

Power Network Analysis

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Week-02

Lecture-09

Lecture 09: Synchronous Generators-basics of 3 Φ machines

Hello everyone, welcome to lecture 4 of week 2 on the course Power Network Analysis. In this particular discussion we'll start with a new module which is going to be on synchronous generators and we'll specifically start with the basics of how these rotating machines behave in general. We'll start with the basics of rotating machines and then gradually we will dig deep into specifics about this synchronous machine synchronous generator. so far in the previous lectures we have been able to cover two important modules one on the recapitulation of basic circuit principles and detailed discussion on how transformers operate what their behavior is what are three-phase transformers and the beauty or importance of having per unit analysis in analyzing three-phase ac power networks where there could be different components elements in terms of generation transformers transmission and load So if we talk about synchronous generators to be specific, It's well known that majority of power generation, it happens through these three-phase synchronous machines, which we also call as alternators. And it is important to understand the steady state as well as dynamic behavior of these synchronous generators or alternators. Specifically, we will understand the steady state behavior of these machines in this current module, whereas the dynamic behavior will be discussed in the last two modules, specifically in fault analysis and stability analysis.

Why it is important to understand their steady state behavior or dynamic behavior? I'll talk about the dynamic behavior to start with. It is important to understand the dynamic behavior of synchronous generators because the behavior of these machines essentially indicate what could be the maximum fault currents that a network can experience in the condition of a fault. And in case some disturbance happens, what sort of stability actions or control actions can be implemented so that the synchronous generators operate in synchronized mode. We'll talk about synchronized mode in the next few upcoming lectures in this particular module.

So that's where the dynamic behavior becomes important. Steady state behavior is essential specifically from the perspective of the module which we'll talk about is power flow analysis, where we will understand how these generators are modeled or what role they play in steady state studies, one of them being the power flow analysis. That's where these steady state models would be useful. In general, all rotating machines, three phase machines, they have more or less, theoretically speaking, they have more or less similar structure or behavior. Each of these three phase rotating machines, they essentially have a stator part and a rotor part.

The stator part essentially comes from the word stationary, which means there is some circuit or some device or element in these three phase machines which does not rotate or does not move. It remains stationary. So that particular corresponding element or component is called as stator. And if stator word comes from stationary, so rotor word essentially indicates the component or element in the machine which essentially is rotating. that's what the rotor term comes in.

Generally these stator and rotor cores they are made up of laminated ferromagnetic material so that the corresponding core loss be it eddy current or hysteresis loss as as minimum as possible. These losses also happen in three phase transformers or single phase transformers so the idea behind having laminated course remains the same to minimize the corresponding core loss because these are electrical machines so they would also have certain currents induced in these cores. And in these cores, stator and rotor cores, we also have certain slots in which certain conductors can be placed and these conductors can carry current. Depending on the type of machine, these currents could be AC currents or DC currents for general three-phase AC machine. And in between these stator and rotor cores, there exists an air gap.

Depending on the type of machine, the width or the gap of this air in between stator and rotor can vary for larger or compact machines this air gap is smaller whereas for small machines this air gap can be comparatively larger depending on what type of losses one machine can endure while not affecting its efficiency to the extent possible. So if we talk about a comparison between synchronous and induction machines, induction machines, it's well known that the air gap field or the MMF which exists in the air gap, it rotates at synchronous speed. Synchronous speed is often denoted by the symbol or the variable N_s . while the rotor rotates at a speed less than the synchronous speed in motoring mode for induction machine or motor for induction generator the rotor rotates at a speed just above than the synchronous speed so it all depends on what the slip value is in terms of motoring or generating action for induction machines the field current is the only source of excitation for this air gap to exist in the induction machine and essentially the rotor which core which carries conductors It essentially has induced AC currents and those of you who want to sort of refresh how induction machines are or where these nature of currents come in, I would request them to please refer to the relevant textbooks. The rotor

current induced in induction machines is a AC current and its frequency is different from the current from the frequency of the stator.

So basically the rotor current frequency is called as a slip frequency which depends on what is the machine slip. Whereas the field current carries current which is same as the source frequency of the electrical side. And this excitation current induction machines it's responsible for creation of this air gap field which is rotating in induction machines and how the rotation happen we will discuss about that in this particular lecture itself toward the end few slides. The current which is required to induce this air gap MMF or field needs to be lagging current because of the inductive behavior of the rotor core, field core and the corresponding conductors. So essentially induction machines, they generally operate in lagging power factor mode irrespective of whether they are operating in motor mode or generator mode.

Now the distinction between motor and generator, the notion is very simple. A motor is any electrical machine which converts electrical output to mechanical output and that is what decides the direction of this real power flow whereas a generator is a device or a machine which converts the mechanical input fed from the turbine into electrical power output specifically in terms of real power so that is the segregation between generator and motor and for induction machines be it motor or generator the reactive power is always drawn from the electrical side so that this air gap mmf field can exist for the machine to operate And that's the reason why reactive power is always drawn from the excitation of the source side irrespective of induction machine operating as generator or motor. In synchronous machines, the notion is a little different. In usual induction machines or simplified machines, Whereas synchronous machines, they are doubly fed machines in the sense the three-phase windings on the stator, depending on the generating mode or motor mode, they carry AC currents. Whereas irrespective of synchronous generator or motor, the rotor windings always carry external DC supply current.

And hence there are two sources to be fed for this machine to operate and because of this unique nature or behavior the air gap field and the rotor they both rotate at the same synchronous speed inside the synchronous machine the speed of this synchronous value synchronous speed N_s it depends on what is the source frequency and number of poles which are induced or created in the induction machine because of this doubly fed nature of the synchronous machine be it generator or motor it can operate at all power factors could be leading, could be lagging, unlike the induction machine. And there are two typical types of rotors available in synchronous machines. One is called as salient pole machine, in which we have non-uniform air gap between stator and rotor, whereas we have a non-salient machine or a cylindrical pole machine where the air gap is uniform. Please have patience. We will discuss about this particular aspect in the next few slides to come.

As a result, the air gap flux in the synchronous machine, it is resultant of two fluxes. One flux or MMF is because of the stator current and the other is because of the rotor current which is being driven by a prime mover in generating mode or it is driving a mechanical load in the motoring mode. So, as a result the air gap flux is resultant of stator flux in synchronous machine as well as rotor flux. Induction machines basically the air gap flux is consequence of stator current and depending on whether it is generating mode or motoring mode the reactive power is sort of inherently withdrawn from the electrical side no matter whether the induction machine is behaving as generator or motor. The same however is not true in case of synchronous machine and that is where this figure comes into picture.

If a synchronous motor exist which converts electrical output to mechanical output so that is what dictates the direction of real power in motoring mode depending on the level of excitation or the quantum of rotor current in the rotor circuit which is DC current the Motor can also deliver reactive power to the electrical side as well as absorb reactive power from the electrical side. And that is what it segregates or makes the difference of leading and lagging. When an element is delivering reactive power, we often associate it to be behaving like a equivalent capacitor for capacitors the power factors are essentially leading and hence over excited synchronous motor or tends to operate in a leading power factor mode whereas under excited synchronous motor when it absorbs reactive power from the electrical side it intuitively behaves as a equivalent inductor wherein induction or inductors the power factor are lagging and hence it behaves as a lagging power factor mode. Similar analysis or similar analogy is also applicable for generating mode where real power is being sort of delivered from the mechanical side to the electrical side. The reactive power can be sort of delivered as well as absorbed depending on the level of excitation.

So coming to our first element which is the stator windings or armature windings. They are usually three-phase windings for three-phase machines and unlike the notion of these windings being placed at few concentrated slots in the stator core for better utilization of the stator in synchronous generators. The windings are often placed in a distributed manner and windings corresponding to one phase need not be placed in one slot. These windings for corresponding to a particular phase can be present in multiple slots so that the core utilization is as high as possible and it also helps in producing a rotating stator magnetic field in the air gap thanks to the nature of AC currents which are present in the synchronous generator or motor and also the fact that these slots for a particular phase of a winding they are intently spaced apart as 120 electrical degrees in the stator core. And that's the reason why combination of the arrangement of filter windings as well as the nature of armature current in the filter windings, a rotating air gap field is produced.

Rotor as mentioned can be of two types. It could be a cylindrical rotor or a salient pole rotor. The cylindrical pole rotor looks something like this with the figure which is shown over here. What has not been intently shown are the slots for stator windings. So as discussed earlier in this particular slide where the windings of stator are placed in a distributed manner, what I mean by distributed manner, let me show you that.

So basically this is the stator core to define first. This is the rotor core and the white gap which is visible in between stator and rotor is nothing but the air gap. as can be seen at any point between stator and rotor if we compare the air gap width it is more or less uniform and that's the reason why cylindrical rotors have uniform air gap between stator and rotor for the rotor core there are two set of windings which have been shown one set of windings are carrying current which are out of plane of this particular slide. So the dot here essentially means that the current which is flowing in these set of windings they are upward towards the slide plane whereas the rotor windings on the other half they are carrying current in a form of cross which means they are into the plane of this particular slide that means they are carrying current into the particular slide. So now if we recollect our right hand rule which we also talked about in context of transformers for the windings which are present on the left hand side which are carrying current out of the plane if we apply right hand rule then for every such dot current if the thumb points to the direction of the current direction the other four fingers they would curve in the direction of the corresponding magnetic flux which would be produced by these currents.

So essentially for the out of plane currents the flux is basically in a counter direction as has been shown here whereas for the windings which are present on the right hand side the current is into the plane so the thumb points downwards whether the fingers would curve in the direction of the corresponding magnetic flux. And now if we see the corresponding magnetic flux, so let's say for one particular winding if I were to draw the corresponding magnetic flux is let's say in anticlockwise direction whereas a counter winding over present over here the corresponding flux they are all closed field lines so the corresponding flux is in magnetic flux is in clockwise direction and if I were to add or superimpose all these fluxes essentially it would mean that the effective flux because of this rotor current or in the rotor score the flux is leaking out or moving out of the rotor core from the upward direction and the same flux lines since they are closed lines they are entering the core into the downward direction. Now remember in physical magnet magnetic flux lines always originate from the north pole outside the magnet and they enter the magnet into the south pole at the outside Whereas inside the magnet, magnetic flux lines originate from the south pole and terminate at the north pole. So if we apply the same analogy in the cylindrical pole arrangement here, that's what gives us the notion of equivalent north and south pole. That's how this rotor core, which is carrying rotor current, DC current, as shown on the left hand side and right hand side of the particular

core results in this rotor core behave as a electromagnet having the north pole and south pole marked like this.

Now if this particular rotor is behaving as a electromagnet and remember in synchronous machines this rotor is coupled to the turbine for generating mode or some mechanical load in motoring mode. So this rotor is actually not stationary it is either rotating in clockwise direction or in anticlockwise direction because of the mechanical load or the turbine. So essentially if this rotor is rotating as determined by the speed governed by the corresponding turbine or the mechanical load If we have to see how this rotating magnet which is having some flux originating due to out of it because of the rotor current, how this flux is being observed at the stator. So, let us talk about what is present in the stator. So let me erase few particular points here.

On the stator, as mentioned, we have three-phase stator windings, which are not concentrated, but they are distributed. Let's say segregate this stator core into three halves, where each of these three halves, they are at an angle of 120 degree to each other. Pardon me for the inconsistency in precisely marking these angles. If I can segregate this core into three equal halves, each of these halves having an angle of 120 degree at the center, resulting in the entire angle to be 360 around a point, then probably one half of this 120 degree can correspond to phase A windings. The other half could probably correspond to phase B windings and the other half, third half may correspond to phase C windings.

And on all these windings or slots, there are multiple slots present where there are different numbers of armature windings and each of these armature windings may carry current, may not carry current depending on whether the machine is electrically loaded or not. This is just a conventional notion of how the slots would look like on a stator. And specifically for cylindrical rotor, air gap is uniform as already mentioned. It's usually used for high RPM turbo alternators, specifically for steam or gas turbines. They tend to have long axial length.

And since the speed is high, corresponding centrifugal force also tend to be high. So in order to limit the centrifugal force, not doing any mechanical damage to the rotor or the stator, the diameters of cylindrical rotors are intently kept small to minimize the centrifugal force. As already mentioned the field windings they are distributed also on the rotor which are also carrying DC current. If we talk about a salient pole rotor then the air gap is non-uniform as can be easily seen on this particular figure. There are two positions, position A1 and A2 where the air gap is maximum whereas in position A3 and A4 the air gap is minimum and salient pole rotors they inherently have are used for low speed alternators basically for hydro turbines centrifugal force is not a concern so the diameters of these Serient pole rotors could be higher, the axial lengths however are kept smaller and the DC currents on the rotor, so basically this is the rotor here and similarly this is the case for stator here.

Whereas in stator there are certain set of windings which refer to currents ingoing whereas the other winding are carrying current out of the plane. so the rotor winding here carries DC current for this particular north and south pole if we have to figure out what currents these windings are carrying let's say this is rotor winding 1 rotor winding 2 then it's very easy that for a north to exist here the current should be out of the plane here as per right hand rule so basically this is the corresponding magnetic flux line same for winding 2 it should also carry current out of the plane so that the flux gets additive corresponding currents over here they are into the plane as a result of which the corresponding flux lines yes they are in a anticlockwise direction. So the rotor windings they also carry DC current and rotor rotates at synchronous speed in synchronous machines and hence the name synchronous generator. The rotor MMF also rotates at synchronous speed driven by the turbine of the mechanical load. The pole faces in the salient pole rotor, they are intentionally tapered so that the flux distribution remains as close as sinusoidal or rotating in the air gap between rotor and stator and the flux density tends to be maximum at these pole faces which are the pole faces over here.

So the flux density is very high compared to the positions A1 and A2 because the air gap is larger. and the axis along which the rotor flux density is maximum in salient pole machines is called as D-axis or direct axis. So essentially this is what the direct axis is. If direct axis can exist, there can also exist an axis along which the air gap is maximum and the corresponding flux density is minimum, which we call as quadrature axis.

The flux density is minimum there. As a result of these rotating MMF, because of the rotor current in the air gap, the stator also tends to see sinusoidal flux distribution, which is moving at synchronous speed, as a result of which voltage can be induced in the stator windings. That's essentially what we will talk about in the next lecture.

Thank you.

Note :- There is no equation in this lecture.