Electrical Machines – II
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Lecture – 82
Synchronous Motor Operation Phasor Diagram and Power Expression

Welcome to this Synchronous Machine lectures and we were discussing generator mode of operation of cylindrical type synchronous machines.

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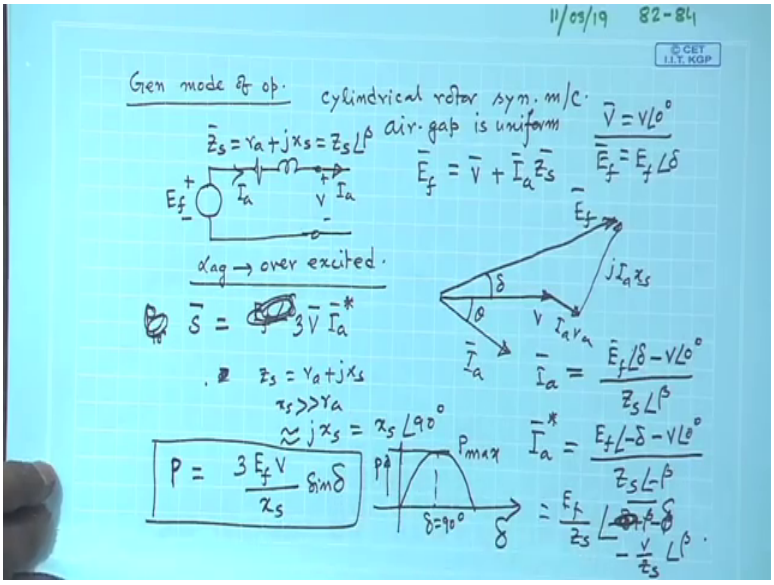

Cylindrical rotor synchronous machine where the air gap is uniform air gap is uniform and synchronous machine equivalent circuit is much simpler than the case of induction machine because of the fact there is no magnetising branch present here.

So, the equivalent circuit will be something like this plus minus E f and then r a plus jx s synchronous impedance which is often called Z s and I was writing it as some magnitude Z s angle beta, beta will be closed to 90 degree because the value of x s is much higher than r a and this is the thing and suppose the terminal voltage. This is per phase all the voltages and currents are here. And, therefore, in case of generator mode of operation suppose the generator delivers a current of I a that is the per phase current, then it is true that E f will be equal to V plus I a into z s bar.

And, based on that we did last time very quickly, I will tell this is the terminal voltage, this is generally taken on reference V 0 degree and then suppose it is supplying a lagging power factor load I a. So, this is the power factor angle of the generator at which it is operating to the external world and this plus I a r a, I a r a plus j I a x s, j I a x s gives you your E f and in case of generator mode of operation, E f will be always above V and this gives you delta. E f the length of E f is a measure of the field excitation and length of V is a measure of approximately the resultant field ok.

Therefore, a this generator supplying a lagging power factor load is over excited. So, it is lagging power factor, it is over excited we know that over excited. And then I told you if you want to find out the expression of power and torque so, power delivered total power delivered by the machine should be calculated like this S is equal to this is the current delivered to the load. So, it should be E f this voltage I mean I will do like this V into I a star this is the visual thing we will do so that we get the expression of real and reactive power simultaneously.

And, since V is V 0 we know that E f can be written as E f angle delta where delta is a positive number and then what I did, I just wrote I a; I a is this way. So, I a should be equal to E f delta minus V angle 0 degree divided by this Z s beta this is I a. So, I a star is needed. So, I a star will be simply E f, all angle should be made negative minus V 0 divided by Z s minus beta which will be equal to E f by Z s and this will be minus delta plus beta. No, this will be beta minus delta beta minus delta this first term and this will be minus V by Z s angle beta.

So, this we substitute it here. I will not repeat. So, I have substituted this here. Then, total power will be 3 times this and we get an expression of the complex power delivered to the load. If both the terms become positive; that means, it is delivering really kilowatt which in case of generator, it has to be always positive the real part and imaginary part, if it is positive it means it is delivering a lagging power factor load.

And, then I told you that this Z s which is equal to r a plus jx s x s is much higher than r a. So, what people do? Often people use this approximation that this is jx s which is equal to x s 90 degree. And, if you do that the real power output of the generator is a very famous equation and that is equal to magnitude of E f magnitude of V divided by x s into sin delta.

Since synchronous machine runs at constant speed, this itself will be the expression of the torque if you want to know it in Newton metre divided by 2 pi this speed of the machine that is MS mechanical speed, you will get the expression of the torque and P delta curve will be sinusoidal which at distinct magnitude P max and P value of P max is proportional to terminal voltage into E f by x s this is delta. Maximum power or torque it can develop is 90 degree, this side is power ok. So, we did this.

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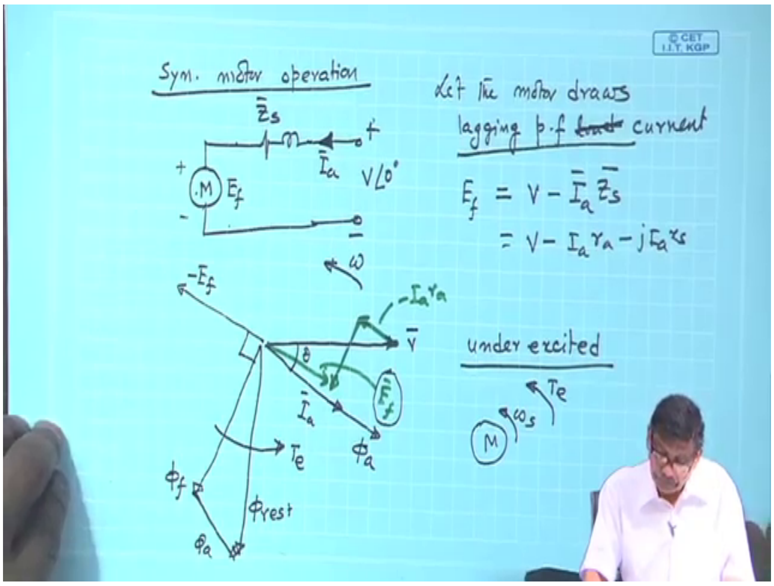

Now, today what I will first; so, we are still dealing with cylindrical rotor synchronous machine, but what will be the expression for power and torque for a synchronous motor operation synchronous motor operation ok. We will first draw the phasor diagram and try to find out the expression of the torque.

In case of synchronous motor operation, I will draw like this, this is this, the impedance is Z s as usual and here it is bus voltage V which is angle 0 degree volts and since it is operating as a motor I will show that it is drawing power from the source. So, I a I will assume inconsistent with the supply voltage which is supplying the motor. So, this will be the thing and this voltage will be your E f, voltage between these two points.

Now, so, let the motor draws lagging power factor load, lagging power factor load, lagging power factor current. It is load is mechanical load on the shaft and it draws at some steady operating point it draws like that. Then, I will say that this E f should be equal to V minus I a z s; this will be the magnitude of the rms voltage.

So, how to draw it? So, the drawing of this phasor diagram will be I a r a minus j I a x s ok. So, we first draw; please carefully follow me what I am doing this is V. Then I have told it is drawing a lagging power factor current. So, this is my I a ok, then from V I have to subtract this r a and x s draw first I subtract. So, minus I a r a, it will be like this is minus I a r a and then j I a x s is like this. So, minus j I a x s will be 90 degree to this and this length is much higher compared to this length although it is.

So, you will get your excitation voltage E f and this angle is theta the operating power factor of the machine angle between V and I a is your theta. So, this will be E f. One thing I can say; say a motor draws lagging power factor current length of E f is nothing, but length of excitation EMF means the rotor field this length denotes. V denotes what? The resultant field. Therefore, you can easily see resultant field is more than E f and it will act as a motor.

So, in motor mode of operation, it is essential to draw the phasor diagram in this way at least this is the convention I will follow. In case of generator when you draw V, it delivers power to the outside world in case of motor, it draws power from the source. So, it should be consistent with the supply. So, I a I have drawn like that.

Now, in the same way as we have done in case of generator we can suppose I want to know where is my phi f, where is my phi r and where is my phi a. Obviously, this will be the direction of armature flux or armature mmf along the maximum value direction, it will be pointed this is phi a. Now what is E f? This point you listen carefully unlike generator.

Now, E f is the generated voltage inside the machine and it is polarity will be like this and it will be inconsistent. If this is EMF is allowed to act alone, it would have driven current in this direction. Therefore, to take that into account your actual E f is actually here minus E f you have to take; if you want to get information about phi f correctly. And, then I know this is phi f this will be your phi f, 90 degree lagging the induced voltage and then phi a plus phi a will give you the resultant on net EMF phi r. This r is not rotor resultant.

So, here also I find that phi resultant is more than phi f. Therefore, it is under excited. Of course, while solving for problem, you need not it is not necessary to draw E f phi f phi f phi r all the time, but only one thing I will tell that this is all phasors are rotating in the anticlockwise direction omega like this. In this case, this is the rotor field phi f this is the net field. Therefore, the torque will be in this direction electromagnetic torque developed by the machine.

And, we know it should be because in case of motor mod, if this is the direction of rotation electromagnetic torque must act in this direction and it is therefore, consistent. In case of generator, I showed you that phi f was behind phi resultant. So, the electromagnetic torque was in opposite direction as that of the direction of rotation and we know that therefore, this will be this thing. So, in this case once again, I can find out what is the total power drawn by the motor.

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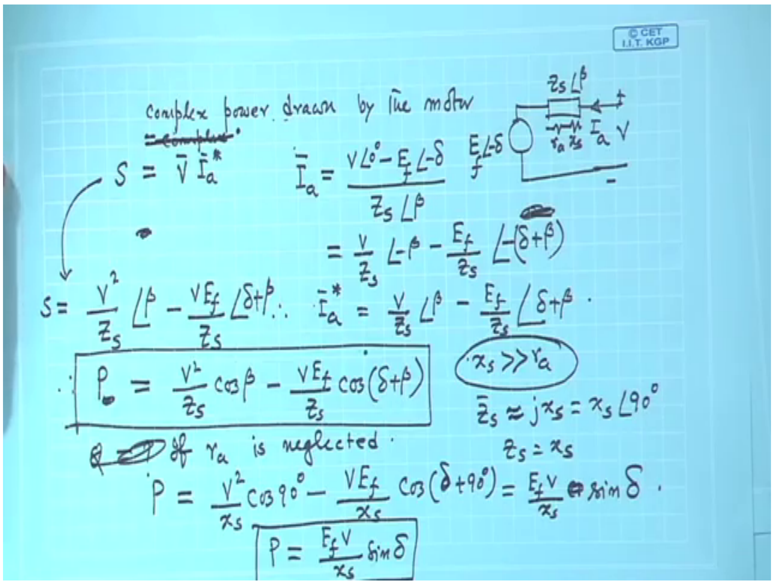

Complex power drawn by the motor drawn by the motor will be how much? This is the I will draw it here once again. This is your Z s angle beta and this is your here you do not fumble ok. This is terminal voltage and it is drawing a current like this and also you note that in case of motor mod E f will be always below V. In case of generator mode, E f will be always above V. No matter whether it is lagging or leading. So, E f will be always above V in case of generator and E f will be below the terminal voltage when it is motor mode.

Therefore, I will assume this voltage E f to be E f minus delta this is the thing and this is the armature current. Got the point? Therefore, I will say that power drawn should be once again power delivered by the source complex power drawn by the motor is equal to complex power. Anyway it need not be written complex power delivered by the source it will be equal to V I a star. This will be the thing [FL].

Now, once again I have to calculate I a f. I a star I have to calculate. So, first I calculate I a. This time I a is V 0 degree minus E f minus delta by z s angle beta and this will be equal to V by z s minus beta minus E f by z s and minus delta plus beta; this will be the thing. So, minus delta plus beta over I have written. So, it is equal to like this; if we this bar confused as you it is like this. Therefore, this will be the thing.

Therefore, I need I a star in this one; so, I will calculate it here. So, this is V by z s angle beta minus E f by z s and this angle will be delta plus beta. Therefore, your S will be complex power delivered will be V angle 0 degree into this, that will be V square by z s angle beta minus V E f by z s angle delta plus beta.

Therefore, real power drawn by the machine P part will be V square by z s into cos beta minus V E f by z s cos delta plus beta. This is the expression for the real part that is the how much kilowatt it is drawing and that is the work which will it will do on the motor. Of course, after subtracting the rotor copper loss; not rotor copper loss, stator armature loss. This is r a and z s. Total power drawn is real power drawn is this of which a portion will be lost in this one I a square r a, and the remaining portion it will do the mechanical work. That way when you do the numerical, you will come to know.

So, this is similarly I can find out Q which I am not doing the imaginary part how much reactive power it is drawing ok. So, this is the thing. Then what I told? These expressions you can memorize; if you have lot of memory, otherwise it is not necessary. What I will do with the numbers I will calculate straight away with a scientific calculator, you get quickly this results, no doubt about it.

But, one result is important which is a special case that is since once again x s is much higher than r a. Therefore z s can be written approximately as j x s only and which is nothing, but x s 90 degree. So, in this case if for this case if r a is neglected, then the power drawn will be V square by z s magnitude will be only x s. So, V square by x s and cos 90; this fellow goes and minus V E f by x s magnitude of Z s into cosine delta plus 90 degree and cos 90 plus theta is minus. So, this will become E f V by x s into sin delta sin delta. Got the point?

Therefore, the expression of the power if r a is neglected which is often the case, power system engineers will neglect do not bother about r a. They will simply neglect r a represent the power system synchronous machine in terms of x s and alone with the understanding that armature resistance is much smaller compared to x s synchronous reactance of the machine. And you will get this, same expression as that of generator and motor; the question is where it is.

Therefore, to conclude this so, this a lot of problems you can solve by whether r a is given or not, whether r a can be neglected or not; you can solve a lot of problems in this method. So, the expression of the real power which is most important E f V by x s sin delta is same for motor and generator mode. So, nothing to worry, but only thing you should be clearly knowing whether the machine is running as motor or generator because the direction of armature current, you have to them assume accordingly and calculate; whether it is E f minus V by z s in case of generator it was like that and delta was positive and in case of motor current is being drawn from the supply. So, that is the case.

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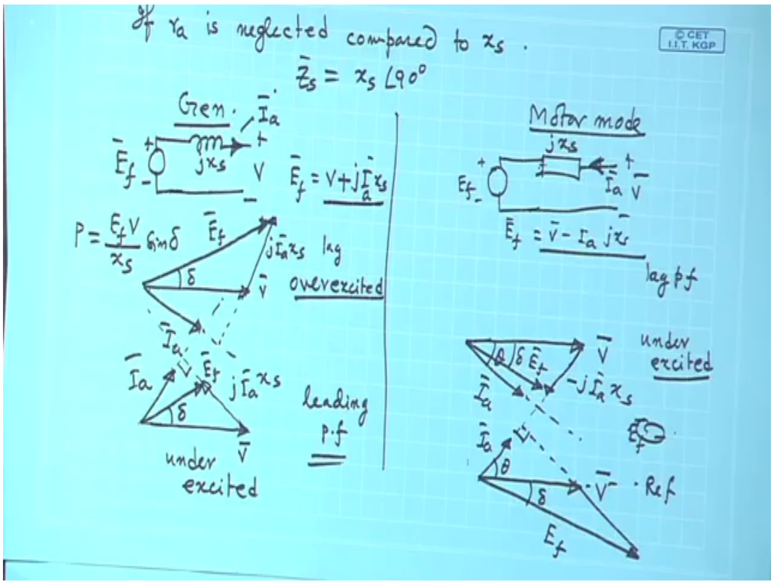

Now, what I will do? I will once again because this is often done. If r a is neglected; neglected compared to whom? Compared to x s. Neglected compared to x s, then your z s becomes just x s 90 degree, is not? Under this condition I will just draw the phasor diagram very quickly. It is a worthwhile exercise to pursue.

See, suppose I will draw it here like this, this side I will draw generator mode and this side I will draw motor mode motor mode. So, in generator mode what is the thing and draw this circuit diagram that is only jx s nothing else and here is it is V and here is it is your excitation voltage. And, it is generator mode current is delivered to the bus or to the load at a terminal voltage V. So, it must be it is direction must be properly drawn, it is this.

Then, I know that E f is equal to V plus j I a x s is not. Now, if it is lagging power factor, I will draw it like this. Terminal voltage, begin with terminal voltage. Suppose lagging power factor I a, then there is no I a r a now. So, I a jx s will be perpendicular to this j I a x s and it will be your E f and this angle is delta over and so, this is the thing.

If suppose, the generator is supplying leading power factor load, then what should I do? V is here suppose the generator is supplying a leading power factor load I a. Whether leading or lagging this equation is true. So, V plus j I a x s I have to draw. Here is your I a direction. So, a draw a line which will be perpendicular to this I a line and this will be your j I a x s and this will be your excitation voltage and this will be angle delta.

So, this is leading power factor load, leading power factor load. So, in case of leading power factor load lagging or leading no matter E f will be always above V for generator mode. Only thing in case of leading power factor load length of E f is less than V length of E f is a measure of rotor field and rotor excitation field that one and V this length is approximately equal to E r resultant field.

Therefore, this will be measure of the resultant field. So, what should I say leading power factor generator is it over excited or under excited? Under excited because length of E f is less. So, under excited and this is E f length of E f is greater than b. So, it is over excited. I am not going in this phasor diagram to the level of phi f and phi r because length of E f I know, it is a measure of phi f; length of V is a measure of resultant field. If I am asked I will be able to draw, but for problem solve solving from electrical sides it is not necessary what I am telling. So, this is the thing.

In case of motor mode, what is the expression of real power drawn by the machine? It will be simply E f V by x s sin delta that is all I am not writing the expression of q that can be easily found out. In case of motor mode, so, first you draw this E f, here is your Z s; Z s means only jx s reactance and here is your supply voltage V and it draws a current of I a. This direction of current assumption is important you can just compare.

Then what I will do? I will once again start from the V terminal voltage suppose the motor is drawing a lagging power factor. So, this was lag, this was lead leading power factor. So, suppose lag power factor. So, motor is drawing a current of I a like this and this angle is the power factor angle at which it is drawing and there is. So, from V E f is V minus I a jx s. So, V minus. So, j I a x s is this way; so, negative of that.

So, it will be what you should do? You should draw a line perpendicular to this and this length will give you minus j I a x s and this fellow will be your E f and this angle will be delta. E f will be below V, everything will be in place; if this convention is followed. Is it under excited or over excited? Length of E f is less than less than length of v. So, it is under excited; just opposite to that of a synchronous generator if it is drawing lagging power factor current, it will be under excited.

And, what will be the leading power factor case? V; suppose this is I a, this is theta. So, V minus j I a x s will be your E f it is written their this is the equation. So, V, so, j I a x s is like this. So, negative of that. So, it will go like this such that this angle is 90 degree and this will be your excitation voltage and this is delta. So, if this is the reference excitation E f is greater than V it is over excited. So, we will continue with this in the next class.

Thank you.