Electrical Machines - II

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Lecture – 44
Maximum Electromagnetic Torque and Slip at which it Occurs

Welcome to the next class.

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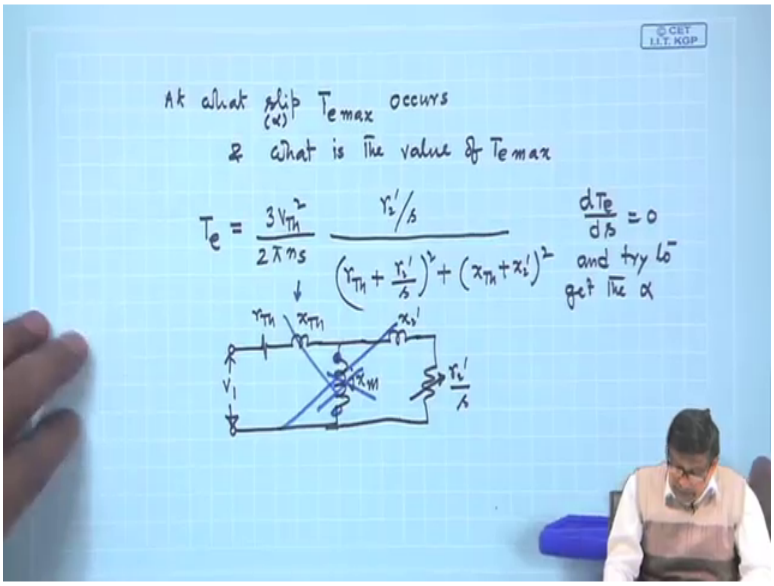

So, we were telling about we want to calculate the slip at which maximum torque occurs. Of course, this can be done by differentiating this and get it. But because we have already developed the equivalent circuit, it can be done in a much more simpler way, instead of trying to differentiate it and set it to 0 get the value of alpha.

So, I refer to this equivalent circuit, but since I am writing r Thevenin's x Thevenin's of course, this thing is not there, by mistake I wrote jx m. So, it is a simple series circuit, so, I better redraw it here.

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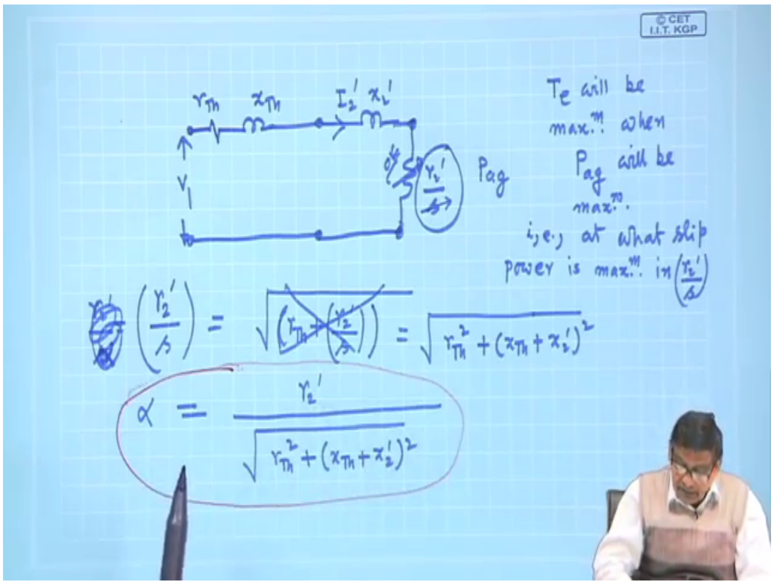

So, the Thevenin's equivalent circuit is now r Thevenin's x Thevenin's and there will be no x m because already Thevenin's equivalent between these two circuits, I have found out this is V 1 and this is x 2 dashed and this is r 2 dashed by s.

So, you want to maximize the torque. And what is the torque? You recall, I told you that the power in this resistance is P a g and P a g is also a measure of torque. Because P a g by is some constant number 2 pi n s gives you torque in Newton meter or P a g itself in synchronous what gives you the electromagnetic curve developed by the machine. Therefore, if you look at this equivalent circuit in which I am varying s here.

So, torque will be maximum, T e will be maximum when P a g is maximum. If here the power is maximum at what slip? If I can calculate that, then torque will be also maximum because torque is nothing but P a g that is the whole idea. Therefore, in this circuit it is now a circuit problem there is a circuit forget about motor, there is the variable resistance here, why it is variable? Because s will be changing, I want to find out at which s T is maximum.

Therefore, I want to maximize the power in this resistance. So, why not apply maximum power transfer theorem which we have already run, learn, and do not try to just differentiate this expression of torque. Nor not like this way we will not do. So, T e will be maximum when P a g will be maximum; that is at what slip; what slip? Power is maximum in this resistance r 2 dashed by s. That is what you have to find out and we know it is an ac supply.

So, all the impedances looking from this can be considered to be the impedance of the source along with V 1, V 1 is the source as if it is the internal impedance and here is a variable resistance. And power is maximum when r 2 dashed by s this value of the resistance is equal to the magnitude of the impedance of this internal impedance of the source; that is it must be equal to this r Thevenin plus r 2 dashed by s sorry it will be equal to square root of r Thevenin squared plus x Thevenin's plus x 2 dashed whole square. It is at that value of slip torque will be maximum. That is this is equal to nothing, but r 2 dashed by alpha.

I am I am interested to know what is the value of alpha? Anyway, we put it like this. If this is the case then this is the slip at which maximum torque will occur will be alpha is equal to r 2 dashed under root this one. This is the result in one stroke we get this result no differentiation. So, at this value of slip maximum torque will occur. Then the next question was, then what is the value of this maximum torque?

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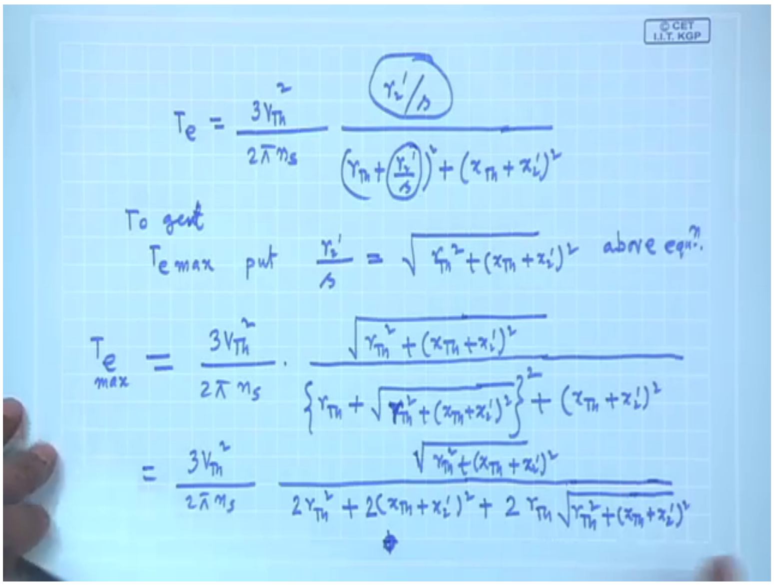

T e max T e general expression of T e is equal to many a times I have written it is nice to write over and over again so that it comes to we easily can write it. So, this is equal to this was for any value of slip r 2 dashed by s this is r Thevenin's plus r 2 dashed by s whole squared plus x Thevenin's plus x 2 dashed whole square. This was the general expression of that.

Now, if you want to calculate T e max, to get T e max put r 2 dashed by s because s comes along with r 2 dashed. So, r 2 dashed put r 2 dashed by s to be equal to this thing, put this above, in the above equation. And then your T e max will be equal to 3 V Thevenin squared by 2 pi n s is there, then on the top the this one is nothing but this, so put that. Plus x 2 dashed whole square divided by r Thevenin's plus these r 2 dashed by s, put once again the same thing plus of x; that means, plus x 2 dashed whole square this will be the value of T e max. Now this is squared hm.

So, this will be the value of T e max. Now it looks quite it do not try to memorize this, because no point. But only thing is this can be further simplified in a nice form. For example, you expand the numerator then what will happen there will be r Thevenin's square plus x Thevenin's square, a plus b whole square like that and also here will be another x Thevenin's square coming is not? It will be like that a you just expand it. And here, it was correct know? Are you getting? So, this is equal to 3 V Thevenin squared by 2 pi n s into. So, it will be r Thevenin square let me write a square plus b square, here it should be r Thevenin's know. Please note that this is r Thevenin's I by mistake I wrote.

So, this is r Thevenin's; so, if you remove this. So, a square plus b square will give you 2 r Thevenin square, plus x Thevenin's plus x 2 dash squared. So, this is a square plus b square plus 2 a b term, it is some routine I mean simplification algebraic manipulation nothing great work, but anyway let us do it in longhand.

So, 2 a b term plus x Thevenin's plus x 2 dashed whole square. So, what I will do it, I will write it there was 1 x Thevenin's plus x 2 dashed whole square coming from here and there was already there. And on the top, it is 1,, no 1 it is under root this one, r Thevenin square plus x Thevenin's plus x 2 dashed whole square. Now what we will be doing is very straight now I know what to do.

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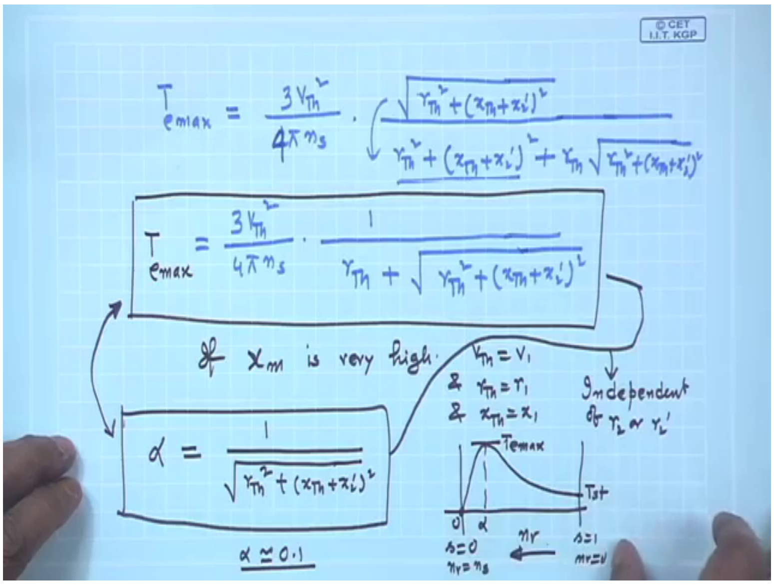

So, T e max, maximum value of the electromagnetic torque will be 3 V Thevenin squared by 2 pi n s and you see there is a 2 you can take common ok. So, that it will become 4, I will write it like this; this 2 and this 2 pi n s and then ok.

Let me this step let me write so that. So, on the numerator it will be r Thevenin squared plus x Thevenin's plus x 2 dashed squared divided by this is r Thevenin squared plus these 2 I have taken outside. So, x Thevenin's plus x 2 dash squared plus r Thevenin's square root of r Thevenin squared plus x Thevenin's plus x 2 dashed squared it will be like this.

And you know the next step is obvious that is this 4 pi n s is there. What you do? You bring this numerator term below ok. Divide both numerator and denominator by this. So, that it will become 1 here and here it will become if you divide bring this down it will be r Thevenin's from this and it will be r Thevenin squared plus x Thevenin's plus x 2 dash squared. That is all no further simplification is possible.

This will be the, so bring this down. So, this will yield when you divide this term and this cancels out and r Thevenin's. So, this is the expression of the T e max ok. You must agree with me. If x m is also neglected in the equivalent circuit if you neglect x m then r Thevenin's and x Thevenin's will be simply r 1 and x 1. If x m not neglected, if x m is high, very high is high. So, that in the equivalent circuit, x m come in parallel this x m, then can be treated as open circuit. And then of course, your V Thevenin's will be equal to V 1, your r Thevenin's will be equal to r 1 and x 1. And it is already in that Thevenin's equivalent form source with its internal resistance if x m is very large compared to this r 1 x 1 this series things it is up here.

So, if x m is high, then you know V Thevenin will be equal to V 1 and r Thevenin's is nothing but r 1 and x Thevenin's is x 1. You just remember that, so that you can calculate the electromagnetic term very efficiently.

So, 2 things we have got. 1 is the value of the slip at which maximum torque occurs that is alpha and that value was equal to I wrote earlier, that value was equal to 1 over square root of r Thevenin squared plus x Thevenin's plus x 2 dash squared

This is the slip at which maximum torque occurs and this is the value of electromagnetic torque. So, these are the 2 most important formula of a 3-phase induction motor. The problems are like this that all equivalent circuit parameters are known. Then sketch the torque slip characteristics, take some typical values of slip and in today's in terms of today's way of calculating you can write a small program slip changes from 0 to 1, calculate T e from these two expressions, sketch it and then you can also calculate T e max. And the slip at which T e max occurs means this is the torque slip characteristics I told you it was like this is s equal to 1, this is s equal to 0 and this is the slip at which maximum torque occurs and this is T e max.

And this of course is the starting torque T starting. What the point? This is 0 and if you have drawn like this then speed is doing this. This is n r equal to 0, I am sorry. This is nr equal to 0 and this is n r equal to n s ok.

So, for a well designed machine what I was telling, alpha is of the order of 0.1 or so and this is the torque slip characteristics. Now, the important things about torque slip characteristics is that; you note that the value of this slip at which maximum torque occurs and the value of the maximum torque, these two things these two are independent of the value of s. These two quantities independent of r 2 or r 2 dashed r 2 and r 2 dashed are one and the same thing reflected value.

Therefore Te maximum and alpha, the slip at which maximum torque occurs are independent of the value of alpha ok. [FL] we will come to this slightly later, but let us now try to understand what is going to happen to these torque slip characteristics if rotor resistance is increased.

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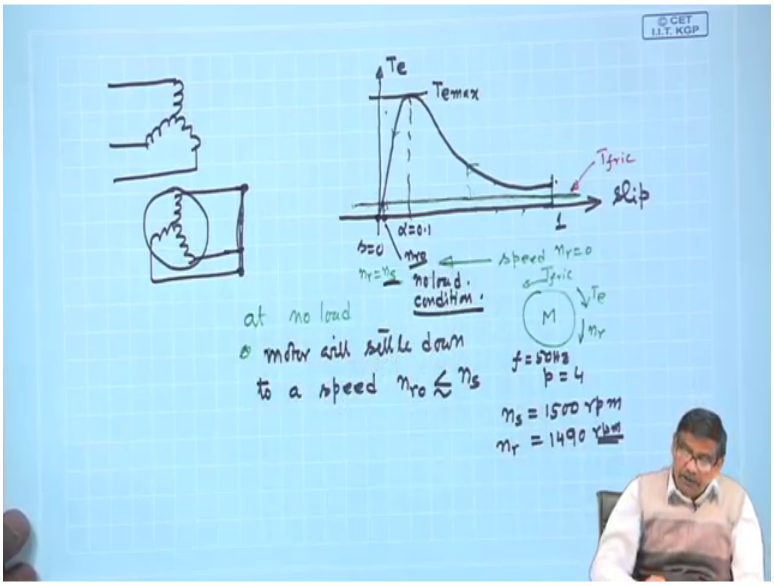

For example, I have told you this is your stator which you are energizing and this is your rotor which also houses a 3-phase winding and I will I showed it to be shorted that is fine. And the torque slip characteristics, we now have a fair idea and this torque slip characteristics was like this. This is slip to 1, now and this is T e max.

The machine in any case can produce this much of maximum electromagnetic term. Opposing torque you do not know ok. It has nothing to do with the load torque. It is machines capability; if it runs at this slip it will develop this much of torque. Therefore, your load torque must match that at that point and that is the thing. Now, this is the alpha whose value is about 0.1 [FL].

Now, let us do this small thing. To understand, to use these torque slip characteristics to understand many interesting thing of the induction motor this is T e. For example, suppose on the shaft of the machine, there is a small frictional torque present ok. This is T friction, this line is T friction. Then, what is going to happen when you switch on the supply? At that time, slip was 1 and we say that this is the starting torque and opposing torque is this much, so T starting is greater than T friction, so machine will accelerate.

And also do not forget that this side is speed. Always draw these two things to avoid any confusion. This is the n r equal to 0 and this is n r equal to n s. So, the motor will accelerate because on the motor two things are acting, one is T e electromagnetic, another is a constant value of T friction. And therefore, machine will start accelerating n which direction? Because T e is greater than T friction, so, it will start increasing its speed in the clockwise direction itself. Direction of electromagnetic curve decides the direction of rotation where the machine is operating as a motor.

Therefore, speed will rise speed is this. So, operating point it was here, then it will move because slip is increasing. At this point what is happening? When it reaches this much of speed electromagnetic torque is still greater than T friction, it will accelerate. Here also any value of speed you take machine goes on accelerating. Of course, rate of acceleration depends upon the difference of these two torque, but nonetheless, T e is T friction, machine will go on accelerating.

And eventually it will come here also. Then the difference of torque is highest the rate at which its speed is increasing it will become much more. In fact, if you do some experiments on induction motors on no load details and you have switched on the supply you will find machine is accelerating then suddenly it is accelerating very fast, perhaps it is crossing this zone at that time. But nonetheless, T e max is greater than T friction it will accelerate an operating point will shift.

And in this way it will come here when the electromagnetic torque developed by the machine will be equal to the opposite T frictional torque and machine will settle there. Therefore, it will run at a speed very close to synchronous speed. This is n s in terms of speed. The operating point will be this one. It has to develop certain amount of electromagnetic torque which will match the friction and yes the machine is capable of doing that and it is here it does so. Therefore, at no load; at no load; no load means only opposing torque is frictional torque at no load speed machine motor will settle down, motor will settle down to a speed called n r 0, no load speed, n r, no load.

The this point this is n r 0 to a speed n r 0. Where these two torque balances and this n r is less than, but very close to n s, that is what I want to tell. Why it is very close to n s? Because T friction itself is small and machine will settle down there.

Suppose to give you some example in terms of numbers, suppose it is a 4 pole machine and supply frequency is 50 Hertz, then synchronous speed is 1500 rpm. Then what I am telling, n r will be very close to 1500. Depending upon of course, actually how much is the frictional torque which is very little, whoever has designed the machine bearing this that he must have taken that into account and n r may be say 1490 rpm.

So, it will be the operating point under no load will be very close to the synchronous speed n s, but less than that. Had there been no friction at all, then machine would have accelerated, accelerated, accelerated then this line is not there and it will come here. When the opposing torque is 0, electromagnetic curve developed by the machine is 0, and machine will settle down to synchronous speed. Anyway, that is a very ideal situation. That is why we tell the slip of the machine can vary from 0 to 1 for motoring mode.

And synchronous speed that it will run is not a practical proposition, because there will be always some; however, small it is some frictional torque will be there. And the intersection of this opposing torque and this torque slip characteristics will determine the operating point under no load condition, so, this is no load. We will discuss further, because this torque slip characteristics as I told you can help me to understand many other finer points of a 3-phase induction motors.

Thank you.