Electrical Machines – II
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Lecture – 81
Completi Phasor Diagram and Expression for Complex Power

So, welcome to the next lecture and you know last time we were trying to find out what is the total power delivered by a synchronous generator whose terminal voltage is V 0 degree.

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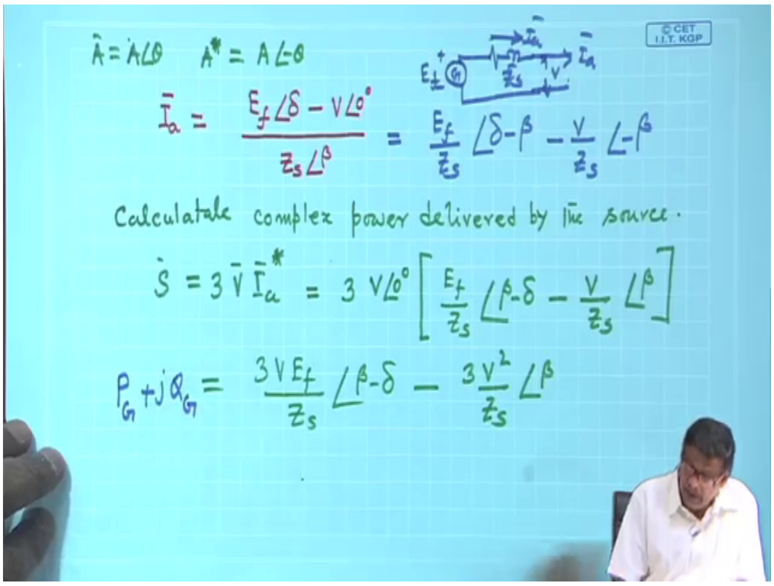

And always draw the equivalent circuit like this here, this is E f and it is generator mode that you also do not forget to write and this is your impedance Z s and then this is your terminal voltage V and it delivers a current of I a bar. And so, this is how I a can be found out you find out this voltage minus this voltage by Z s, this will give you current in this direction. And once you get that the complex power delivered by the sources is 3 V I a star; we just did some complex algebra here to get this.

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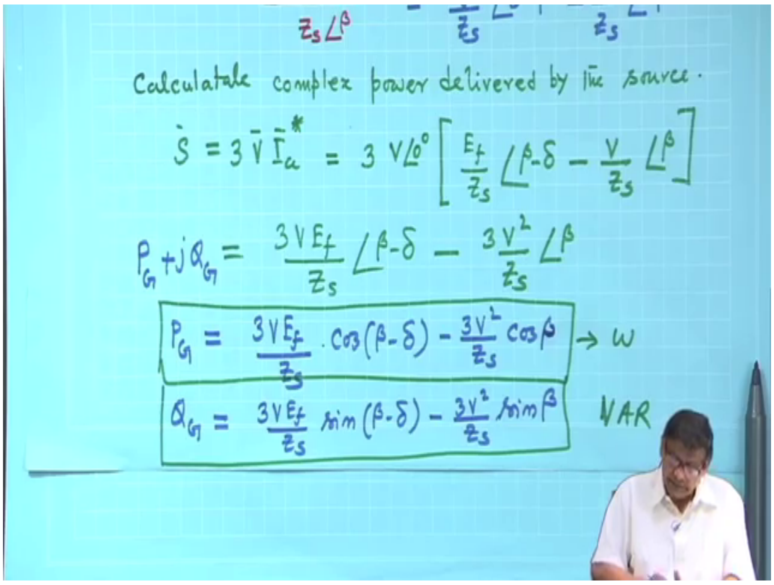

Now, this of course, will be a complex number and the real power if you write like this the power delivered by the generator real and reactive power I will say that P G real power delivered will be the real part of this and this. So, you find out that 3 E f V E f by Z s; real part of this is cosine beta minus delta very simple. Similarly minus 3 V square by Z s this is also cosine beta; so, real part of this and real part of this.

Similarly, reactive power delivered I will write Q G generator delivers this much reactive power and it will be equal to 3 V E f by Z s the sin components imaginary part. So, this will be minus I mean sin of beta minus delta and then minus 3 V square by Z s and this will be also sin beta sin beta is that clear. So, this is the a powered real power in watt and this is the reactive power in VAR Volt Ampere Reactor that is delivered by the generator.

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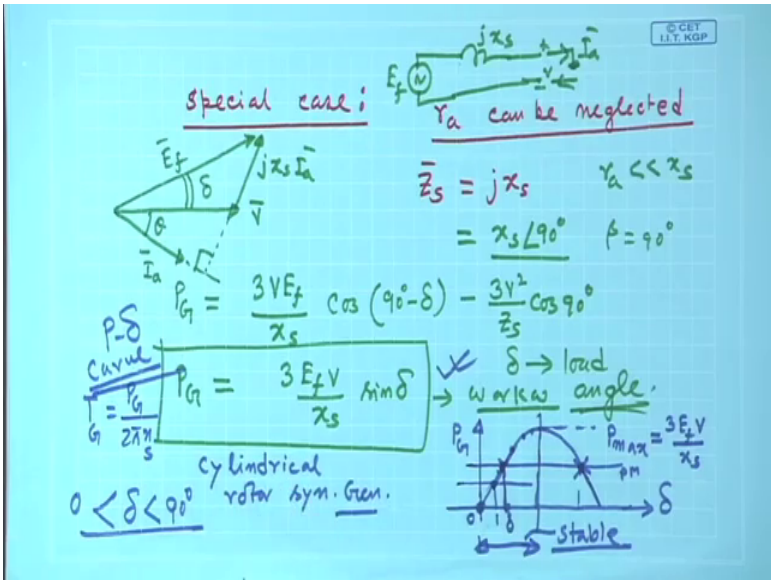

As a special case if. Soso, I am not sure whether you should remember this formula because I do not remember. Anyway for a numerical problem it is better you calculate in this position I a get whatever for how many formulas one will remember. But, one thing is certain one special formula is there that one should remember that is a special case.

When we say that r a can be neglected; r a can be neglected. If r a can be neglected; that means, Z s I am assuming it is Z s and the reason for this I already told you because of the fact armature resistance r a is much smaller than x s. So, that r a part if you neglect it will be like this.

In this case, then Z s become x s 90 degree, is not? So, I will put then for P G real power output will be equal to 3 V E f Z s is x s I will put like this into cosine of beta; beta is than 90 degree here. So, 90 degree minus delta and then minus 3 V square by Z s into cosine 90 cosine 90 which will be 0 and this will be equal to 3 E f by V x s synchronous reactance into sin delta that is the thing. This is one of the formula worth the remembering.

What it says that the real power with which we are interested that is watt or kilowatt how much power it is or megawatt how much it is delivering the expression of that it depends upon the excitation voltage, product of excitation voltage and terminal voltage divided by synchronous reactance very easy to remember into sin delta and what is delta? In this case for this particular case, how this phasor diagram will look like? It will be very simple because in this case I have assumed your equivalent circuit to be E f your Z s no r a. So, jx s synchronous reactance and here is your V terminal voltage and here is your load current I a are you getting. So, this is the thing V.

So, in this case, the phasor diagram will look like terminal voltage V that is V 0 degree and it is delivering suppose lagging power factor current I, a load power factor is suppose theta I a theta, then to V no I a r a only thing I a jx s you have to add. So, drop a perpendicular here extend this jx s into I a it will be here 90 degree and here is your E f.

So and here is the angle delta in this case of course, load angle that V is delta. Therefore, the power delivered to the load depends upon the excitation voltage, product of excitation voltage, terminal voltage all are per phase divided by reactance in ohm into sin delta where delta is this angle delta as you know is often called load angle sorry. So, this is the expression is that clear. So, this is the thing.

Now, it is the real power mind you this real power whatever is delivering must be coming from the prime mover whoever is driving this, is not? This kilowatt is the real power ok. It is used to buy some consumers. Therefore, this much of power must be supplied by the prime mover. Prime mover in which form energy is spread? If it is a steam turbine we are burning coal; if it is water turbine we are using some potential energy of the water resources; if it is diesel we are burning diesel the amount of coal needed to burn. Now, will become more the moment you start drawing power extract power from the generator or more diesel is to be burned.

So, the amount of real power supplied by the generator decides how much fuel is to be burned to deliver that amount of power. See after all it is a system where I am putting mechanical power and this one. So, this is this similarly I can calculate Q G, but this is most interesting formula. And this curve you can if you sketch it will be like this assign function. These are all for cylindrical rotor synchronous machine cylindrical rotor synchronous generator it will be something like this a sin curve this is delta and this is the real power P G and this is P max which is equal to 3 E f by into V by x s ok.

Now, in general when a machine is connected to the infinite bus, V is fixed; you do not have any control over V terminal voltage. However, you can play with E f to increase the level of power if you increase this P delta curve will be something like this we will discuss this after sometime, but this is the thing. Now, what is the torque axis? Torque is nothing, but power I know; in this case there is no copper loss taking place, as if there is no loss in the armature circuit. Whatever power is outputted that much power is drawn in from the mechanical side and a balance operating point will be obtain somewhere here, is not? And speed is always constant.

So, steady electromagnetic torque; electromagnetic torque developed by the machine will be P G and this is the torque in synchronous what you can say straight away., but But if you divide by that 2 pi n s where, n s is in a rps you will get the electromagnetic torque developed by the machine. And I will say the prime mover torque is must be also same, but in the opposite direction.

When the machine is operating under no load condition operating point will be here 0. Go on increasing the load, the value of delta will come in at this point it will operate here, at this point it will operate here like that. Can it operate here? Suppose, load is such that delta is this much. So, power and torque is synonymous in case of synchronous machine when you are considering steady state operation ok. Therefore, it is operating at this some delta at this point suppose.

Now, I find there are two operating point. You can easily show that this operating point will be not a stable operating point, why? Because a slight disturbance around this point in delta suppose rotor advances a beat you will find that this is prime mover thing prime mover torque. You will see it will the torque will decelerate the motor just like that and it will come to stop.

So, up to delta equal to 90 degree, this is the stable operating point. Like the induction motor I explain it can be also explained in this. So, P delta curve is most important curve of a synchronous machine, neglecting r a, it becomes much simpler like this. And between so, delta general varies between 0 to 90 degree. Of course so, that it does not go near to the delta critical value which is 90 degree because if delta becomes more than 90 degree it will enter into unstable zone and you will not be able to operate this synchronous machine in the unstable zone.

Therefore, delta must be in between 0 to 90 degree typical values of delta may be 10 degree 5 degree 20 degree it should be in this linear zone preferably and well below this unstable zone. So, anyway this curve P delta curve it is often called is very much useful P delta curve understood. Therefore, I will come to this curve slightly later once again if I have done the motor phasor diagram, but the fact is that a very simple expression of power delivered by the synchronous generator if it is operating at some load angle delta can be easily computed provided you know the excitation voltage as well as the terminal voltage ok.

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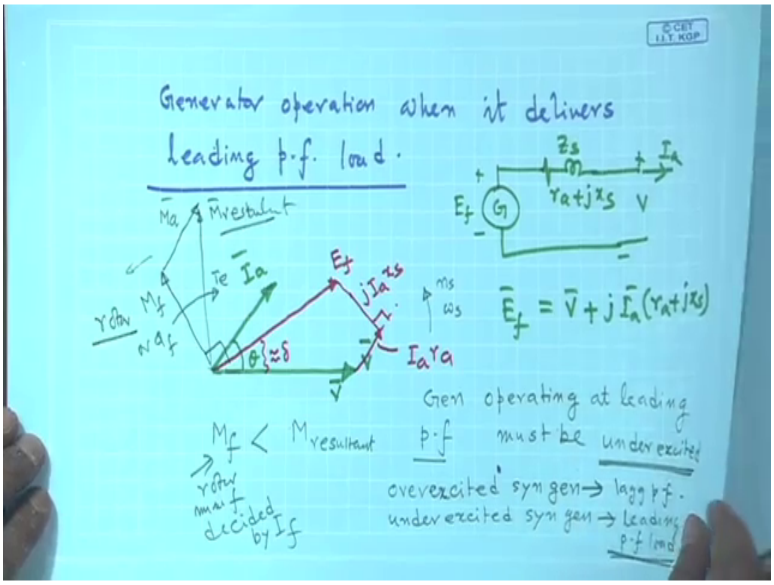

Now, suppose I will just draw for generator operation, I will draw the phasor diagram. Generator operation when it delivers when it delivers leading power factor load; leading power factor load it will be like this. So, how I am drawing generator plus, minus, here is the E f, here is your Z s. I will now draw for this whole thing Z s. This is r a plus jx s and this is your terminal per phase voltage V and I am saying it is delivering a leading current.

Now, let us see how to draw phasor diagram. So, this is V and it is leading current. So, suppose this leading current with respect to V is this is I a follow me carefully, but this equation is true E f is equal to your terminal voltage plus j I a into r a plus jx s, is not? So, this is what I will do. So, V plus I a r a I will add this is small and then to this I must add j I a x s such that this angle is ninety degree and this length is much higher than this fellow. So, j I a x s I am not breaking up j x al and x ar and then, you will get E f.

You see this is this one is your V green one terminal voltage green V and armature current. This is the power factor angle of the load, that is there and this angle between these two will be close to the delta E f and because V will be equal to E r we have seen

[FL]. Now, where is your phi f? Phi f is here perpendicular to this red line here will be your phi f or M f or phi f is not this will be M f and where is your resultant field?

M f this is the rotor field; mind you, M f this is the rotor field which induces E f then M f plus your M a is along this line. So, M f plus M a and this will be your M r, M resultant because M r do not say it is resultant field. The notations I have used in case of synchronous machine is rotor field is E f net field is M r sometimes I am writing, but it is resultant field M r because M f plus M a this is M resultant.

In which directions all the phasors are running? In this direction suppose ns or omega s in electric radial ampere second all phasors are moving. In which direction electromagnetic torque is developed it is the rotor field, it is advanced with respect to the resultant field. Therefore, electromagnetic torque must be this way consistent in case of generator operation. Electromagnetic torque is in opposite direction of rotor. All phasors are moving with speed n s in this direction and this is the thing, but in this case you know to one thing this M f it depends upon field current excitation. M f length of M f will be less than M resultant that is this one resultant action.

And then what should I call? I will call a generator operating action at leading power factor; leading power factor must be under excited. Why under excited because field current decides M f and that field mmf rotor mmf decided by rotor current, decided by I f is less than m resultant you can easily see if it is leading power factor and therefore, it must be under excited.

Therefore, we conclude that a synchronous machine operating as a generator if it is delivering leading power factor load then it will be operating as under excited mode. Under-excitation, over-excitation the idea of that if you have this complete phasor diagram you conclude that whether this rotor field M f compare the length of the rotor field and the resultant field. If the rotor field length is less than the resultant field it must be under excited we call it. In case of lagging power factor load we have seen that it will be over excited.

So, a synchronous generator if it is over excited it must be supplying a lagging power factor load. So, over excited synchronous generator over excited earlier we have seen that over excited synchronous generator supplies lagging power factor; lagging power factor load. Under excited synchronous generator will supply leading power factor load, is that clear? Therefore, this is how this can be done.

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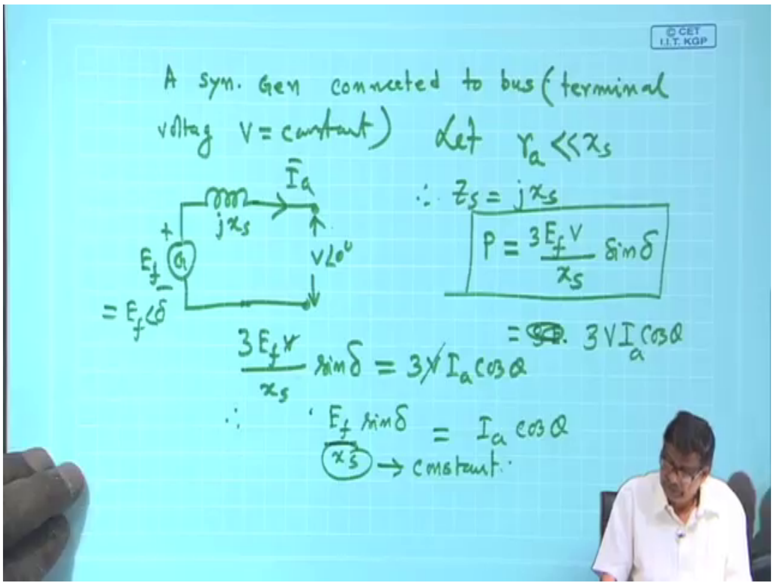

Now, what I will do whatever time is left that we will see we will consider now asynchronous generator; a synchronous generator connected to infinite bus connected to bus; means terminal voltage V is constant I cannot change that. And let for simple understanding of the what is going on the phenomena that I am going to discuss it will be much easier because after all r a is very small compared to x s.

Therefore, Z s is equal to only jx s pure reactance. So, under this condition just this is the generator mode this is plus minus E f and here is your bus V which is 0 degree and it is delivering a current I a and this is jx s is not and under this condition we know power delivered by the generator and this E f is E f delta.

So, always take the terminal voltage which is constant as your reference, so, 0 degree. So, P is equal to we have already seen E f V by x s sin delta very simple relationship ok. So, this is the thing, but it is also true this real into 3, per phase it was like that. It is also true this thing is 3 E f no. E f 3 V I a cos theta, is not? So, what I am telling is 3 E f V by x s into sin delta must be equal to also 3 V I a cos theta from the power factor of the load angle between V and I a I could also calculate the real power output and that must be same as this why not same quantity is we have connected. So, it will be like this of which you note that then it will be from both sides V goes and the x s is constant. So, it will be E f sin delta by x s is equal to I a cos theta. X s and E f suppose x s is constant.

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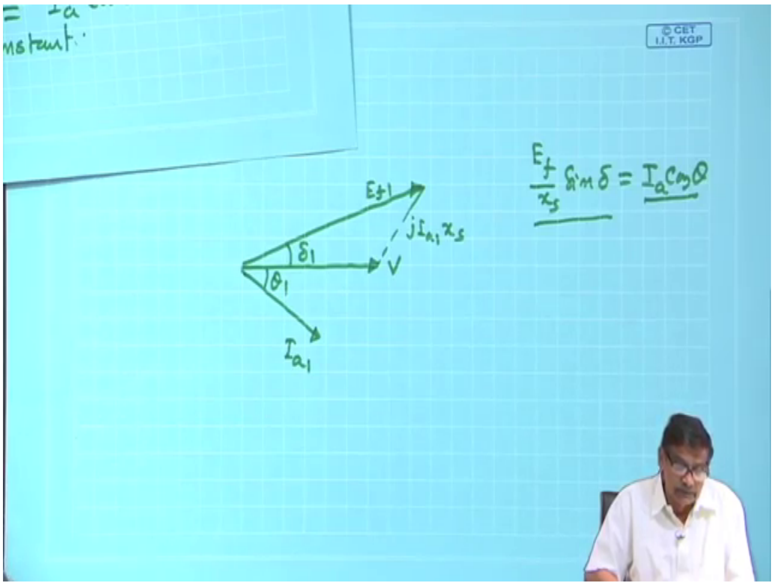

Suppose, the machine is operating at lagging power factor then I will draw it only one thing I will tell and then today I will conclude. It is very, but get the idea this is a post terminal voltage V. Suppose, the generated is operating at some power factor angle theta 1 delivering a current of I a 1, is not? So, this is and where is your E f? V plus j I a x 1 this will be you your excitation, E f 1 and what is the load angle? Delta 1.

So, we have seen that E f by x s sin delta is equal to I a cos theta. Suppose, the real power I am not going to change because they I told you real power means how much fuel you are consuming. I am keeping that fixed I will not allow it to change. It means that whatever real power I am pumping into the system which is held constant and I am not going to change that which we will ensure that output power is also constant in this lossless machine armature copper loss is also not there. Therefore, this conditions must be satisfied.

Anyway, we will continue with this discussion next time. But, please go through this derivation part on your own; this algebraic manipulation in this fashion. Very quickly you can do it. Use calculator you can also try some numerical problems from your books etcetera.

Thank you.