**Electrical Machines – II**
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**Lecture – 79**
**Armature Reaction and Synchronous Reactance Basic Phasor Diagram**

Welcome to this lecture on Electrical Machines. And we are this few lectures including today's lecture will be very important so far as synchronous machines analysis part and its equivalent circuit is concerned.

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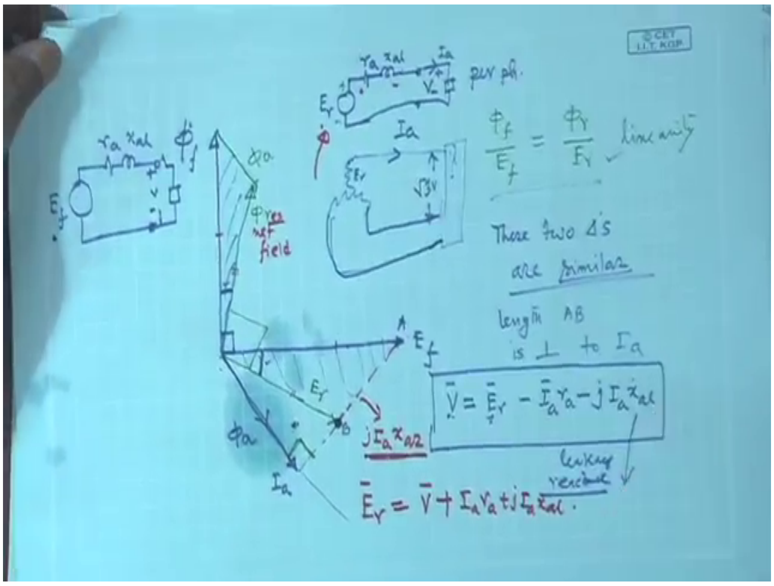


We recall that last time I told you that a synchronous machine when the field is excited with this switch open, there will be some voltage induced E f whose value directly depends on the field current and since the AC side is open circuited if it is open circuited, this same f will appear across V as there is no current.

However, the moment you load the machines by some loading or connected to the bus feeding power to the bus, then what happens? There will be armature current which will be delivered to the load like this ok. So, terminal voltage is line to line voltage root 3V per phase equivalent circuit will be V. Let us assume that this armature current is lagging perfect in nature, then this circuit is inductive including the load as well as its internal leakage impedance r a and x al. So, armature currents will lag this E f by some angle; it is expected to be, but mind you this is not the power factor angle. Power factor angle is the angle between V and this I a, terminal voltages which is appearing across the load and current deliver to the load; the angle between them is the power factor angle.

But, what happens is this that when the armature carries current, there will be now apart from the rotor field; their will appear this stator field which will be also rotating at synchronous speed. And therefore, the resultant field will be this phi a plus phi a; phi a will be along like a because it is a rotating field this is armature current and we know this is rms value. So, maximum across occurs here. So, armature rotating field will be along this like. So, phi f plus phi a; if you do parallel to this I have drawn you get phi r.

And if this is the net field present in the machine; this is not rotor field, net field net field; resultant field. So, this two together will decide phi r and therefore, E r will be lagging phi r by 90 degree and then I have shown that this length considering these two triangles, these are similar triangles. This length AB is perpendicular to your I a phasor.

Therefore, your equivalent circuit will be E r and it is delivering a current I a and this is the r a plus x al is the leakage impedance per phase of the armature coil. Therefore, E r minus I a r a minus j I a x al if you subtract this drop here, you will get the terminal voltage or in other words some it can be also written as E r is equal to terminal voltage plus this drops here. So, this will be I a r a plus j Ia x al; this will be your E r.

E f is not there because the E f was the induced voltage per phase when the machine was under no load condition when the switch was opened. But, the moments which is close we find that the resultant field in the air gap which causes the induced voltage in the coils that changes to E r which is different from E f. But, this change in voltage, we find that this voltage this length is perpendicular to I a. Therefore, we can assume that change in voltage from E r to E f will be can be considered to be a reactance voltage ok.

Although that reactance physically is not there, but I can always think that this change in voltage may be attributed some reactance voltage drop which I will call it as I a x ar. So, E r is there and from E r, I can say that if you add this reactance voltage drop; you will get back E f. So, the picture now looks like that instead of dealing with E r what we will be dealing with E f and that can be obtained by considering this change in voltage from E f to E r as a reactance voltage drop.

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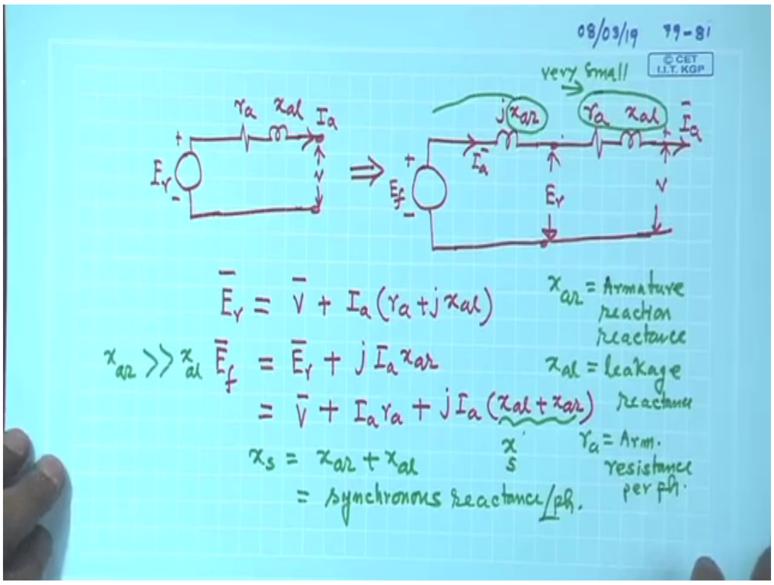


In that case, the this equivalent circuit which I earlier I drew with E r only E r plus minus and this is the leakage reactance drop per phase x al and this was your terminal voltage V and it is delivering some current I a; this is fine. But then what I will tell this same thing what I am telling I will now say, E f is there that is the excitation voltage under no load condition when that switch load switch was opened that thing is there. Then here, you have one reactants j x ar and then I will show my E r here E r and then your r a x al r a x al and then your terminal voltage V phase and it is delivering a current of I a.

So, that you know that E r; if you start from this terminal voltage will be V now these are all phasors plus all I a into r a plus j x al you will get E r and your E f is nothing, but same armature current is flowing. Therefore, E r it will be E r plus j I a x ar and your full equation will be V plus I a r a plus j I a x al plus x ar.

Now, this x ar is a given a name it is called the armature reaction reactance that is why the subscript ar is used. So, x ar is a it is a fictitious reactance and it so happens that this becomes perpendicular to I a and proportional to I a this length is therefore, it can be attributed to a reactive voltage drop reactance voltage drop and therefore, x ar is called armature reaction reactance. And what is x al? x al is leakage reactance as it happens with any coil leakage reactance per phase and what is r a? R a is the armature resistance per phase armature resistance per phase, say everything is per phase per phase.

So, and these two together is given a name, it can be considered to be a single reactance and it is called it is written as x s; x suffix s and x s which is equal to x ar plus leakage reactance is called the synchronous reactance. A very important reactance whenever people talk about synchronous machine, they will ask what is the armature resistance per phase, what is the synchronous reactance per phase; synchronous reactance.

Now, here one must understand this r a and x al, the armature resistance per phase and leakage reactance per phase, these are very small which is always very small like internal resistance of a battery or things like that. So, these are small, but this x ar is quite high. x ar is a many times higher than your x al very large compared to x ar.

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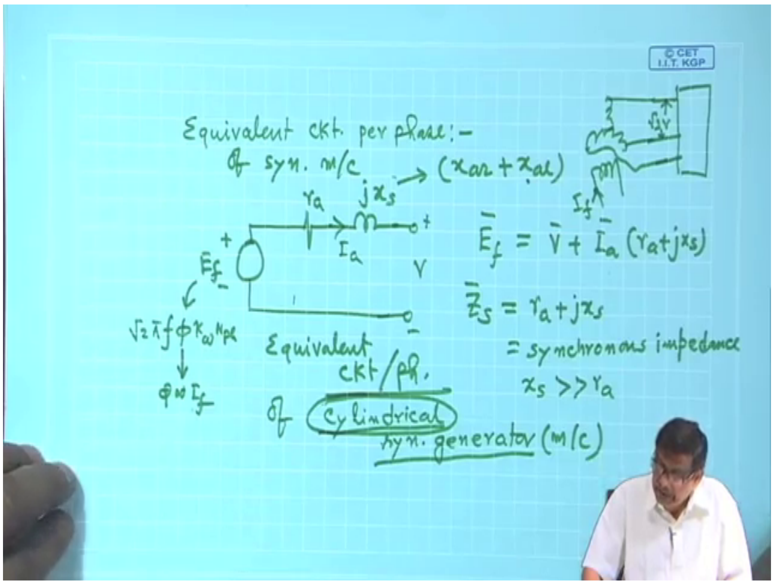


Therefore, after knowing this we can say ok, we will not go to the this E r thing if necessary we will calculate, but henceforth the equivalent circuit. Therefore, will it look like equivalent circuit per phase of synchronous machine will then look like the excitation voltage E f and armature resistance r a and the synchronous reactance x s. Mind you x s always recall; it is equal to x ar plus x al leakage, this is small. And then your load terminals or bus terminals whatever it is V all are phasors I a and I will simply say E f is equal to V plus I a into r a plus j x s.

This impedance is called synchronous impedance of the machine which is equal to r a plus j x s is another synchronous impedance and also here also it is true that x s is much larger than r a. For example, to give you a typical value if suppose the armature resistance per phase is r a, your x s may be 5 times 8 times larger that is if r a is 1 ohm, it may be x s may be 5 ohm or 8 ohm. So, many times larger this x s is in compare to r a or also in compare to x al.

Therefore, sometimes, so, this is the equivalent circuit per phase of a cylindrical synchronous machine. Cylindrical synchronous generator mode, we are considering generator or synchronous machine operating as a generator. So, this is the equivalent circuit, understood? So, this point must be understood.

Therefore, we observe one thing that is unlike the induction motor equivalent circuit of a synchronous machine is much simpler because of what there is no parallel branch like x m and r cl in parallel across the supply we used to show for a induction motor, but that parallel branch is not there. So, it is a greater relief I mean computationally very simple circuit. E f, what is E f? E f is the no load induced voltage when there it is I a is 0, then the terminal voltage will be V will be equal to E f if I a equal to 0 because there will be no drop and when the machine is loaded of course, V will be E f minus this drop and you get the terminal voltage.

There is nothing in parallel because of the fact that is the magnetizing current for a synchronous machine, it is never drawn from the bus or you must understand from this terminal. These two terminals; here if you operate the synchronous machine in isolated fashion, there maybe load that is all, but the exciting current is provided by a separate DC source which is connected across the rotor terminals of the machine which creates flux. Therefore, because of this thing the equivalent circuit of a cylindrical synchronous generators or synchronous machine in general will be very simple will come to the motor mode after sometime.

So, that is it, this is the phasor diagram. E f is a mind you it is equal to root 2 phi f flux per pole K w into N phase of the stator and this phi is I have assumed directly proportional to I f. Therefore, in a synchronous machine, if this is your armature, this is your field, this is your excitation current DC and here is the voltage and here you are connected some 3-phase load. So, this voltage 3-phase load, if it is this voltage is the root 3V and excitation voltage will be inside the machine and this is the internal impedance of the synchronous machine as it is this is the thing.

Now, I have used the term cylindrical synchronous machine. What does it mean? It means there are actually two types of synchronous machine ok.

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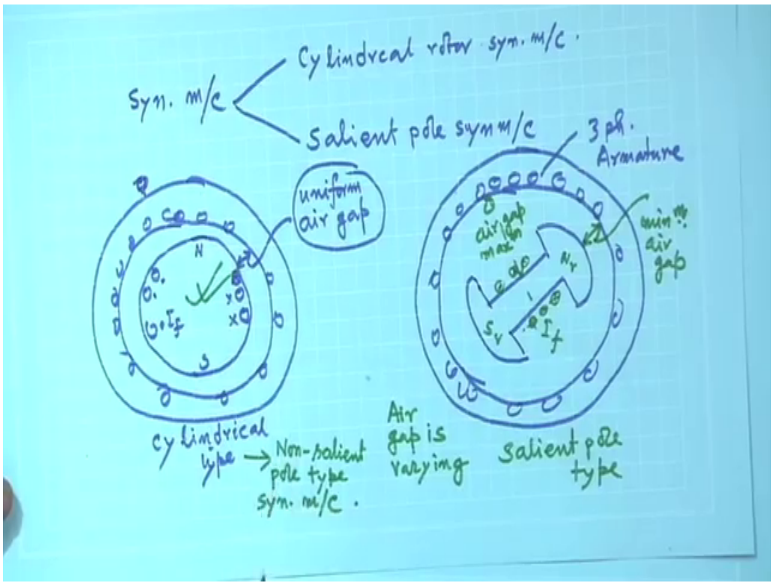


Let me write it and presently I am talking for a synchronous machine maybe of two types; one is called cylindrical rotor and another is salient pole synchronous salient pole synchronous machine, cylindrical rotor synchronous machine.

Structurally, it is like this. In case of a cylindrical synchronous machine, this is the stator which has got 3-phase distributed winding on the stator inner periphery in this slots we have discussed and rotor is also cylindrical in structure and where there will be coils; simple winding coils where I will pass DC current say cross this side and dot this side. So, that this will become a North Pole, this will become a South Pole of the rotor a sort of permanent magnet not permanent magnet and electromagnet kind of thing and it will be so, the here is I f, your DC current.

And in this machine, this is the air gap which is uniform air gap. So, this is cylindrical type cylindrical type and this salient pole type is this one the 3-phase winding will be housed in the on the stator just like this machine 3-phase winding all along this r y b phase all these things 3-phase winding 3-phase armature, get acquainted with these terms.

Armature means AC windings of a synchronous machine ok, it will be like this. But, in the rotor, it is salient pole type structure that is it will be somewhat like this and you have coils wound around it like this. So, that if this carries cross current, this will carry dot current then also this will become North Pole South Pole of the rotor N r, S r and is your field current I f ok.

So, this is salient pole type ok. So, if I rotate this field, then also there will be induced voltage as this fellow was doing. So, however, in this case air gap is not constant air gap is minimum here. So, air gap is varying; air gap is varying, it is minimum here minimum air gap and along this line, air gap is maximum is not air gap maximum in between it will have various values.

Therefore, in case of cylindrical machine, air gap is uniform and in case of salient pole type synchronous machine air gap is non-uniform. The analysis of this salient pole type machine that is why it becomes slightly involve, we will discuss that later. So, till now whatever armature synchronous impedance I have defined and obtained it is actually corresponding to a cylindrical type synchronous machine where air gap is constant ok.

So, a cylindrical type is also sometimes called non-salient pole for obvious reasons. So, it is also called non salient pole type synchronous machine ok. So, this so, we are presently we are doing this. We will take up the salient pole maybe after few lectures. That is also simple, but it will be slightly involved because of the fact that air gap is not constant.

Therefore, coming back to this equivalent circuit of the synchronous generator mode of operation I have done there is induced voltage and it delivers current from the plus. This is how is generated mode is shown and this is your terminal voltage understood.

Now, we are going to do one of the most important thing, that is one good thing about synchronous machine is the equivalent circuit is very simple to handle per phase; only thing between the terminal of the machine and this excitation voltage there appears a series in impedance of r a plus j x s of which x s is much larger compared to r a. What people sometimes do that even they neglect r a to get quickly the results, computations then becomes further more easier. In fact, power system engineers they will not bother about r a while calculate I mean modeling a transmission line and a synchronous machine they will simply say it has got only reactance synchronous reactance because the effect of r a will be small to calculate say fault current in a system and so on.

So, nonetheless we will take r a x s together and try to find out the expression of power and torque developed by the machine. [FL] Before that I just do this phasor diagram of the synchronous machine, after doing this; I will just draw the phasor diagram.

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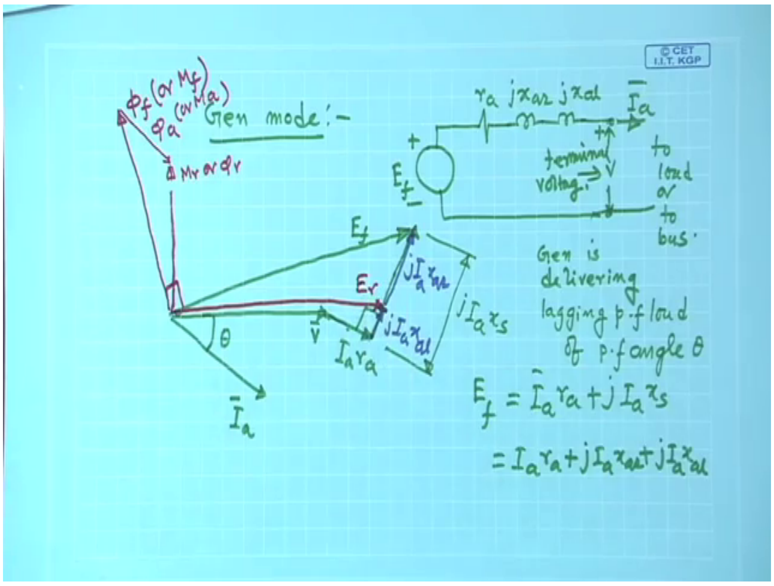


So, to so, generator mode; follow me very carefully what I am doing. Generator mode, equivalent circuit is like this; this is E f, no load voltage and here is r a, here is x ar j and here is j x al and here is your terminal b and it is operating as a generator means delivering current to be load or to the bus to load or to bus.

So, it is customary generally to draw the phasor diagram in this way; take this voltage V terminal voltage of the machine which I am calling V first draw this and suppose let us assume generator is delivering lagging power factor load of power factor angle theta. Then, I must draw my I a here, this will be my armature current I a this is my terminal voltage V is terminal voltage right terminal voltage ok. So, V and this angle is now power factor angle because angle between V and I a.

Then, I know E f is I a r a plus j I a x s which is I a r a plus j I a x ar plus j I a x al, that is all. So, I add these voltages, so, V plus let me use same colour. V plus I a r a, I will add; this is I a r a, then j I a x s, it will be 90 degree to this. And you will get your E f and in this one I a r a this length of course, I have drawn quite large compared to this these are the really small I a r a is small and then it is not drawn to this small, but nonetheless it is much bigger than this fellow.

Not only that then I a r a if you want to get also E r, it will be I a r a you can show this as two things. So, this length is I a x s j I a x s of which a little of this one is j I a x ar x al leakage impedance small and the remaining is your j I a x ar. It will not be necessary to break up x al and x ar to find out the expression for power or to find out the expression of the torque.

But, here I want to show you. So, V plus I a r a plus j I a x s will give you E r. Only thing I will just complete this one by saying whether my fields E f is this one; so, this will be your phi f or M f or I mean whatever armature M f or phi f will be like this it is a uniform air gap machine. So, armature M f and phi f will be same thing and this angle will be 90 degree.

Where is your M a? So, phi f plus M a if you drew you will get M r is it not? You will get M r. This is phi a or M a and you will get M r or phi r resultant field you will get. So, this is the resultant field, this is the rotor field and you know phi r M r will give you E r; E r will land up here. Anyway, we will continue this in this next lecture, but this phasor diagram you please understand thoroughly ok.

Thank you.