Power System Analysis
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Lecture - 13
Synchronous Machine Model

Welcome to lesson 13 on Power System Analysis. In this lesson we will talk about Modeling of Synchronous Machine.

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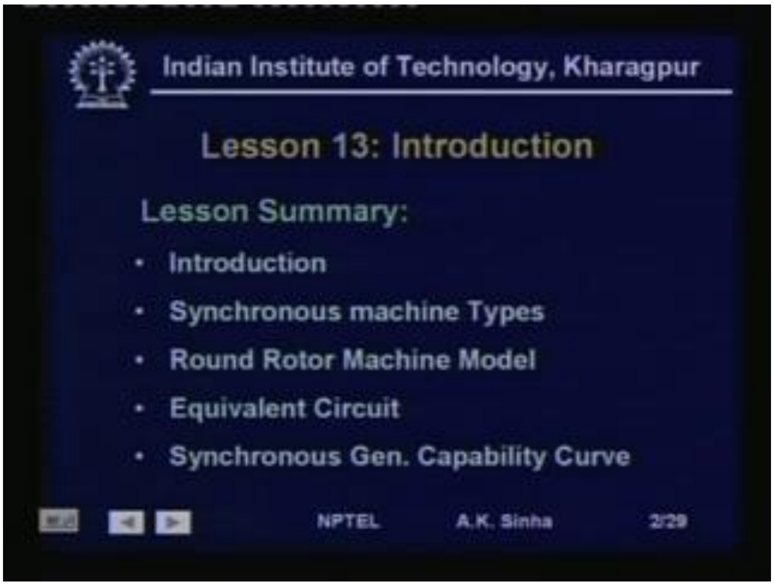

First we will give an introduction to synchronous machine. Then we will talk about different types of synchronous machines, which are used in power systems. Then we will talk mostly about modeling of round rotor machine. We will get into the equivalent circuit for the round rotor machine and talk about the synchronous generator capability curve.

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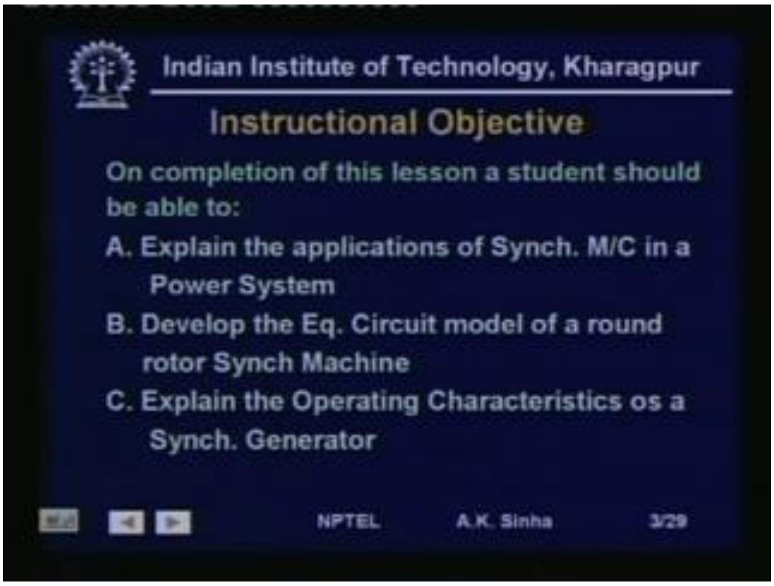

Well once this lesson is over we should be able to explain the applications of synchronous machine in a power system, develop the equivalent circuit model of a round rotor synchronous machine. And explain the operation, operating characteristics of a synchronous generate. Well what is a synchronous machine? A synchronous machine is a machine which has a rotor, which is excited by a DC winding and on the stater it has three windings for three phase power.

The synchronous machines are mostly used in power system as generators. In fact, all the generators that are used in for electrical power generation are synchronous generators. Some places we use these machines also as motors that is synchronous motors. The advantage of using these machines as synchronous motor in some of the places are that the speed is constant, it depends only on the frequency. So, if the frequency of the system remains constant their speed is going to be constant.

Another advantage of these machines is that you can control the reactive power. The consumed by these machines or delivered by these machines. In fact, as I said earlier all the generators from small size to very large size up to 1000 mega watt or even more are all synchronous machines.

Now, those machines have a peculiar characteristics, that the frequency of the generated voltage and current is dependent on two parameters. One is the speed at which the rotor is rotated by the prime over and the number of poles that these machines have.

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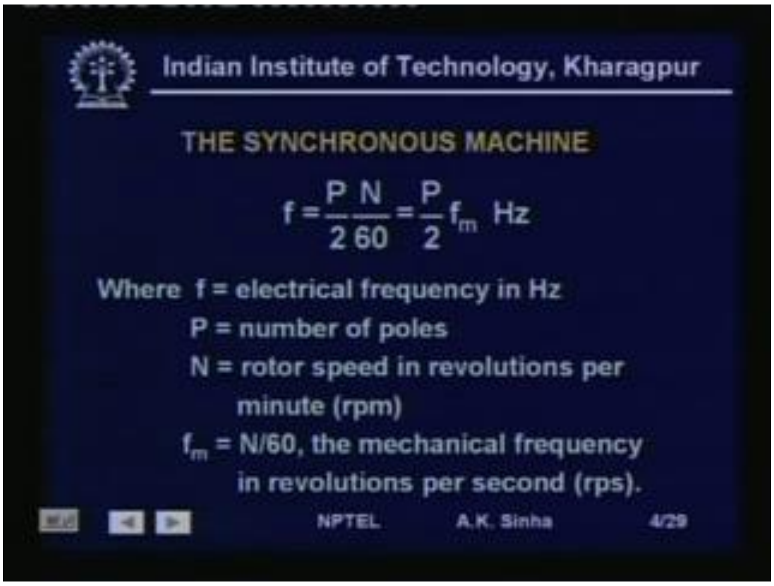

So, this relationship as you can see here is given by f the frequency of supply is equal to P by 2 into N by 60; where P is the number of poles of the machine, N is the speed of the rotor and rpm. This we can also write as P by 2 into f m where f m is equal to n by 60 the mechanical frequency in revolutions per second.

Therefore, if we say that we want to have a 50 hertz supply and we are using a two pole machine. Then we know that we have to run these machines at 3000 rpm. Because 50, f is 50 P is 2. So, 2 by 2 cancel out. So, 50 is equal to 3000 by 60. So, N has to be 3000. So, if we have 4 pole machine then we have to run it at 1500 rpm and so.

So, there is fixed relationship between the number of poles the speed of the machine and the frequency of the generated voltage. Since, we run our system with 50 hertz in India. Therefore, all these machines having 2 pole 4 pole or even higher number of poles have to run at certain fixed speeds only.

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Now, we generally have two types of synchronous machines. One we call as the round rotor machine, where the rotor is built up of solid cylindrical iron on which we have a winding, which is excited or connected to a DC voltage. And this will allow a current to flow in their winding and thereby it produces a field. Now, this field as shown here will produce a North and South pole like this, if the current is flowing in this direction. And the axis of the field will be like this.

Now, we have this part of the machine which we call the stator. Now, this stator has slots in which we have the coils of the winding placed. Now, coils of the windings are placed in this case it is shown that each phase winding has just one coil A and A dash, B and B dash and C and C dash like this.

So, when we rotate this rotor at certain speed, the flux which is produced by this is going to cut these windings after going through this air gap. It will cut these windings. And thereby it will produce or induce voltages in these windings. And thereby you will have voltages across the terminals of the of the three phase winding.

Since these windings are placed in such a way that first the if the field is aligned with a winding then the voltage which is induced in a phase a winding. After rotating this rotor by 120 degree we will find that field will be aligned with the B axis of the B winding. And therefore, voltage the maximum voltage will be induced in B winding and so on. Therefore, what we find is the voltage in the 3 phases will be 120 degree out of phase from each other. That is phase A leads phase B by 120 degree and similarly phase B will be voltage will be leading, the phase C voltage by 120 degree and so on.

And this is how we produce a balanced 3 phase voltage in synchronous machine. Now, round rotor machines are generally used in turbo generators, which are basically run by means of steam turbines, where you can get high efficiency at high speeds. Therefore, these are high speed machines. Also here we see these round rotor machines are generally two pole machines. And you need to run these machines at 3000 rpm to get a 50 hertz supply.

Therefore these need to be run at 3000 rpm, which is good speed for a turbo generator having high efficiency or at steam turbine, which provides high efficiency around that speed. But in many cases specially where we are using hydel turbines. The speed of the turbine may not be that high. And in those cases we need to use machines, which will have to have more number of poles depending on the speed at which the turbine can run.

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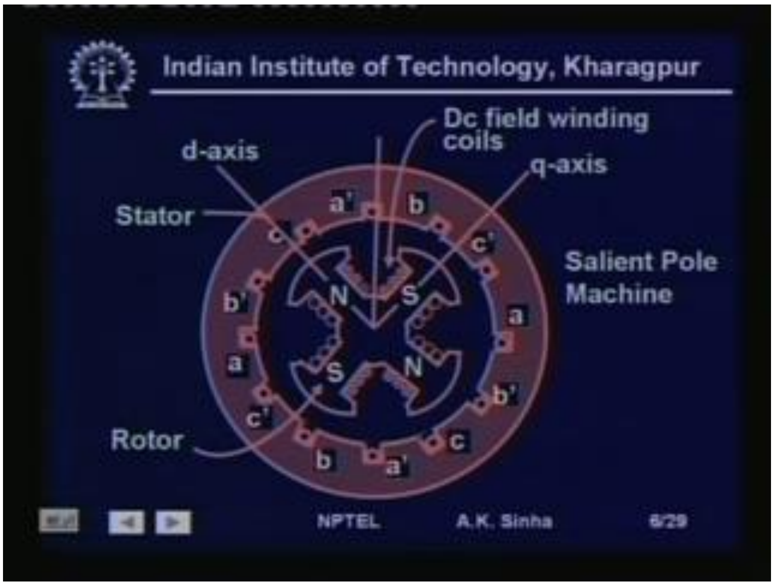

So, for these hydro turbine machines or machines which are connected to hydro turbine they have more number of poles and these machines are called salient pole machines. As you can see here in this figure, this is showing a 4 pole machine with a North pole here, a South pole here, then again a North pole and a South pole.

This machine for producing the voltage and currents at 50 hertz will have to run at 1500 rpm. Since many machine hydro turbines run at much lower speeds. So, depending on that the number of poles are also many more. Now, the difference between the salient pole machines, these machines because these are called salient pole, because these poles are very clearly visible here. And therefore, these machines salient pole machines.

Another thing that we find with them is that the magnetic circuit here is not same all around the rotor. That is we find the air gap here is much lower. Whereas, the air gap here is much higher. That means, the magnetic circuit is not having a uniform air gap or not having the same kind of reluctance all around. Therefore, these machines are somewhat more complex to analyze.

These machines also have these; the poles of these machines again are provided or excited by means of DC. So, a direct current is passed through the windings on these machines, where we can see these process are showing the current going into the coils around this point and at this point they are coming out. So, we see this as the flux lines will be in this side. So, this becomes a South pole; similarly this will become a North pole and so on.

Here again we have the 3 phase winding on the stator and we see here that we have a coil which is there for each pair of poles. That is each coil is now here 180 degree apart, but this 180 degree is the electrical degrees. Because here what we see is that, if we have a winding here like this, then this pole once it goes through one full revolution. We would have found that it the coil cuts flux first by this North pole, then by this South pole, then this North pole and this South pole. That means, the voltage the induced in the any of these coils would have gone through two full cycles.

So, when this pole rotates or this rotor rotates by one revolution the voltage would have gone through two cycles. That means, 720 degrees whereas, the mechanical rotation of the rotor would have been only 360 degrees. And therefore, we say that the electrical angle and the mechanical angle are not same in these machines.

In fact, the relationship between electrical angle and the mechanical angle is with electrical angle is equal to P by 2 into mechanical angle, where P is the number of poles. So, in case of 4 pole machine the electrical angle is equal to twice the mechanical angle and so on; for a 2 pole machine electrical angle and mechanical angle will be same.

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Next, we will try to build a circuit model for a 3 phase synchronous machine with round rotor. Now, here if we see what we have is we have 3 phase windings, the axis of the winding is for phase a winding will be like this. Similarly for phase b winding it will be like this and for phase c winding it will be on this side and so on. So, we will have the axis of these windings 120 degree out of phase from each other.

Now, we can since in general the winding on the stator is distributed winding that is you have slots all over the stator. And the winding is distributed among them. Otherwise we will be wasting a lot of iron and would not be utilizing that iron by placing windings in all over them, therefore most of the windings. In fact, all synchronous machines have distributed winding, but they can always be considered as a concentrated coil with axis same as the axis of the winding.

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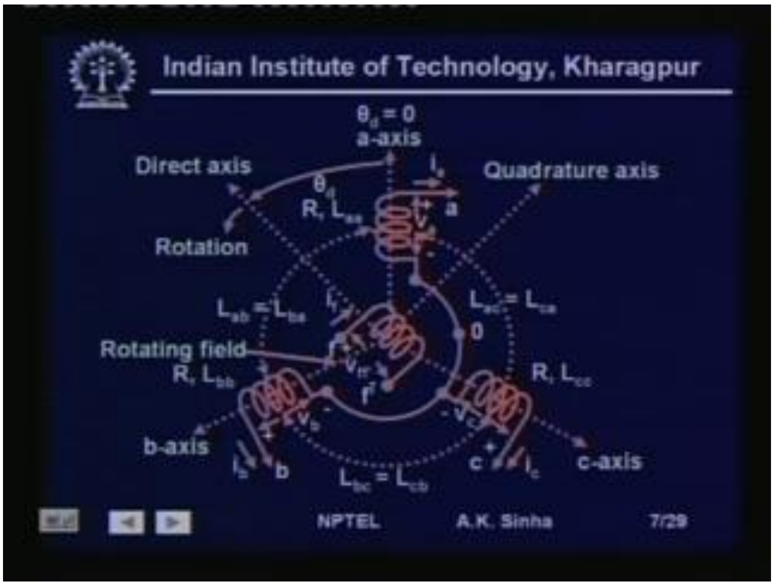

So, with that we can consider this synchronous machine as having a rotor with a winding and the stator having 3 phase windings, this a phase a winding phase, c winding and phase b winding like this. Now, what we generally do is one end of these windings are connected to together and this forms the star point. And we say that the stator winding is connected three phase stator winding is connected as a star winding.

One of the advantage of using star connected stator is that the voltage that you get across the any two terminals is root three times the voltage which will come across the phase us or 1phase of the winding. Therefore you can have a much higher line voltage for these machines, whereas the insulation required for these windings will be that required for phase voltage only.

This makes the manufactures the manufacturing of these machines, somewhat cheaper as insulation required is somewhat less. Now, here if we see this diagram, we have this field winding which is rotating. Now, at a particular instant like this it has an angle theta d, where we are saying d is this the axis of a is the direct axis. The axis of a is the reference axis and theta d that is when the axis of the winding, rotor winding is coinciding with this theta d is zero. Whereas theta d is the angle of the rotor field winding from the reference or the axis of phase a winding.

Now, each of these windings if we see will have a resistance and will also have self inductance. So, we have for phase a, a resistance R and self inductance L a a. Similarly for phase b we have resistance R and self inductance L b b, and for phase c resistance R and inductance L c c.

Since these are all symmetrical winding having exactly same features. Therefore, L a a will be equal L b b will be equal L c c. And similarly R will also be same. The winding of the field has a inductance, which is L f f, self inductance L f f. Also since these windings are stator windings are stationary and they will have also some mutual inductance between them, because they are having the same magnetic circuit. So, any current flowing in this will also be influencing this winding or the field in this winding.

Therefore we have mutual inductances between them between a and c it is L a c and which will be same as L c a. Same between a and b we will have L a b and L b a as the mutual inductance, between b and c we will have L b c, which will be equal to L c b. Again we will have also mutual inductances between the field winding and the stator windings, that is we will have inductance L a f between phase a and the field winding. Similarly between b and field winding we will have L b f and between c and field winding we will have Lcf.

But as we are seeing here this windings since it will be rotating. So, this mutual inductance between the field and the rotor are not going to remain same all the time. When this field winding axis coincides with the axis of a. We will have the maximum amount of mutual inductance. Whereas, when it is at 90 degree there will be hardly any mutual inductance between them. Therefore the mutual inductance between the rotor field and the stator windings are going to depend on the rotor position that is on angle theta. So, with this let us now try to build the circuit model for this synchronous machine.

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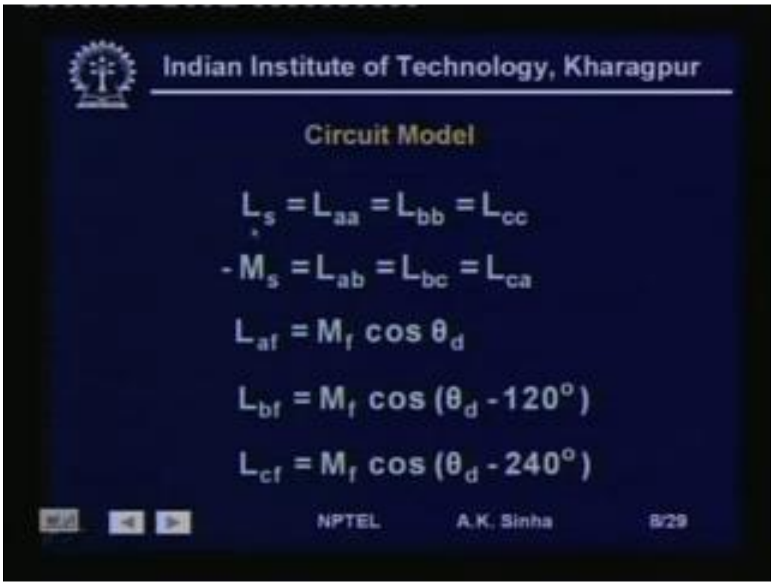

Now, we said L a a is equal to L b b is equal to L c c. That is the self inductance of the three phase windings, which we write as equal to L s the self inductance of the stator winding. Similarly, the mutual inductance between the three stator windings L a b is equal L b c is equal to L c a because all the three stator windings are placed at symmetrically to each other.

This we write as minus M s, because these mutual inductances are going to be a negative constant values. So, L L that is the self inductance and the mutual inductance between the phase windings, These are going to remain constant because this is a stator circuit and these windings are stationary with respect to each other. Also we have seen earlier that the mutual inductance between the stator and the field winding is going to depend on the angle between the axis of the field and the stator winding.

So, L a f is going to be equal to some constant m f into cos theta d. That is as we said earlier if these two are coinciding that is direct axis or the axis of the field winding, coincides with the ax axis of the phase a winding. Then we are going to get this theta d is equal to 0 and we will have the maximum mutual inductance between them. That we can see here L a f is equal to m f cos theta d when theta d is 0, this is going to be equal to m f that is the maximum value of L a f.

Similarly, L b f will be equal to m f cos theta d minus 120 and Lcf will be equal to m f into cos theta d minus 240 degrees. This is happening only because we are measuring the angle of the direct axis. That is the axis of the field from a reference, which we have chosen to be the axis of phase a.

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So, with these inductances, now known in this form we can write down the flux linkages with each of these windings. That is the flux linkage of winding a is going to depend on the current flowing in that winding as well as current flowing in the other stator windings. And it is also going to depend on the current flowing in the field winding.

Therefore we have lambda a, lambda a the flux linkage with winding a is equal to L a a into i a plus L a b into i b due to current flowing in winding b plus L a c into i c this due to current flowing in the winding c. That is stator phase c winding and L a f into if that is the current flowing in the field winding. Now, substituting these for L a f, L a c L a b and L a a we get this as L s into i a L a a is L s and L a b and L a c are equal to minus M s. So, we get minus M s into i b plus i c plus L a f into i f.

Then we can write for phase b this should read b. So, lambda b is equal to L b a into i a that is the flux linkage of winding b due to current flowing in winding a. Plus L b b into i b. That is the flux linkage of winding b due to current flowing in winding b and L b c into i c flux linkage of winding b due to current flowing in winding c. Plus L b f into if that is flux linkage of winding b due to current flowing in the field.

Again substituting for this L b a, L b b, L b c and L b f we have L s into i b minus M s into i a plus i c plus L b f into if that is L b c and L b a are replaced by minus M s. Similarly, the flux linkage of winding c can in the same way written as L c a plus L c a into i a plus L c b into i b plus L c c into i c plus L c f into i f, which reduces to L s into i c minus M s into i a plus i b plus L c f into i f.

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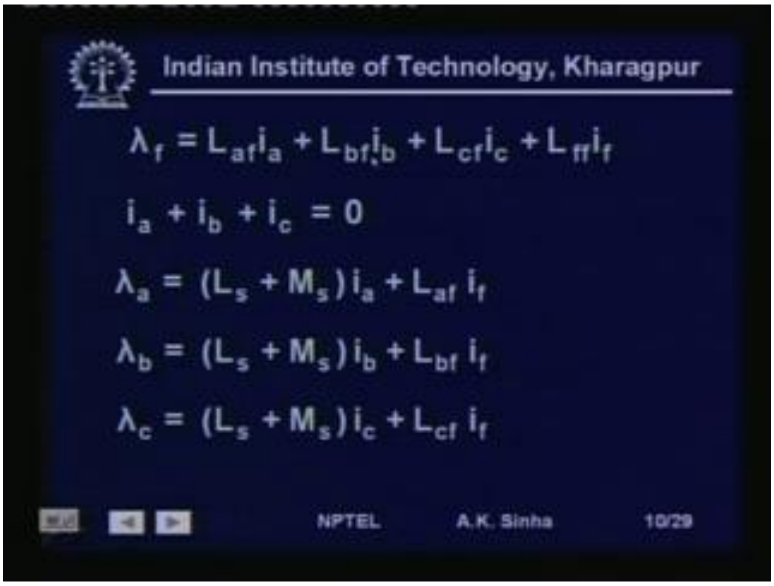

And the flux linkage of the field winding lambda f is equal to L a f into i a that is the flux linkage of winding field due to current flowing in stator winding i a L b f into i b flux linkage of field. Due to current flowing in phase stator phase b winding L c f into i c. Again the flux linkage of field due to current flowing in stator winding of phase c and L f f into if that is flux linkage in the field due to current flowing in the field winding itself.

So, this gives us the flux linkage relationship. Now, if we are talking about the balanced operation of the system. Then we have the some of the three currents at any instant equal to 0 that is i a plus i b plus i c is equal to zero.

Now, which means that i a is equal to minus of i b plus i c that is minus i b minus i c is equal to i a. So, using these identity we can now write lambda a is equal to if we see from here lambda a is equal to Ls into i a minus Ms into i b plus i c. Now, i b plus i c is equal to minus i a, because i a plus i b plus i c is equal to 0. So, we can write L s plus M s into i a plus L a f, i f is equal to lambda a.

So, L s plus M s into i a plus L a f into if is equal to Lambda a. In the similar way Lambda b is equal to L s plus M s into i b plus L b f into if... And Lambda c is equal to L s plus M s into i c plus Lcf into i f. So, this is what gives us the relationship for the flux linkages of the three stator coils.

Now, for steady state operation we have the rotor speed constant that is rotor will be rotating at a synchronous speed. As we said if we want fifty hertz supply then for a two pole machine the rotor should be rotating at 3000 rpm that is at a constant speed of 3000 rpm.

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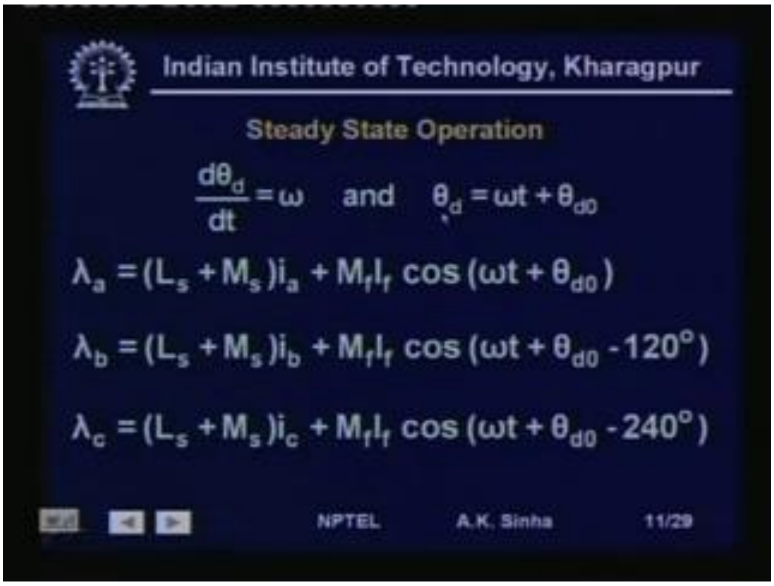

Now, if the speed is constant this means d theta d by d t is equal to omega, which is the speed in radiance per second that is constant. So, from here we will get theta d is equal to that is if we integrate this we can write this as theta d is equal to omega into t plus theta d 0, where, theta d 0 is the value of the angle at time t 0, which we can choose at any arbitrary point. And this omega is basically the synchronous speed of the rotor.

Now, using this theta d value as omega t plus theta d 0, we can write the flux linkages now, in terms of omega t and theta d 0 as L s plus M s into i a plus M f i f into cos omega t plus theta d 0. Now, here if you recall we had L a f is equal to M f into cos theta d. Now, we are replacing this theta d by omega t plus theta d 0. So, L a f is Mf into cos theta d, which is equal to M f into cos omega t plus theta d 0. So, substituting this we will get here as Ls plus Ms into i a plus Mf into i f cos omega t theta d 0. Similarly lambda b the flux linkage with stator winding b of a stator winding of s b is equal to L s plus M s into i b plus M f i f into cos omega t plus theta d 0 minus 120 degree. And for flux linkage with for stator winding c is equal to Ls plus Ms into ic plus Mf If into cos omega t plus theta d 0 minus 240 degrees.

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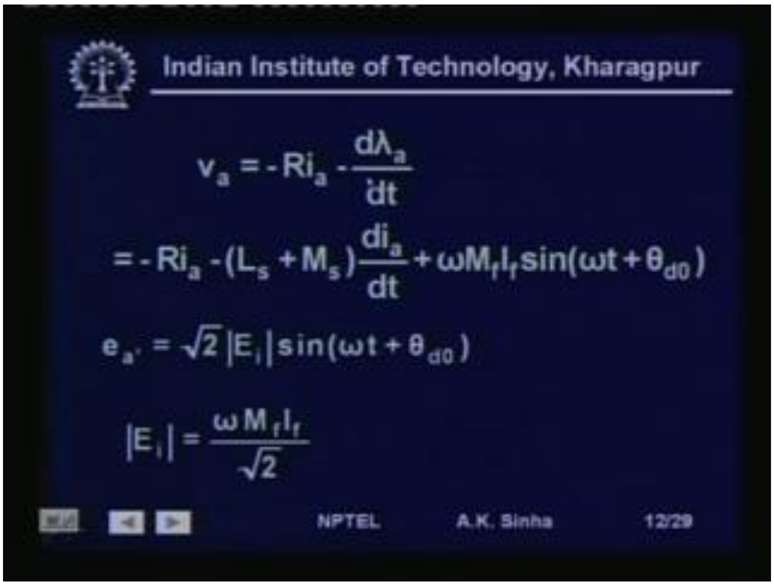

Now, the voltage across these windings can be written as V a for phase a the voltage of across phase a winding will be equal to minus R i a minus d lambda a by d t, where R is the resistance of the winding, i a is the current flowing through it. Now, d lambda by d t gives us the voltage, because of the cutting of the flux. So, if we go back to this diagram the voltage V a here is going to be equal to R into i a. And the sign is negative because we are considering this machine as a generator and the current is flowing out. So, we have the voltage V a here, which has a positive potential here at any instant of time and the current is flowing in this direction. Therefore, we have to use that negative sign.

So, we have V a is equal to minus i a R a minus d lambda a by d t that is because Lenz's law will be putting this voltage in the opposite direction. That is the voltage induced is also going to be positive here and negative here.

So, using this we have the relationship here as V a is equal to instantaneous voltage V a is equal to minus R into i a minus d lambda a by dt. And again substituting for lambda a here we can write this as minus R into i a minus L s plus M s into d i a by d t plus omega Mf If sin omega t plus theta d 0. That is if you differentiate this lambda a as shown here with respect to time t. Then we will get this relationship here L s plus M s d i a by d t plus omega M f i f sin omega t plus d theta d 0.

Now, this we can write as this is a voltage drop in the winding and we can write this voltage here, which is the voltage which is induced. In under steady state conditions or say when the current is 0, that is when the machine is not loaded under that condition i a is equal to 0 and d i a by d t will also be equal to 0. In fact, d i a by d t will be 0 under a steady state condition.

So, when the machine is unloaded or under open circuit condition then we have these two terms first two terms minus R i a and minus Ls plus Ms d i a by d t as 0. And the only term which will be there will be this omega M f i f sin omega t plus theta d 0. This is what we call as the voltage is which is coming, because of the excitation provided by the field winding and the rotation of the field winding at speed omega.

And since this voltage this voltage which is produced by the field winding is there when the machine is the machine is unloaded. Then this is equal to this that is why we call this voltage many times as the induced voltage or the excitation voltage or the no load voltage of the machine or the generated voltage of the machine.

And here we have written this as ea dash that is the generated voltage in phase a is equal to root 2 times E i into sin omega t plus theta d 0, where we are writing this E i is equal to omega M f If by root 2. And this is this E i is giving us the magnitude of the Phasor voltage produced by the excitation feet.

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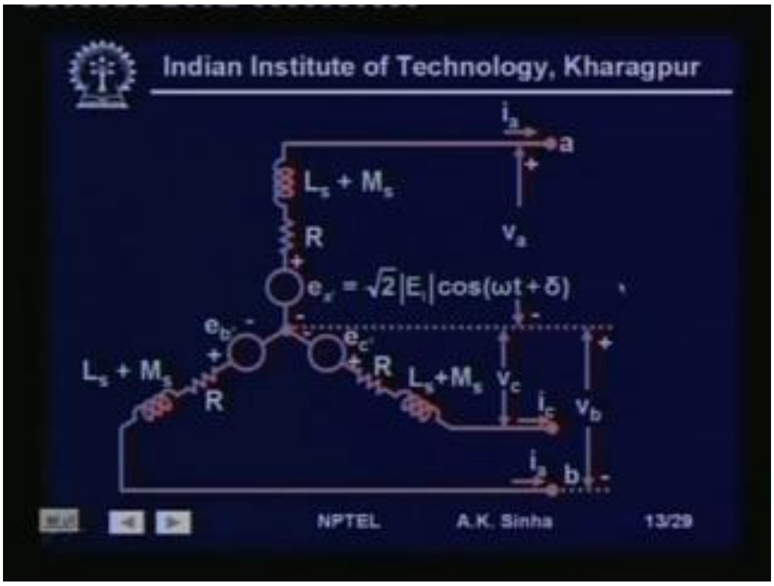

Therefore now using these relations that we have developed till now we have this voltage V a equal to the no load or the generated voltage due to the field ea dash minus R into i a. The current is flowing through this minus L s plus M s into d i a by d t that is the voltage drop due to the inductance of the coil.

So, Ls plus Ms into d into i a and this R i a are the providing us the voltage drop and this e a dash is the generated voltage due to the field or the rotor field, which is rotating at a speed omega. Since all the three phase windings are symmetrically placed and have the exactly same number of turns and the distribution. Therefore, the same thing will be happening to phase b and phase c except that they will be 120 degree out of phase. That is phase b will be lagging phase a by 120 degree and phase c will be lagging phase b by 120 degree and so on.

Therefore we can see that the circuit model for the synchronous generator will look something like this, where we have the voltage sources or the generated voltage e a dash in phase a and resistance R and the inductance the effective inductance L s plus M s here. So, in each of the phase like this; similarly phase b will have generated voltage e b dash resistance R and L s plus M s the effective inductance.

And phase c will have similarly e c dash and R it is resistance and L s and M s it is inductance effective inductance. And what we will get is the 3 phase voltages at the terminals a b and c. And if we connect it to a balanced three phase load then we will have balanced three phase currents flowing from the terminals of these machines into the load.

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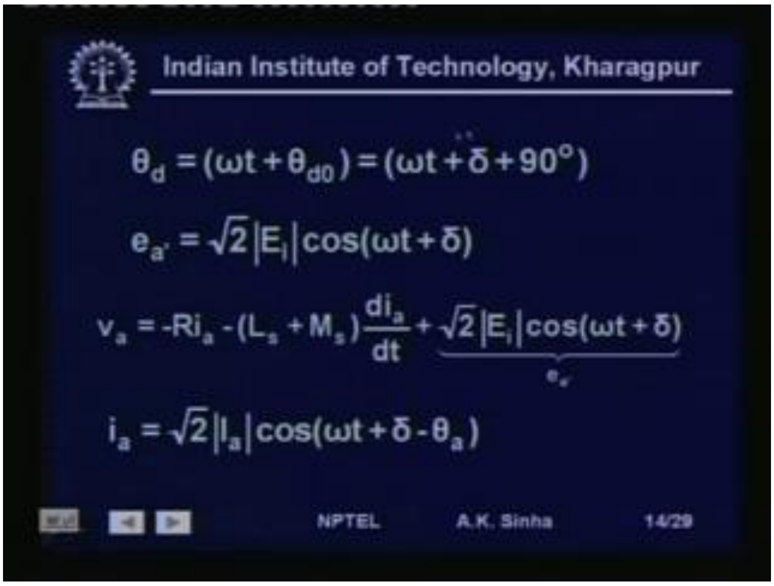

Now, we had written theta d is equal to omega t plus theta d 0. Now, we can write this theta d 0 as delta plus 90 degrees. Because if we say theta d 0, actually what is theta d 0? Theta d 0 is showing the position of the field winding with respect to the reference. That is a axis, phase a axis and if we have put an angle delta, which is equal to theta d 0 minus 90 then what is this angle delta showing. This angle delta is showing the position of the quadrature axis or the axis which is lagging the direct axis by 90 degree, so if we go back and see from this diagram.

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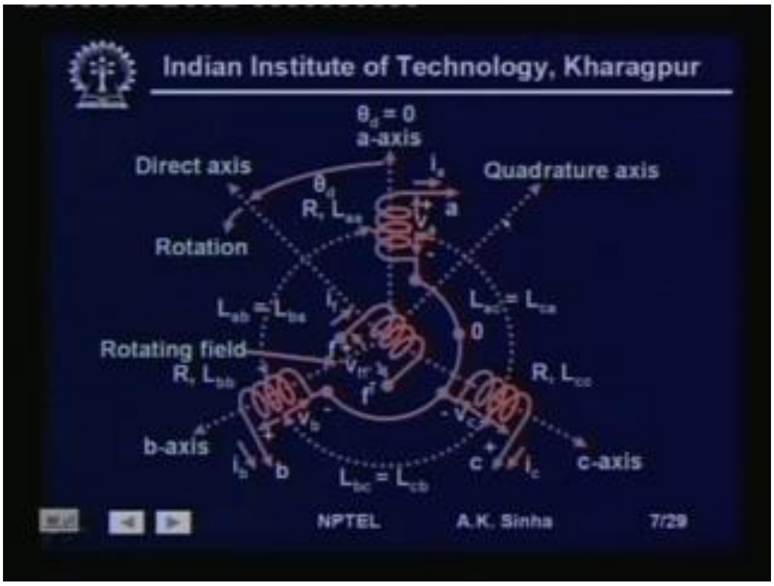

We have a direct axis that is the axis of the field which is at sometime. Suppose this is the position at t is equal to 0. Then this is theta d 0, then what is theta d 0 minus 90 is showing the position of the quadrature axis with respect to the reference axis and that means, this is showing us the angle delta.

So, delta is showing the position of the quadrature axis with respect to the reference. So, if we write in that fashion then omega t plus theta d 0 is equal omega t plus delta plus 90 degree. Then we can write e a dash is equal to root 2 E i into cos omega t plus delta. And therefore, we can write V a is equal to minus R into i a minus L s plus M s d i a by d t plus root 2 E i cos omega t plus delta, so instead of writing this relationship as omega t plus theta d 0. We are writing it in terms of delta. That is the with respect to the position of the quadrature axis. So, here we can write this in this form that is V a is equal to minus R i a minus L s plus M s d i a by d t plus root 2 E i cos omega t plus delta. Actually this is the generated voltage e a dash.

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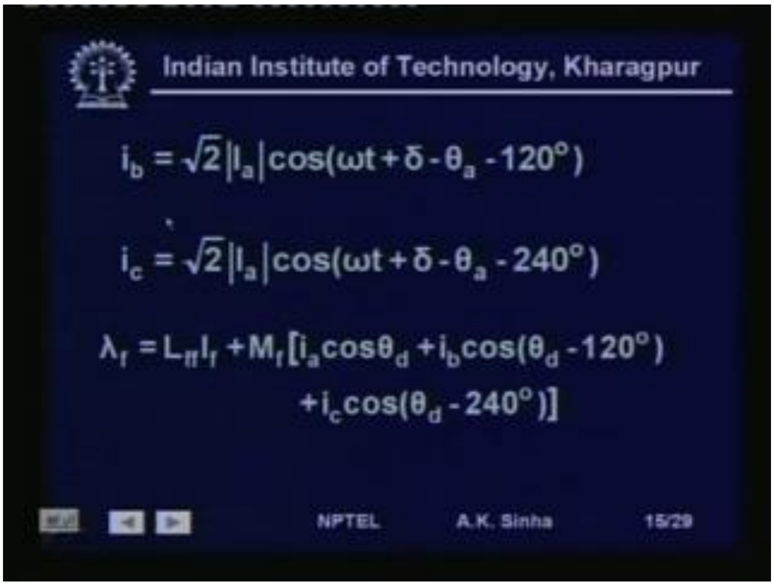

Now, if we have a current, which is lagging this generated voltage e a dash by an angle theta a. Then the current can be written as root 2 i a cos omega t plus delta minus theta a. And similarly i b and i c will be similarly displaced by one twenty degree from phase a current. So, i b will be root 2 i a cos omega t plus delta minus theta a minus 120 degree and i c will be root 2 i a cos omega t plus delta minus theta a minus 240 degree.

So, this is showing the balanced currents, which will flow if we connect a balance load across the terminals of a synchronous generator Now, let us go back to the flux linkage of the field winding, which is we had seen is given by lambda f is equal to L f f into i f. Now, here we are writing this capital I f mainly, because we are exciting the field winding with a dc current which is constant all the time. Therefore, we are replacing this small i f which means instantaneous values. Since this value is constant we are replacing it by capital I f. So, we have lambda f is equal to L f f into I f plus M f into now we had i a cos theta d plus i b cos theta d minus 120 degree plus i c cos theta d minus 240 degrees.

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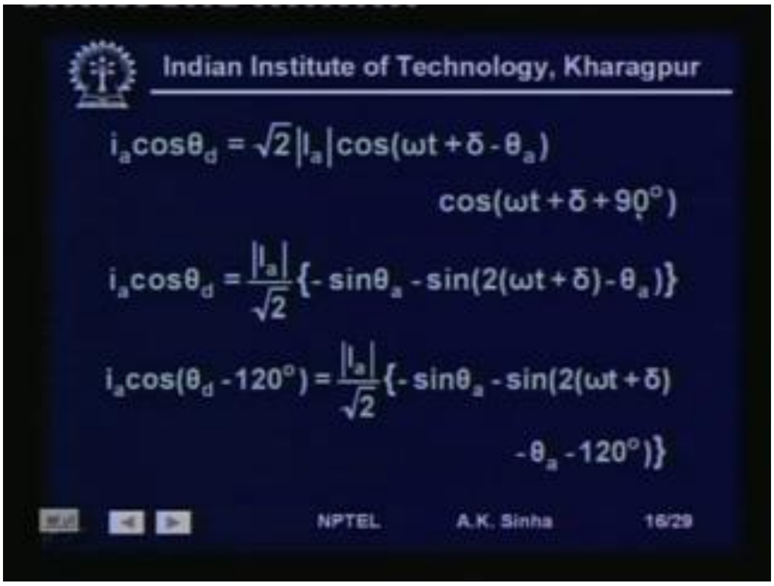

Now, we have i a cos theta d is equal to root 2 times i a into cos omega t plus delta minus theta a into cos omega t plus delta plus 90 degrees, if we write this i a, i b, i c in this form. Then writing for i a, and writing for cos theta d, we can get these relations as for i a we are writing this, root 2 I a cos omega t plus delta minus theta a, and for theta d we are cos theta d we are writing as omega t plus delta plus 90 degrees.

And similarly if this we can write as i a cos theta d is equal to i a by root 2 into minus sin theta a minus sin 2 omega t plus delta minus theta a. That is cos a, cos b, if we use this relationship trigonometric identity then we can write this in this form as sin theta a. This is omega t plus delta as a and theta. So, we should from here we can write this as i a cos theta d is equal to i a by root 2 into minus sin theta a minus sin 2 into omega t plus delta minus theta a, which is showing as second harmonic current or the current at double the frequency that is 2 omega t is coming. So, we can write this again for i a cos theta d minus 120 degree again can be written. Similarly in this fashion as i a by root 2 minus sin theta a minus sin twice omega t plus delta minus theta a minus 120 degree.

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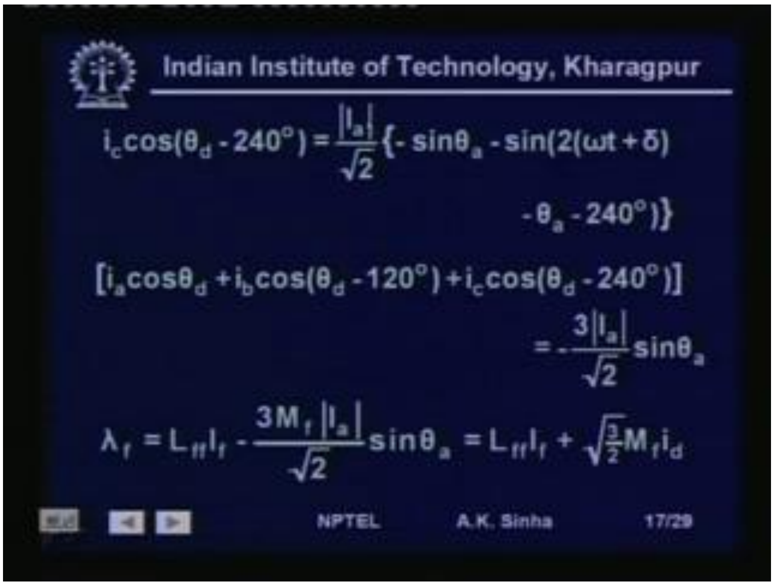

Similarly, i c cos theta d minus 240 degrees can be written as i a by root 2 minus sin theta a minus sin 2 omega t plus delta minus theta a minus 240 degrees. Now, if we sum these three, then we will find that this is equal to three times i a by root 2 into sin theta a. Because the sum of all these three second harmonic terms. If we this term here, sin twice omega t plus delta minus theta a, sin twice omega t plus delta minus theta a, minus 120 degrees.

And this sin twice omega t plus delta minus theta a minus 240 degrees. If we sum them up we find that their sum is going to be 0. Because they are three balanced terms displaced having equal value and displaced by 120 degree from each other. Therefore, we get this term as equal to this much and therefore, lambda f is equal to L f f into I f minus 3 M f into i a by root 2 into sin theta a this we can write as L f f into I f plus three by root 3 by two into M f into i d.

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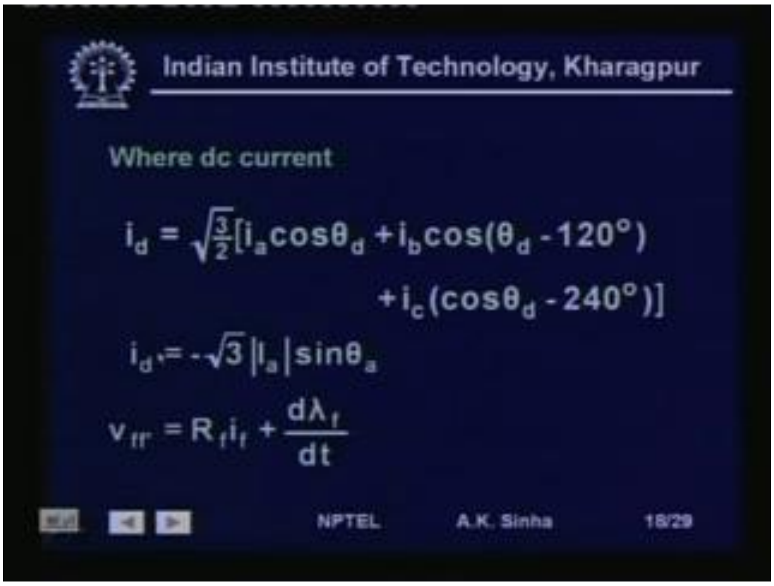

Where we have i d is equal to root three by 2 i a cos theta d plus i b cos this term which is same as root three times i a sin theta a. Now, what is this meaning this is simply saying that the effect of these three currents flowing in the stator three phase stator winding is can be seen as a direct current flowing in a winding, which is rotating along with the rotor winding, because it is seen that this effect can be seen as a direct current i d with a mutual inductance M f. So, between the two stator winding and the rotor winding and the current a constant current flowing through it.

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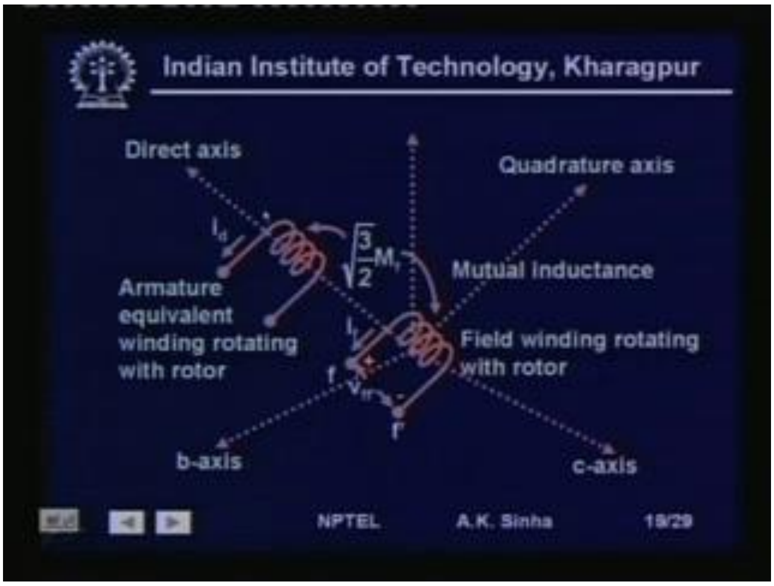

So, this can be represented by this diagram, where the effect of the 3 phase winding currents can be seen as a rotating armature equivalent winding rotating with the rotor, and having a mutual inductance of root 3 by 2 Mf. This is also trying to say one thing that is during steady state operation the rotor winding, which is rotating at synchronous speed is basically also seeing how winding or in the air gap of flux, which is also rotating at the same speed. And that is all, this is what happens when we have the stator a 3 phase stator winding, which is supplied or which is inducing this voltage and currents, which are symmetrical with respect to each other.

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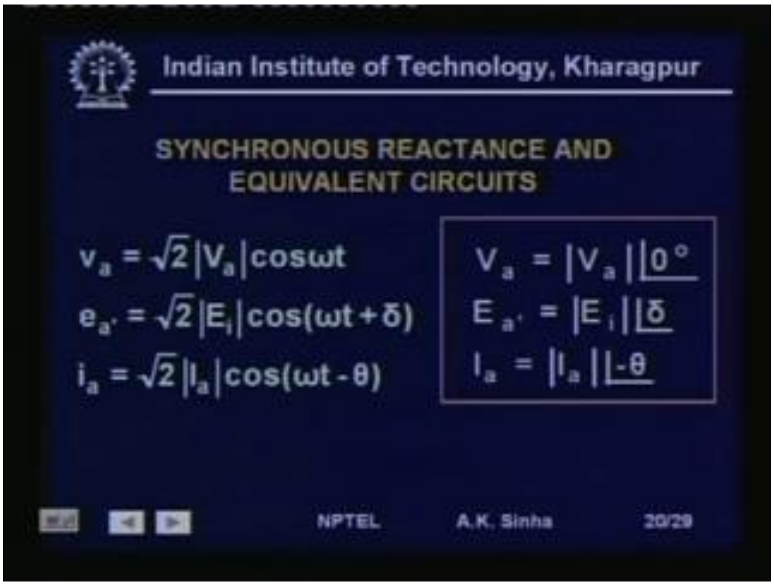

Now, we will talk about synchronous reactance and the equivalent circuits. We have v a we can write the instantaneous voltage v a as equal to root 2 V a capital V a cos omega t. E a dash the induce voltage or the generated voltage as root 2 E i cos omega t plus delta and the current i a is equal to root 2 I a cos omega t plus theta. Or in Phasor forms as V a is equal V a angle 0 E a dash is equal to E i angle delta and I a, as I a angle minus theta.

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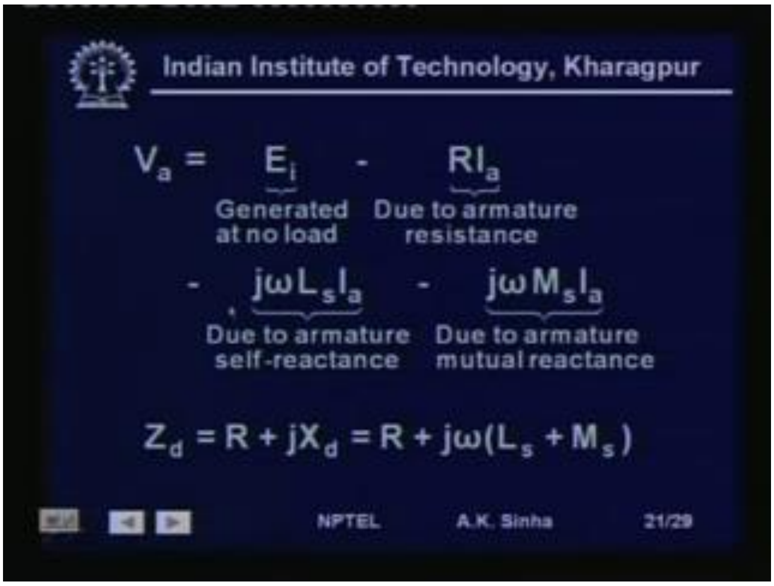

And here we can write this V a is equal to E i minus R into I a minus j omega L s into I a due to armature self reactance minus j omega M s into I a due to armature mutual reactance. So, this we can write these terms due to the inductances can be put as together. And we can write this as the impedance total impedance seen by the winding as Z d is equal to R plus j X d which is equal to R plus j omega L s plus M s.

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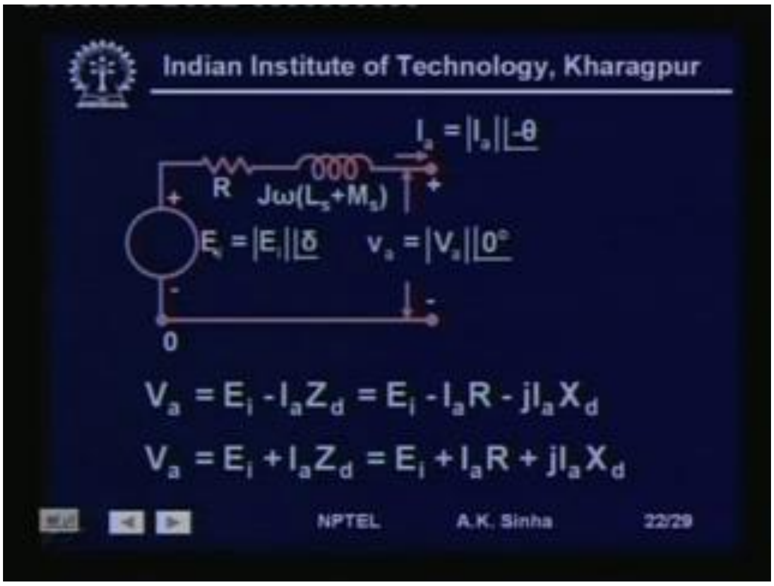

And we will get the equivalent circuit as a voltage generated E I, which is E i and angle delta and the resistance of the winding R and the inductance offered to this as j omega L s plus M s. So, this is the reactance and the current I a are flowing we have chosen V a as the reference angle. That is why E i is now, at an angle delta. Leading V a by at an angle delta and I a is having is lagging V a by an angle theta. That is we are having a node which is reactive in nature or having a power factor, which is inductor.

Therefore we can write V a is equal E i minus I a Z d; where Z d is R plus j omega L s plus M s. If we use this machine as a motor, then I a will be in the reverse direction. And the equation will be like V a is equal to E a plus I a into Z d because I a, in that case will be like this and Va will be the applied voltage which will be higher than that. So, with this we stop today and we will discuss more about this model in the next lecture.