On Power System Dynamics, Control and Monitoring
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Lecture – 03
Power System stability (Contd.)

So we will be we are back again. So, with the in that previous one we have seen that your this thing.

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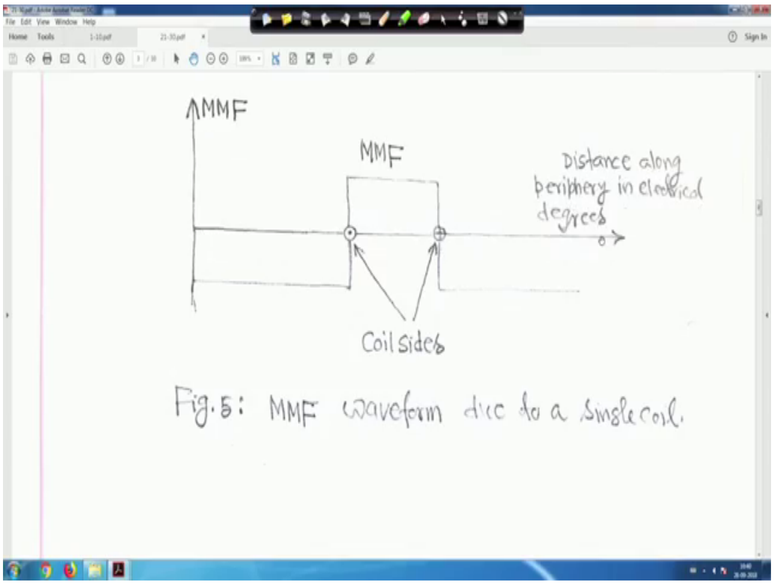

This is the single coil, but if you have more number of coil, then the shape of the MMF wave that is it will be like this.

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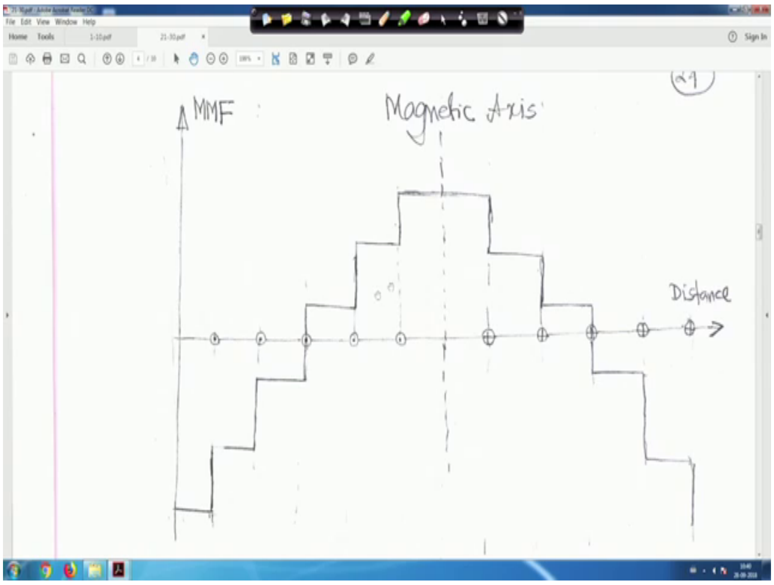

And if you add more and more ultimately this will be you know taking the shape of sinusoidal wave form right. So, this side is your distance and this is your MMF this is the magnetic axis right and this side shown that everyone plus plus plus this is dot dot dot dot. So, you know this right.

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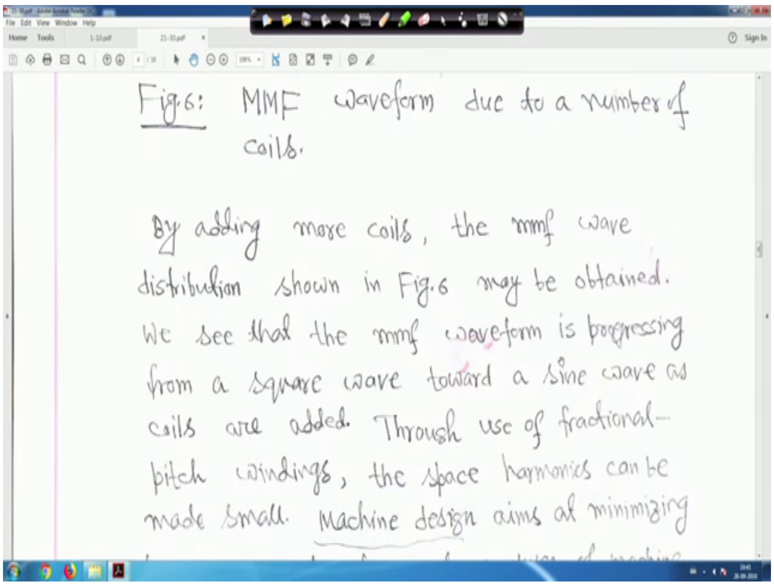

So, so by adding more coils the MMF wave distribution shown in figure 6 may be obtained we see that the MMF waveform is progressing from a square wave towards a sine wave right, as coils are added. If you add more coils, so it will be your step slowly and slowly it will be like a sinusoidal waveform right; through use of your fractional pitch windings, the space harmonics can be made small, machine design aims at minimizing harmonics and for most analysis of machine performance it is reasonable to assume that each phase winding produces a sinusoidal distributed MMF wave right.

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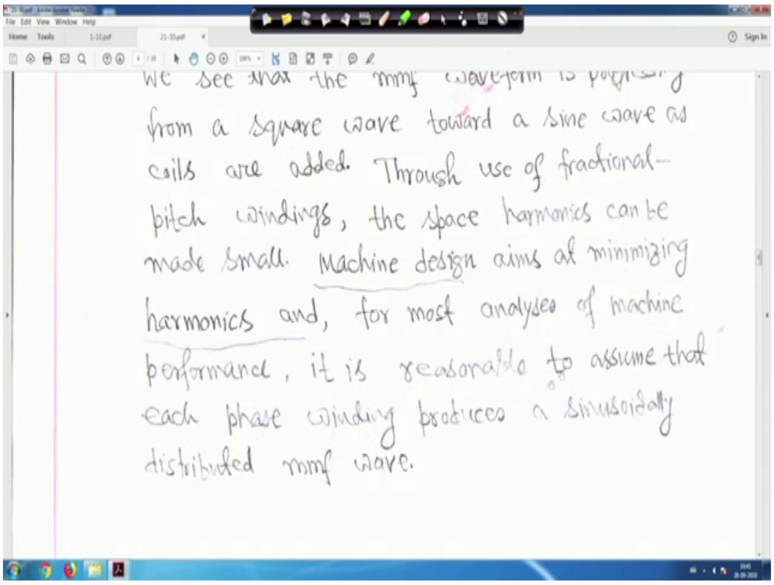

So, the windings are then said to be sinusoidally distributed. So, the harmonics may be considered as secondary from the viewpoint of machine performance.

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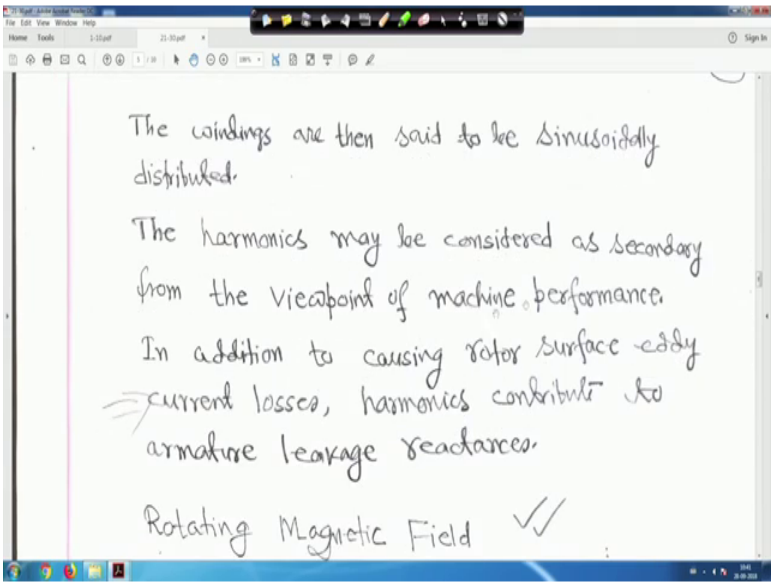

So, in our in this course we will not study that harmonics another thing, but in the in the beginning something we have to discuss right. In addition to causing rotor surface eddy current losses harmonics contribute to armature leakage reactance also right.

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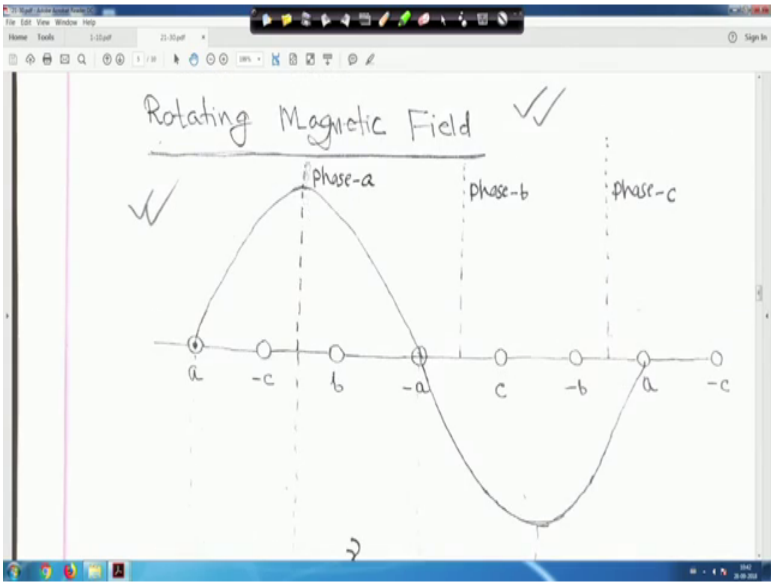

So, now next is the rotating magnetic field. So, this is phase a, phase b, phase c I marked. This is your a and this is your minus, this is your b and this is your showing is minus and this is your what you call c and this is your c minus right. That is 1, I mean I told you one thing that when if you take that in one side, the current entering into the phase right if it is a plus then leaving the your phase then it will be minus.

So, that is your plus or dot now we represent right. And this is that your rotating magnetic field this is phase a, only phase a is shown and it is a sinusoidal. Similarly for phase b and phase c and this is your from the center of these thing this is phase a exis right, this gamma is measured in this direction right.

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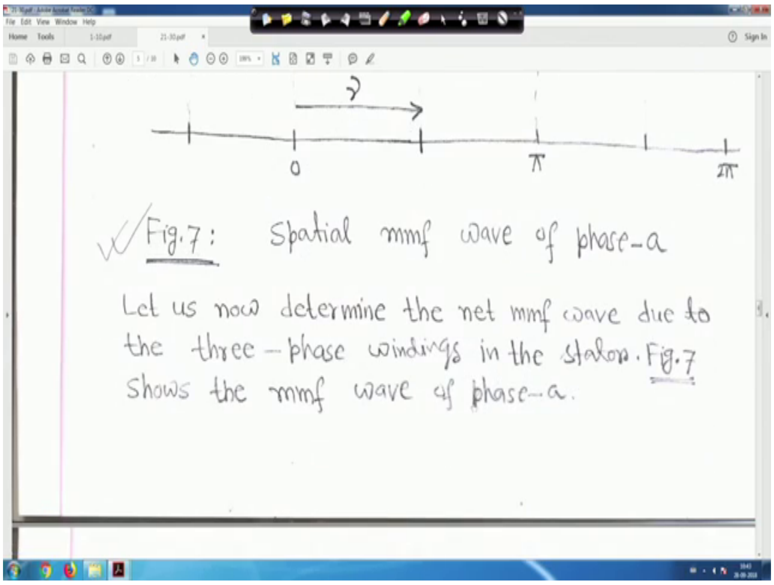

So, if you this, this is actually spatial MMF wave of phase a, this is figure 7 right. So, let us now determine the net MMF wave due to the 3 phase windings in the stator. So, figure 7 is shown the MMF wave of phase a, only phase a, we are showing. Similarly phase b and phase c that 120 degree apart that you know right. So, in this case your what you call gamma representing the angle along the periphery of the stator with respect to the centre of phase a.

So, this is our centre of phase a right and this angle is measured from this these direction that is gamma right along the stator periphery.

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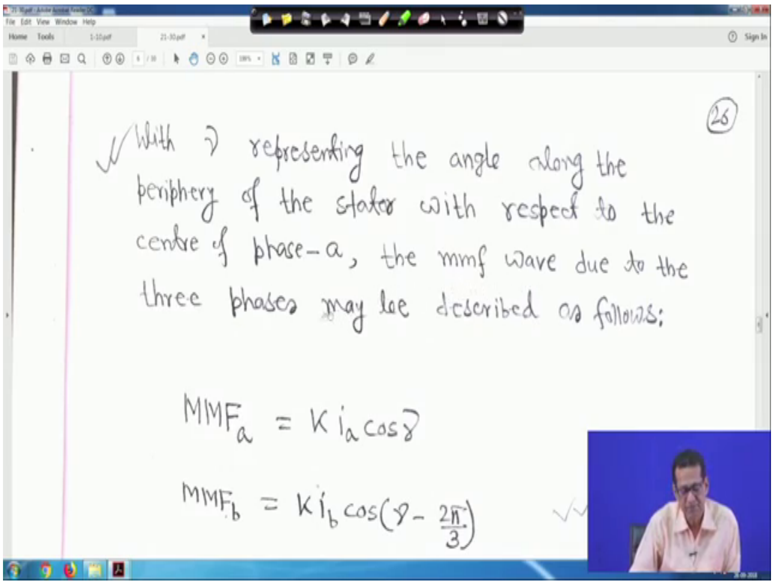

So, in this case, your; what you call the MMF wave due to the 3 phases may be distributed as follows. We can write MMF for phase a we can write k into ia into cos gamma. So, this gamma is measured from this the, from this position, so it will be k k is some constant. So, k into ia say cos gamma right. Similarly your for phase b it will be your you know you know this from abc sequence though it will be Kib cos gamma minus 2 pi by 3 and MMF c will be Kic cos gamma plus 2 pi by 3 right.

Now, where ia ib ic are the instantaneous values of the phase currents right and k is a constant.

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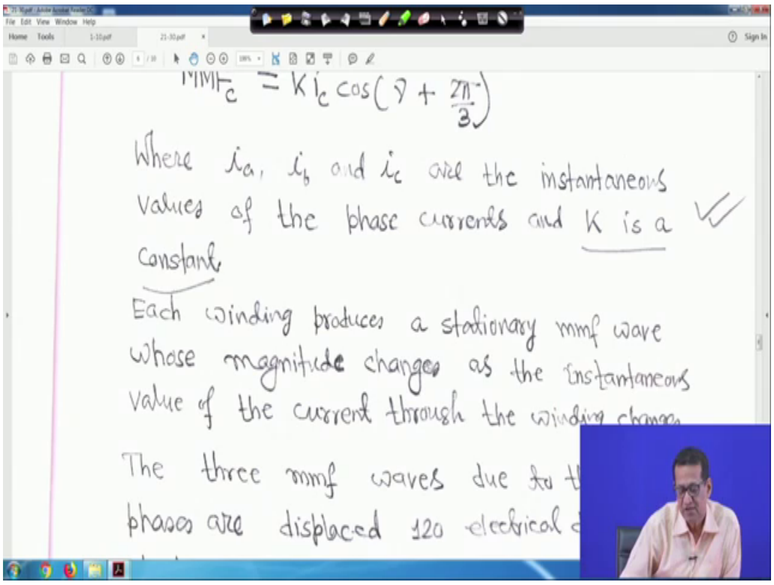

Now each winding produces a stationary MMF wave whose magnitude changes as the instantaneous value of the current through the winding changes right.

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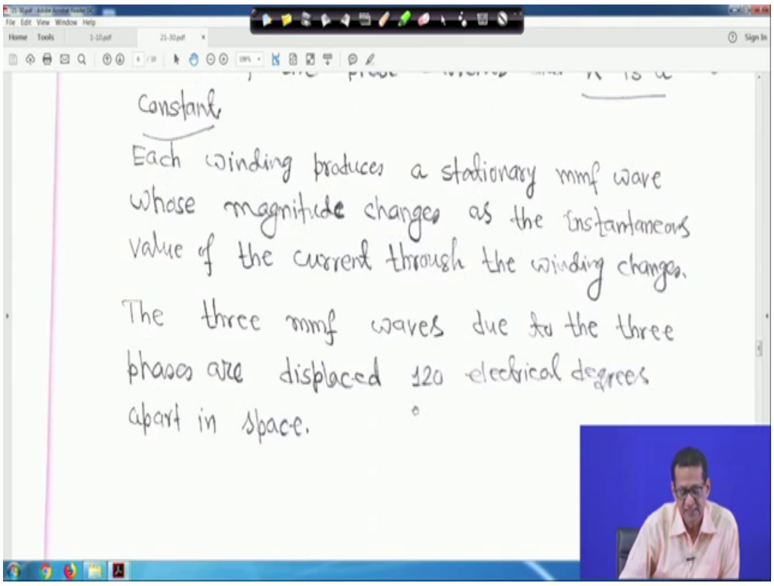

The 3 MMF your waves due to the 3 phases are displaced 120 degree electrical degrees apart in space that we know because from 3 phase studies your have studied. So, you know all these right.

So, now with balanced phase currents suppose we are in this course we will only consider the balanced thing right.

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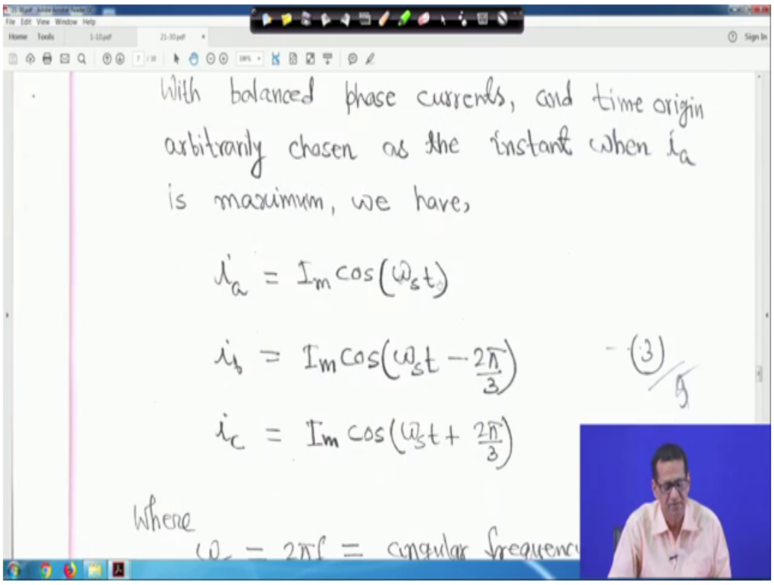

And time origin arbitrarily chosen as the instant when ia is maximum we have, you can write ia is equal to Im cos omega st, ib is equal to Im cos omega st minus 2 pi by 3 and ic is equal to your Im cos omega st plus 2 pi by 3, only thing is that this equation number these equation number it will be equation 5 not 3 right, it will be equation 5 right. So, let me clear it.

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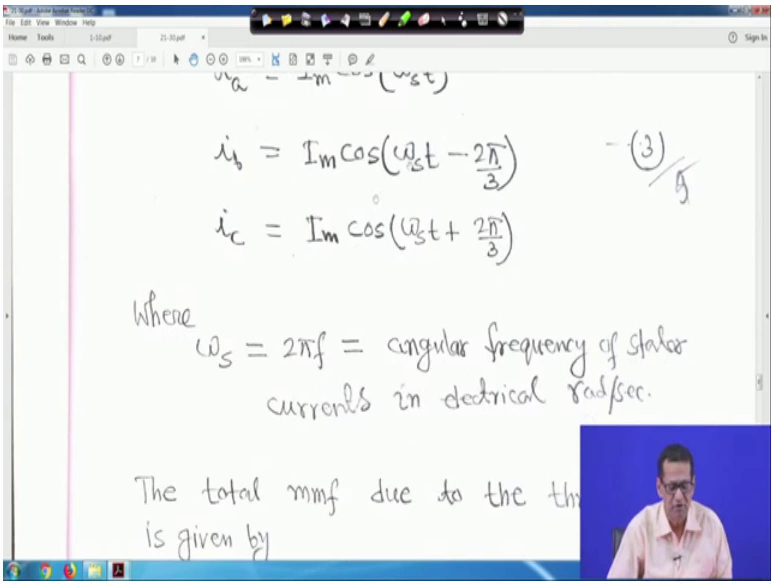

So, omega s that you know, that is it is 2 pi f that is your angular frequency of stator currents in electrical radian per second right, the total MMF due to the 3 phases is given by MMF total that is MMFa plus MMFb plus MMFc.

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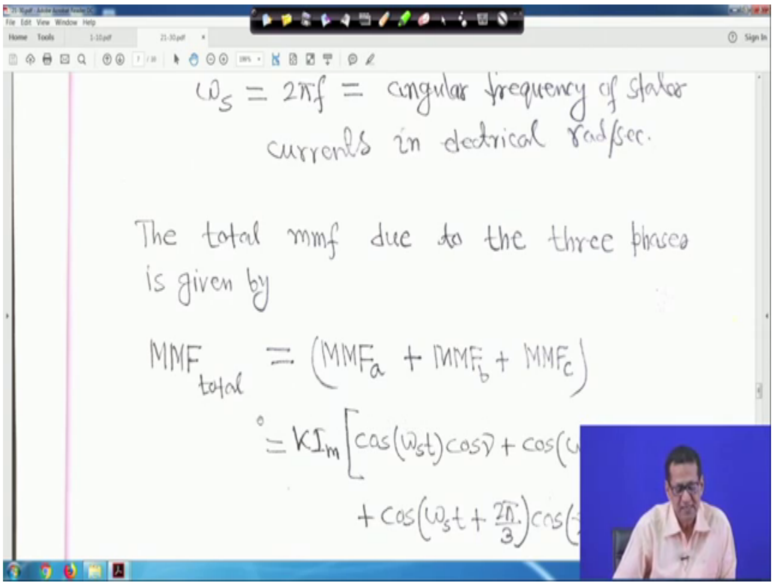

So, all these things you substitute right because MMF here it is here it is K into ia cos gamma Kib cos gamma minus 2 pi by 3 and kic cos gamma plus 2 pi by 3. ia i value of ia ib ic substitute here from this equation from this equation, you substitute here this is actually equation 5 right.

So, therefore, if you do so, it will be like this, it will be like this and if you simplify the simplification usually yourself right otherwise it will consume more time.

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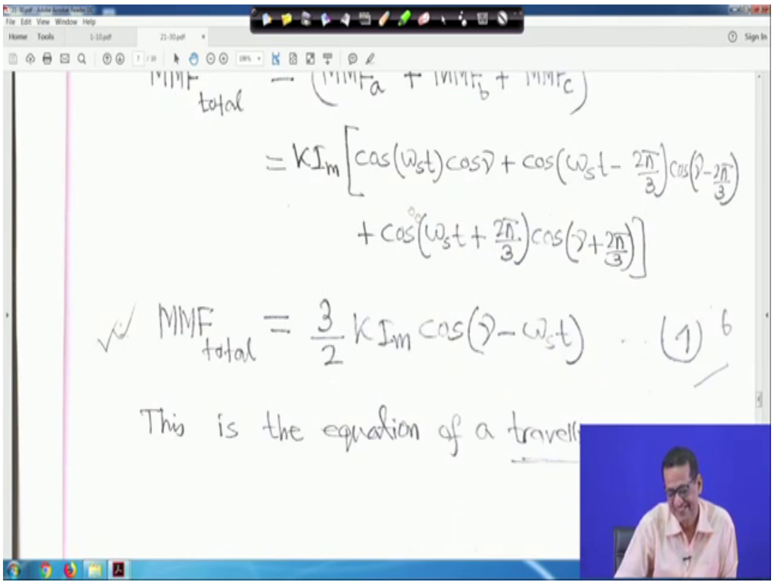

So, this simplification this is actually equation 6 not 4 right, I have written, but it is actually I have written here this is equation 6 not 4, it is equation 6 right. So, if you simplify it will be 3 by 2 K Im cos gamma minus omega s t right. Therefore, this equation is equation of travelling wave right, which we have studied in power system course right. So, these equation now it is a basically it is a travelling wave right equation of travelling wave.

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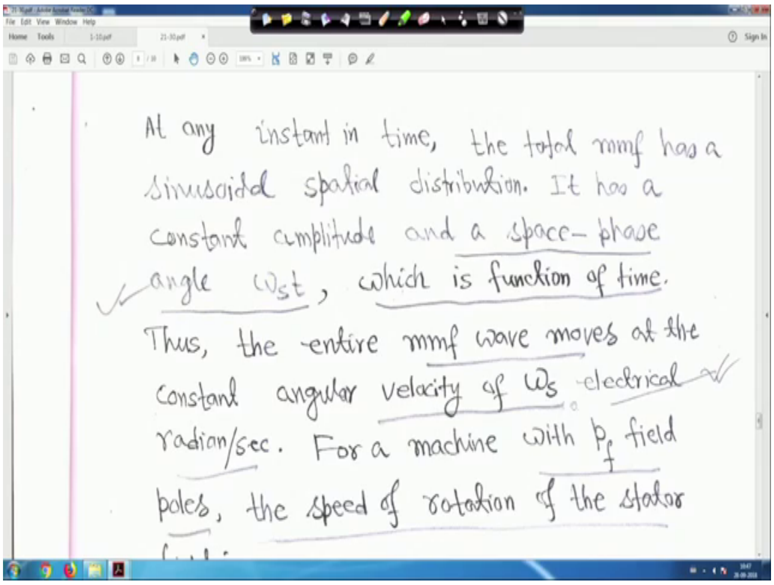

And at any instant in time the total MMF has a sinusoidal spatial distribution. So, basically it is function of cosine. So, basically nothing, but a sinusoidal distribution right, it has a constant amplitude that is your 3 by 2 K Im the constant amplitude and a space and a space phase angle omega st. So, this is your omega st and your omega s is equal to angular frequency that is 2 pi f angular frequency of stator currents in electrical radiance per second right.

So, now this which is function thus the entire MMF wave moves at the constant angular velocity of omega s right electrical radiance per second because, it is 3 by 2 K I m right cos cosine of your gamma minus omega st right. And for a machine with pf field pole suppose you have pf number of field poles, the speed of the stator field right sorry speed of the rotation of the stator field we know omega sm will be 2 pi f your 2 by p f omega s, that is mechanical radiance per second. This you know also from your synchronous machine study or you can write ns is equal to 120 f by pf or you can write 60 omega s m upon 2 pi this is your revolution per minute, this is equation 5 a this is (Refer Time: 08:09) equation 5 b right.

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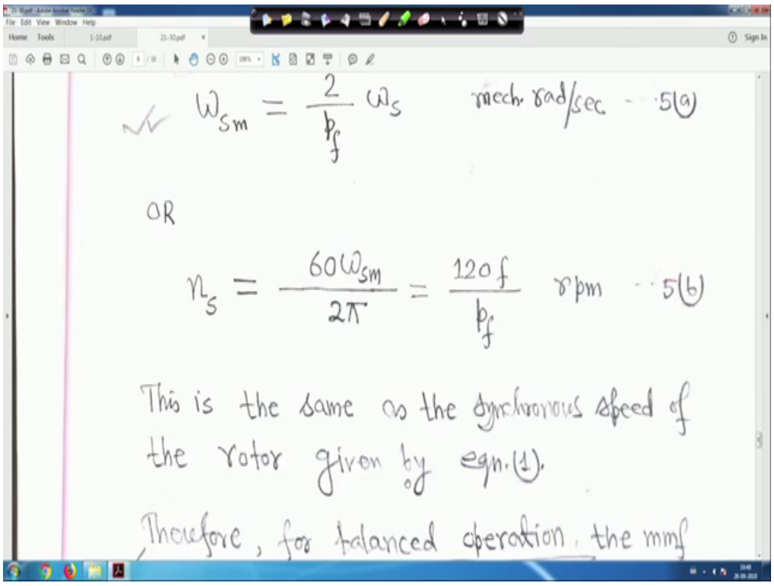

So this is the same as the synchronous speed of the rotor given by equation 3 actually, it should be equation 3, it will be equation 3 not 1 right. So, it will be equation 3. So, this is the same as the your what you call the synchronous speed of the rotor given by equation 3.

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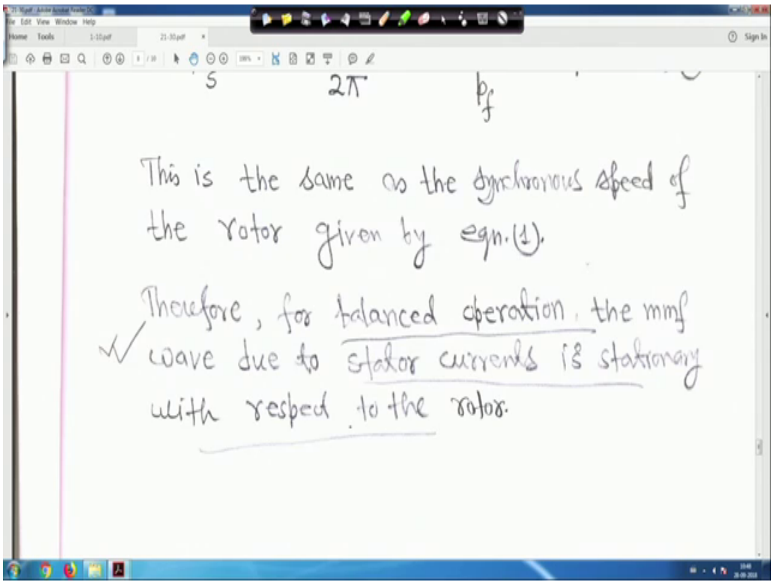

Therefore for balanced operation the MMF wave due to stator current is stationary with respect to the rotor right because both are moving in a same speed. Therefore, from the balanced operation the MMF wave due to stator current is stationary with respect to the rotor.

So, now it if you make it the MMF field and for MMF for field and MMF for stator right stator MMF and field MMF if you plot this is your what you call this is your MMF for stator and this is for MMF for field right this is omega r and this is omega s.

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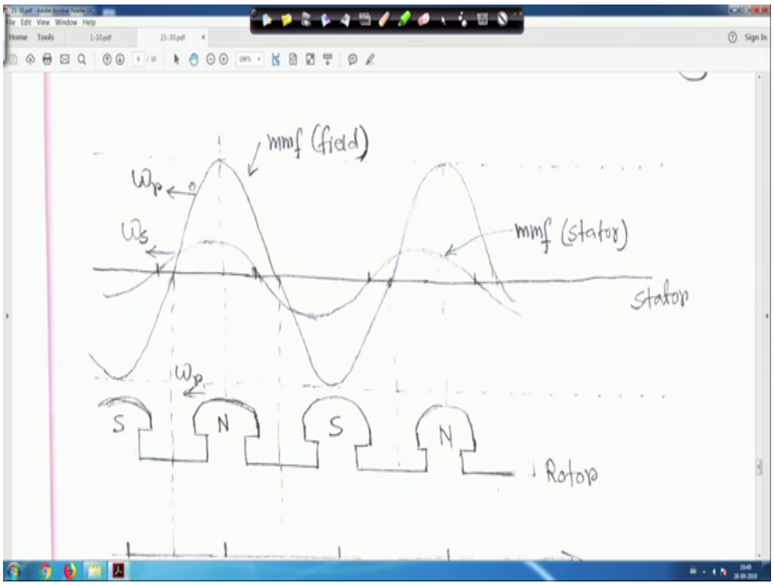

And these are your, what you call these are cut or if you make it less kind of view right. So, this is SN SN that is the pole and this is your omega r the rotor speed say and this one your what you call this is your 0 pi 2 pi this side is electrical radian this is rotor and this is your stator, stator field the stator MMF and this is your field MMF right.

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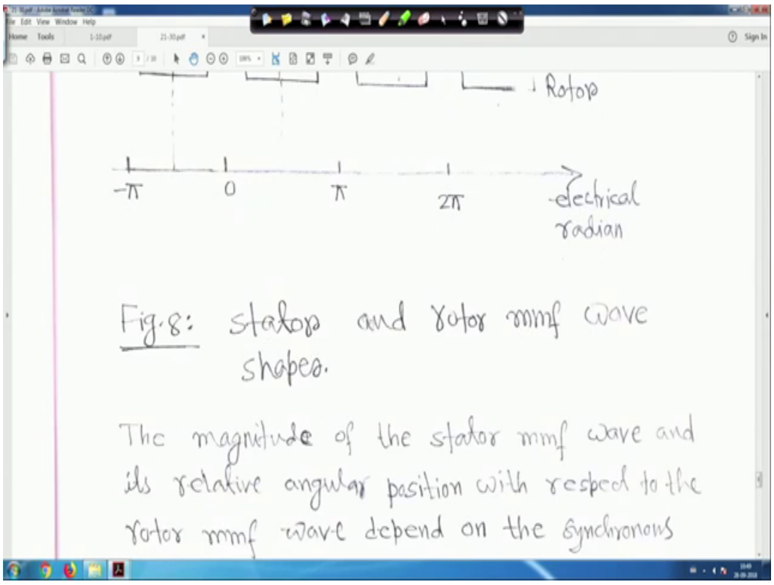

So, in this case what will happen? The stator and rotor rotor MMF wave shape right.

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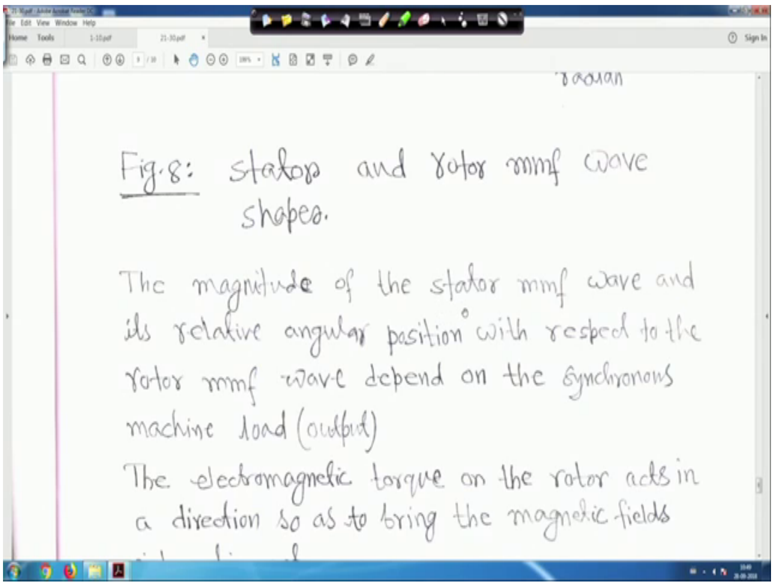

The magnitude of the stator MMF wave and the, and its relative angular position with respect to the rotor MMF MMF wave depend on the synchronous machine load right.

So, this is actually from your I believe you have studied from your machine study the magnitude of the stator MMF wave and its relative angular position with respect to the rotor MMF wave depend on the synchronous machine load; that is the output right.

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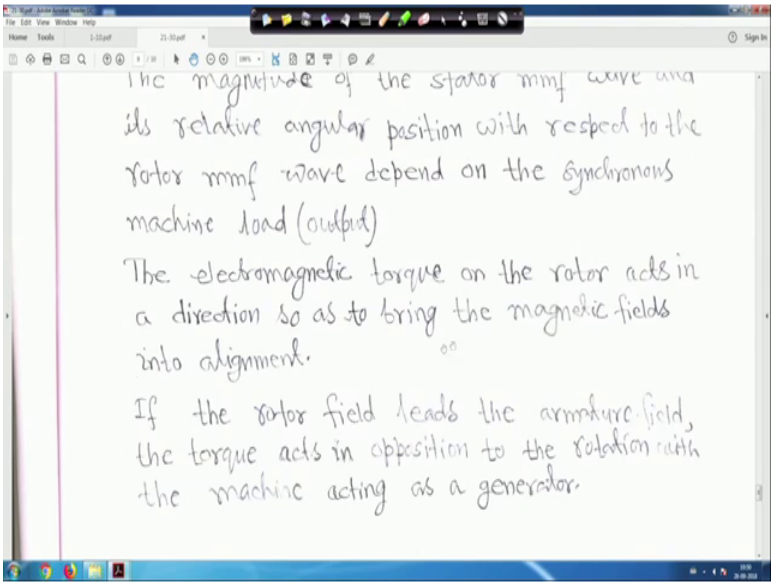

That means, that means the electromagnetic torque on the rotor acts in a directions, so as to bring the magnetic fields into alignment. So, if the rotor field leads the armature field the torque acts in opposition to the rotation with the machine acting as a generator; that means, if the machine act as a generator the rotor field leads the armature field right and the torque acts in opposition to the rotation with the machine acting as a generator.

So, I will put a small question to you, this is your rotor field and this is your stator that is your and this is your stator field stator MMF and rotor MMF right. So, from this diagram if you make this kind of diagram it is a generating mode or it is in motoring mode right. This is the simple question to you and answer is lying here. So, you will when your will your go through this video and you put this your answer in the forum right. So, if the rotor fields leads the armature field, the torque acts in opposition to the rotation with the machine acting as a generator; otherwise opposite will happen.

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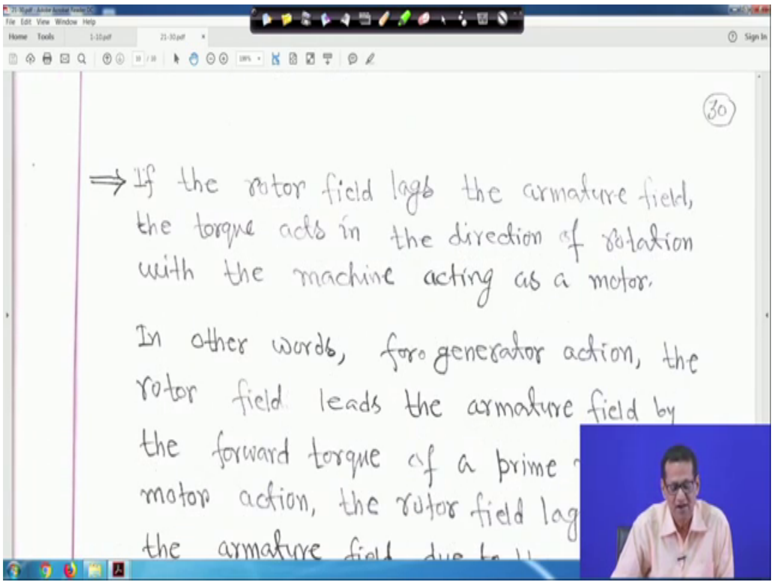

Or if the rotor field lags the your what you call armature field, the torque acts in a direction of rotation with the machine acting as a motor right.

But our objective here for this course throughout this it will be your only synchronous generator right. So, in other words, for generator action the rotor field leads the armature field by the forward torque of a prime mover, prime mover means for a thermal power plant it is a turbine right. Therefore, for generator action the rotor fields leads the armature field by the forward torque of a prime mover. This thing you should keep in your mind as a general knowledge right.

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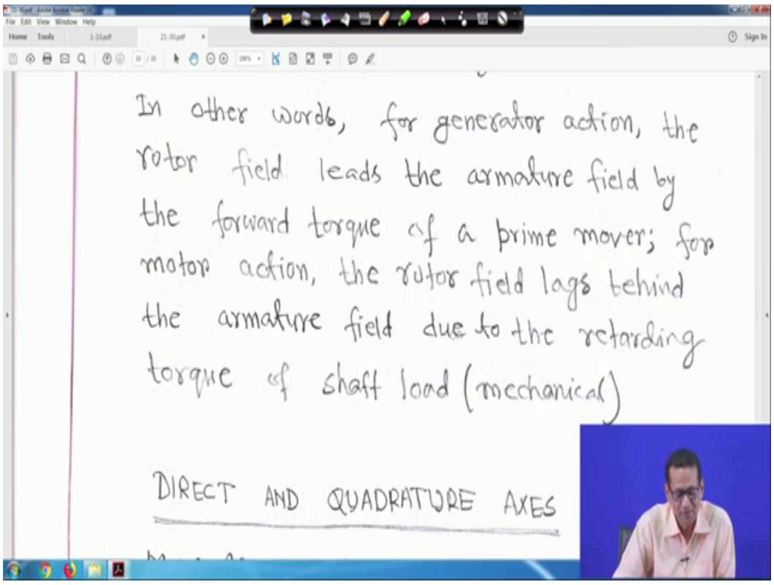

For motor action, the rotor field lags behind the armature field due to the retarding torque of shaft load that is mechanical type right. So, next is the direct and quadrature axes.

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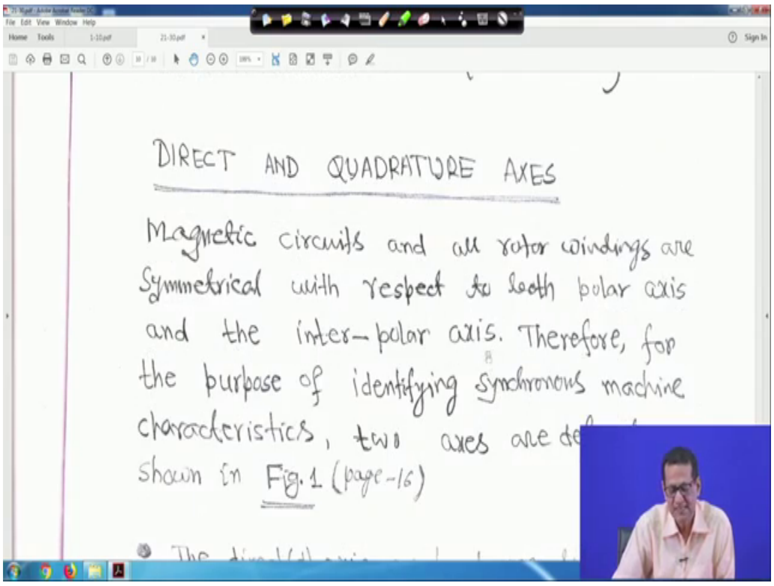

Now magnetic circuits and all rotor windings are symmetrical with respect to both polar axis and the inter polar axis. This already you have studied in your electrical machine. Therefore, for the purpose of identifying synchronous machine characteristics 2 axis are defined as shown in figure 1; that is your page 16 when you will go through this I am not going back right. So, it is figure 1, just already we have seen d axis, q axis. So, that was on page 16.

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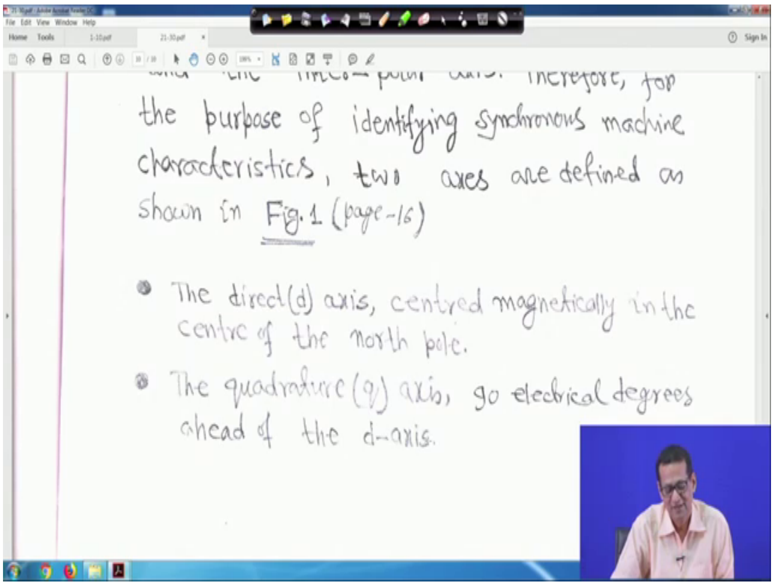

Now, the direct axis centred magnetically in the centre of the north pole that go to the diagram 1, there you will see that already we have discussed. And the quadrature axis your what you call 90 degree electrical degrees ahead of the d axis.

This is our what you call we have made this way, but they for this as per your this thing I triple E standard. So, with this just hold on we will go to the next one.

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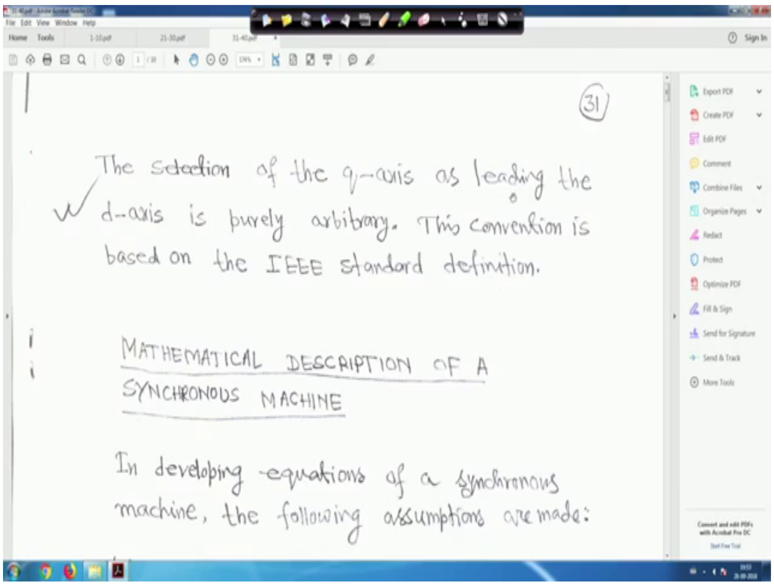

The selection of the q axis as leading d axis I told you that q axis leading d axis by 90 degree right is purely arbitrary, this convention is based on the I triple E standard definition right. Next, that we will come to that your mathematical description of a synchronous machine right, so in developing equations of a synchronous machine the following assumptions we will make.

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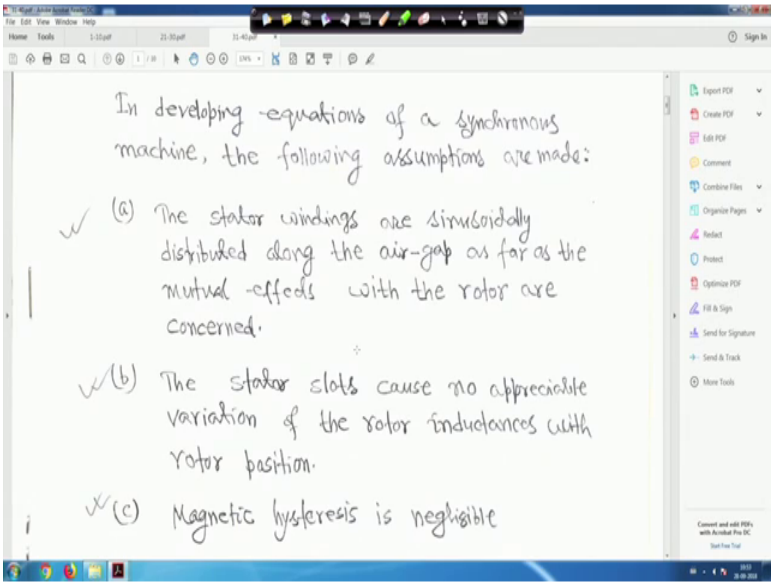

The first assumption is the first assumption is the stator winding are sinusoidally distributed along the air gap as for as the mutual effects with the rotor are your concerned right, this is the first assumption. Now second assumption is that stator your slots cause no appreciable variation of the rotor inductances with the rotor position, this is another assumption. Third assumption is magnetic hysteresis is negligible right and another assumption is there that is your saturation right.

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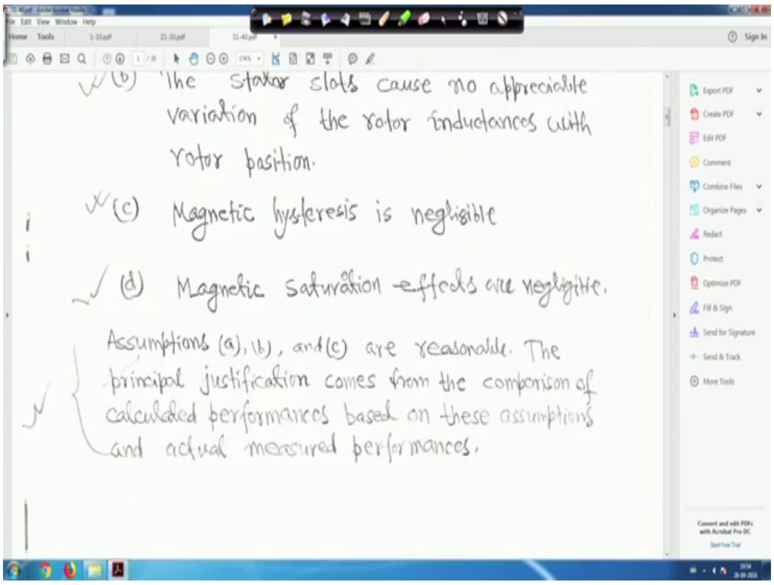

So, another assumption is the magnetic saturation effects are negligible right. So, this 4 assumptions we will make and your just hold on and that assumptions your a b c a b and c these 3 assumption are reasonable right. The principle justifications come from the comparison of calculated performance based on these assumption and actual measured performance; that means, theoretical and the and the measured both were compared by your assuming all these thing and they are very close to each other. So, these assumptions are more or less valid right.

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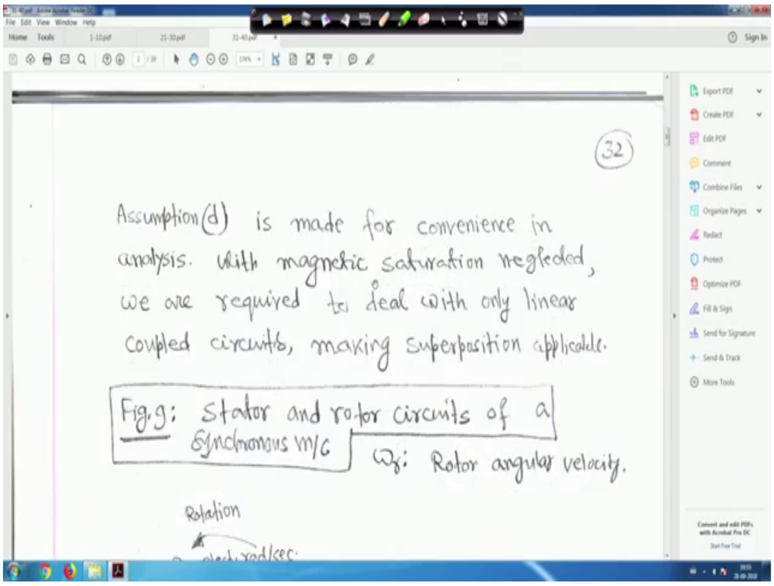

So, and the forth assumption is made for convenience in analysis with magnetic saturation neglected, we are required to deal with only linear coupled circuits making superposition applicable. For research and other purpose research purpose you have to consider everything all non-linearity right, but here for the class room studies we will only consider your, what you call that your linear couple circuit analysis that kind of thing. So, now, this is your stator and rotor circuit of a synchronous machine and omega r rotor angular velocity.

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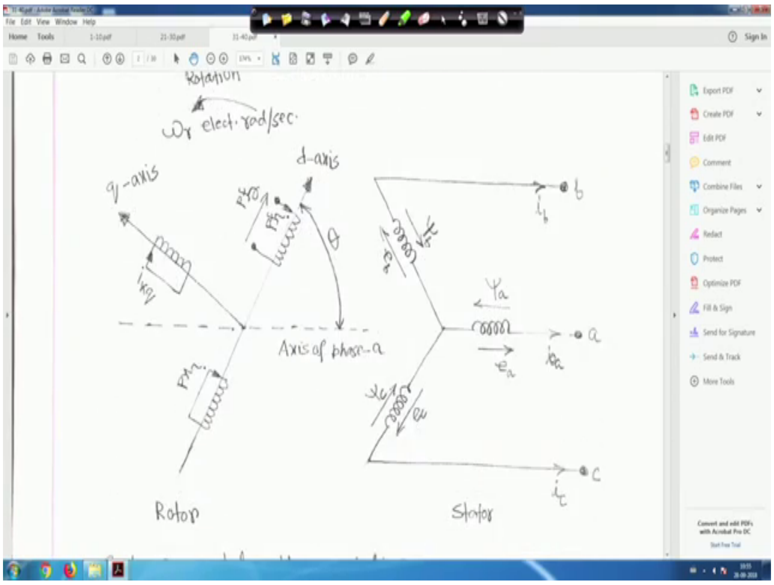

Now, here that your this schematically it is made like this. So, actually this is your what you call that your stator side and this is your rotor side. So stator you have a 3 phase, your phase a, phase b, phase c this is my phase a, this is my phase b this is my phase c and this is current living this living this terminal. Later I have mentioned, but I am telling you that when current living this terminal, we will take it as a positive convention right for the stator.

And this is voltage e a nomenclature I will give later right e a, e b this is my e a, this is my e b and this is my e c the voltage. And this is the flux linkages obvious what you call of phase a, this is phase b, phase c and all these things you have to consider the mutual coupling also right without that we cannot know.

So, this side is a stator part and this is the axis of phase a. Now this is your, what you call this is actually efd, I have written in other way right actually this is your field voltage d c field voltage this is actually e f d. So, this is efd right and this current is i f d entering into the your what you call that your field winding. So, this convention will be positive convention right.

And now you have amortisseur windings right both along the d axis along the q axis and they are short circuit itself and it is just mentioned that is ikd, this is actually ikd, I have written in just other way right and this is your ikq, this is your ikq.

So, this is d axis and this is q axis right and these 2 are amortisseur. k represent actually your 0, 1, 2, 3 if there is no amortisseur winding right then that means, k is 0; otherwise 1, 2, 3 like this, but hardly we will find 1 or 2 such your what you call this amortisseur winding, one will be along that d axis another may be along the q axis right.

But for generalization we will use that k, that notation k we will use ikd and ikq and this is the field current here it is ifd right, this is your ifd and this is the rotation of the your what you call the rotor and this is omega r electrical radiance per second right. And this is the axis of phase a, this is the axis of phase a, this is the axis of phase a, and this is d axis and d axis leading your axis of phase a by angle theta right. And then that mean; that means, the q axis right leading this one will be 90 degree plus theta because this is your 90 degree, so 90 degree plus theta right.

So, this is your what you call that your schematic diagram of synchronous machine right, but when we write your and this is the flux linkage psi a, psi b and psi psi c in this direction and this is ea, eb and ec right. So, this is your what you call that your schematic diagram and from this only we will write the equation, but later all the flux linkage equation you write and you have to consider that your mutual one; that means, a flux linkage with your in a phase a right; that means, mutual also due to current ib and ic also due to the field current also due to that amortisseur winding current ikd, ikq all mutual effects we have to consider for detail analysis right. So, this is a schematic diagram.

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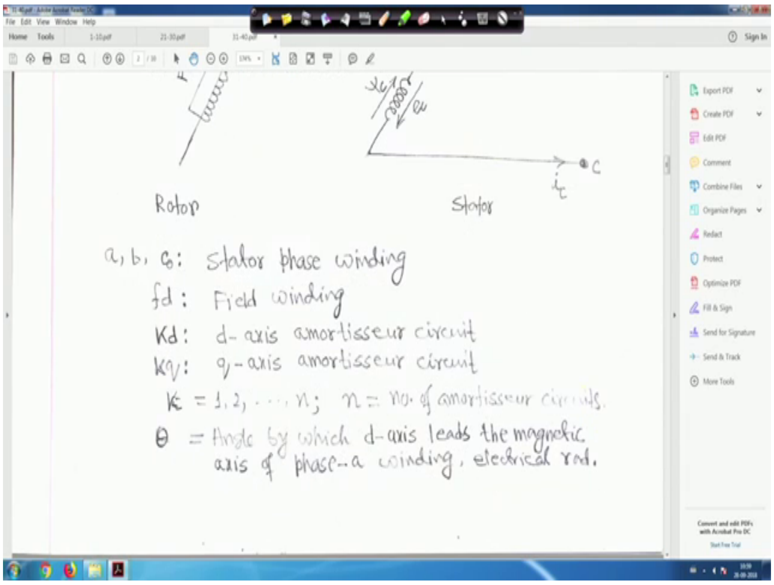

So, now the nomenclature is now given whatever I said abc stator phase winding. So, this is my abc the stator phase winding, fd field winding that is here we are making know suffix fd here here and here also it is field winding fd right and Kd d axis amortisseur circuit this is your Kd d axis and Kq q axis amortisseur circuit right and K is equal to 1 to n, n is number of amortisseur circuits. If there is in that case if you put suppose K is equal to 0, there will no amortisseur circuit and this should not be there and this should not be there, but which is not reality 1 or 2 will be there right.

So, your theta is equal to angle by which d axis lead the magnetic your magnetic axis of phase a winding electrical radiance per second. This I have also told you right. So, this is the nomenclature. Now, so figure 9 shows the circuit involved in the analysis of a synchronous machine. So, this is your figure nine and this figure 9 is not at the bottom I have marked it as a top, this is your what you call just hold on. So, this is your figure 9, this is actually figure 9, I marked it on top right and omega r the rotor angular velocity.

So, therefore, figure 9 shows the circuit involved in the analysis of a synchronous machine and from this circuit only we will write all these equation after that slowly and slowly we will develop the block diagram representation.

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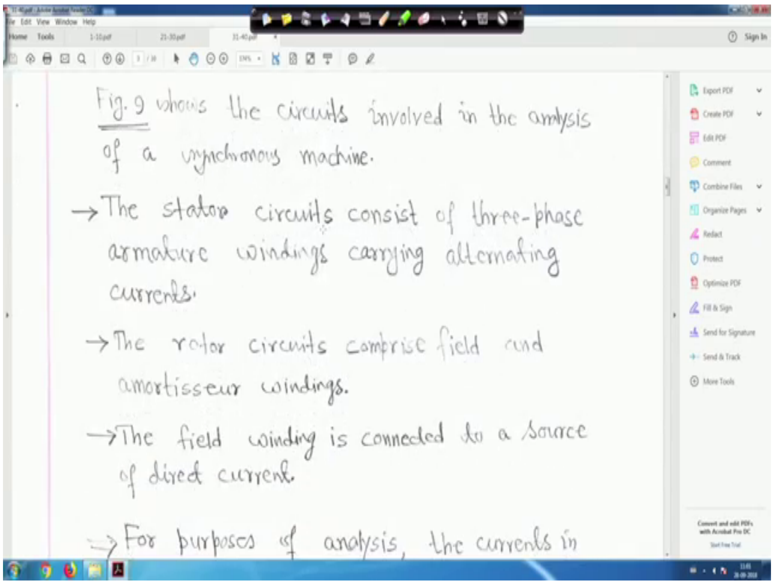

So the stator circuits consist of 3 phase armature windings carrying alternating current. So, this is your the stator circuit this carrying alternating current ia ib and ic in 3 different phases right. The rotor circuits comprise field and amortisseur windings. So, this is my this is our rotor circuit it has a field as well as amortisseur winding on d axis and q axis right and for the at the field winding is connected to a source of direct current, I have told you earlier the field is given as a your what you call the dc voltage right.

So, for purpose of analysis, the currents in the amortisseur that is a solid rotor and or damper windings may be assumed to flow in 2 sets of closed circuit closed circuit because this circuit is closed itself right.

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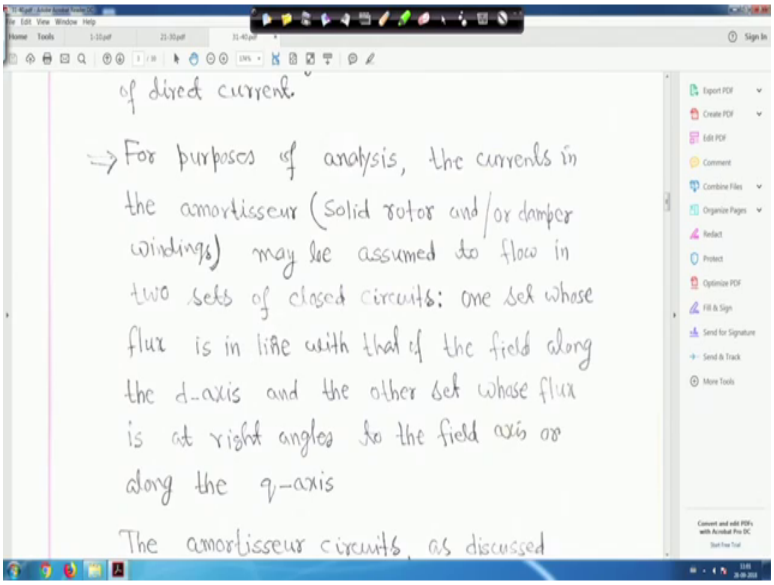

One set whose flux is in the line that if the field along the d axis; that mean here this one it will be along the d axis right and it will be your among the q axis. And your what you call and the other set whose flux is at right angles to the field axis or along the q axis right; that means, this one, either it is along the q axis or it will be right angle to the d axis.

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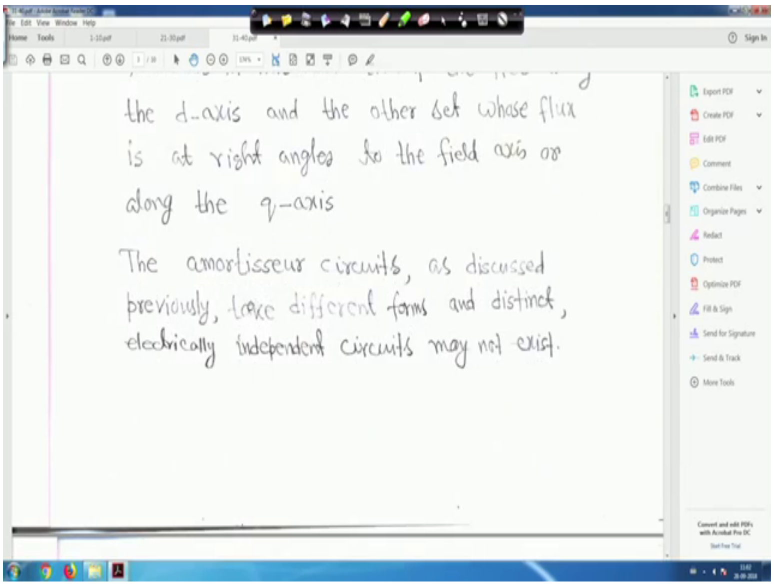

So, the amortisseur circuit as discussed previously take different forms and distinct electrically independent circuit may not exist right.

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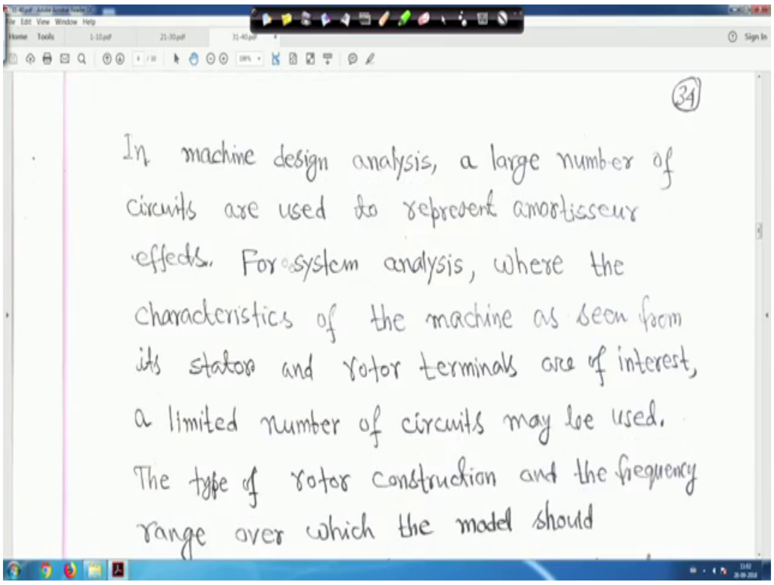

So, in machine design analysis a large number of circuit are used to represent amortisseur effects right. For system analysis where the characteristic of the machine as seen from its stator and rotor terminals are of interest, a limited number of circuit may be used. The type of rotor construction and the frequency range over which the model should accurately represent the machine characteristics determine the number of rotor circuits.

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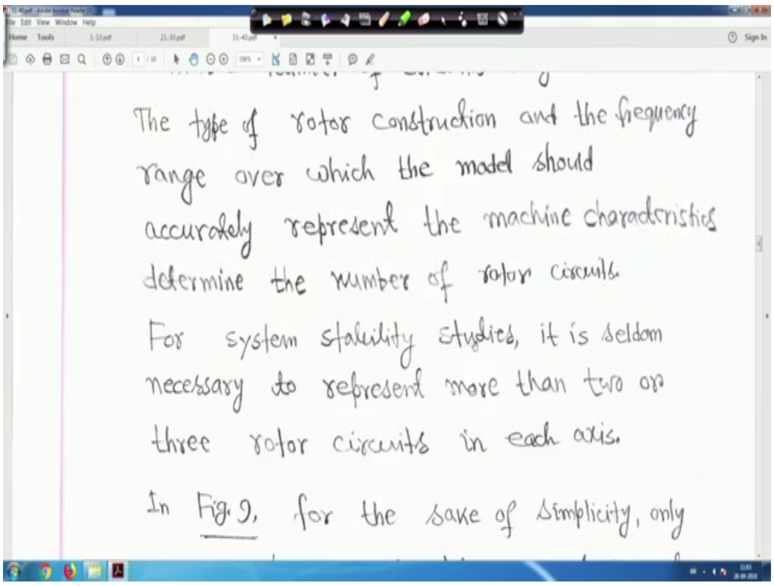

For system stability studies, it is seldom necessary to represent more than 2 or 3 rotor circuits in each axis right.

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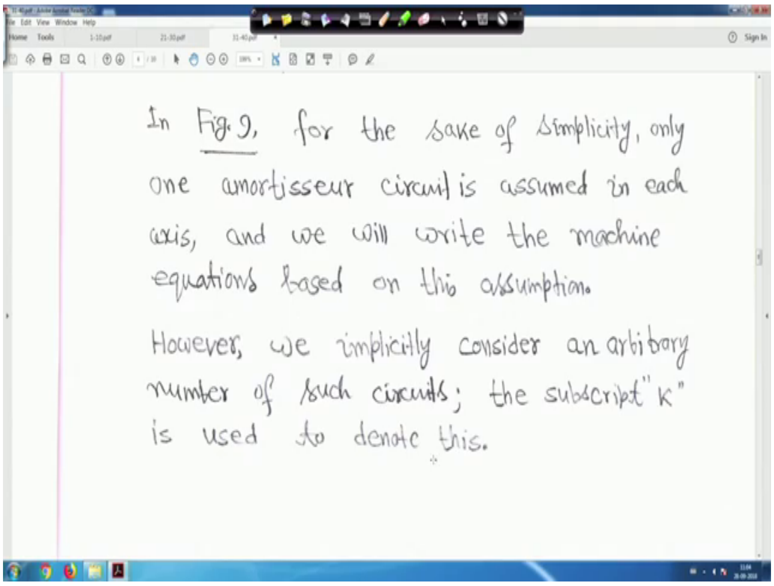

So, in figure 9 that is the previous figure right, for the sake of simplicity only one amortisseur circuit is assumed in each axis and we will write the machine equation based on this assumptions. Then what will happen? Our analysis will be slightly simper right otherwise things will be unnecessarily become complicated because synchronous machine itself later we will find the things are very complicated particularly the particularly those equations and small perturbation equations we will find things are very complicated.

So, because huge mathematical developments are there right so that is why we will make only one each but in general, we try to represent that is your iKd or iKq. So, however, we implicitly consider an arbitrary number of such circuits the subscript K is used to denote this right. So, this is actually subscript k were used that is iKd iKq right.

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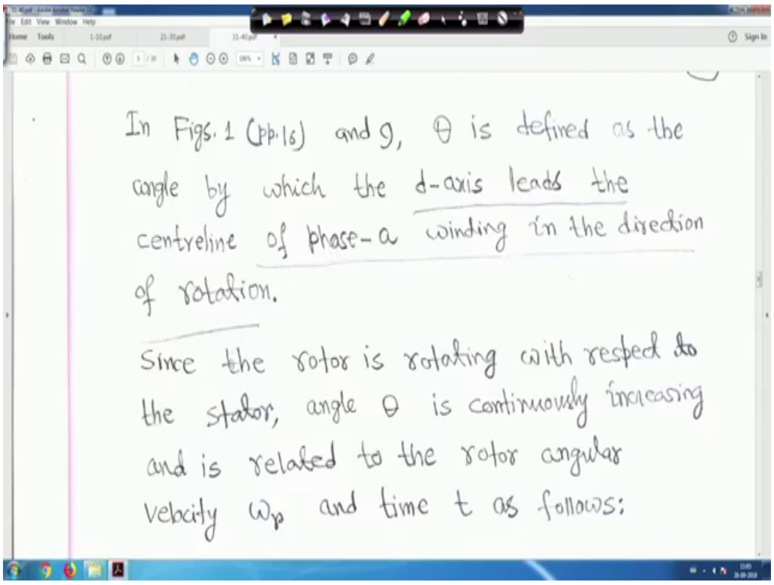

Now from figure 1 it will be actually it will be your figure 1, it will be page 16, right just go to I am not going back again right. So, your page 16 your figure 1 and figure 9 theta, this we have theta is defined as the angle by which the d axis lead the centre line of phase a winding in the direction of rotation that already that already your just wait that already I have told you right. Here right, the d axis is leading this one phase a axis of phase a by theta right.

So, so therefore, since the rotor is rotating with respect to the stator right, angle theta is continuously increasing and is related to the rotor angular velocity omega r and time t as follows, we know theta is equal to omega r t no equation number is given here, no equation number is given here right.

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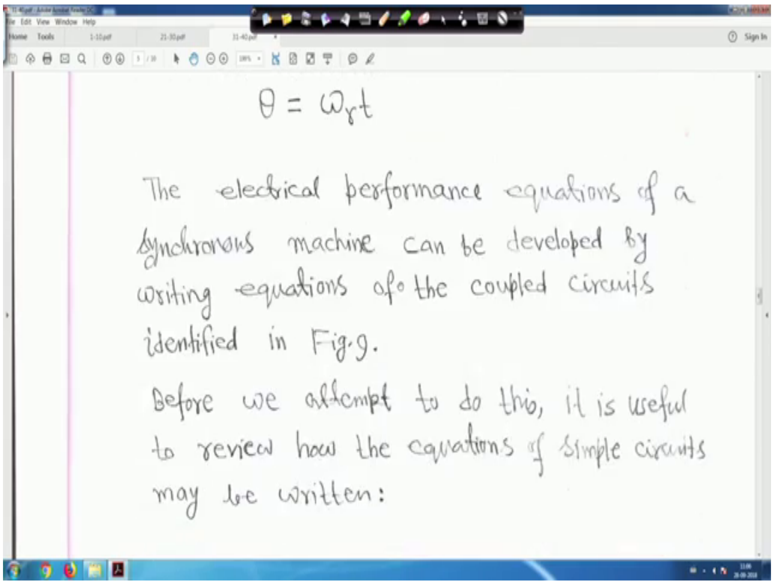

The electrical performance equation of a synchronous machine can be developed by writing equations of the coupled circuit identified in figure 9. So, this figure actually we have to add by the couple circuit and concept and we have to write down all the equations that is like psi a, psi b and psi c all this equation and also the voltage equation e a, e b, e c right.

So, all these in terms of psi a and stator winding, so also have resistances that also you have to consider, you cannot neglect that right. So, all these things we have to write using that couple concept of couple circuits, which already we have studied in first year.

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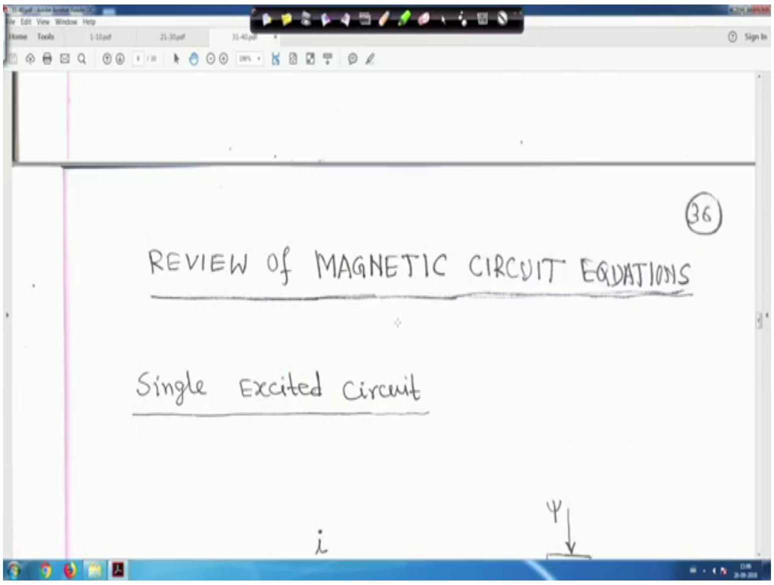

So, question is that your now before going to do that right, so as we have to study couple circuit, so we will just brush up our memories right.

So, what we will do that, that we have to review the magnetic circuit equations in a brief because, already we have studied the magnetic your couple magnetic circuit in your first year these things or if you want to brush up your memories for this particular thing that in fundamentals of electrical engineering, the first year course which I have recorded and it is ongoing now right. There we will see that magnetic circuits and couple circuits are explained in detail right.

So, same concept we will be apply that but your what you call just to just to brush up our memory before writing those say your what you call that your synchronous machine equation, we have to review our magnetic circuit equation right in a brief. So, first is a single excited circuit right.

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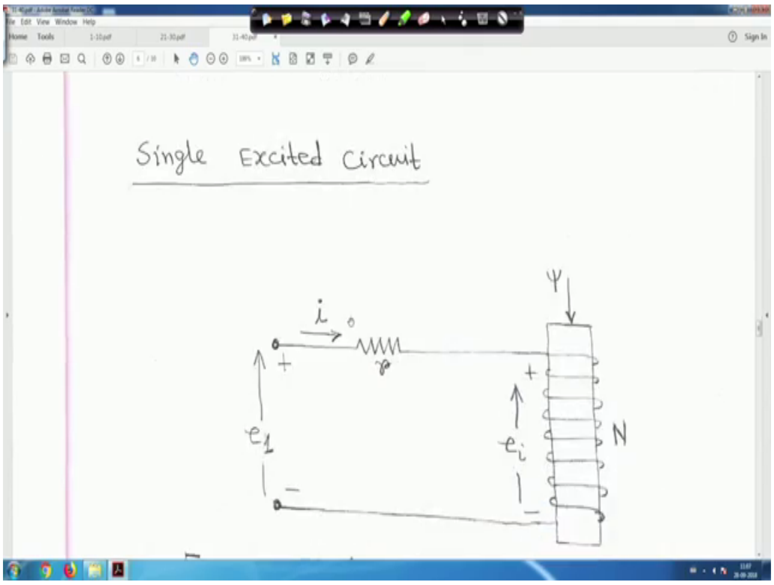

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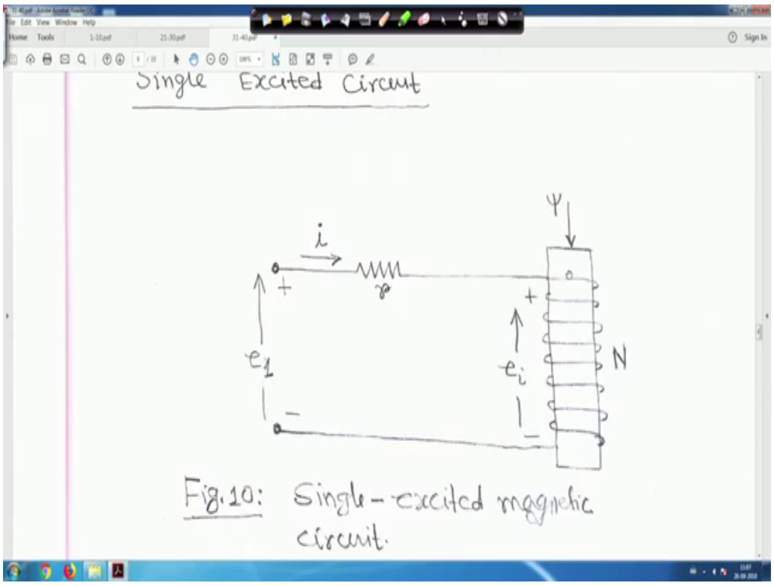

So in this case you consider this is a coil right, this is a coil its number of trans is N flux linkage is psi right and it has a resistance say it has resistance r right and this is the current i and this is the voltage plus minus it is given e, one single excited magnetic your what you call, single excited magnetic circuit. Here no couple circuit only single excited circuit right and this is the flux linkage and this is the number obtain say N.

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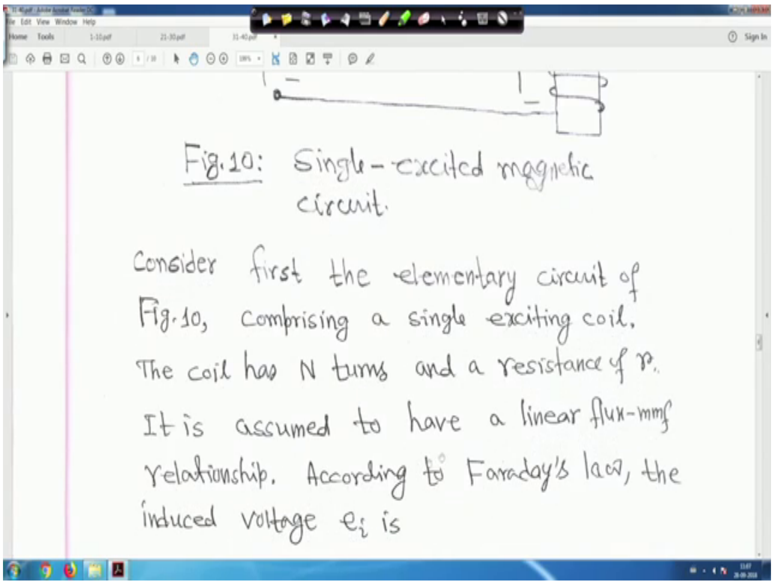

So you consider first the elementary circuit of figure 10. So, this is figure 10 right. So, comprising a single exciting coil this is your coil, the coil has N turns and a resistance r and it is assumed to have a linear flux MMF relationship. We will assume the flux versus flux and MMF it is a, it has relationship is linear. So, the coil has N turns I told you and a resistance r, it is assumed to have a linear flux MMF relationship.

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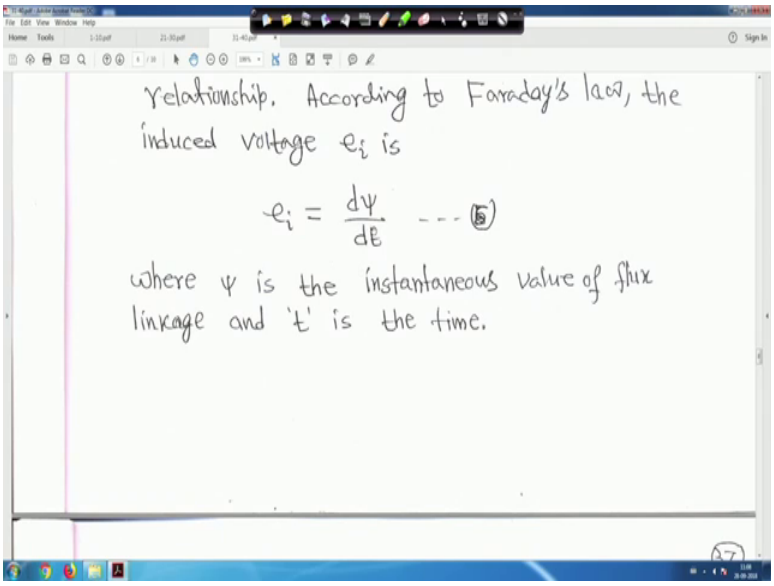

Now according to faradays law, the induced voltage ei is given as ei is equal to d psi by dt because these voltage actually it is ei right this voltage is ei.

So, here it is ei right, it is ei and this is the number often same. So, ei is equal to n d psi dt right. So, therefore, it is ei is equal to d psi by dt this is equation 6, this is equation 6 right.

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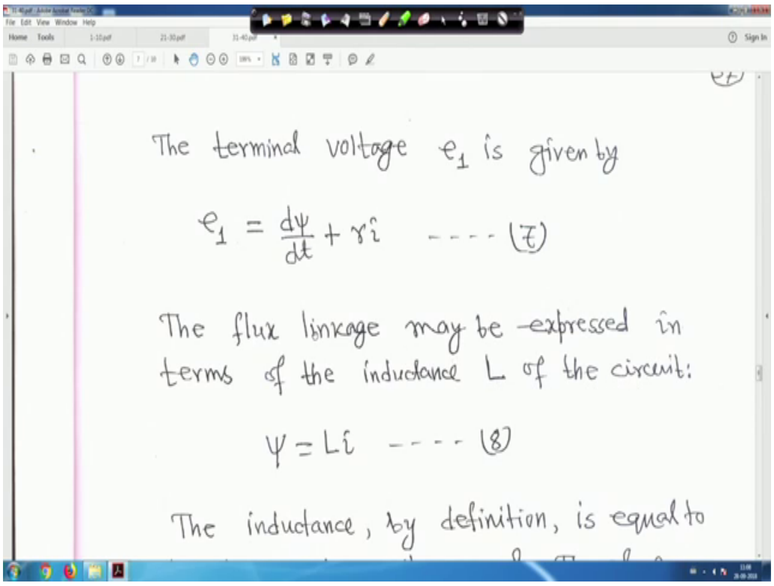

And the terminal voltage the e 1 is given by e 1 is equal to d psi plus t r i, but e i is equal to d psi by d t. So, d psi by d t plus r i not going back to the previous it is understandable. Therefore, the flux linkage may be expressed in terms of the inductance L of the circuit we can write psi is equal to Li, this also you know this is equation 8 right.

Therefore the inductance by definition is equal to the flux linkage per unit current right. So, therefore, we know that N phi is equal to Li this is also you know right. Therefore, L is equal to N phi upon i. Now numerator and denominator you multiply by N, so it will be N square upon N square into phi upon N i right, but permeance P is equal to phi upon Ni right. Therefore, L is equal to N square into P that is N square into permeance this is equation 9, where P is equal to permeance of magnetic path.

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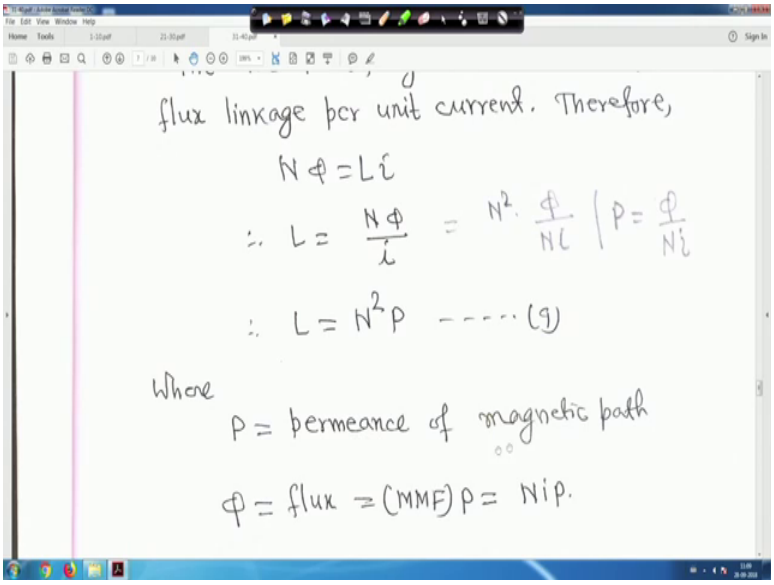

There an flux phi is equal to right, flux from this equation only from this equation only and then flux phi is equal to this phi is equal to flux is equal to MMF into P right that is from this equation this is your MMF right therefore, phi is equal to Ni into your P that is Ni into P that is MMF into P right.

So, next your what you call, so this is for simple linear circuit rights and next we will take your couple circuit, first before taking synchronous machine, but we will.

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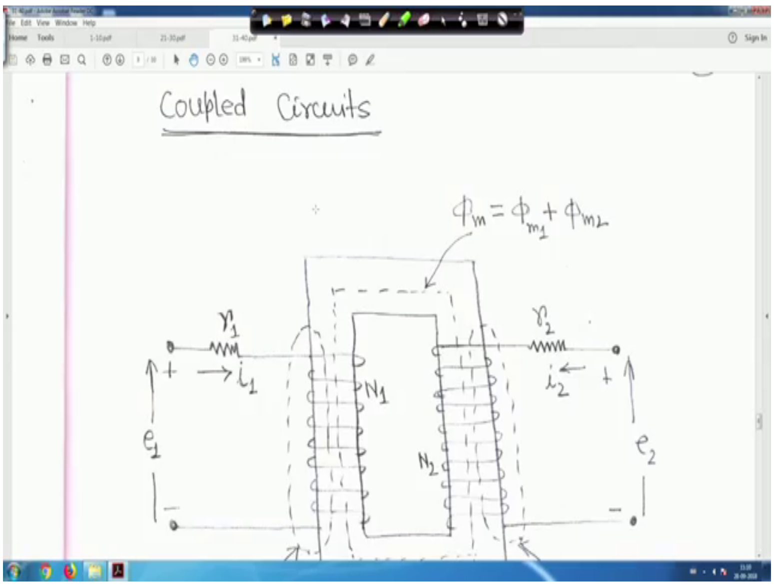

Thank you very much, we will be back again.