Electrical Machines
Professor G. Bhuvaneswari
Department of Electrical Engineering
Indian Institute of Technology, Delhi
Lecture 37
Synchronous Machines -Equivalent Circuit and Phasor Diagram

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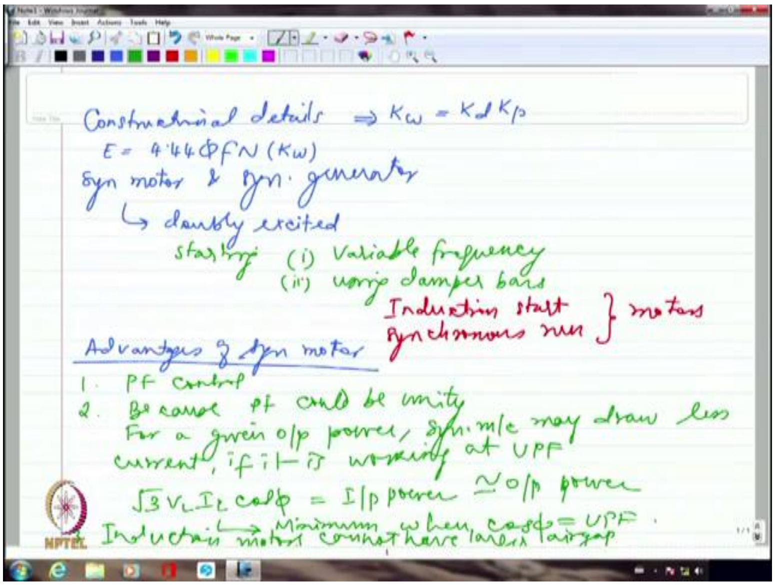

We talked winding factor $k_w = k_d k_p$, because the winding is distributed and also you are not going to have a pitch of 180°. So this gave us the voltage equation which is similar to a transformer equation but we will have to multiply that by k_w that's what we said as the voltage equation.

After this we actually looked at the basic principle of synchronous motor and synchronous generator. So we send that synchronous motor we are going to have doubly excited, so it is going to be excited from both the armature site as well as field side. Armature is going to get a 3-phase supply, field is going to get a DC supply and the field is going to be dragged along with the armature revolving magnetic field.

So the armature revolving magnetic field essentially drags the rotor along and that is the reason why rotor has to rotate at synchronous speed or it cannot rotate at all. So if at all I am trying to start it, I have to start it in all probability with two of the methods. One may be using variable frequency wherein I am going to give sufficient time for the rotor to catch up with the stator revolving magnetic field.

The stator revolving magnetic field is going to probably rotate initially at 1 rpm or less then it is going to slowly increase in its speed because of which the rotor can be dragged along that is what is going to happen in variable frequency starting.

Whereas in the other case where I am going to use damper bars which are very similar to squirrel cage rotor bars in an induction machine. These are going to be short-circuited because of which they are going to develop a small amount of torque not a very large torque. So I would call that torque as induction torque. So these motors are induction start synchronous run motors.

So these are the two methods of starting and we also said that major advantage of a synchronous motor. So as far as the advantages of synchronous motor I am not talking much about the advantages of generator because you do not have any other option you use only synchronous generator. If I have to generate a large capacity electricity power, then I have to use only synchronous generator. So there is no point on talking about in what way it is better than induction generator because induction generator is hardly ever used they are not used very commonly.

So I am talking about motors, if you look at synchronous motors one major advantage I am going to have is power factor control because I am exciting it from both sides. So the flux what I am providing from the rotor side can be just sufficient it can be a little more than what is needed it can be a little less than what is needed.

So I may be drawing a magnetizing current from the armature side, if I am having a shortfall in flux I may draw no magnetizing current at all if the flux is just sufficient. I might return some amount of reactive power to the 3-phase mains if I am having excess amount of reactive power fed on the rotor side.

So I will be able to make the armature behave like an inductor or capacitor or just a resistor which is actually going to draw the armature is going to draw in which case only a unity power factor current if it is behaving like a resistance. So the current will be just sufficient to generate torque which is actually the real power component.

One more advantage we said was because the power factor could be unity. I would say the current drawn that is for a given output power, synchronous machine draws less current. I would say rather may draw less current if I am working at unity power factor.

So if the machine is working at unity power factor, the current drawn because I am going to say that $\sqrt{3}V_L I_L \cos\phi = \text{Input power=Output power}$, if I assume that the efficiency is almost unity. In which case $\cos\phi$, in the case of the induction machine has to be 0.8 or 0.85 at the most whereas in the case of synchronous machine it can be unity power factor. Due to which for a given voltage and for a given power I_L will be minimum when $\cos\phi$ is unity.

So I would say that the current drawn by the synchronous machine is generally somewhat smaller as compared to I am talking about the armature side ofcourse. The current drawn by the armature will be somewhat smaller as compared to the stator current drawn by an induction motor normally at a given rating both of the ratings are the same.

If I look at the power factor in all probability synchronous machine power factor will be much better or at least close to unity. One more advantage which I had not mentioned earlier is if I am having the rotor and stator, the rotor is sitting inside the stator, the air gap has to be as limited as possible in the case of an induction machine.

Because I am providing the magnetizing current also from the stator side and necessarily that flux has to link with the rotor if I want to generate a torque. If the air gap is more the leakage will be more. If the leakage is more to produce the same amount of torque I might require the same amount of flux linking. If the air gap is more I might have to produce more overall flux so that the useful flux still corresponding to the original quantity when the air gap was smaller.

So I have to make the air gap as small as possible so that the magnetizing current drawn in the case of an induction machine becomes really-really small as small as possible. So I cannot afford to have a little larger air gap where as in synchronous machine I can afford to have a little larger air gap. If I have to do that maybe there is some kind of load which is going to have a little torsional motion. It will rotate normally about an axis but there may be a little torsional motion which may go and hit the stator if there is not enough leverage or enough margin available.

So in the case of synchronous machine I would be able to use those synchronous motors even in those loads where I may expect some amount of torsional motion or some amount of vibrations in the rotor. Whereas in induction machine I cannot afford to increase the air gap because the more I increase the air gap the leakage will increase, the power factor will become worse and worse. It is going to make the power factor much worse, so that is the reason why induction machines cannot have larger air gap.

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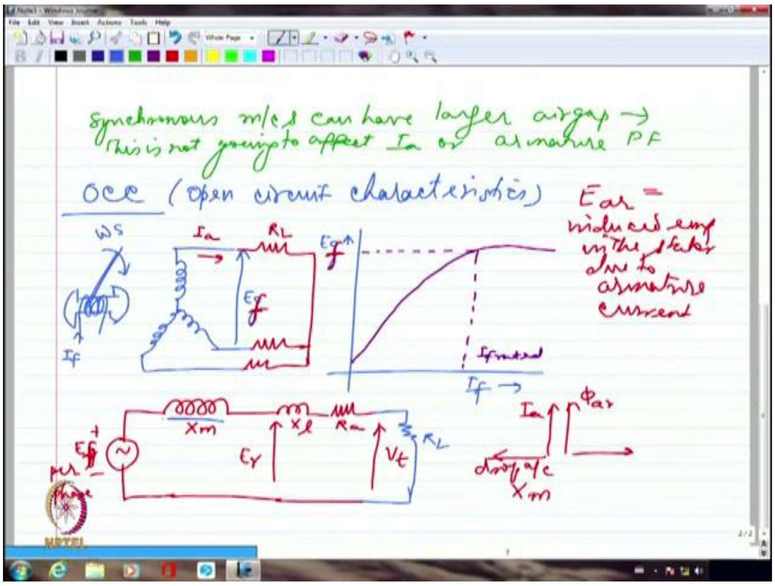

Whereas synchronous machine can have larger air gaps. Because anyway it is not going to affect the armature current or armature power factor. Whereas it does affect the power factor in the case of an induction motor very adversely. So I cannot increase the air gap the case of an induction machine whereas I can do that in a synchronous machine.

We said field can be varied and we are going to look at what is the generated EMF under open circuit condition of the armature. See in the case of synchronous motor I am providing excitation anyway from the rotor, so I can increase the flux or decrease the flux essentially by adjusting the rotor current I do not have to play around with the armature current or armature power factor. So the air gap will not affect the armature current or armature power factor.

So let us try to take a look at OCC once again. So in OCC that is the open circuit characteristics or magnetization characteristics what we talked about in the case of DC machine. What we are looking at is if this is my field, and I am going to show it as though I am just winding it like this it is not really wound that way but this is the field and I am injecting a field current here I_f. And I have an armature and normally the armature of a synchronous machine is specified like this. It is a 3-phase stator similar to induction motor stator.

So what I am going to do is to measure the voltage what is generated here may be line to line voltage at synchronous speed then the rotor is driven at synchronous speed and I am injecting a current I_f which is a variable current, it is not a constant current. So I am going to inject a current I_f, so what I am going to look at is how much is E_g for different values of I_f. This is what is the open circuit characteristics of the machine when it is functioning as a generator clearly.

So what I am going to see is basically maybe it will start at some value like this and then it will go into saturation. This is how it is going to function as far as the OCC is concerned. So I may get probably the rated voltage at some point like this, this is what is my rated voltage. So which means this corresponding field current will be rated field current. That is how the rated field current is normally decided that is going to be rated field current.

Now I have this open circuit voltage. Actually when I am going to connect the load across these, so I let us say I connect the 3-phase resistive load I am just showing as though I am connecting 3-phase resistive load here. Then it is a generator obviously I am going to load it electrically so I am connecting a 3-phase resistive load here. When I am connecting a 3-phase resistive load each of them is going to draw a current which is probably I_a, I am saying this is I_a per phase because it is any way star connected phase current and line current are the same. So this is going to be the per phase current which is being drawn by this load all the 3-phase loads. Now these are 3-phase currents.

If I have 3-phase current in a space distributed winding that will create a revolving magnetic field. So I am going to have two fields in the air gap just like what I had in the case of an induction machine as well. Induction machine I had one field from the stator and the other field was because of the induced current and induced EMF in the rotor that was also 3-phase so both of them were revolving magnetic fields created by virtue of 3-phase currents being pumped in through 3-phase phase distributed winding.

In this particular case, I have one revolving field because of physically revolving magnet. The rotor is revolving physically and that is at synchronous speed, so that is definitely going to create a magnetic field which is revolving in nature. The other one is due to the 3-phase currents that are passing through the 3-phase winding of the armature which is also revolving in nature.

Now both these things are going to definitely induce EMF in the stator winding itself. Please remember stator winding is stationary both these things are rotating at synchronous speed. Because of which I am going to have both of them actually inducing EMF of same frequency. The frequency will not be any different, the frequency will be different only if the 2-phase had been rotating at two different speeds, they are not rotating at two different speeds.

So I am going to have basically two EMF induced at the same time. One is due to I_f which was injected originally which created the magnetic field from the rotor side which was already rotating at synchronous speed because of my prime mover. The second one is created because I have connected a load now until I connect a load now that is not existed. So if I actually look at my armature equivalent circuit alone I will have an excitation EMF or E_g or E_f. Generally, many of the books mentioned this as E_f, so let me also mention this as E_f. E_f is the induced one. This is the induced EMF in the stator due to field only not due to armature only due to field.

So I have an induce EMF which I am showing as a voltage source E_f. Now after this I am definitely going to have one more induced EMF which is due to the armature current which I may specify as some E_{ar} due to armature reaction the induced EMF in the stator due to armature current itself. So now when I look at the resultant, I have to look at the resultant of these two EMFs before I say what is there in the armature terminals of my machine. This armature reaction EMF actually I can specify as a reactance drop as simple as that because after all it is due to flux and if I say armature reaction, armature current is probably along this direction the flux will also be along the same direction roughly.

So this is I_a, this will be ϕ_a or ϕ_{ar}. So the induced EMF is going to be I can write it as $-E_a$ or this way or $+E_{ar}$ this way it is essentially $\frac{d\phi_{ar}}{dt}$ multiplied by of course number of turns all those things. So I am going to have basically the induced EMF which will be lagging behind probably the current if I am taking this as a reactance drop as simple as that.

Reactance drop always you are going to have the voltage leading the current, so I can take this as the drop across X_{ar} or let me called this as X_m. So I am going to have a reactance which is specifying what is the amount of voltage induced in its own self that is the stator winding itself which is due to the armature current that is its own current.

So whatever is available here I may have called that as the resultant EMF that is available in the armature terminal. And whatever flux originally I said I assumed that I_f created a flux and it was linking completely with the stator. It may not that mean there will be definitely leakages from either side. If there is leakage I have to show one more reactance which will represent probably the leakage which will not linked this both stator and rotor, there will be definitely total flux produced if I say is 1 Weber. Maybe 0.9 Weber will have linked with both the stator and rotor.

Rest of 0.1 probably will linked only with individual member alone, in which case I am definitely not going to see the repercussion of this in terms of torque production or power production. Whichever does not link both the member that is a waste. So I am showing this wastage what goes away because of the air gap that is existing between the stator and rotor all the flux produced by the rotor will not linked with stator.

Similarly, all the flux produced by the stator will not link with the rotor, so I am going to have some amount of leakage. Now I have resistance also, armature will have some resistance definitely. So let me called this as R_a whatever I am drawing is per phase very clearly I am not drawing it for 3-phase everything is per phase.

So even E_f what I am mentioning should be per phase. So this actually gives me the equivalent circuit of my synchronous machine in general and this is what is available as V_t, the terminal voltage. Now whatever I have connected as R_L if I may call this as R_L I should connect that R_L here. This is the load resistance per phase. R_a is basically whatever is the inherent resistance of this armature winding. The armature winding is thick, it is made up of copper alright but still it may have 0.1 ohm or 0.01 ohm as the resistance depending upon how much is the length and what is the thickness and so on and so forth.

So I will have a resistance drop, I will have some portion going as a wastage due to leakage and rest of it what I am showing is actually the mutual that is existing between the rotor winding and the stator. One thing I want you guys to understand is, will the rotor winding have an induce EMF due to the stator flux? No, why? It is rotating at the same speed exactly. The rotor winding will not have any induced EMF whatsoever from rotating magnetic field created by the stator because the rotor is rotating already at synchronous speed.

So when the rotor winding is looking at stator flux or the air gap flux which is the resultant of the original revolving magnetic fields flux created by the rotor plus whatever is the new flux created by the armature current. Both of them are rotating at synchronous speed. So obviously the rotor will look at that field as though it is stationary because the rotor itself is rotating at synchronous speed. The relative velocity is zero.

Both are, rotating at the same direction at the same velocity whether the north and south. Either they are aligned, they have to be aligned. One is north on this side and south on the other side. The other one will be south on the other side, north on this side obviously they have to be that way. How can they lock up otherwise? So there will be a drop and one more thing Lenz's law should tell you this. If there is no drop, the voltage should have reach to an infinity. The question is why should you take this as a drop?

So you have to take it as a drop very clearly what is question was that if both of them are rotating in the same speed they should be additive. If they are additive how can you take this as a drop? You have to take this as a drop because one more thing I_a what I have taken now I have taken as a resistive load, who says it has to be only resistive. It can be inductive; it can be a capacitive. Depending upon that the currents are going to have different phase shifts.

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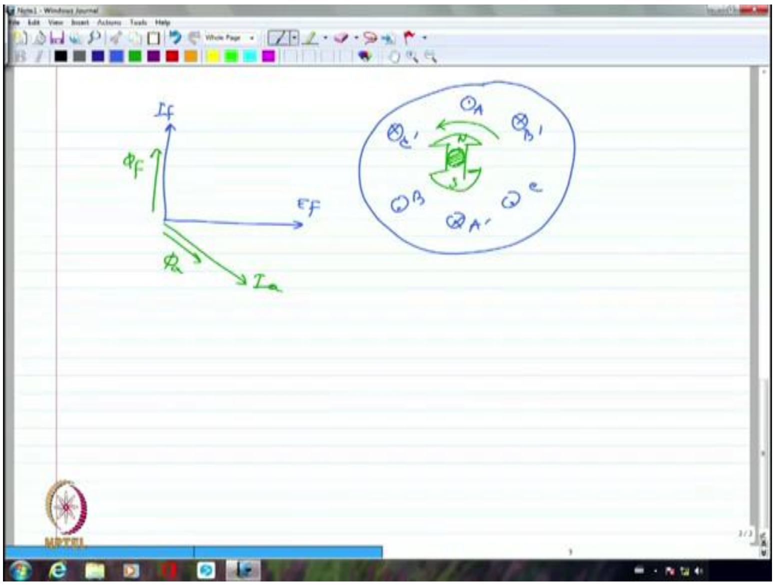

For an example letter say I am talking about I_f like this, may be the E_f induced EMF in the armature is at 90 degrees. The current what I am talking about in the armature circuit it will be almost in phase if I am talking about a resistive load. It may be at lagging behind at some other angle depending upon whether it is an inductive load.

So if my I_a is somewhat like this then please note ϕ_f is here, ϕ_a may be somewhere here depending upon what is the reluctance offered and so on and so forth. So now I have to look at please note that ϕ_f and ϕ_a may be rotating at the same speed but they are not in phase with each other. The two fluxes are not exactly in phase with each other not at all. So if I am having a north pole of the stator revolving magnetic field currently at some position say X equal to theta equal to X, I cannot say the north pole of rotor will be at the same position not at all.

Student: Can you please explain the working of generator?

Professor: Working of the generator, if I am having a magnet created either by a permanent magnet or electromagnet. So this magnet is being rotated at synchronous speed with the help of a shaft which is in the middle which is attached to a prime mover. The prime mover is making sure that the rotor is rotated at a particular speed, synchronous speed.

Now I have A phase, B phase and C phase windings here. So these are the windings which are shifted from each other by 120 degrees. So this is A, A^l, B, B^l and C, C^l. I am going to have induced EMF in A, A^l then subsequently after 120 degrees I will have it in B, B^l then is subsequently I will have it in C, C^l. And I am assuming that the air gap I have shaped or windings I have placed and all those things are sinusoidal in nature because of which I am going to have a sinusoidal induced EMF in all the three phases, they are shifted from each other by 120 degrees. Then it is all open circuit condition.

If I connect a load on the armature, all these things are going to carry current until then it had only induced EMF. So I did not have specifically 3-phase current flowing through this. Now when I connect a load I am going to have 3-phase current flowing through these windings. The load what I connect can be inductive, capacitive, resistive depending upon I may have a unity power factor current, I may have lagging, I may have leading current. When I have these currents they are going to create again revolving magnetic field.

The resultant of these two will be the overall air gap flux which the armature will eventually look at. So although the armature is looking at the resultant of both the fluxes I am trying to bifurcate them in the equivalent circuit. One portion I am showing as E_f which is confining itself only to the rotor flux. In another portion what I am showing as X_{ar} or X_m that is actually talking about what is the induced EMF due to the armature currents which I call as armature reaction or armature flux based induced EMF.

These two together actually make up for I am showing that as a drop because you cannot have even at a unity power factor whatever further and further addition of voltage, it is not possible to bring it over to infinity. So Lenz’s Law very clearly says that has to be in the opposite. So if I actually show it in an equivalent circuit.

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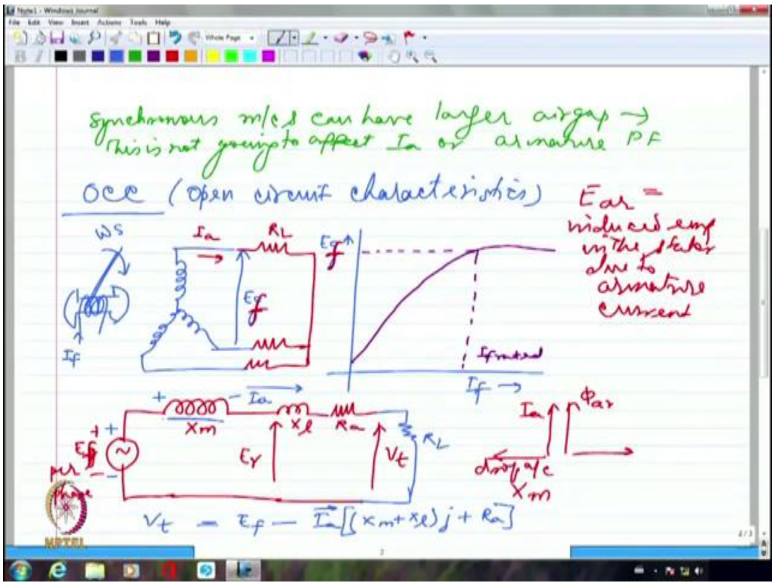

I should show this is plus and this is minus and I have to show this is plus and this is minus. That is how we get overall terminal voltage $V_t = E_f - I_a\left((X_m + X_l)j + R_a\right)$.

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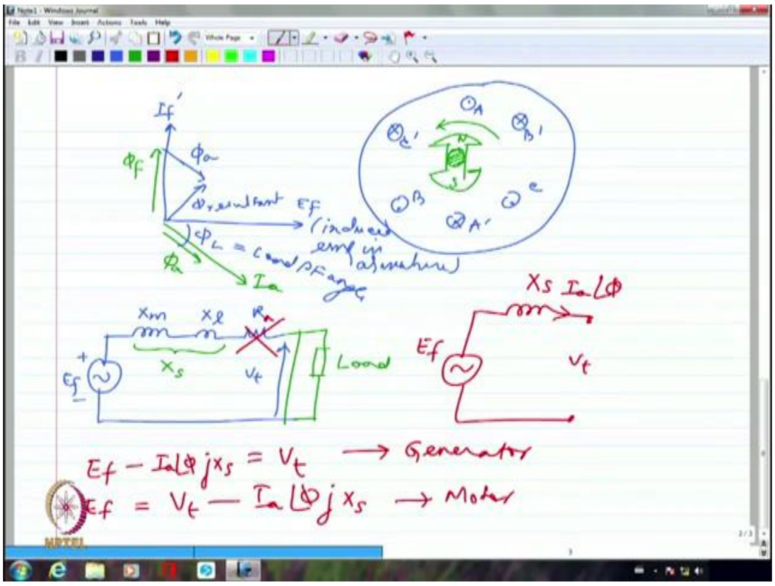

Student: Filed current is actually DC how can it be drawn in Phasor diagram?

Professor: Field current is actually DC; how can we show it in a phasor diagram? Phasor diagram always shows all the vectors are rotating at 50 Hertz. You cannot show DC in phasor diagram. It is wrong to show a DC in phasor diagram please understand because we are showing relative shifts.

All of them are rotating none of them are stationary. What we are doing is the DC current although is injected into the rotor, you are physically rotating it. So the DC current is not producing a revolving flux, you are physically rotating it to create a revolving flux. So you can look at DC current as an equivalent per phase AC current in a 3-phase system. So there is an equivalent we have to calculate.

So rather than mentioning this as I_f, let me mention this as I_f^l. I_f^l is equivalent AC current then I visualize the DC current from the revolving magnetic field due point. The DC current is definitely having 0 frequency, it is not a rotating phasor, but I am looking at it from the viewpoint of the revolving magnetic field, that is the reason I am able to specify that damp I_f as a phasor, a rotating vector.

I am able to mention it only because I am looking at this whole thing rotating at synchronous speed. So although physically I am rotating the magnet it is equivalent to the electrically creating the revolving magnetic field, how does it matter? I am looking at a magnetic field which is revolving, so I am looking at an equivalent AC current that would have produced the same strength of magnetic field as I have produced now with the DC current which I am rotating at synchronous speed.

There will be a voltage drop definitely the resistance will be there but we are not unduly worried about it. If I have to calculate I_F I have to say it is V_f whatever I am applying, V_f is a DC voltage and R_f which is the field resistance. So I should say $\frac{V_f}{R_f} = I_f$ which is a steady state current. I am not going to have any transients because I have placed on particular voltage I am not disturbing it. I am giving that excitation for quite a sometime as simple as that.

So now if I look at the resultant I have to look at the resultant of these two this is ϕ_f and this is going to be ϕ_a. Now whatever is the resultant is ϕ_r. I am looking at the two fluxes, I have taken the resultant. No, just now we have talked about it. We will not have any induced current in the field because the field is rotating at synchronous speed, it will not show any relative velocity.

Both of them are rotating at synchronous speed, if I look at ϕ_a or ϕ_f both of them are rotating at synchronous speed. So ϕ_r will also rotate at synchronous speed. Orientation is different you can see from the resultant but all of them are rotating at synchronous speed, so if you sit in the rotor you will see only a constant field. So where is the question of $\frac{d\phi}{dt}$?

Stator is actually stationary I have not made the windings rotate, have I? No, stator windings are stationary that is the catch. Rotor is rotating, stator the name itself because it is stationary. So stationary windings will get induced EMF you just cannot do anything, such a beautiful mechanism which was probably conceived again by Tesla. Because 3-phase generation started only later, initially it was all DC generation.

What Edison did was all DC generation, he made a small power system within New York City and he showed that DC transmission could be done. They lit up many streets, streets in New York and ultimately they also realized that the voltage drop is really-really large as you go to longer distances. Especially they were transmitting at very small voltages.

So the currents were large as well, voltage multiplied by the current was power it was DC, so the currents were large as well, so there was a huge amount of drop that was taking place. And later on Westinghouse and Tesla with Tesla brain, Westinghouse realized Tesla kind of talked about transformer then he came to induction motor, then he talked about the 3-phase generation. So all those things were paving the way for AC transmission all of them together.

Student: Although the field current is in field winding and armature current in armature winding, how they are represented as 90 degrees to each other?

Professor: If I am having I_f here. It is inducing an EMF not in its own self, it is in another winding. It is inducing in another winding. So I am showing the other windings induced EMF as though it is getting 90 degree shifted because $\frac{d\phi}{dt}$. So sine and cosine very clearly 90 degrees shift. So this is the induced EMF in the armature.

Now this induced EMF is now being connected to a 3-phase load, if it is resistive I should have shown this I_a in phase with E_f because it is inductor I have assumed it is somewhat inductive, I shown this at an angle which is decided by approximately whatever is the load power factor angle. This is the load power factor angle.

So this is my I_a, I_a and flux should be in phase with each other there its own flux. And similarly I_f and its own flux should be in phase with each other. We are ofcourse neglecting hysteresis. Hysteresis says the flux should lag behind the current you are neglecting hysteresis ofcourse. And we are assuming that the currents are perfectly sinusoidal. They will not be sinusoidal if I am talking about magnetizing current alone.

But armature current consist of mainly the load current hopefully it is sparely sinusoidal. So I am neglecting hysteresis saturation all those nonlinearities I am neglecting and I am saying that flux is proportional to I_f and it is in phase with I_f. So this is what is the phasor diagram basically, for the machine which I have not still included the equivalent circuit parameters. We will look at that as well. Let me probably redraw that equivalent circuit once again this is E_f which is the open circuit induced EMF in the stator side per phase.

I have X_m, which was actually responsible for the armature EMF which is actually perceived as a reactance drop. Now I have the leakage then I have the resistance, this is my V_t and here is my load. I am not showing whether it is resistance, inductance circuit capacitance, this is my load. So this is my per phase equivalent circuit of the synchronous generator or synchronous motor, in general synchronous machine. Now the leakage and X_m put together we call that as the synchronous reactance X_s. Please note one thing, in transformer, in induction motor X_m was coming in parallel, this damping is coming in series. So I am going to have X_s value to be really-really large.

The leakage of an induction motor normally will be only 10 to 15 percent or even less in fact it will be 7 to 8 percent very often, percent I am talking about per unit values. Whereas in the case of in transformer it is only 3-4 percent. In the case of synchronous machine because your synchronous reactance is the magnetizing reactance plus the leakage together I am going to have this to be a very-very large value, it can be greater than 100 percent sometimes.

So you are going to have a very large value as synchronous reactance which tells me when I calculate regulation eventually the drop could be pretty large. So I would say the drop in that X_s itself could be pretty large. So there are designs which try to minimize this X_s to help regulation. There are designs which do not minimize X_s because in case a fault occurs. What do you mean by fault? If suddenly a short-circuit occurs at the terminals. What is going to limit the current? Only synchronous reactance.

Resistance is really-really small in most of the machines because we want to have the efficiency as high as possible, even 1 percent drop in efficiency or 5 percent drop in efficiency can cause a huge amount of power. You are talking about 400MVA and so on and so forth. So 400 MVA even 1 percent is 4 MVA I do not want to lose out so much of power.

So I would like to improve the efficiency as much as possible normally in synchronous machine.

Because the larger the machine we pay more attention to the design to make the design much better to maximize the efficiency. Because the impact of every percentage will be huge amount of megawatt that is the reason. So normally we are going to have very low values of R_a in most of the synchronous machine. In fact, unless we are calculating the efficiency very often we will even neglect this. So if you are asked to draw simplified equivalent circuit of a synchronous machine its very-very simple.

You will just say this is E_f you are going to have a reactance is X_s, this is V_t which is available as simple as that. This is the overall equivalent circuit of the synchronous generator or synchronous machine in general. Only difference would be that if I say this current is I_a ofcourse if the power factor angle whatever it is, so $I_a\angle\phi$. I am going to have $E_f - I_a\angle\phi\, jX_s = V_t$ in a generator.

In a motor it will just other way around because I am applying V_t and what I am getting on other side of the back EMF or counter EMF is E_f that is still be there. It is not that it will go away somewhere. So I will have basically $E_f = V_t - I_a\angle\phi\, jX_s$ this will be true for a motor.

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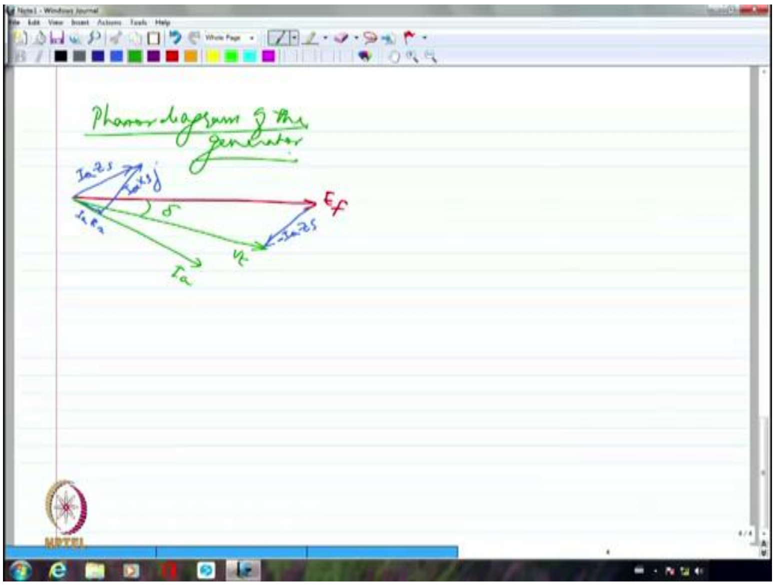

Now if I draw the phasor diagram for this machine. R_a is generally very-very small if X_s is 100 percent R_a maybe 1 percent or even less. So when we are looking at $R_a + jX_s$, X_s dominates heavily over R_a, so you can afford to neglect R_a unless you are calculating the efficiency. Because efficiency calculation will involve $I_a^2 R_a$ losses, whatever is the loss there you have to take care of that when you are calculating the efficiency, so this is important.

And if you are talking about a motor you will have to take the frictional windage losses and something like that. Similarly, if you are talking about a generator and starting off from the mechanical side you have to say mechanical power input minus whatever is the frictional windage losses will be actually given to the machine as the mechanical power which will be converted into electrical power.

So let us say this is my E_f for a generator maybe my current is somewhere here. So what I need to do is, to first of all construct a triangle corresponding to I_aR_a if at all I am looking at resistance also perpendicular to that will be I_aX_s. Please note I_aR_a should be minuscule compared to I_aX_s. This is of course I_ajX_s that is why 90 degree shift we have shown. What is the addition of these two will be I_aZ_s if I may call that as synchronous impedance.

What I need to do is to subtract this I_aZ_s from here, this is $-I_aZ_s$, $E_f - I_aZ_s = V_t$. Please note V_t will generally lagged behind always E_f in a generator. Please note that E_f lags behind and this angle is δ. So E_f corresponds to the induced EMF corresponding to your revolving magnetic field created by the rotor. V_t is the resultant magnetic fields overall induced EMF minus whatever is the drop and you are looking at the whole thing as the phasor diagram for the generator.