Power System Dynamics and Control
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Module No. # 01
Lecture No. # 11
Modeling of Synchronous Machines

Our course so far is concentrated on the general analysis of dynamical systems, we now move on to an important part of this course, that is the modeling of several part system components, in particular we will concentrate in the next few lectures on the modeling of the synchronous machine. Now, a synchronous machine is a very important, you can say the most important component of a power system, the modeling of it requires a little bit of effort, we will actually be taking out to transient model of a synchronous machine.

We will of course learn some interesting new concepts like the use of a time variant transformation in order to make the synchronous machine flux, differential equations, linear time in variant. But to put matter first in perspective, just let us look at where we stand in relation to the content, which we intend to cover in this course. So, let us just you know, shift our attention to what point we are exactly in this course at the present time.

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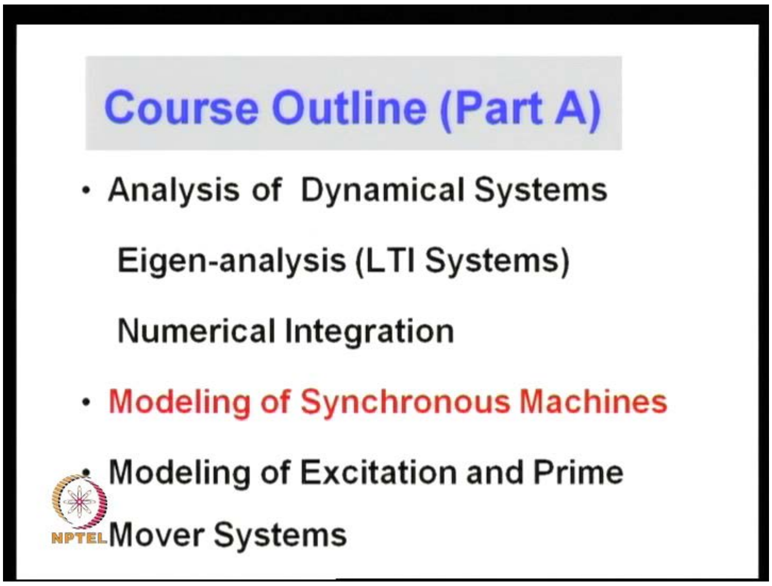

So, we have actually done the analysis of dynamical systems, in particular we studied the use of Eigen value analysis in linear timing variant systems, and we also learnt the techniques for numerical integration of ordinary differential equations.

We now move to the modeling of the synchronous machine, we will be further off course considering the modeling of several other components like excitation system, prime mover systems, and in fact transmission lines and so on. Of course there is a lot more to come remember that the part b of this course you can say, will really try to, eventually try to get a few inferences about the nature of the behavior of interconnected power systems. We should also look at power system stability analysis tools and how we can use all this analysis to improving system stability.

So, now we really move on to modeling of the synchronous machine, it will be a instructive to first look at how practical synchronous machine looks like, in fact what I show you right now is steam turbine driven generator, it is of around two hundred and ten mega watts.

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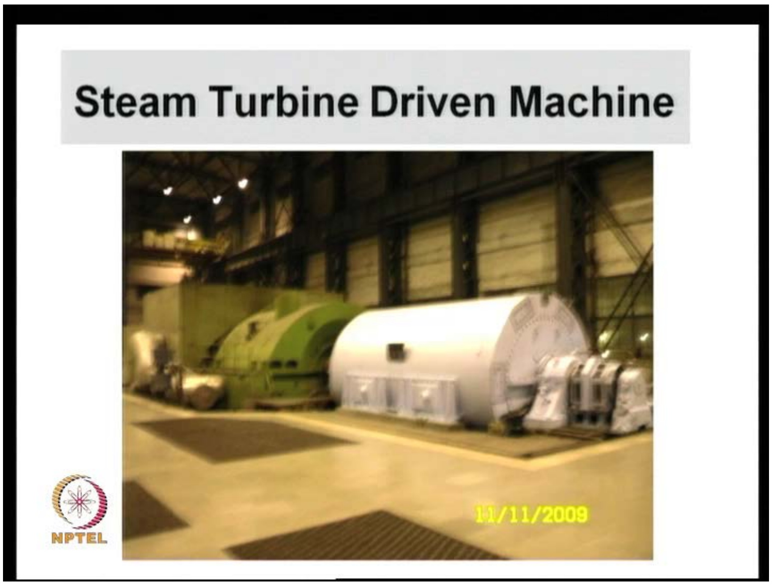

So, you can look at this photograph, what you see in white here is in fact the synchronous machine and what you see in green are the various stages of the turbine, the steam turbine which is drive this machine, right on this side are the bearings and what you will see, what you see here right at the end, is actually slipping and brushes, which convey the excitation voltage to the field winding, which is off course rotating in this synchronous generator.

So, this is how a steam turbine synchronous machine looks like off course, our analysis will cover all means both steam turbine driven as well as hydraulic turbine driven synchronous generators.

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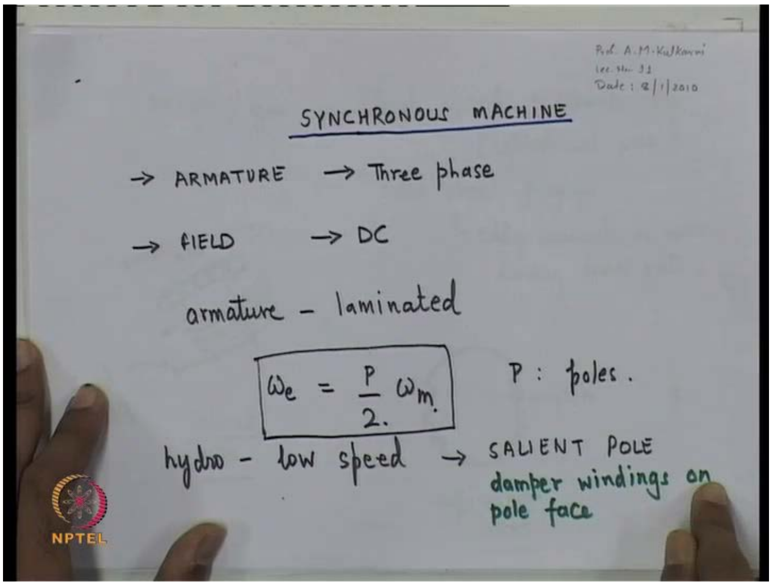

So, let us move on to the nuts and bolts of this. Just some basic basic review, a synchronous machine in fact has got two kinds of windings, you can say the armature winding usually present on the stator are in fact three phase winding, the three sets of windings and you have got a field winding, which off course is fed with D C voltage, the armature is laminated, the armature is laminated, because the armature windings which are housed on the armature in fact, see a time varying flux.

An important relationship which you should keep in mind is that, the voltages which are generated the emf, the alternative voltages which are generated in the armature due to a rotating field, the D C field created by the field winding as well as, when the machine is loaded you have a rotating field created by the three phase armature windings. The emf generated have the frequency which is given by omega e, which is the electrical radiant frequency is p by tow times the mechanical rotational frequency, where p is the number of poles.

So, you have got omega e is equal to p by two is equal to omega m. Normally steam turbine driven machines are in fact high speed generators, they run at in our fifty third system they run at three thousand rpm in a two pole machines. On the other hand, hydro machines are low speed and are salient pole constriction, which basically have many poles, I mean many pole pairs so that, you know in a steam turbine driven machine off course we have got one pole pair, in salient pole machines you can have many, many pole pairs.

Now, usually the salient pole, what is the, what are the other electromagnetic, what is the other electromagnetic environment which you see? Off course the field winding, the armature winding are housed on a ferromagnetic material, but we also have what are known as damper windings or basically squirrel squirrel cage kind of damper bars on the pole face of salient pole synchronous machines.

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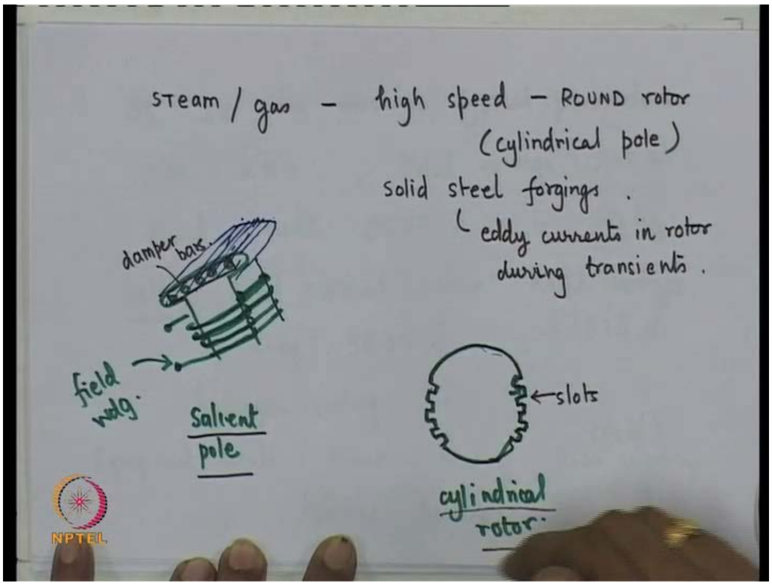

So, that is usually seen of course, in a steam gas turbine which has high speed you also have a round rotor construction, there are only tow, you will have only one pole pair there is 2 poles and you have a cylindrical pole, here round rotor.

And the rotor is usually made out of solid steel forgings so, even the rotating you know, the rotating field winding is housed on a solid steel body and because of that you can have eddy currents in the rotor during transients so, that is one important point, you can have eddy currents in the rotor during transients in a steam or gas turbine off course, in a low speed turbine salient pole machine the pole phases are laminated.

Now, this is how usually your steam turbine rather hydraulic turbine pole face will look like so, there is a pole face, you will find at the field winding will be housed here, and this, on this pole face you have this damper bar you say short circuited at the end of the so, your damper bars they are not. So, damper bars are kind of embedded on the pole face and then, they are short circuited at the end.

So, they are basically are like a cage on a induction machine. The basic function of these damper bars is basically to you know, damp out transients you know, normally both the field wind the flux created by the field winding as well as the three phase rotating flux, as well as the rotary motion of the rotor are all of the same speed so, you do not have actually any of generated on the on the bars of this this damper bars. But during transients of course, you have got currents in these and they are intended that intended to damp out any transients which are occurring. So, in fact in a cylindrical rotor machine the solid steel body of the rotor itself creates eddy currents, which perform the same function.

On a cylindrical rotor the field winding is housed in slots of this kind so, clots have wedge which not have clear in this, they were wedge keep the windings in place. So, you have got the windings are basically placed in the slot in the cylindrical pole machine.

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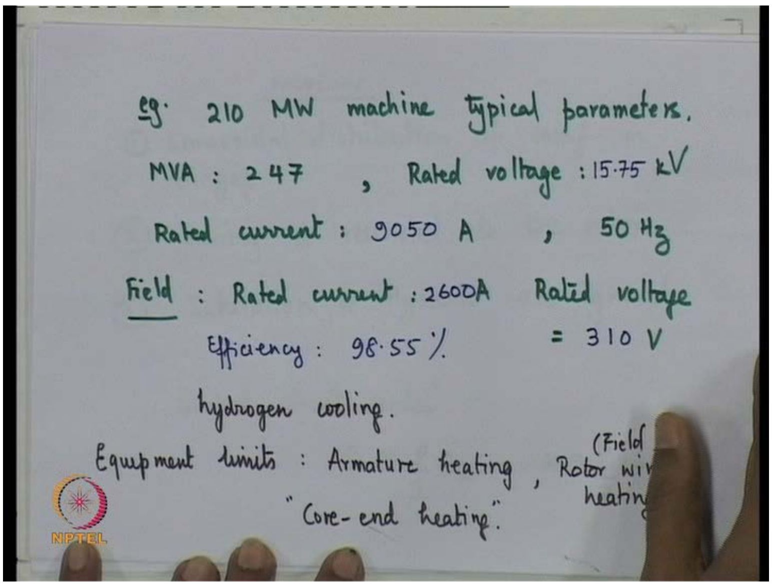

Now, just to give you a good feel consider two hundred and ten mega watt machine, generator that is. The typical parameters could be for example, in fact this 210 mega watt machine is a typical generator, which was used in the electrical power rate the many, many, many of them at present in the Indian power rate. The MVA is 247 so, you can actually calculate the rated power factor from this, and this, the rated voltage is 15.75 kilo volts, the rated current is almost one kilo, well ten kilo amps roughly, it is 9,000 more than 9,000 amperes, it is off course a fifty hertz machine.

Now, when I say rated current rate meant it is a maximum continuous rating of the armature current so, when I say rated current is the armature current. This off course does not mean that you cannot have current higher than this, for a short while every electrical equipment can tolerate about you know 10 to 15 percent over current, but only for about 10 to 15 minutes.

So, the maximum continuous rating is around 10 kilo amps of course, there are lot of heating due to this so, a machine like this is cooled by hydrogen. Similarly, the field has got a rated current of 2600 amps, when I say rated current, what it means is that the current which flows in the field winding in order to get the rated voltage under loaded condition, that is full load condition or the rated load conditions.

The rated voltage similarly, is three hundred and ten volts and the efficiency can be very heights in this case around 98.5, this is only of the generator am not talking about the turbine etcetera.

So, this is the efficiency only of the generator. One important which you should note, which you shall again discussed later is that, the field current rated current is 2600, but under no load conditions the amount of current required in the field to generate rated voltage, again under, let me repeat, under no load condition that is, the open circuit conditions the amount of current needed to generate this rated voltage at the armature terminals is in fact much lower than this, it may be half or slightly lower than half of this. Remember that once you load the machine the flux picture in the machine gets changed, because of the current in the armature winding so, you may actually have to have more current in the field to get this rated voltage.

So, this this current in fact is the current required under rated conditions so, under no load conditions to get 15.75 you may require less than half of this current and corresponding less than half of this voltage. So, this is an important point which you should remember now, there are three kinds of limits which you may encounter.

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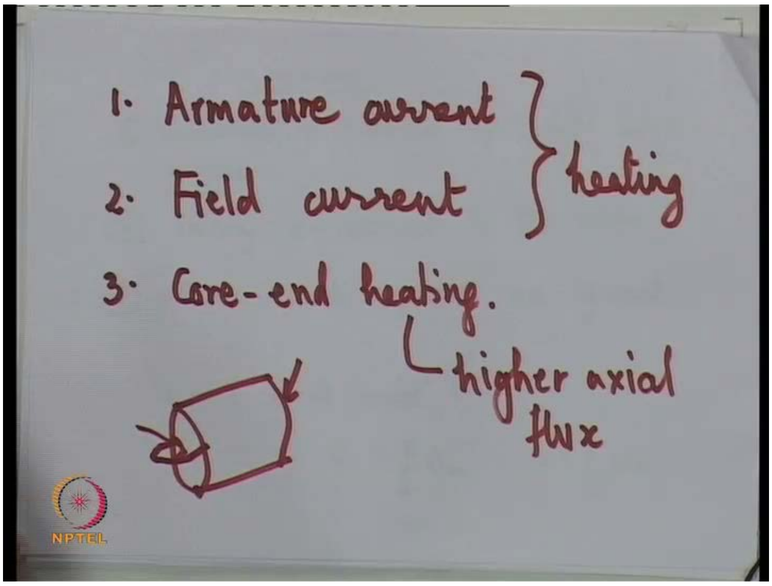

I just write this on a separate sheet of paper, the three kinds of limits which you may encounter. One is the you know generator is armature current limit or rather I should say the armature heating limit, which is off course determined by the armature current.

The second limit which you will encounter is the field current limit so, you cannot have current more than a certain value otherwise it will cause heating, simple i square r heating which may be more for which there is off course a limit so, you should ensure off course that the current will never go above the rated current that is, in this case in the example which I said nine zero five zero for off course, for a short while as I said you can have a slight over rating.

Similarly, similar thing applies for the field also, the field current should not exceed its rating, but off course for a short while you can have a higher than the, you can have higher than the rated current for you say about 10 to 15 minutes that is that is permissible.

Now, this, so, these are the two things which prevent you from you know, the kind of limit the amount of you know power and reactive power you can have, in in in short you can never exceed the m v a rating of the machine so, your root of p square plus q square, where p is the real power and q is the reactive power should not exceed 247, otherwise you will find that since the voltage is always be maintained near about this value the current will get, exceed current rate, current will exceed its rating so, your m v a is typically will always be off course, you have to maintain root of p square plus q square less than 247.

Now, the field current limit also prevents you from increasing the q beyond a certain point, remember in a synchronous machine by changing the field current you can change the reactive power, but you cannot go on increasing the reactive power after a point, you will find that the field current hits its limit. So, even though you have very low real power you cannot have q very high, because for that you require very high field current.

So, our p and q in some sense are limited by both these limits so, you have to find out the you know safe operating region for a synchronous machine and ensure that these limits are not exceeded. In some machines, in some steam turbine generator driven generators you will find that you have another limit is called the core end heating limit, this is caused by higher actual flux in the end region of a synchronous machine.

So, if you got a synchronous machine this is called the end region, this is the end region of a synchronous machine where actually the windings come out and go in again so, that is called a end region of a synchronous machine. Now, it is seen that under, if you under excite the machine that is reduced the field current such that, the synchronous machine starts absorbing reactive power, you have a situation of higher action flux. Of course, the explanation of this is beyond the scope of this course, but I refer you to a paper which appeared quite some time ago by Farnham and Swarthout, just a movement.

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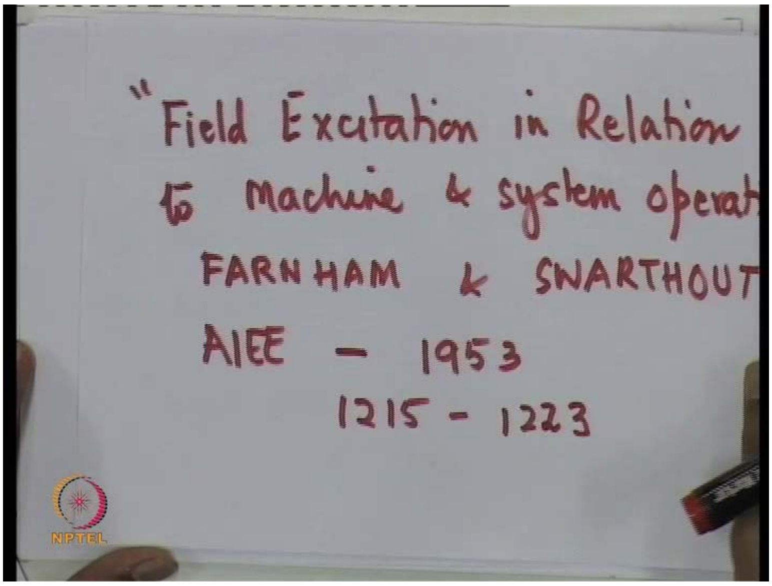

So, I just write down this reference for you, if you are interested in knowing the effect of all these limits I refer you to this. Field excitation in relation to machine and system operation so, this is the title of the paper by Farnham and Swarthout and it appeared in IEE transactions, AIEE because there was no IEE at that time in 1953, the page number 1215 to 1223 so, this is a copy of this paper.

So, I request you to, those who are interested in finding out more about why we have this heating limit, you can of course refer to this paper. Now, off course this core end heating is not a limit seen by all machines it is only for specific, usually steam turbine driven machines.

Now, one the main objective of this lecture really is to discuss the modeling of a synchronous machine. So, before we go into modeling we should off course look at what are the basic assumptions that we have now, remember that no modeling can be perfect, in the sense that we for example, in fact if we try to do some kind of perfect modeling you will find that the problem becomes all together intractable.

So, if somebody says that, well ill use Newton's law as well as Maxwell's equations and derive all the equations of a synchronous machine right from scratch with no assumptions what so ever, you will find that it is almost impossible to get anywhere. So, what we will do is, do a simplified modeling with a understanding that the modeling which we are going to do will be valid for certain kind of transits, in particular we will be actually taking out what is known as a lump circuit model of a synchronous machine so, obviously this kind of model will not be adequate to you know, study the phenomena which are which are affected by parasitic and so on.

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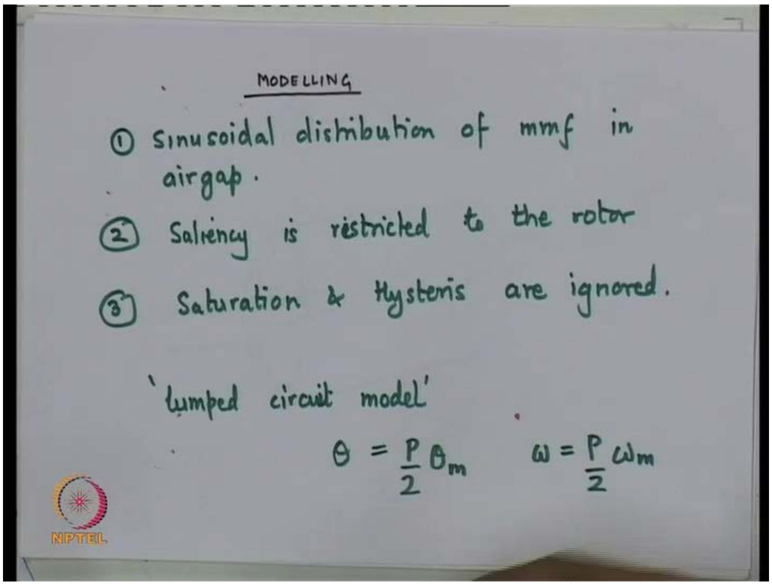

So, what will have is the lump kind of circuit model and roughly you can say that phenomena or phenomena which have rates of change, which are or which kind of last more than say one milli second can be studied reasonably well by these kind of model.

Now, I just read out the main assumptions which you are going to make. One of the important assumptions we are going to make is that, is going to be a sinusoidal distribution of mmf in an air gap so, the air gap in this synchronous machine will see a sinusoidal magnetite motive force so, this is an assumption, actually we do have almost sinusoidal distribution of mmf, because of the winding arrangements which are used in a synchronous machine.

Another assumption we will make is that, saliency is restricted to the rotor that is, we will not be considering the saliency due to the slots on the stator winding, on the stator so the as you know the armature winding is the housed on the stator, and you have got slots in it to house the windings now, we will neglect the saliency which occurs or the changes in reluctance which occur due to the slots on the stator.

So, only saliency which will be considered is due to the rotor structure. Another very important assumption which will make is that, saturation and hysterias are neglected so we can consider the machine as more as a linear magnetic circuit, and because of this assumption we will be actually be able to simplify our analysis to very great extent, off course at some point or the other you may have to relax this assumption of saturation to get realistic answers, but to get a basic model we will make this assumption, what we will do is, we will create this model based on this assumption and try to have some kind of correction to that model in order to take into account saturation so, these are kind of pragmatic approach we can follow.

And as I said some time we will be getting a lump circuit model, we will not be modeling things like parasitic capacitances or winding capacitances and so on. So, our model is effectively restricted to the study of relatively slow transients not fast transients. One more thing off course which I have mentioned some time back is that, if you look at the angular position or the rotor position, and if you look at the phase of the e m f which are developed or for example, speed of or rather the frequency of e m f which are developed on the armature winding they have this relationship, this is something which we just did some time back. The electrical speed or the frequency of e m f generated on this armature windings is equal to p by 2 rimes omega m, omega m is the mechanical frequency in p is the number of poles.

So, just remember this before we go on for the actual analysis. What we will so initially is kind of do a simplified analysis of a synchronous machine, for a 2 pole machine and we will try it infer later, what would happen if you would have got many poles.

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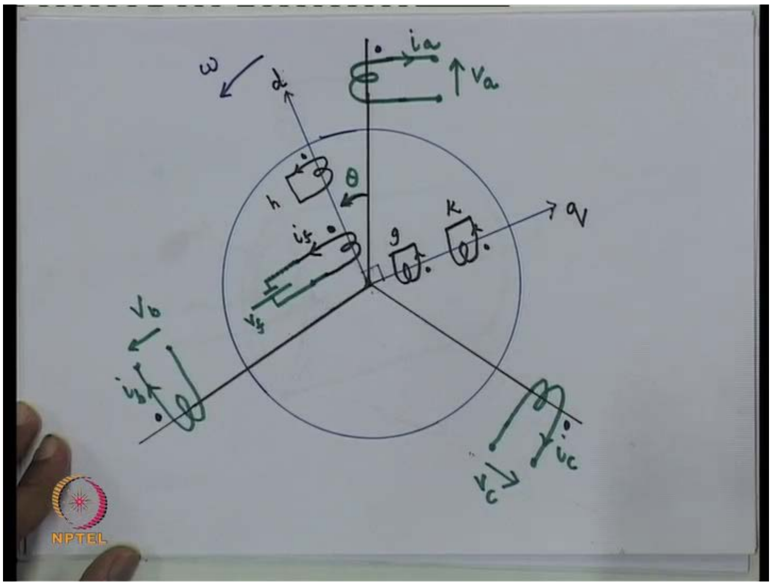

So, what we will do essentially is considered first a fall a two pole machine, actually whatever will be doing does not, we do not lose generality, because later on we will see that it really does not matter whether it is a two pole machine or a four pole machine as long as a we take into account the correct equations but, the basic derivations look practically similar.

We represent synchronous machine, this is schematic representation of a synchronous machine, you have got three windings on the stator, this is the a winding, b winding, c winding, we assume that the rotor moves in this direction so, whatever happens in the a winding happens to the b winding after some time so, there is a phase e lag of one twenty degrees between the b and the a winding, and c and the b winding respectively.

Now, one important point now, this is an important thing, what are the electromagnetic circuits on the rotor off course, there is a field winding so, you have got this what you see here is the field winding.

So that, field winding is off course fed from a D C voltage source, now one more interesting point which you should notice that you also have other electromagnetic circuits though they are not necessarily in the form of windings. What we are for example, in a synchronous machine a steam turbine prevent generator may have eddy currents on the rotor, in case of hydraulic driven turbines you have got actually a squirrel cage winding, squirrel cage like winding on the pole face.

So, what you really see is that the effect of these the eddy currents, or what are known as the squirrel cage currents, or the damper currents as these are all alternative names. The effect of this is captured using these coils which are short circuited on them self, after all a damper winding or eddy currents are a kind of a circulating current.

So, you have got what? A basic damper winding is represented by coil of this kind off course these, this is an approximate representation for example, in steam turbine driven generators, you do not actually have, you may not have any specific damper bars the eddy currents are there, but there effect is captured by these windings as well as windings on this axis. So, you can have eddy currents on this axis, you can have circulating currents on this axis as well as this axis, this let me just clarify one point the axis on which of this field winding is also called a direct axis, the axis quadrates to this direct axis is called a quadrature axis so, d axis, direct axis, quadrature axis.

So, what we do is model three windings for the face windings, which are on the stator and you have got a field winding and these three other windings are cumulatively kind of you know, representing the damper winding and eddy current effects.

Now, you may ask why two? Why not three? or why two? Why not one? the answer to this question is that, this is the model and we will try to fit our observations into the model. So, what we will do is we will assume that, there are two windings which completely capture the response of a two windings of a two windings of the quadrature axis, and two windings on the direct axis, which completely capture the effects of the rotor circuits.

So, this is an assumption in the sense that somebody may say you can have more, the answer is yes, you can have more, but often it is seen is as far as team turbine generators are concerned you require these these many windings, and there parameters to represent the kind of dynamics which you will see from actual measurements, observations in actual tests which you will do. In fact for hydraulic turbine machines it may be even possible to represent the whole system by a lower order model, that is using lesser number of circuits, in fact in some cases you may neglect the k winding when we are modeling a hydraulic turbine, because a model consisting of these number of windings with their parameters can accurately representing represent the kind of observations which are seen in the tests.

So, right now let us derive the model for you know these three stator of windings a field winding, and these other three circuits which represent eddy and cage or damper winding effects.

And then, if required later we can simplify things by opening one of these windings, and get a lower order model, but let us initially get a higher order model and try to represent our system. Remember of course, that when I say that, this is a winding this is schematic representation, I have talked of the axis of the field winding this is the axis of the a winding, this is the axis of the b winding, this is the axis of the c winding what do I mean?

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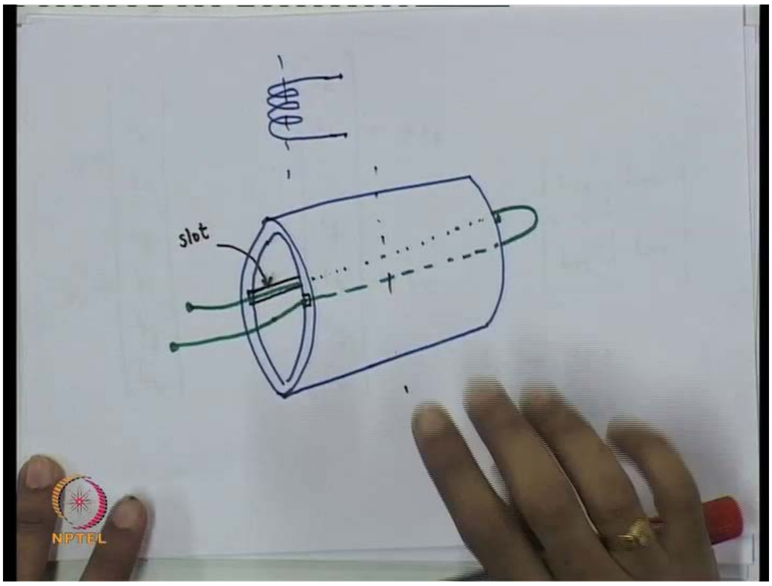

For example, when I say that, this is the a winding and this is axis, what I mean is off course that you’re a winding round like this, this is the overhang portion of the end reason of the machine this is just one winding.

So, this winding means a is schematically represented like this and its axis is like this so, this is what I mean by axis of a winding. And a schematic representation like this is actually implying a set of winding which are in this plane and they flux, they cause the current flows to them would be like this.

So, this is what I mean by axis of a winding. Now, what we need to do off course when we are representing this as a circuit is compute the various mutual and self inductances between all these windings.

So, you may want to for example, have the mutual inductance between this windings and this windings, or this winding and this winding, and off course these things will be dependent up on the angle theta right now, we are talking of a two pole machine so, there is no distinction between mechanical angle and physical angle, electrical angle or the mechanical speed and the frequency of the e m f which are generate so, they are exactly (( )). So right now, let us restrict our attention to a four pole machine, two pole machine sorry.

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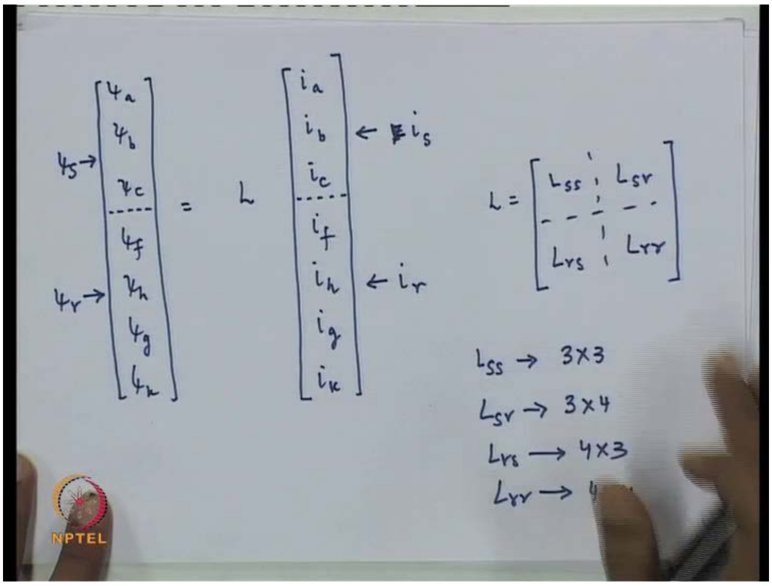

Now, so, what we need to do if you want to describe the machine is basically get a relationship- between flux psi a, and the rest of the currents, i a, i b, i c, i f, i h, i g, i k, are in fact the three windings which capture the effect of eddy currents as well as damper bar, currents currents in damper bars.

So, you have got psi a is equal to a matrix or rather you can say psi a, psi b, psi c, psi f, psi h, psi g, psi k are equal to a matrix L into the currents. So, the structure of this L matrix is in fact L f s, L s r, L r s and L r r, remember i a, i b, i c are what are known as a stator currents so, I will call them as i s together they are what are known as i s, i r is consisting of i f, i g, and i k these are the different windings which we have seen in the previous slide similarly, you have psi s and psi r so, L s s is the matrix relating psi s and i s and it is a 3 by 3 matrix similarly, L s r is 3 by 4 matrix, L r s is 4 by 3, and L r r is a 4 by 4 matrix, because it is the relationship between psi r which is 4 components and i r also which is 4 components.

So, now the important thing we need to derive are these components which are there, here, so, that is the key challenge now. Now, why is it a challenge? One of the reasons why it is a challenge is the mutual inductances in some cases or even some times the self inductances are dependent on the rotor position. Why is that so? Well you can easily imagine that the amount of flux linked in for example, this these coils here due to a current here will change according to the position so the rotor, these are of course on the rotor so, they will change as per the rotor position that is one thing.

Another problem which may occur is, because of saliency you will find that the mutual inductance between the, even the self inductances may change.

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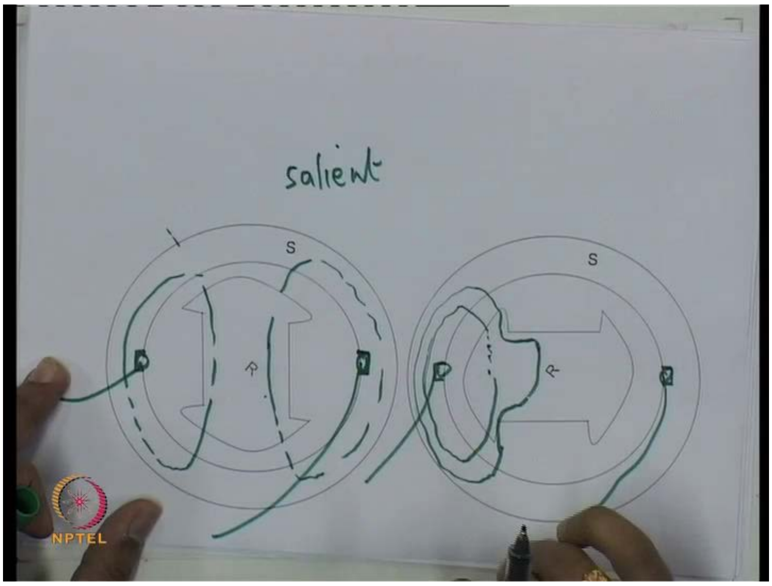

For example, if you look at a coil suppose you have got a winding housed in say just for the time being let us assume its housed in one slot so, if you got a winding housed in this slot, it will try to, and if there is a current flow in this a winding so, the a winding the current say enters here, goes in a machine comes out at the end region at the other end and then again enters in a machine slot and comes out here.

So, if you look at this kind of, suppose this is the a winding, it will create a flux in this in this direction so, you will have flux like this flux of this kind. So, this a winding tends to cause a flux in this direction of course, the amount of flux you will, you can barely imagine that amount of flux which you will get under this condition will be much more than, the flux you will have under this situation, why is it so? Because the reluctance of path is going to be more.

So, if you have got, again current in the a winding suppose it just one winding, you will find that the current, the flux which will be caused tends to stick to the faro magnetic path you know, this is the air gap, this air gap is more on this axis and less here so, you will find that, there is flux which is which goes like this, but the flux here will try to tend to stick to this you know of course, trying to find out a flux path requires you to do a full electromagnetic analysis, but you will notice that the reluctance is likely to be more and the flux created is likely to be less, if the rotor is in this position for a salient pole machine, this is not true of course for a cylindrical pole machine, because the, you will find that practically the reluctance is the same you know for a cylindrical machine.

So, the self inductance of this a winding will also depend on the rotor position so, that is one important point which you should remember. Now, let us, first let us just stick to a cylindrical pole machine.

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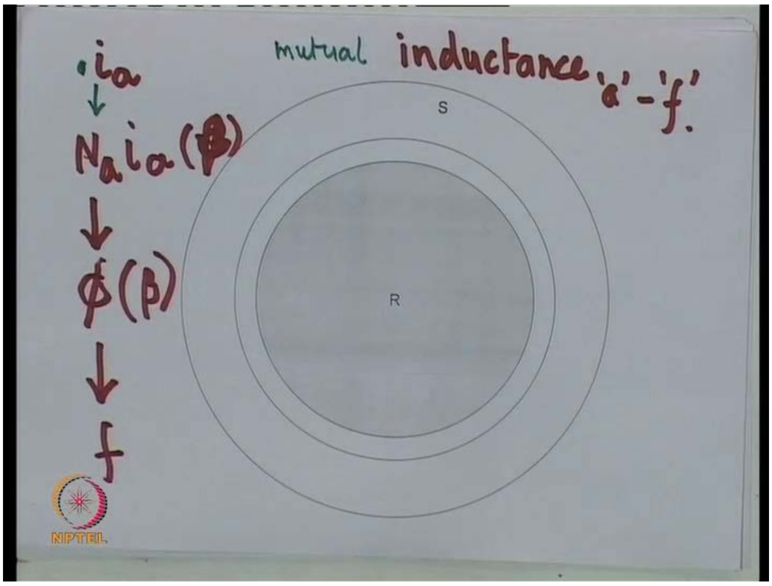

Now, one of the important things which you wish to do is try to see how the flux will be in case, for under, several circumstances. See what we need to do is, if you want to find out the inductance of self inductance or mutual inductance, what we need to do is, first a fall for example, if I want to find out the mutual inductance mutual inductance between the a winding, the face a winding and say the field winding then, what you need to do is, assume that a current flows in the a winding that will off course create a flux an m m f in the air gap.

So, let us assume that is only current in the a winding so, you will have currently in the a winding that will create an m m f, that will be n a into i a, but off course this, I should call this, this is not, the this is the equivalent number of terms so, you will have some constant into i a is the m m f which is caused in the air gap off course, when I say m m f is caused in the core, it is a function of the angular position I will just try to elaborate on this in a few seconds from now.

Now, this is the m m f which is caused which is proportional to by some constant n a into i a, this m m f will cause some flux, but this also this is the function of the angular position. Let us say I call this angular position five for the time being, I call this angular position, will will call this beta may be this angular position is beta, this will cause a flux this also will have a angular distribution it is not a constant value everywhere in the air gap then, you will have to find out what is the component of flux which is linked with the field winding.

So, once you calculate the component of flux which is linked with the field winding, we will be able to compute the mutual inductance between a and f. So, that is the basic you know, procedure we need to apply before we get actually what is the mutual inductance between the winding a and the winding f.

Now, so, how do we actually proceed for example, let us just start off with trying to find out the mutual inductance between the winding a and the winding f so, if I want to find out this this mutual inductance of the winding so, actually I am trying to take out the first component of this rather yeah.

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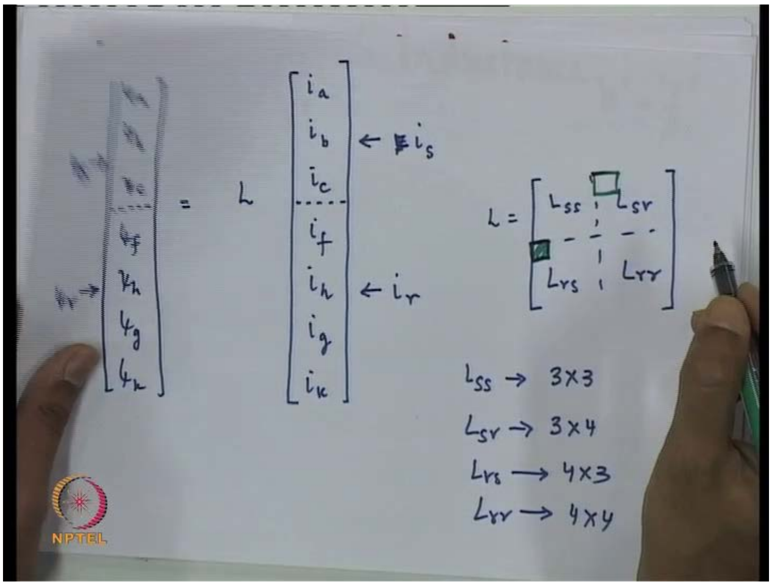

The first component of this L s r matrix so, am trying to get the relationship between flux linked or I am sorry, am trying to get the value of the flux linked to the field winding due to a current i a so, am sorry, what I should be saying is, I am trying to find out this component first.

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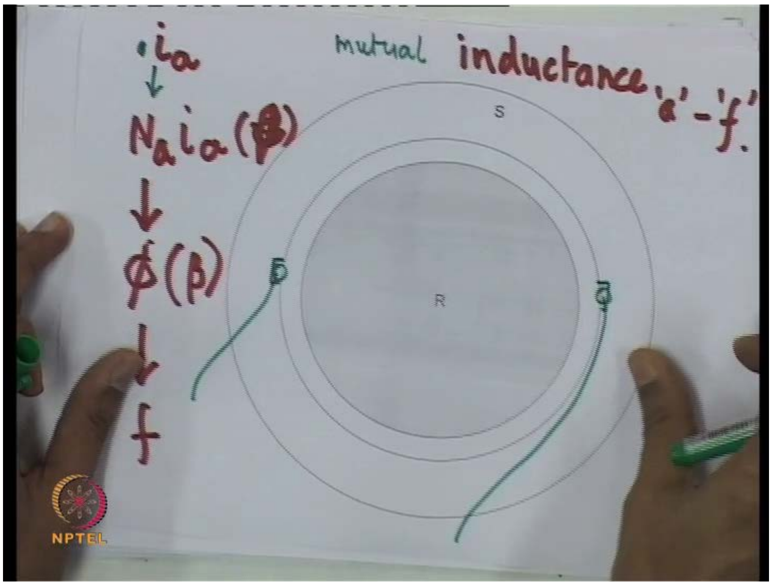

So, just let us see the steps which we need to apply. So, if you have got a current in a in the a winding, let us say the a winding is present in this slot, we will just assume for the time being its concentrated though a concentrated windings strictly speaking will never cause a sinusoidal m m f in the core, but let us say you have got this a winding in this slot. Now, we need to find out what is the m m f due to this a winding, first step.

So, to do that off course, it is going to be proportional to the current and the number of turns and how these windings of the a, how this a winding is distributed. So, let me just redo this in the slightly smaller sheet so that, smaller a diagram.

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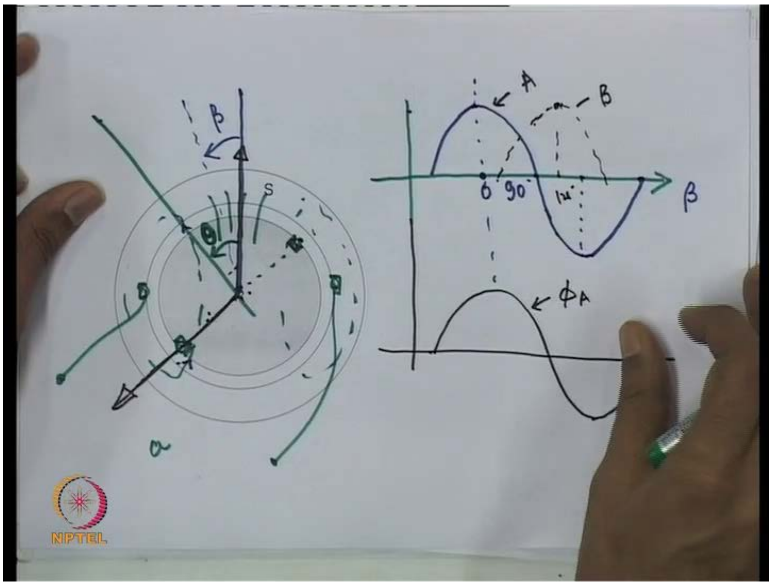

So, if your got a current flowing in the a winding, let us say its distributed actually, but let me just represent it right now by a concentrated winding. So, this is your a winding and a current flow this now, what I have told you before is that the m m f will assume cause by any winding is going to be sinusoidaly distributed in the core, in the air gap.

So, what we will assume is that the m m f which is created by the a winding is going to be sinusoidaly distributed, but off course the b winding also causes a sinusoidaly distributed m m f in the air gap, but one difference is there. The m m f which is caused by the a winding will be maximum or it tends to cause, if you have got a cylindrical rotor off course it will cause maximum flux in this direction.

So, we expect the m m f to be maximum here so, then it tries to cause a flux like this so, you have flux caused is like this so, what we see is that the m m f caused is maximum here. Let us call, let us call this position as the beta position, its maximum here and it tends to drop as beta increases it becomes zero here, because there is relative flux which is caused in these directions by the current a, in fact we will it is practically zero so, there will be no flux entering the core in this direction.

So, what we will assume is that, what we really see is that the m m f is tends to cause a flux, maximum flux, so, m m f will be maximum in this direction in fact it tends to cause maximum flux in a cylindrical machine also in this direction. So, m m f is maximum when beta is equal to zero so, I will just, I will just take this beta is equal to zero point here.

So, this is beta is equal to zero m m f is maximum here, it becomes zero when beta is equal to 90 degrees, and it tends to cause flux in the opposite direction, because it kind of, it causes a flux which comes out of air gap here and goes in here so, the m m f is negative after 90 degrees in this region reaches a peak here.

So, this is basically how your m m f looks like 0, 90, 180 and back here. So, just to make our analysis a bit simplified, whenever I say that the m m f, whenever I kind of represent this kind of m m f by a vector in this direction so, if I show a m m f by a vector in this direction what does it mean? Its maximum m m f is in this direction and it drops out sinusoidaly like this.

So, the m m f of the b winding will be can be represented like this, in this direction. So, when I show a vector like this, it means this. If I show a vector like this, what does it mean? It reaches its peak value at 120 degrees here, this is 120 degrees so, an m m f caused by the b winding, current in the b winding will be in this, will be represented by this arrow so, when I represent the m m f by this arrow I really mean that the flux distribution in the core is something like this, its peaking here at 120 degrees this is due to b winding, this is due to the a winding.

So, this will simplify our analysis a bit by if we represent the m m f by a single arrow, but a single arrow means this so, that is something which you should remember and the distribution we assume is sinusoidal. So, suppose I want to take out the mutual inductance between the a winding and the field winding, what do I need to do is, first take out the m m f, is that okay. Now, once I take out the m m f, I need to compute the flux.

So, the next step is compute the flux now, the flux if it is a cylindrical rotor machine is quite straight forward, because the reluctance of a cylindrical move rotor, cylindrical rotor machine does not change with this beta so, a flux will be practically in for all practical purposes, if the, if there is a current flow only in the a winding then the flux will be simply a replica or scaled you know, scaled way form, which is simply going to be similar to this blue way form which I have drawn here.

So, a flux also will be something like this, in the area. So, this is what a cylindrical rotor machine, the kind of flux which will be created in the air gap due to the current in winding a. Now, whenever am going to try to take out the flux linked to the field winding see, after all what am I going to do, now I have got a flux in the air gap, now what I want to do is, how much of this flux links with the field winding.

So, what do I do is, I, where is the field winding suppose, I want to take out the mutual inductance when the field winding is aligned at an angle of theta suppose, the field winding is aligned at an angle theta, what do I mean by its aligned at an angle of theta, the field winding is somewhere here, is found here. So, the field winding is here at an angle theta so, how much of this flux is actually linking this field winding so I will just redraw this again.

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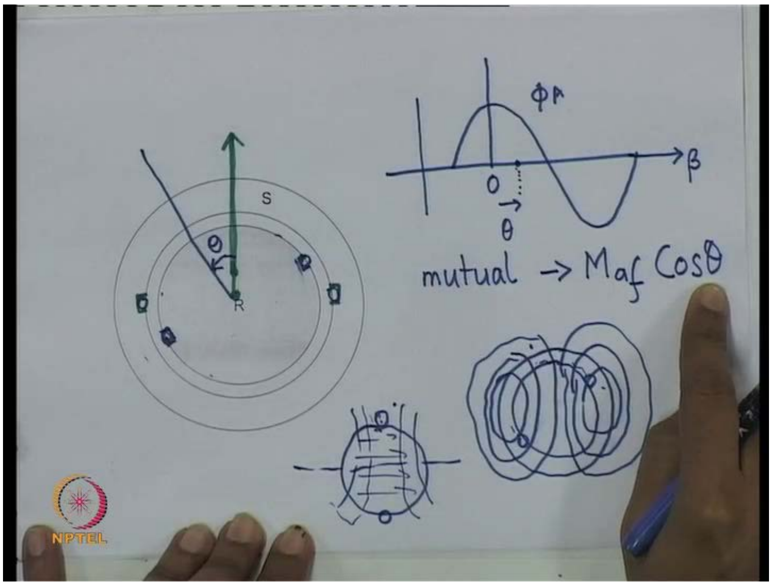

So, I have got the a winding it is causing a flux, which is as I mentioned am representing it by an arrow like this, what it mean off course, this is the peak value is in this direction and drops out sinusoidaly as beta increases.

Suppose the field winding is here, is wound here, am showing it again as just one winding, one turn, but normally it is wound over the periphery and has an axis here similarly, the a winding though I have shown it as just two conductors, actually it is wound over the periphery machine and its has a axis like this so, the field winding axis say at a given point of time the field is aligned, remember the field is rotating, this rotor is rotating so, this field is aligned at an angle theta.

And the flux, and this is the angular position theta from this so, this is beta is equal to zero, beta is equal to theta now, the thing is how much of this flux is actually linking with this winding so, a flux is going actually, if you look at the flux it is, its in this direction I will just redraw it here.

So, that it becomes easy to understand, the flux due to the a winding is going in is of this kind, like this, and maximum of course here. Now, if you have got a coil which is aligned at theta, how much of the flux will actually get linked with it? The answer is that the flux, total flux you will have to compute this, basically the flux density and integrated over this area this this whole area, you can imagine that it is going to be dependent upon this theta so, what is it going to be for example, if theta is equal to zero all this, almost all of this flux will get linked with the field winding, in fact there will be some leakage, but it will be maximum, the linkage will be maximum here and reduce, reduce, reduce and in fact become zero if the.

So, if your theta is equal to 90 degrees you will find that the total flux linking this winding so, you know to link what you need to have is the flux goal suppose, this is the winding the flux needs to go in, now if you look, if the flux is like this and the winding is like this nothing is going in, it is just the flux is in this direction so, no flux is actually linking this winding if theta is equal to 90 degrees so, you can imagine that you flux in fact, the linkage of flux is dependent on theta.

So, it is maximum here, minimum here, zero here in fact the linkage becomes negative because the flux direction is reversed, as far as the field winding is concerned when the field becomes one eighty degrees. So, one can expect that the mutual inductance between that is, the mutual inductance between a winding and the field winding will be in fact have the form m a f cos of theta. So that is the most, this is an important point that the variation of the mutual inductance between the a winding and the field winding is likely to be of this nature.

Let us now look at another term in our inductance matrix that is, the mutual, inductance the self inductance of the a winding, this is again the one simple relatively simple thing to you know imagine.

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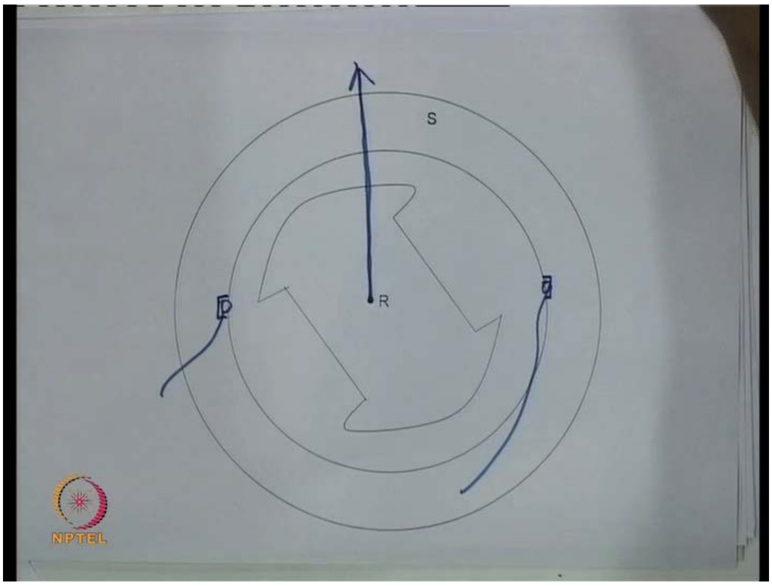

For example, you have got the a winding again, I have shown it as a packed or concentrated winding actually it is distributed along the periphery. Now, if you have got the a winding like this, it causes an m m f whose vector representation, I have just discussed the vector representation sometime ago is this.

Now, if it is salient pole machine again the flux cause will depend on this position, because as I said sometime back your, the flux link position dependent as I said something here like this.

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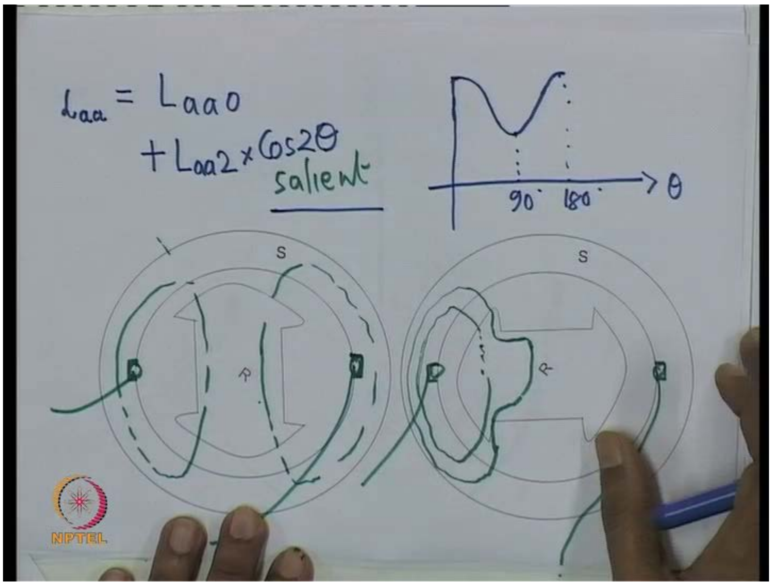

The flux will be maximum here, will be minimum here and then again maximum here so, if you have got a current flow and you have got a salient pole machine, you will, you again your flux linked with the a winding due to a current in the a winding will be dependent on the rotor in case of a salient pole machine, it is not true off course for the cylindrical pole machine, likely to a practically the same flux even in this, even when the field winding is rotated by 90 degrees.

So, it is a cylindrical pole machine in that will not be much of an issue, but if it is a salient pole machine you will find, I will just use this itself, you will find that the flux linked is dependent on position so, we expect the self inductance of the a winding due to, of the a winding in a salient pole machine will be maximum at theta is, that is when the rotor position theta is equal to zero, it will be minimum in this position that is when theta is equal to 90 degrees, do if this is theta and then maximum again when it is 180 degrees. So, one can expect that the self inductance of the a winding in general will be of this form, it will be L a a, self inductance of the a winding is equal to L a a 0 plus some other term L a a 2 let us say, into Cos of 2 theta.

So, our variation will be something like this in fact of course, I have not proved it should be a sinusoidal or co sinusoidal variation, but this follows if you assume that the m m f is actually distributed sinusoidaly, m m f, fluxes, etcetera, all distributed sinusoidaly. You will find that in fact, the flux linked and the m m f are distributed sinusoidaly, you will find that, this is the kind of thing you can expect. So, yourself inductance term will look like this, now more difficult perhaps or to imagine is, what is the self inductance or rather than mutual inductance between the a winding and the b winding.

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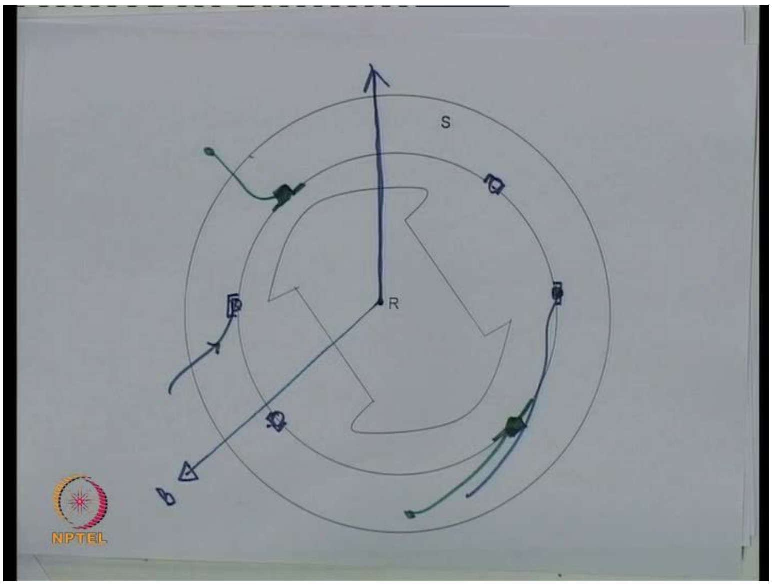

So, what is the mutual inductance between the winding the b winding so, if your got if you are looking at a current flow like this, what is the flux linked with the b winding? Do you remember the b winding, b of the c winding sorry, I will just this is the b winding am sorry, this is the c winding, the axis of the b winding is in this direction.

So, when am talking of flux linked in this b winding which is housed here, again I am showing it as a concentrated winding actually it is distributed, this is the b winding in green, the b winding, what is the flux linked with the b winding, when current is i a flows through the a winding so, how do you solve this problem, now if it is a cylindrical rotor machine there is no major problem as far as deriving this answer.

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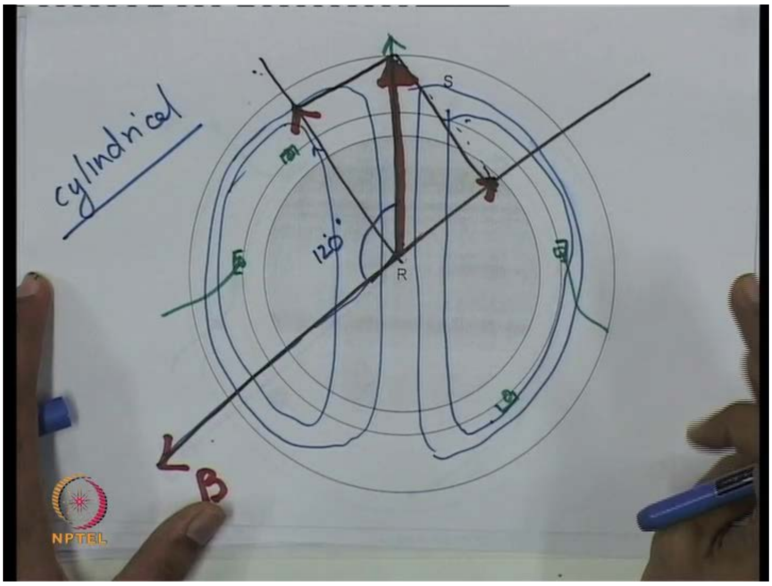

So, if you take a cylindrical rotor machine, you have got the a winding and you have got the b winding. The a winding causes in an m m f n this direction represented by this vector, it means that off course the maximum is in this direction, it drops off sinusoidaly, and the flux also, since actually the reluctance is the same all throughout the air gap in a cylindrical pole machine, the flux also is, can be represented by this vector, but as I mentioned in case of the mutual inductance between the a winding in the field winding, the flux which is flowing in this direction not, the amount it links with the b winding is not the same I mean for example, we had discussed this before, if a flux like this is caused due to the a current in the a winding, how much of it links with the b winding now, what does the b winding see, basically the b winding when I say linked means what is the flux which is passing through the b winding in this direction in this direction.

So, only a, you can say a component of this is actually in this direction to get this what we do is compute the this, this flux vector which I have drawn here it represents actually sinusoidal variation with a maximum here, can be resolved into a vector in this direction, that is you take this direction this is the axis of the b winding, it can be resolved in this fashion.

So, I do not know whether it is very clearly visible or not, basically what am saying is that the flux in a cylindrical pole machine caused by the a winding is in this direction, I will just draw it by a slightly thicker line so that, you can see it there so, the flux vector, remove a vector means that the flux is maximum here and drops of sinusoidaly here.

So, the flux vector is this I can resolve this flux in the b axis direction and a direction 90 degrees to it, this is the b axis so, what really you see is that if there is a current in the a winding and it causes flux like this, only a component of this will actually be there, which will link with the B winding, remember if am trying to look at the fluxes linked to the b winding, I should not look at the fluxes which are like this, I should which I entering b, after all eventually I will be using faraday's law and faraday's law relates to the flux which is going like this into the winding.

So, even if you have got a flux which is maximum here and it is dropping down like this, the amount of flux which is linked to the b winding in fact it is only a component of this flux. So, how much is that component? Well you know that a angle between this and this is 120 degrees so, the flux linking the b winding due to a current in the a winding for a cylindrical pole machine will be simply yeah, is it going to be constant, the answer is yes, because even if this rotor position moves, if this rotor moves this will not change.

So, for a cylindrical rotor machine L a b, that is the inductance between the a and the b winding will be lesser than the self inductance, that is for sure. For a cylindrical pole machine this L a b will be constant now, you may ask the question, what about, what happens when you have got a a salient pole machine, is then the mutual inductance between the a and the b winding of function of the position, the answer is yes.

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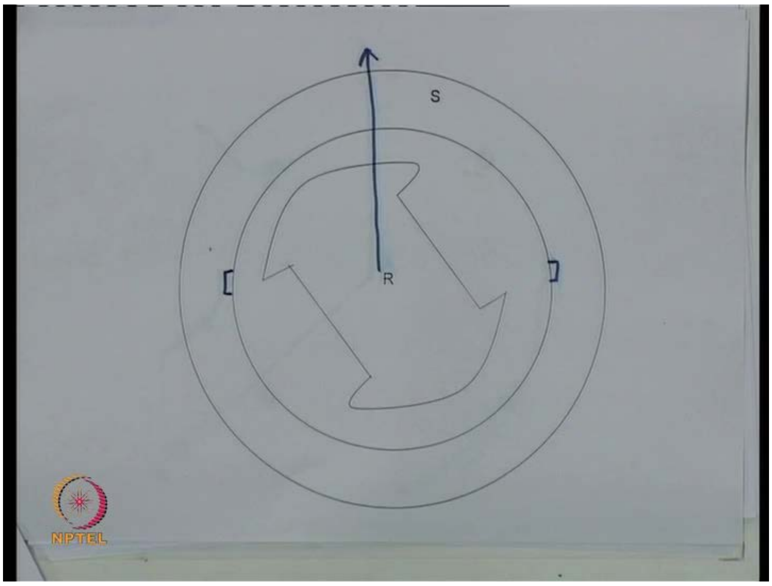

The a a winding and the b, The inductance between the a winding and the b winding is in fact a function of the position, because even if the a winding produces a flux, in the m m f in this direction, the flux need not be having a vector representation in this direction, because even though m m f is like this, the flux is depends in the reluctance of the path and the reluctance of the path is not uniform.

So, what we will do in the next lecture is try to get the mutual inductance between the a winding and the b winding in case you have got salient pole machine. So, just to summarize everything quickly, the mutual inductance between the a winding and filed winding is in fact a function of Cos theta. The self inductance of the a winding or in fact the b winding or the c winding for a salient pole machine it is actually a function of cos 2 theta, for a cylindrical pole machine it is in fact a constant, it is not dependent on theta at all.

So, we will actually take a few more representative cases, in fact what we are doing now is finding out the mutual inductance between the a winding and the b winding, when there is saliency in the rotor.

So, that is something we will resolve in the next class, and there on, we will then calculate the, we will get the differential equations of the machine and then I will introduce you to a very interesting and important transformation of variables called d q transformation.