Power System Dynamics, Control and Monitoring
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Lecture – 04
Power System Stability (Contd.)

We are back again. So, next we will go for coupled circuit, right.

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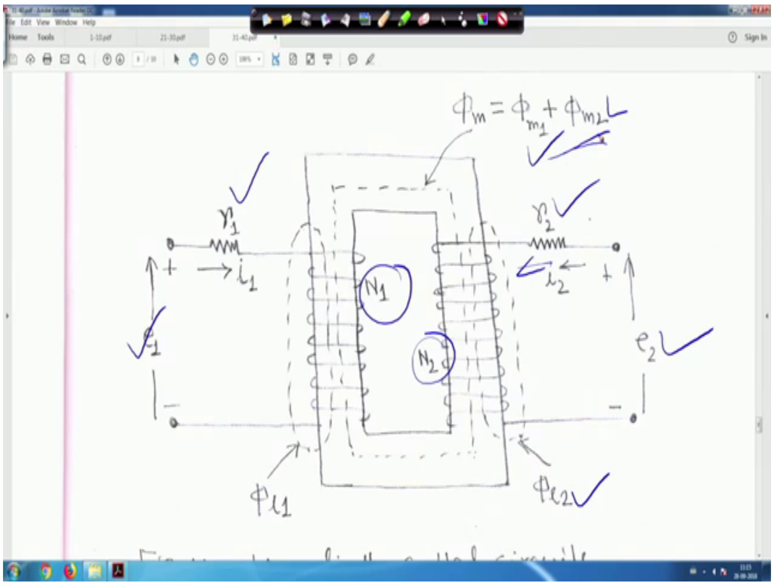

So, this I told you that in fundamentals of electrical engineering couple circuits it is convention other thing how to take mutual induced voltage plus or minus sign everything is explained in detail, right. So, just to brush up our memories for this course, right. So, just I have taken a different example, right.

So, you have here you have a before giving the nomenclature here you have two coils and a your what you call this is a couple of circuit this turn of this number of turns of this coil is N 1 this is your; this is your N 1 and number turns of this coil is N 2, right. And, resistance of this coil is r 1 and it is here r 2, right and this voltage is e 1 this voltage is e 2 and now both the currents i 1, i 2 entering into the your what you call into this into this coil, right and direction of the flux other thing can be applied through your right hand rule, right.

And, now question is that these things this whenever they whenever you have a you have your current is showing to this then the flux what will happen part for your part of the flux wilding this coil N 1, right and part of this wilding this coil that is mutual one that is your this coil that is second coil right with number of turns is N 2, right. So, that means, your what you call that is your phi m 1 because of this one.

Similarly, if you have current i 2 then it will see it is your say your what you call self linkage is your flux will be phi l 2, right and because of this current some flux also phi m 2 wilding this coil, right. So, in this case your phi m is equal to phi m plus phi m 2. So, both if you what you call that if you take the your what you call that your right hand rule, then you will find these two will be additive for this I refer to the fundamentals of electrical engineering, right that magnetic circuit.

So, and these two are your N 1, N 2 number of turns and from that we will write that equation, right. So, in that case actually for right hand rule is that this is your coil if you grasp the coil like this in the direction of the current, then this will be the direction of the flux the thumb will be direction of the flux. So, in this case this is phi 1 and this is entering also if you direction of the current if you grasp it, right. So, it will be also in the downward direction and this is upward directions. So, that is why these two are plus phi m 1 plus phi m 2. So, that is why I refer it I request you that just have a look on that if you have any doubt otherwise I believe that you know this, right.

So, this is your what you call the coupled coil. Now, how to couple circuit? How to write those equations? So, in this case your this is magnetically coupled circuit.

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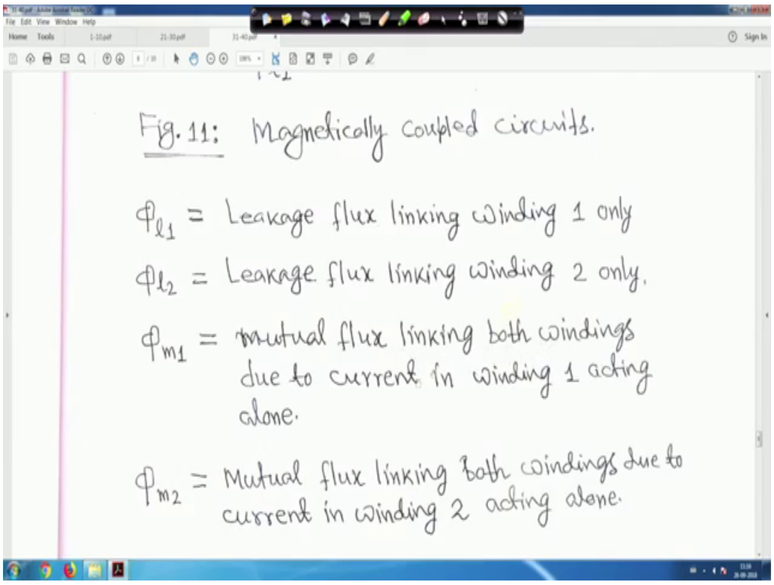

Now, phi l 1, the leakage flux linking winding 1 only this is only they were linking only winding 1; phi l 2 leakage flux linking winding 2 only. So, this your winding 2, right and phi m 1 mutual flux linking both windings due to current in winding one acting alone. I mean this is your phi m 1; so, because of this your what you call because of this current in i 1 most of the flux will link this your coil 1 and part of this also your what you call link that your what you call that other coil. Apart from this coil other coil; that means, total flux linkage of this coil that is N 1; N 1 number of turns basically you have phi l 1 plus phi 1. Because phi l 1 is self linkage, right plus this phi m 1, but this phi m 1 also will link this one.

Similarly, for your other one, right phi l 2 will be there phi m 2 also wilding this one. So, total flux linkage of this coil will be phi l 2 plus phi m 2, but this phi m 2 also wilding this one and this phi m 2 because of this your current i 2 in the second circuit that is your what you call the other coil, right. So, that is why phi m 1 mutual flux linking both windings due to current in winding 1 acting alone, right. Similarly phi m 2 mutual flux linking both windings due to current in winding 2 acting alone, right.

So, this is your what you call that your what you call the coupled circuit. Now, you have to write down the few equation.

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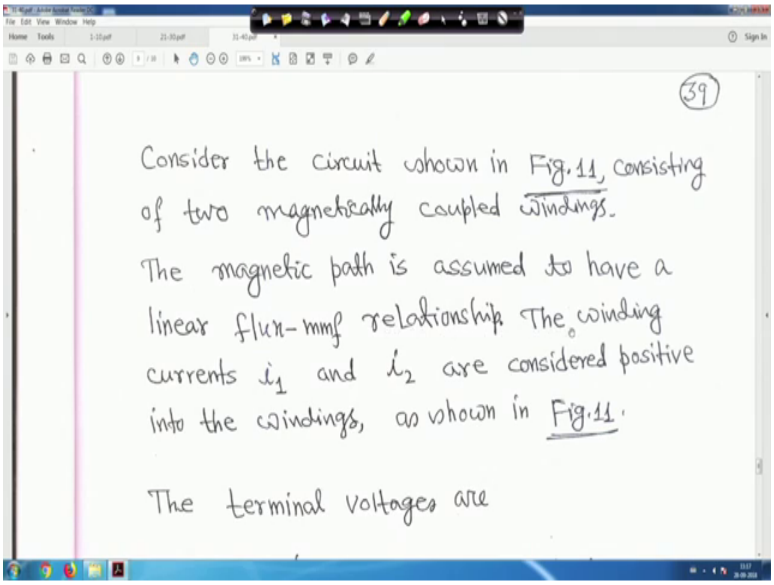

Now, consider the circuit shown in figure 11 constitute of two magnetically coupled windings. So, this is my figure 1, this is my figure 1, right sorry figure 11, figure 11, right. And, therefore, the magnetic path is assumed to have a linear flux-mmf relationship we will assume a linear relationship between flux and mmf, right that is between phi and n i, right. The winding currents i 1 and i 2 are considered positive into the winding as shown in figure 11. So, as this two currents are entering into this coil whereas, shown in it is positive, right some convention we have to make.

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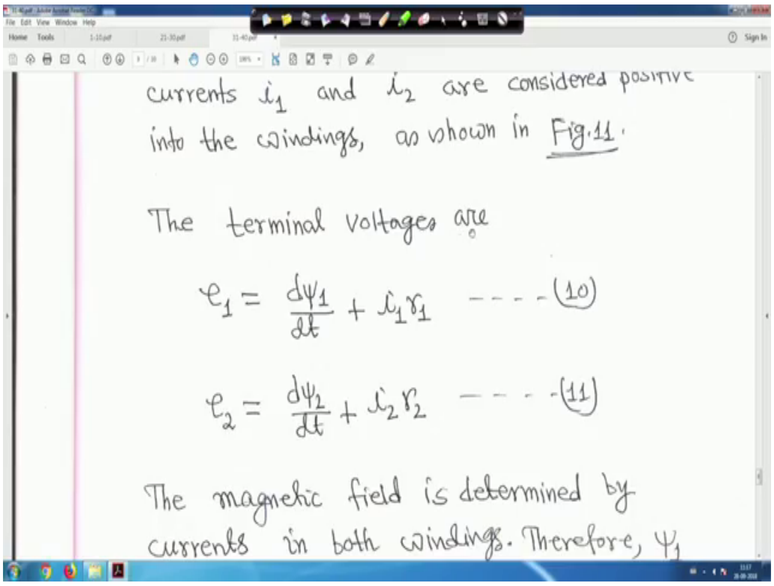

Therefore the terminal voltages you can write for e 1 will be d psi 1 upon dt plus i 1 r 1 and for this coil if you write the terminal about a e 1 it will be i 1 r 1 into your d psi by your dt, right. So, that is your d psi 1 by dt for coil 1. Similarly for coil 2 it will be d psi 2 by dt plus i 2 r 2. So, psi 1, psi 2 are the flux linkages, right.

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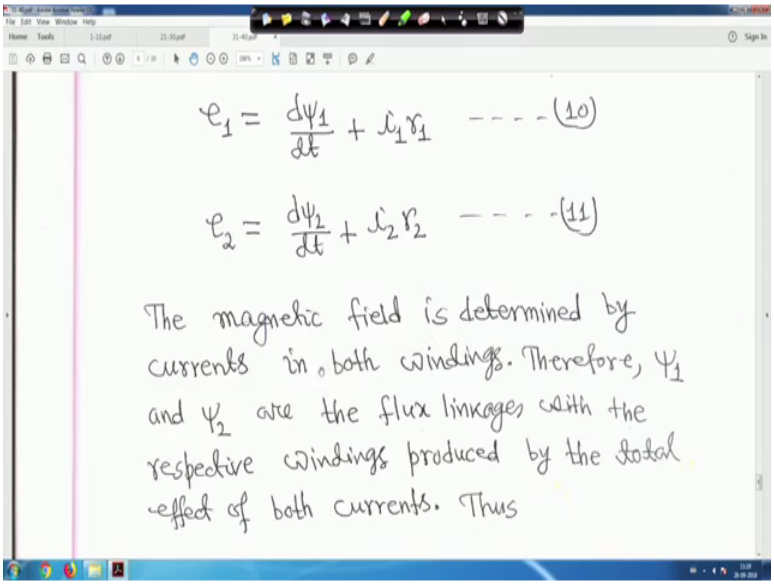

The magnetic field is determined by currents in both windings, right because both winding currents are there. Therefore, psi 1 and psi 2 are the flux linkages with the respective windings produced by the total effect of both currents, right. Thus we can write psi 1 is equal to N 1 into phi m 1 phi l 1 plus N 1 into your what you call phi m 2. Now, if you come to that if you come to this circuit, right.

If you I mean why I am telling these when I write the synchronous machine equation directly we will write and we will find it is easy. For this coil see the your what you call the flux linkages right, one is that your what you call that psi 1 for this thing that psi 1 is equal to that one thing is there that is a phi l 1 is there plus phi m 1 this phi m 1 is also there, right. So, phi m 1 is also there so; that means, psi 1 is equal to current is i 1, right.

So, from that you can make out that your what you call what will be the flux linkage right what about turns. So, in that case it will be N 1 into psi l 1 plus your psi m 1 plus because of these things psi m 2 also there is a flux linkage of psi m 2 here. So, it will be N 1 into psi m 2 these are psi m 2, right.

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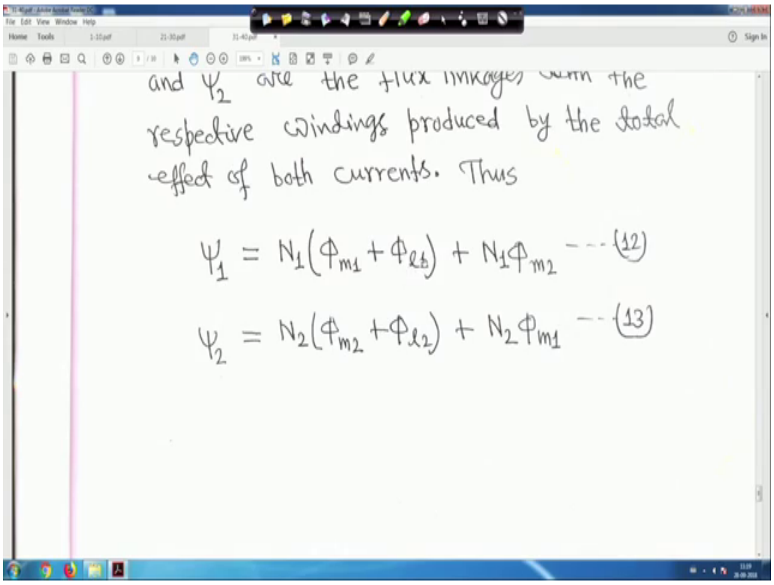

So, that means, that is why these equation this equation is written that N 1 into phi m 1 plus phi l 1 this is your what you call that your phi l 1 plus phi m 1 already linking N 1 and this phi m 2 is coming because of the current in the second coil i 2 and linking this flux their coil your one that is number of you can say N 1 so, that why N 1 into phi m 2. Similarly, this is equation 12. Similarly, psi 2 will be N 2 into phi m 2 plus phi l 2 plus N 2 into psi m 1 just other way, right and this is your psi 1 and psi 2 the flux linkages, right.

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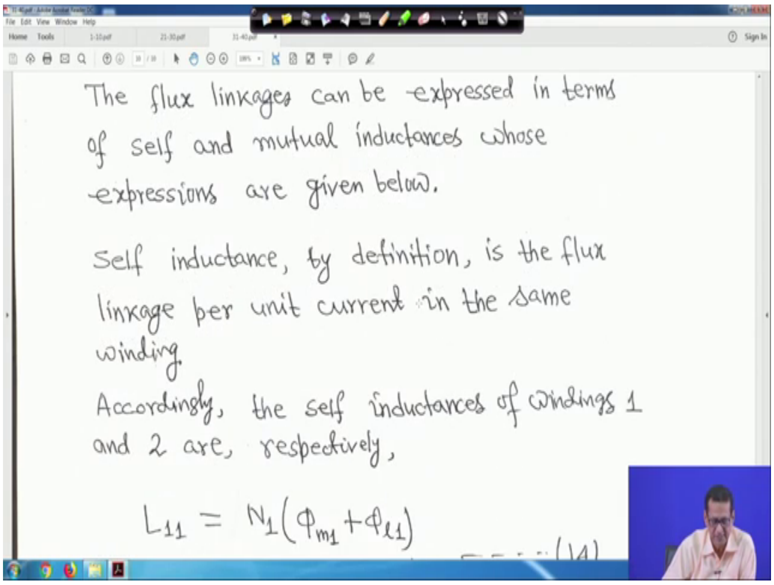

So, that means, the flux linkages can be expressed in terms of self and mutual inductances whose expressions are given below, right we will be see that self inductance by definition is the flux linkage per unit current in the same winding that you know this, right. So, accordingly the self inductances of windings 1 and 2 are respectively you can write L 11 will be N 1 into psi m 1 phi m 1 plus phi l 1 upon i 1 because, if you come to this diagram if you come to this diagram this because of this current i 1 the flux linkage actually phi l 1 plus phi m 1, right. So, and similarly because of this current i 2 flux linkage this coil, right phi m 2 plus phi l 2 and other thing that is mutual one linking that is your what you call that phi m 1 linking this coil also.

Similarly, phi m 2 plus linking this coil also, but our interest is now self inductance. So, it will be basically phi l 1 your flux linking this coil phi l 1 plus phi m 1. So, that is why we are writing that self inductance is this one your L 11 N 1 into phi m 1 plus phi l 1 divided by i 1, right.

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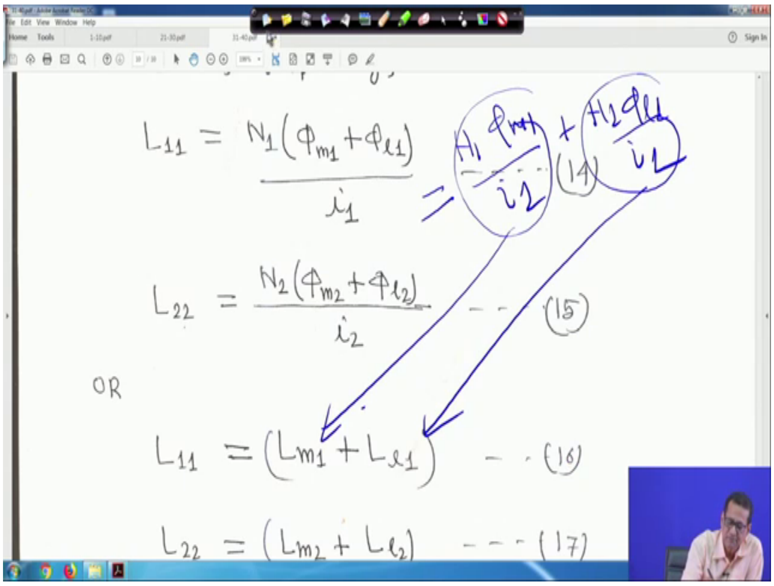

Similarly, for L 22 just same thing N 2 into phi m 2 plus phi l 2 upon i 2; this is 14 and 15, these two equation number, right or we can write l 1 is equal to L 11 is equal to L m 1 plus your L l1; that means, that things we have what we are writing actually this term say this term this term you can break it like this it is N 1 your phi m 1 divided by i 1 plus you can write N 1 phi l 1 divided by i 1, right.

So, this term N 1 phi m 1 by i 1 this is your this one and this term N 1 phi l 1 this is your this term, right. So, this is equation 16.

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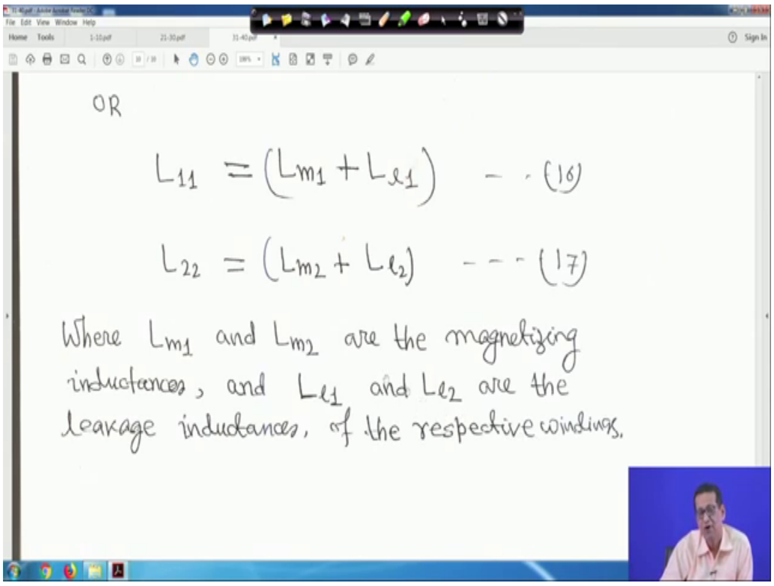

So, similarly your L 22. Similarly, it will be L m 2 it is nothing, but N 2 phi m 2 upon i 2 this is L m 2 plus your N 2 phi l 2 upon i 2 this is L l 2 this is equation 17, right where L m 1 and L m 2 are the magnetizing inductances, right or sometimes we call mutual inductances, right and L l 1 and L l 2 are the leakage inductances of the respective windings. So, just hold on.

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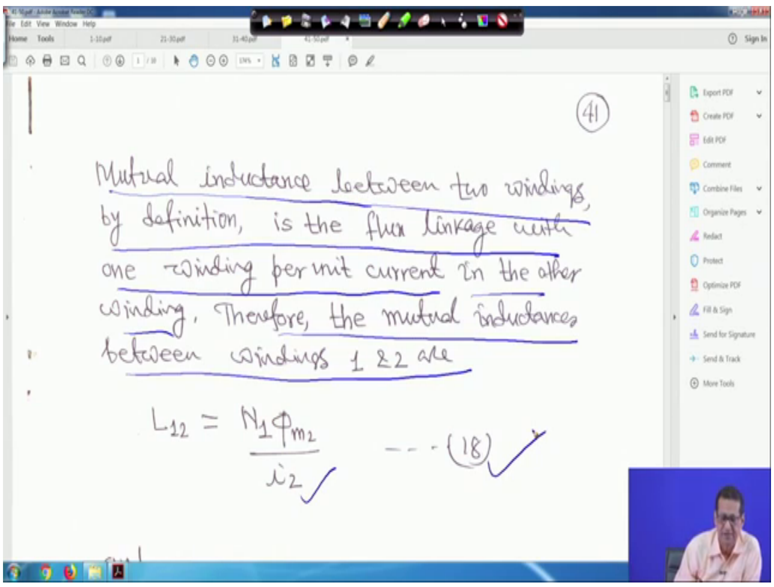

So, now mutual inductance between two windings by definition is the flux linkage with one winding per unit current in the other winding therefore, the mutual inductances between windings 1 and 2 are these also you know, this also you know, right. So, this is your this is your mutual inductance between two windings by definition is the flux linkage with one winding per unit current in the other winding. Therefore, the mutual inductances between windings 1 and 2 are L 12 will be N 1 into phi m 2 and it is actually this phi m 2 this flux actually mutual flux that is linking the coil 1 whose turn is N 1 and that is due to the current is i 2 you can write L 12 is equal to N 1 phi m 2 upon i 2 this is your equation 18, right.

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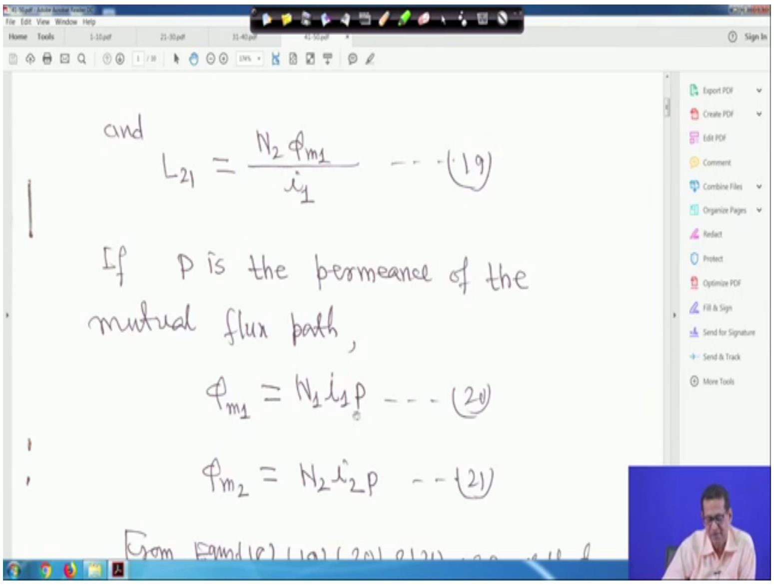

Similarly, your similarly L 21 will be N 2 into phi m 1 upon i 1 this is equation – 19, right. So, if P is the if you assume that P is the permence of the mutual flux path the nu can we know that phi m 1 will be N 1 i 1 into P, right. So, anyway mmf into permeance is equal to flux linkage so, but in terms of your what you call P is the permeance of the mutual flux path then we can write phi m 1 is equal to N 1 i 1 into P similarly phi m 2 is equal to N 2 i 2 into P, right.

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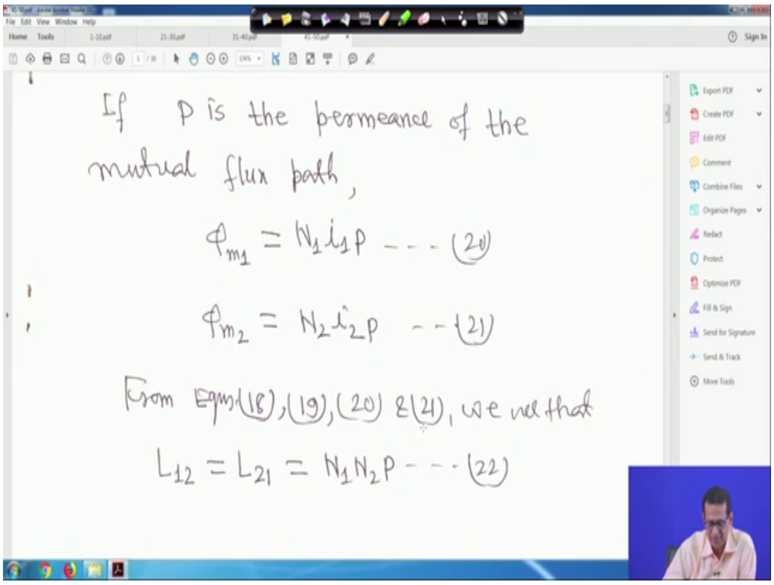

Now, equation is 18, 19, 20 and 21 if you use 18, 19, 20 and 21 you will get L 12 is equal to L 21 is equal to N 1 N 2 is equal to P, right. That means, this equation your what you call your, just hold on I will make it for you these equation you multiply numerator and denominator by your N 1 N 2, right yes, by N 1. If you do so, just hold on; just hold on I will go to the equation – 18, that will be easier, right.

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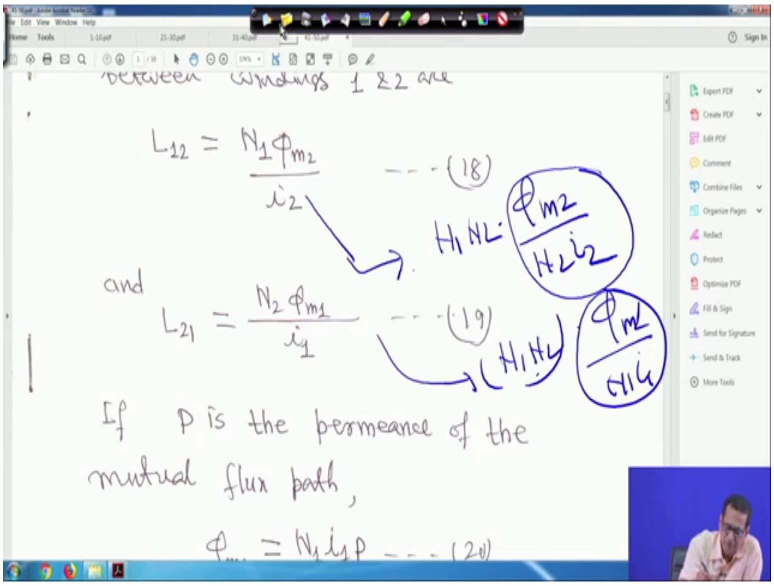

Just hold on these equation if you multiply by your N 1 your N 1 is there, multiply numerator and denominator by your N 2, right and if you do so, then just hold on space is space is not there I making it here these equation I making it here it is N 1 the numerator and denominator we multiplied by N 2 this is N 2 then this one you can write phi m 2 by your N 2 into i 2, right.

So, this is nothing, but your permeance this is your flux by your what you call that your mmf this is N 2 in i 2, right. So, this one you can make it as a P, right that is the permeance. So, that similarly this one if you multiply this one by your N 1 term then it will be N 1 N 2, right; it will be N 1 N 2, then this 1 you can write phi m 1 upon N 1 i 1, this is also expression for permeance, right.

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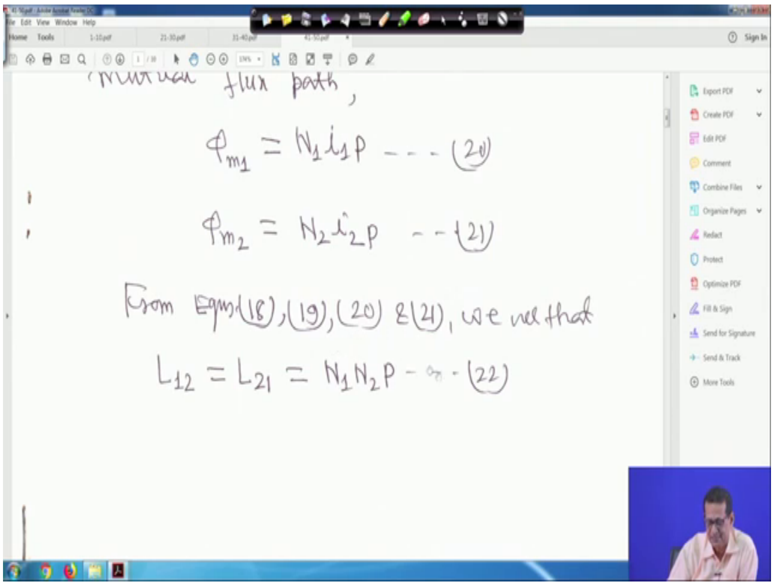

So, that is why if you do so; if you do so; that means, so, that is why this equation can be written as you phi m 1 is equal to N 1 i 1 P phi m 2 we have already written; therefore, these two we find L 12 is equal to L 21 because N 1 N 2 into P because this permeance expressions are given here P P the your permeance for the path P will be remain same right, but your right. Therefore, P is equal to your phi m 1 upon N 1 i 1 or is equal to phi m 2 upon N 2 i 2. So, basically it will be N 1 N 2 into P right. So, that is L 12 is equal to L 21 is equal to N 1 N 2 P. So, that is same this is equation – 22 right.

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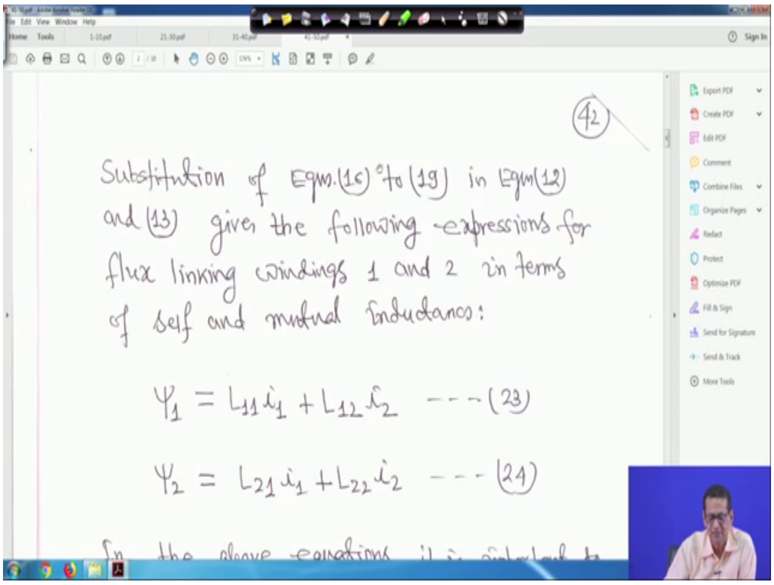

So, substituting substitution of equation 16 to 19 in equation 12 and 13 you give the following expression for flux linkage of winding 1 and 2 in terms of self and mutual inductance. So, if you substitution of equation 16 to 19; that means, your whatever you have in the previous page 16 to 19, right 16, 17, 18 and 19, right. So, in equation 12 and 13 just you do this, I am not going back that is the very simple thing just you do this. So, you will get the flux linkage psi 1 will be L 11 i 1 plus L 12 i 2, right that is equation 23 and similarly psi 2 will be L 21 i 1 plus L 22 i 2, this is equation 24.

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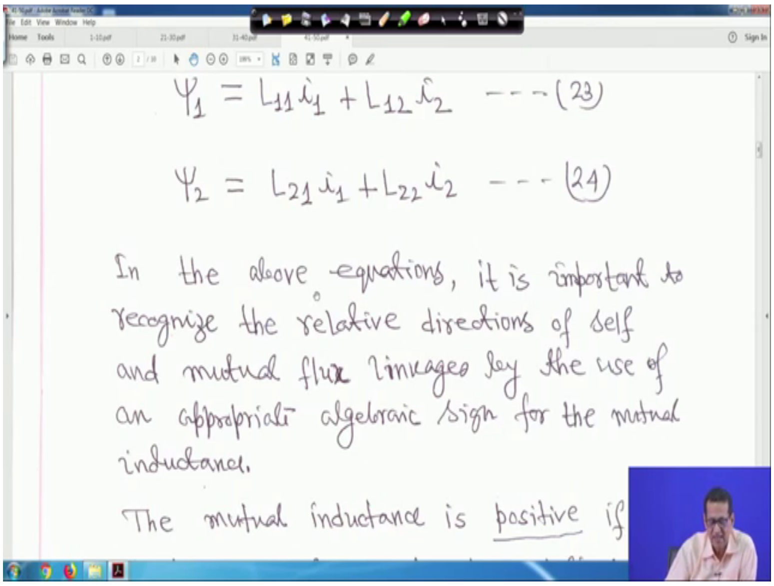

So, in the above equations it is important to recognize the relative direction of self and mutual flux linkages by the use of the appropriate algebraic sign for the mutual inductance, right.

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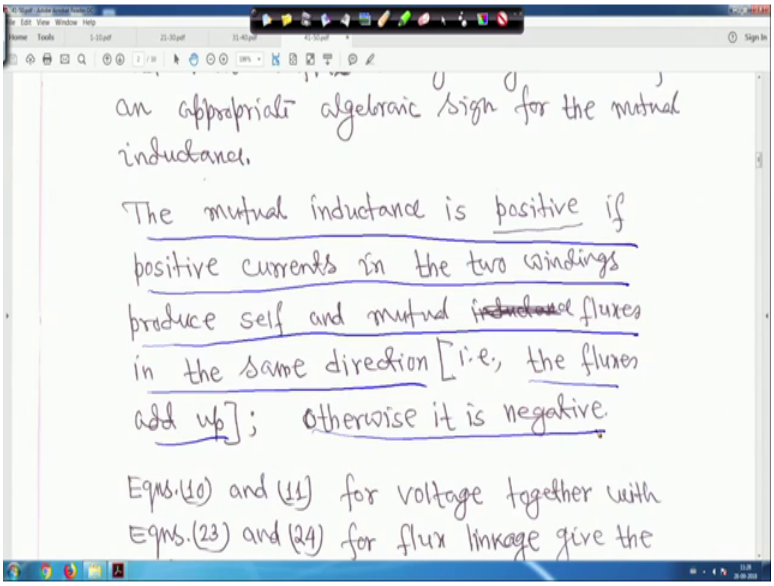

So, the mutual inductance is positive if positive currents in the two windings produce self and mutual fluxes in the same direction, right. So, that you have to this is from your this you have to keep it in your mind. The mutual inductance that is your I am just underlining; in the mutual inductance is positive if positive currents in the two windings produce self and mutual fluxes in the same direction, that is the fluxes add up, right.

So, there we have seen know phi m 1 plus phi m 2, right and just you apply the your right hand rule and change the direction of the current and have a look that is why I refer again and again the magnetic and coupled circuit. You read any book or that fundamentals of electrical engineering course. The magnetic circuit course just brush up your memories if you have if you if you want to have a look on this, right, that is the fluxes add up otherwise it is negative, right.

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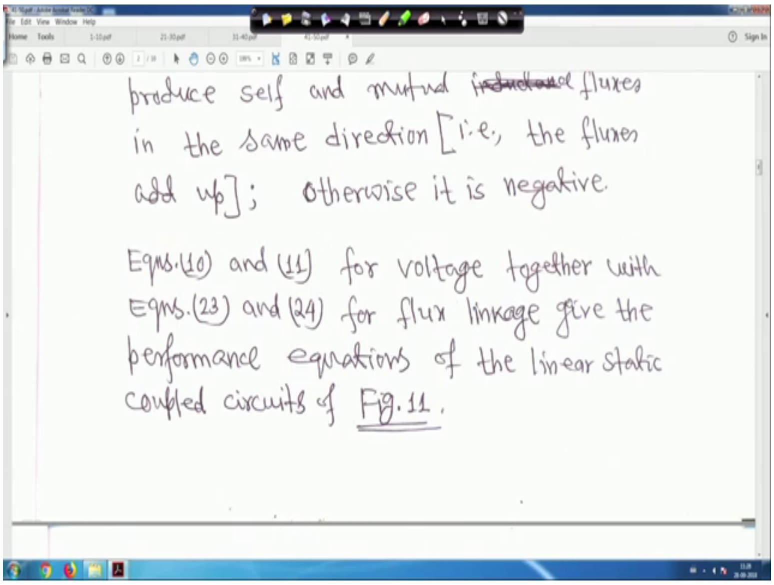

Therefore, equation 10 and 11 for voltage together with equation 23 and 24 for flux linkage give the performance equation of the linear static coupled circuit, right, that is the figure 11.

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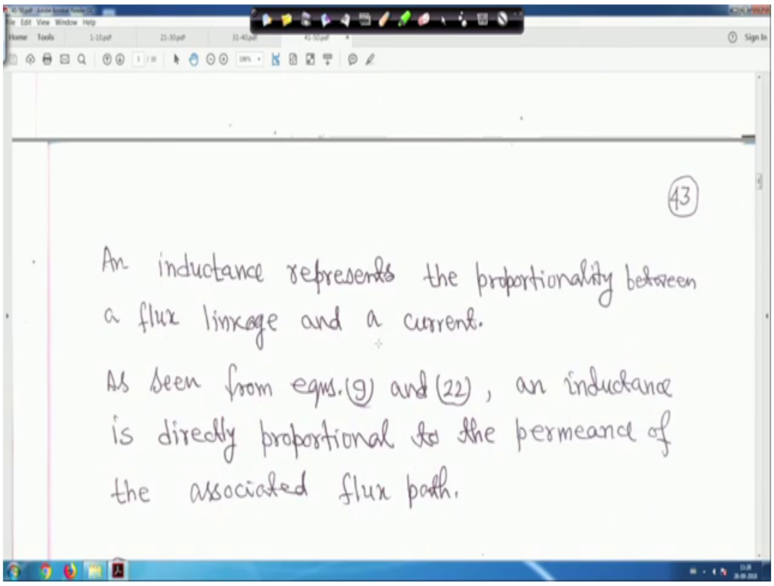

So, now an inductance actually represent the proportionality between a flux linkage and a current, right. As seen from equation – 9 and 22 and inductance is directly proportional to the performance of the associated flux path, right that we have seen.

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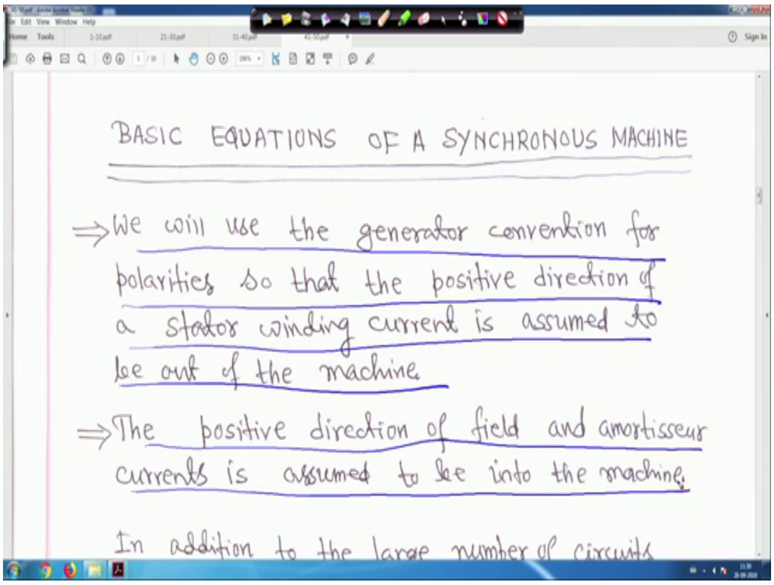

Now, once this is your once this is done, right, then we have to see the basic equations of a synchronous machine, right. So, we will use the generator convention for polarities, so that the positive direction of the stator winding current is assumed to be out of the machine. This when you will write the flux linkage equation these thing should be your in your mind that when we will use the generator convention for polarities, so that the positive direction of a stator winding current is assumed to be out of the machine, right. Therefore, the positive direction of the field and amortisseur currents is assumed to be into the machine, that is your figure – 9, the diagram right I am not going to the diagram, but when we will listen to the video just open the diagram, right.

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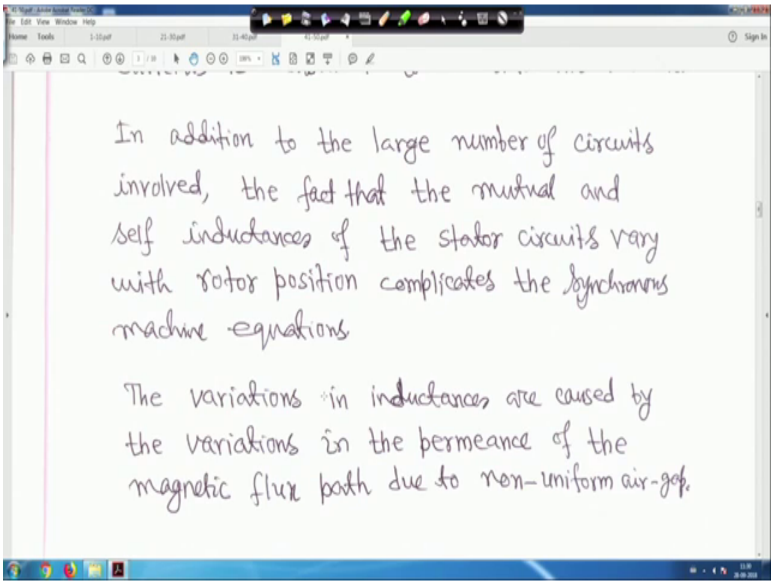

So, in addition to the large number of circuits involved the fact that the mutual and self inductances of the stator circuits vary with rotor position, it complicates the synchronous machine equations, later we will see that, right. So, the variations in inductances are caused by the variation in the permeance of the magnetic flux path due to non uniform air gap, right. So, there permeance also will be vary your what you call it will be a it is not a constant variable and later we will see that will be a double frequency term, right.

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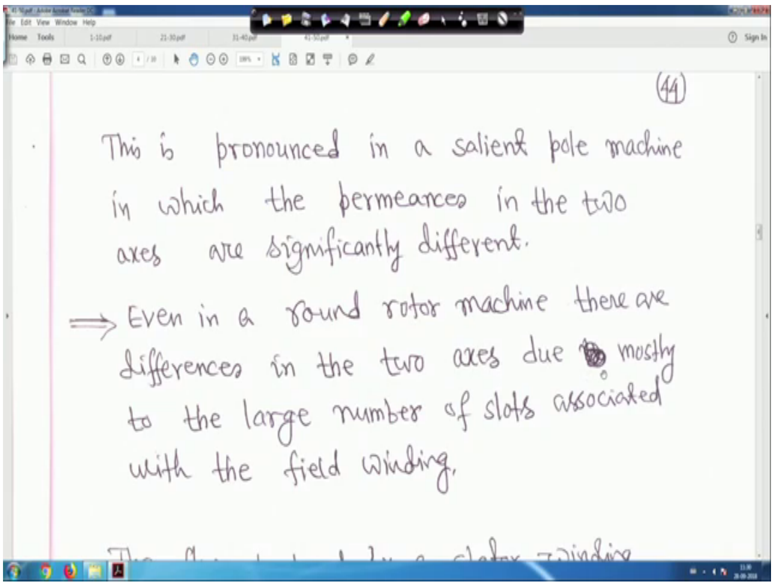

So, this is pronounced in a salient pole machine in which the permeances in the two axes are significantly different right particularly for salient pole machines. Even in a round rotor machines there are differences in the two axes due to mostly to the large number of slot associated with the field winding here also permeance may be different, right.

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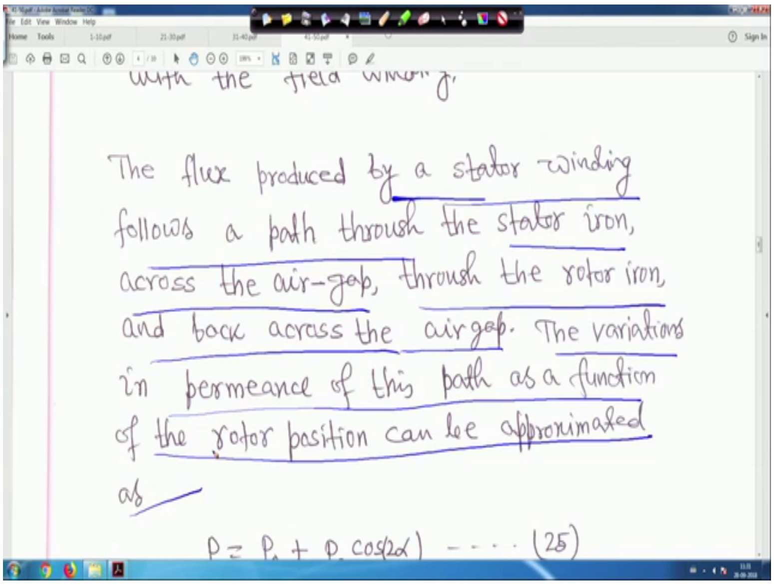

Therefore, the flux produced by a stator winding follows a path through the stator iron, across the air-gap, through the rotor iron and your back across the air-gap. So, the actually the flux produced, right by a stator winding follows through the stator iron across the air-gap and through the rotor iron and back across the air-gap, this you have studied for in synchronous machine, right. Therefore, the variations in permeance of this path as a function of the rotor position can be approximated as.

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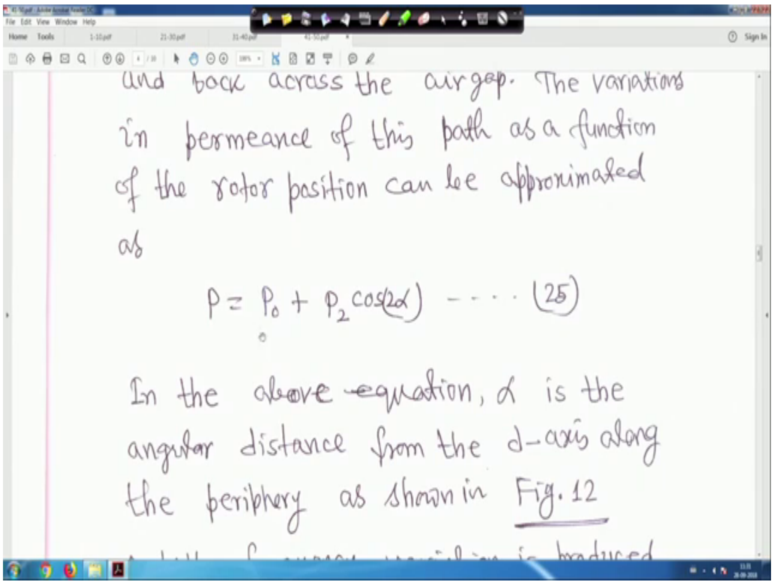

So, what we have what we will do is we will approximate this permeance thing that P is equal to P 0 plus P 2 cos 2 alpha. What is alpha? We will through diagram also we will see. So, this is equation – 25, right. In the above equation this equation alpha is the angular distance from the d-axis along the periphery as shown in figure – 12 before these thing this is figure – 12, right.

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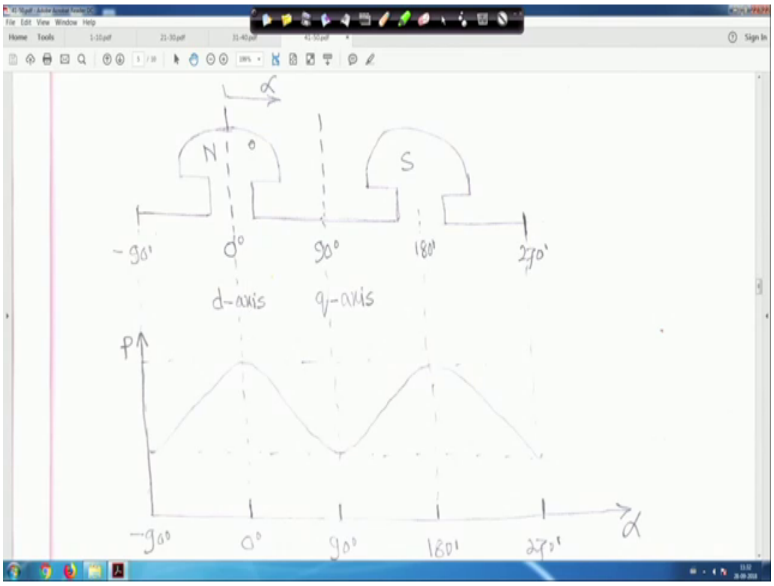

And, this is your d-axis this is from this one this alpha is measured, right and this is your alpha and this is minus 90, 0, 90 degree, 180 degree, 270, this is N-pole, this is S-pole, this is d-axis and this is q-axis, right and your and this side is the your plot of permeance, right.

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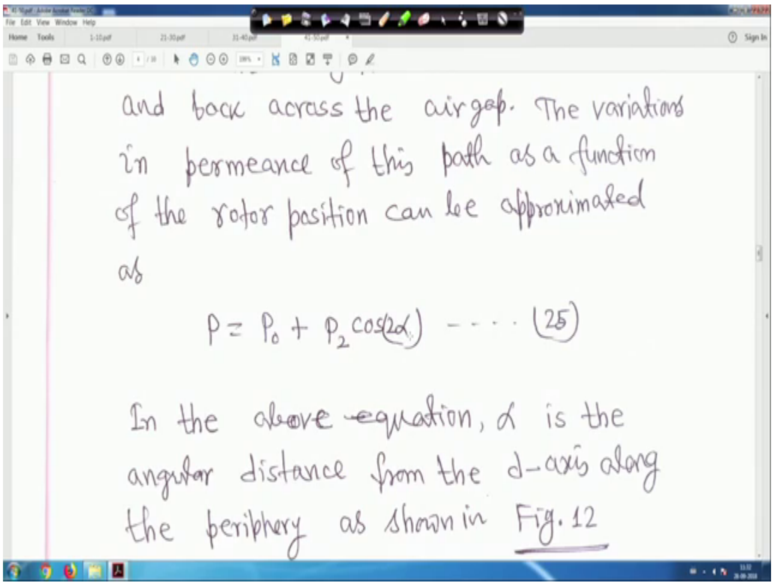

So, when alpha is equal to if you see this when your if you put alpha is equal to minus 19 you have a cos minus theta is equal to cos theta. So, whatever it will come that is your this is your P plot for you just put alpha is equal to minus 90 degree. Put alpha is equal to 0 degree, right if you put alpha is equal to 0 degree it will P 0 plus P 2, right so, that P, q is actually P 0 plus P 2, right and if you put alpha is equal to your what you call minus 90 degree it will be cos 180 degree, right. So, it will be P 0 your minus P 2. So, this is the minimum, this is the maximum, it is a doubled frequency curve sin your what you call sin curve, right. So, variation of permeance with rotor position so, this is your alpha.

So, that is why this you have taken P is equal to P 0 plus this is you have approximated as well. Derivation, other things we are not going for this course we have assumed that this is valid I mean it is valid actually, right.

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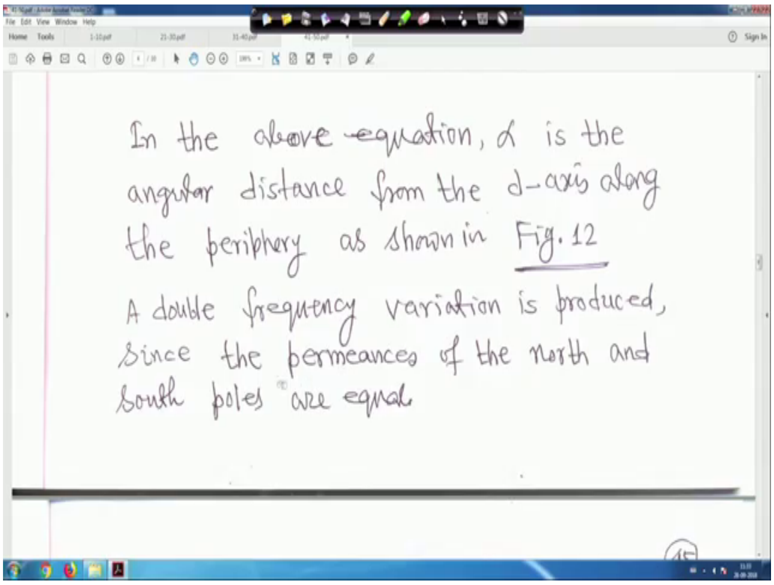

And, so, if you come to this your what you call these thing a double frequency variation just now, I produced since the permeance of the north poles south poles are equal, right.

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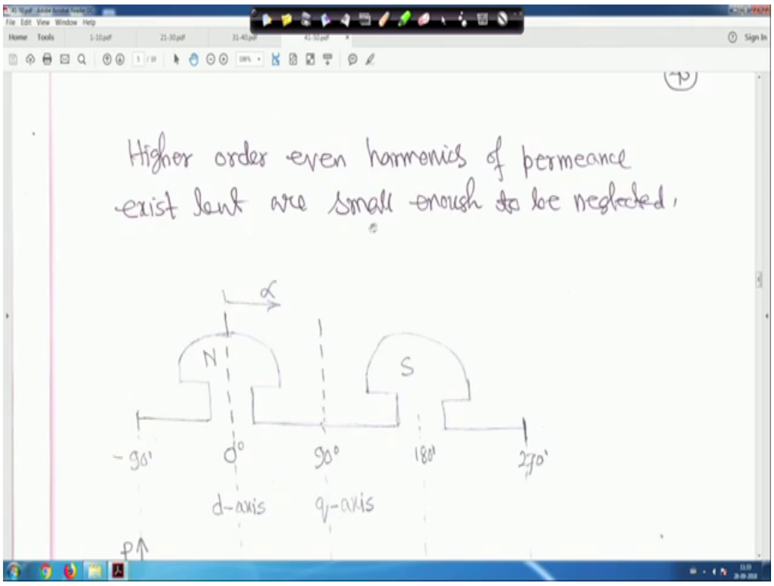

So, that is your higher order even harmonics of permeance exist, but are small enough to be neglected. So, higher order harmonics are not considered, right. Even higher order even harmonics right, not considered.

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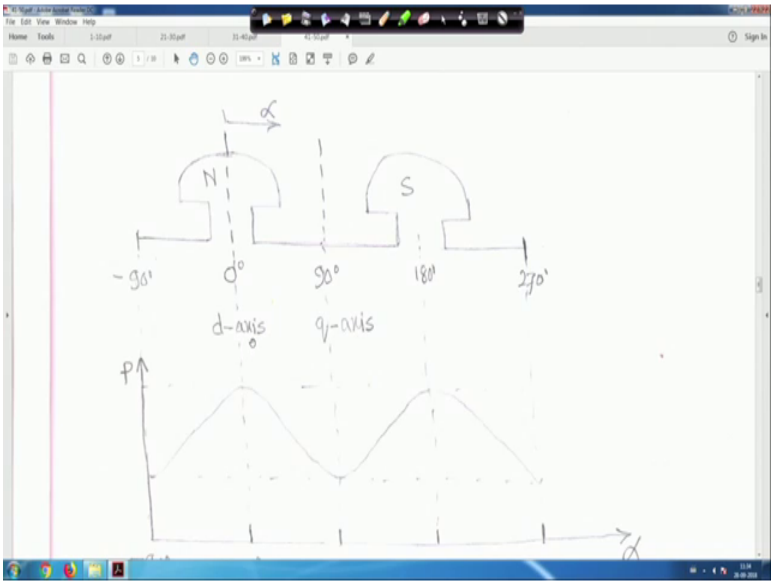

So, this is your figure – 12, right. This is slightly this is this figure is I hope it is readable right just after 3 – 4 hours lecture, you will find everything is ok, one or two figures are like that because of scanned copy from the photocopy, right.

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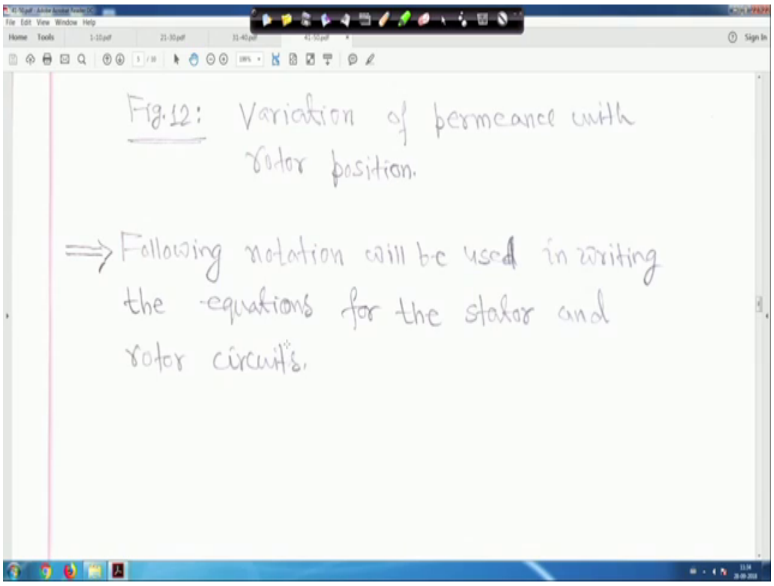

And, following notations will be used in writing the equations for the stator and rotor circuit. So, notation means these are the your nomenclature.

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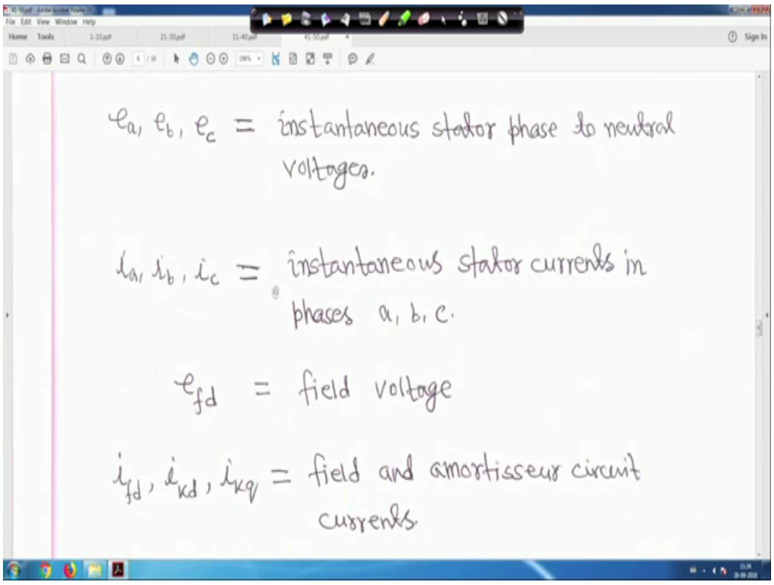

So, again and again I will not come, but I will tell from these thing that e a, e b, e c is equal to instantaneous stator phase to neutral voltages, right. I a, i b, i c is equal to instantaneous stator currents in phases a, b, c. e fd is equal to field voltage that is DC. i fd, i kd, i kq field and amortisseur circuit currents, right.

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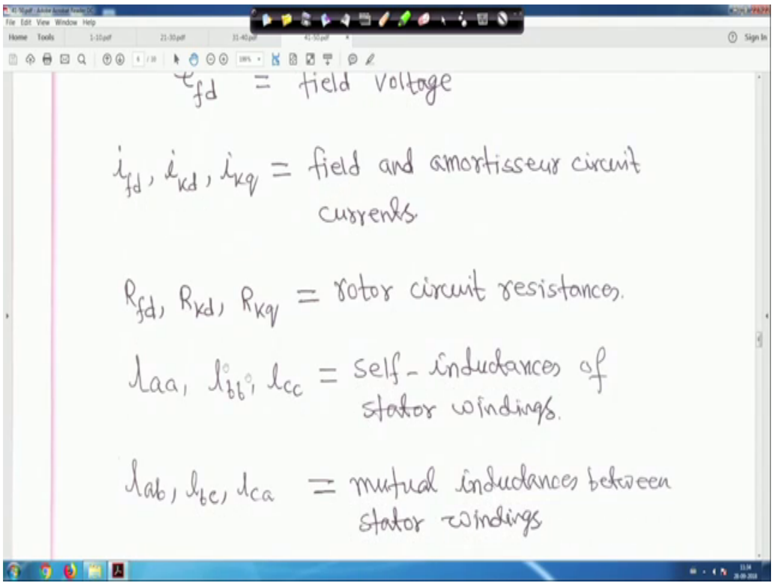

Then, R fd capital R fd, capital R Kd, capital R Kq rotor circuit resistances; this is field resistance, this is your amortisseur winding on d-axis and amortisseur winding on q-axis the resistances are. Then small l aa, small l bb, small l cc is suffix it is self inductances of stator windings, right.

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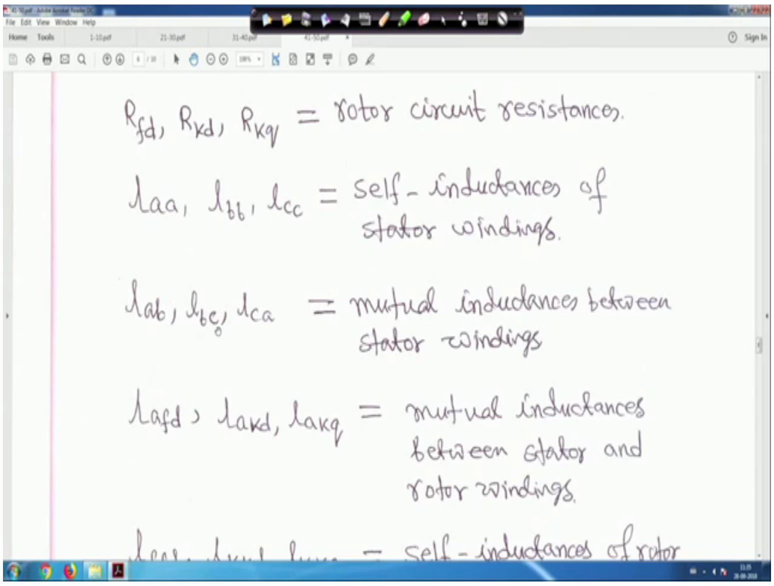

Then small l ab small l bc small l ca is equal to mutual inductances between stator winding, right, then l afd small l afd, small l akd, small l akq is equal to mutual inductances between stator and rotor winding, right.

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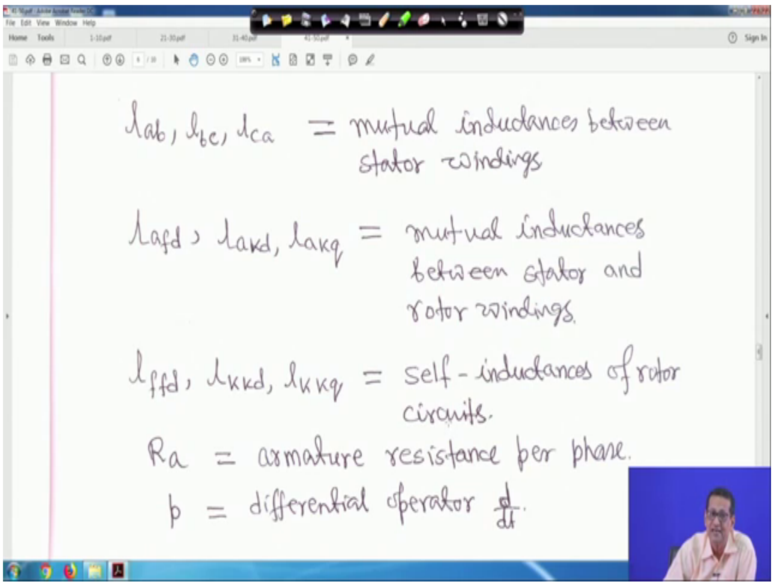

Then, l ffd, l kkd, l kkq that is yourself inductances of rotor circuit, right and capital R a is equal to armature resistance per phase and p is differential operator that is d by dt, right because instead of d by dt we will use your p and later you will see many interesting your things on synchronous machine. So, these are all the nomenclature these are all the nomenclature before moving further, right.

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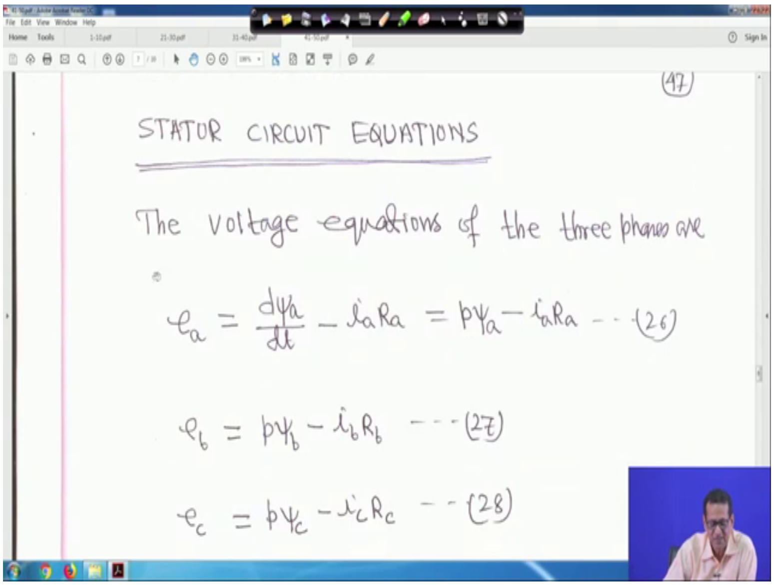

So, now, stator circuit equations. Now, the voltage equations of the three phases are if you go back to whenever you read these thing I am not going back you please go to figure – 9, right you will and just see this how we are writing this just see this. If you look at the circuit of figure – 9, everything is coming from figure – 9, right. So, I am not going back, right. So, then little bit time we will be save just when you will my suggestion to you when you will read these thing that figure – 9 you redraw, right. For draw the whole circuit or if you have a download and you can have a printout also no problem right and just see this once that how you can write looking at the flux linkage equation and the direction, right.

So, it is basically it will be e a plus i a R a is equal to d phi a upon dt look at the direction of the flux linkage whatever is given and the and the e a, e b, e c, right. So, the polarity; so, e a is equal to then you can write d d psi a upon dt minus i a R a and d by dt is equal to p, right that is your i 2 mention you the differential operator we will take d by dt therefore, this equation you can write p psi a minus i a R a this is equation – 26.

Similarly, e b is equal to you can write p psi b minus i b R b, it is 27 p is nothing where differential operator d by dt, right and e c is equal to p psi c minus i c R c for phase c, this is equation 28.

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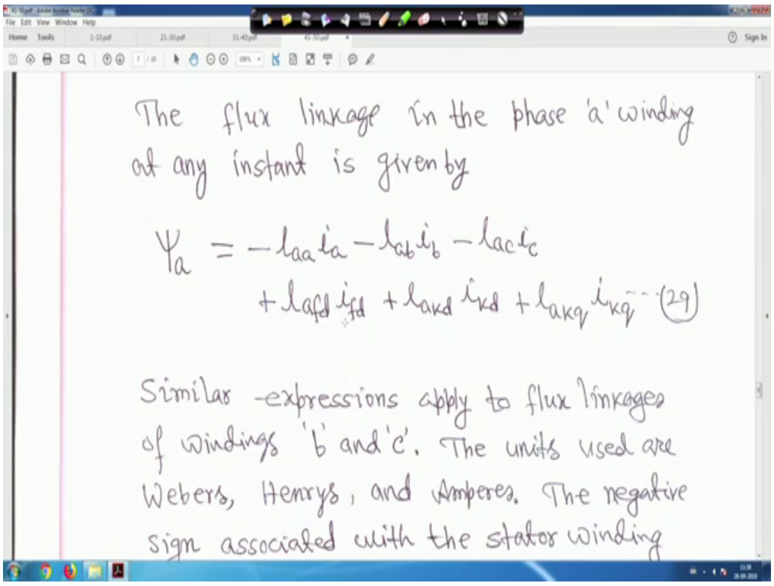

Therefore, the flux linkage in the phase a winding at any instant is given by like this I told you that look at the direction of the flux and I told you once you look at the figure – 9 and the convention we have taken when current leaving the terminal a, b, c we have taken positive direction and for the field winding and for the damper windings on the d-axis or amortisseur winding, on the d-axis or q-axis. When it is entering it we have taken the positive direction and when the current actually leaving the terminal of the stator side that is i a, i b, i c we have taken positive convention and look at the flux linkage in your figure – 9, right just imagine that figure – 9.

So, psi a will be it will be you can write it will be minus la a i a right then minus the mutual 1 will come l ab i b and minus l ac i c, right. Look at the direction of flux linkage and direction of the current the way you have taken your what you call the current leaving the terminal is the positive convention for generator, right, only this part little bit very easy actually very easy actually to write those equations, right. Nothing to be your what you call confused step forward you can write and other is and when you write that all the mutual thing, right that is plus direction because current entering into this field winding as well as current your what you call in the positive direction you have taken.

Similarly, for the amortisseur winding on the d-axis and q-axis. So, you can write plus l afd all the nomenclature is given i fd plus l akd i kd plus l akq i kq this is equation – 29. Similarly, for phase b and phase c you can be written, but we will see later, right. So, similar expressions apply to flux linkage of windings b and c we will see later because we have to consider all, right. The units use are Webers, Henrys and Amperes, right. So, the negative sign associated with the stator winding currents is due to their assumed direction. I just told you, I just told you, right.

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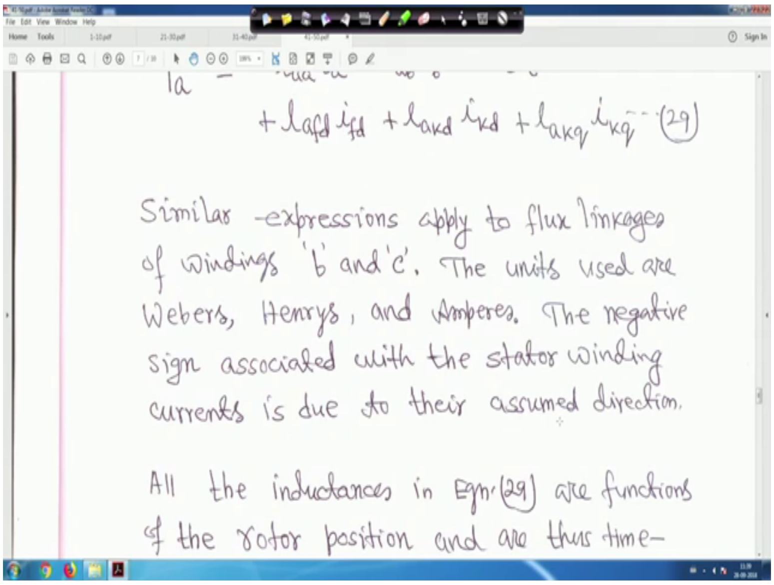

All the inductances is equation - 29 are functions of the rotor position and are thus time varying. So, all these inductances depends on the rotor actually function of the rotor position and their time varying; that means, this makes things more mathematically more complicated, right.

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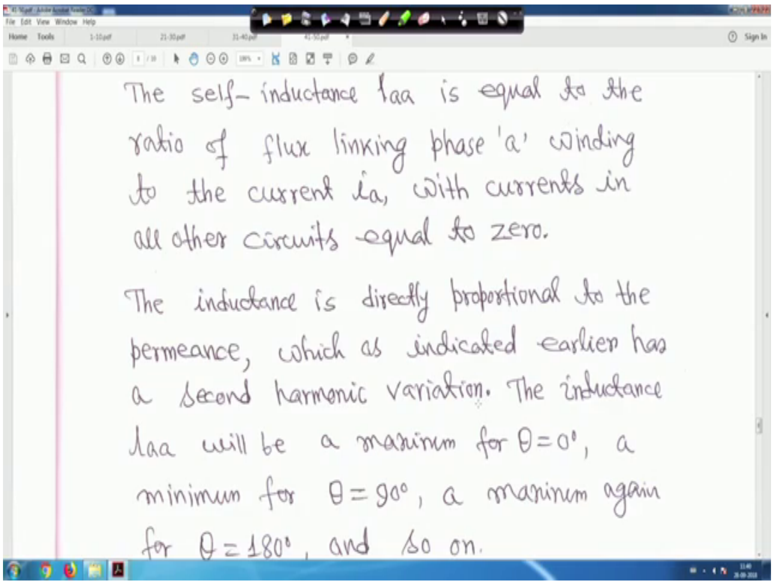

So, stator now all these things your what you call the stator self inductances. The self inductance l aa is equal to the ratio of the flux linking phase a winding to the currents l i a with currents in all other circuit equal to zero. Same that is when your when your reviewing the magnetic circuit philosophy is remain same right philosophy is remain same.

The inductance is directly proportional to the permeance that also we have; that also we have seen which is indicated earlier has a second harmonic variation, right. The inductance l aa will be maximum for theta is equal to 0 and a minimum for theta is equal to 90 degree a maximum again for theta is equal to 180 degree and so on, right.

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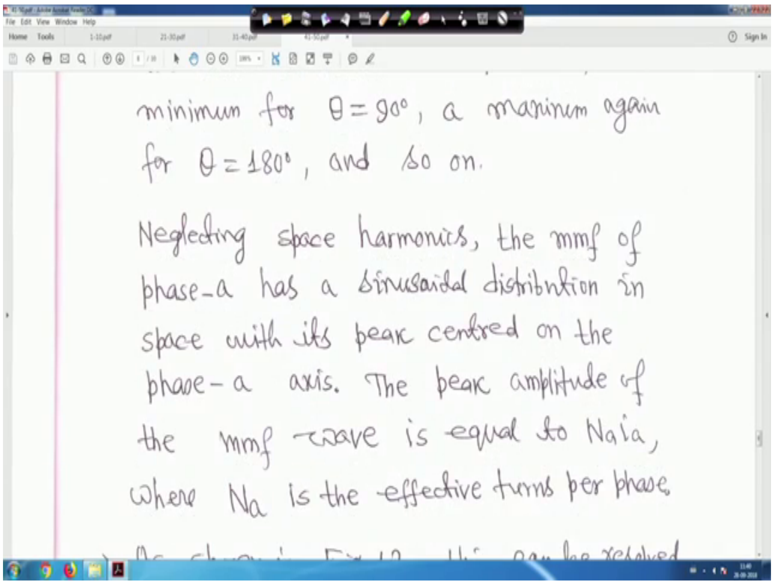

Therefore, neglecting if you neglect the space harmonics, right. The mmf of phase a has a sinusoidal distribution in space with its peak centred on the phase-a axis. Therefore, the peak amplitude of the mmf wave is equal to N a i a that is that your what you call ampere turns, right; where N a is the effective turns per phase so, as shown in figure – 13, right.

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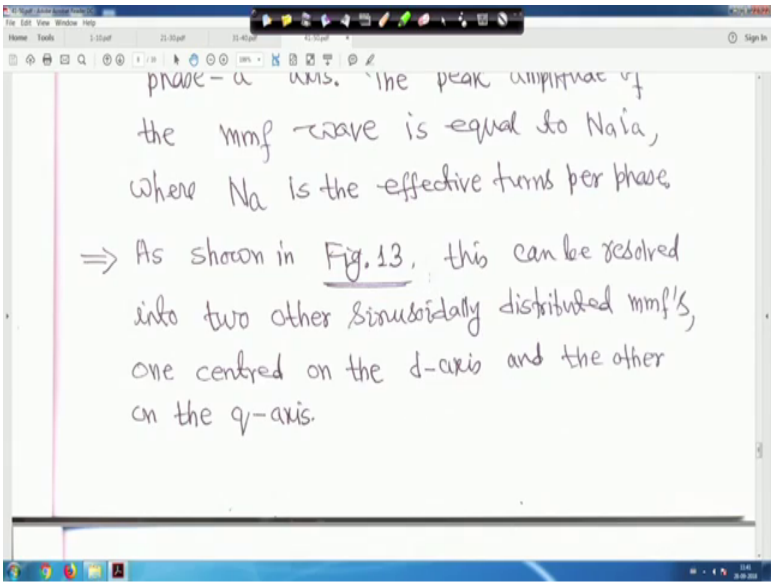

So, this is your as shown in figure – 13. This can be resolved into two other sinusoidally distributed mmf one centred on the d-axis and other on the q- axis.

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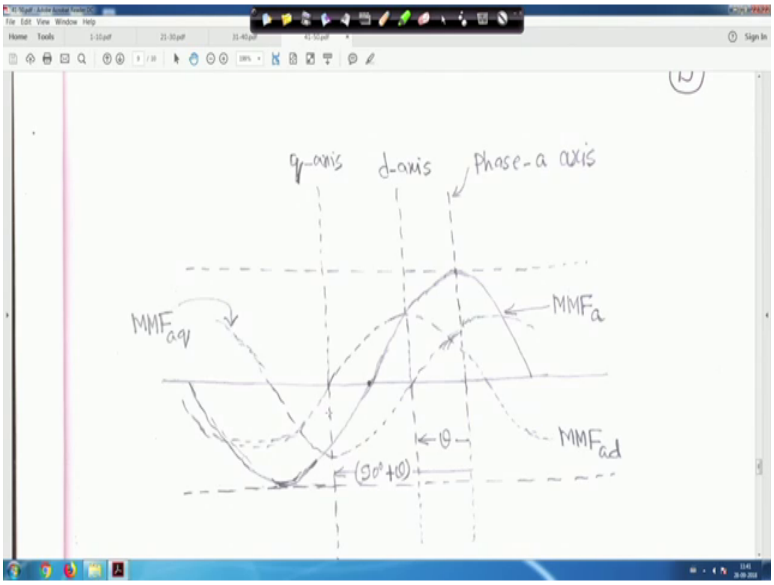

Now, these thing is that we know that your what you call that this is my mmf say N a i a, right and their one component is N a this is d-axis q-axis what coupled N a i a cos theta another is minus N a i a sin theta.

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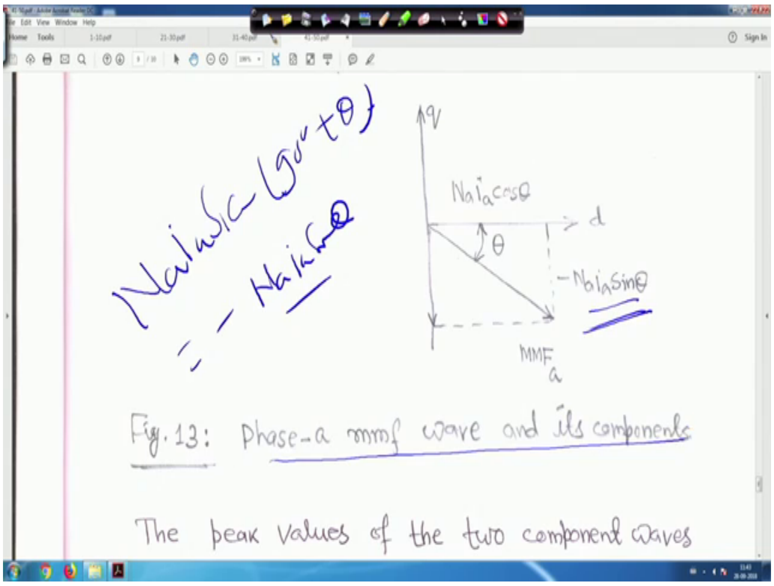

Now, if you look into this. This is my your what you call mmf for phase a. Suppose, this is the MMF plot, right, this is the MMF plot and you know that from axis d-axis actually leaving the phase a by an angle theta, this. That is why this theta is marked and q-axis leaving this one that is total is 90 degree plus theta, right and this is my MMF wave.

Now, if you have if you just make it the two component. This is MMF your for phase along d-axis and this is another one that MMF that for phase a your what you call MMF that is your two break up we have taken this is MMF a one is along d axis that is MMF ad and this is along q axis MMF aq, right.

So, if you if you look into this that one is N a i a cos theta because d-axis is leading phase a by an angle theta and q-axis leading phase a by angle 90 degree plus theta. Earlier we have seen again we will go back to figure – 9, right. Again we will go back to figure – 9, everything is marked there. So, in this case when you write your N a i a it is it is you can basically what will become it will become N a it will become N a i a then it is sin your what you call that one is cos theta another is your what you call minus N a i a sin theta, right.

So, whenever because that is that is your cos 90 degree your what you call that your cos 90 degree plus theta. So, this side will become your minus N a i a this one will become minus N a i a sin theta. So, N a i a cos theta and another will be minus your N a N a i a cos 90 degree plus theta, right that will be your minus N a i a your sin theta, right.

So, these two component that is why it is minus N a i a sin theta. This is phase-a mmf wave for it is your what you call this is phase-a mmf wave and its components. So, two components your two components for these thing your one is your along d-axis, another is along q-axis. Actually these makes our analysis you will be you know little bit your simpler later we will see that, right.

With this thank you very much. We will back again.