent on the steady-state reactants, assuming E naught, which is the internal EMF, which is again given as 1 per unit. So, 1 by 1.2 is the steady-state current, and if we try to find this current in the transient period, the Xd dash value is lower than Xd. So, the corresponding transient current would be higher, and the maximum achievable peak in the sub-transient period would be the maximum possible value depending on the Xd double dash.

Since the reactances follow a decreasing order from steady state to the subtransient period. The currents also tend to follow an increasing behavior from steady state to the subtransient period, indicating that machine transient reactances are not the same. We will take up the next discussion or lecture on understanding what these time constants are and what the behavior of a synchronous machine is, specifically in terms of armature current during a fault, just after a fault, and in the steady state. And you'll also understand the difference between the fault analysis module and the stability analysis module.

Thank you.