**Power System Dynamics**
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**Lecture - 11**
**Modeling of Synchronous Machine (Contd….)**

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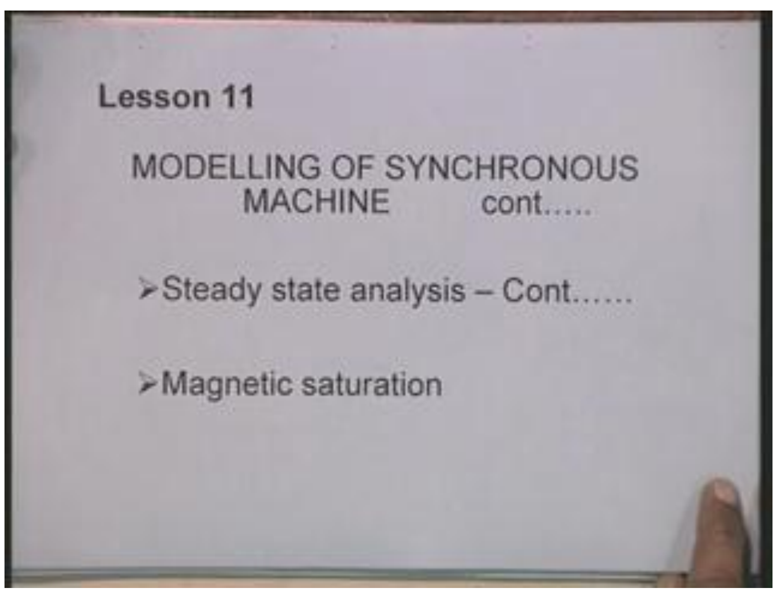

Friends, today we will continue our discussion on modeling of synchronous machine, okay. We will continue on the steady state analysis and then we will talk about the magnetic saturation. Now while discussing the steady state analysis we had discussed earlier that a voltage, a voltage behind voltage behind the impedance $R_a$ plus j times $X_q$ lies along the q axis and that gives us the location of q axis with respect to terminal voltage.

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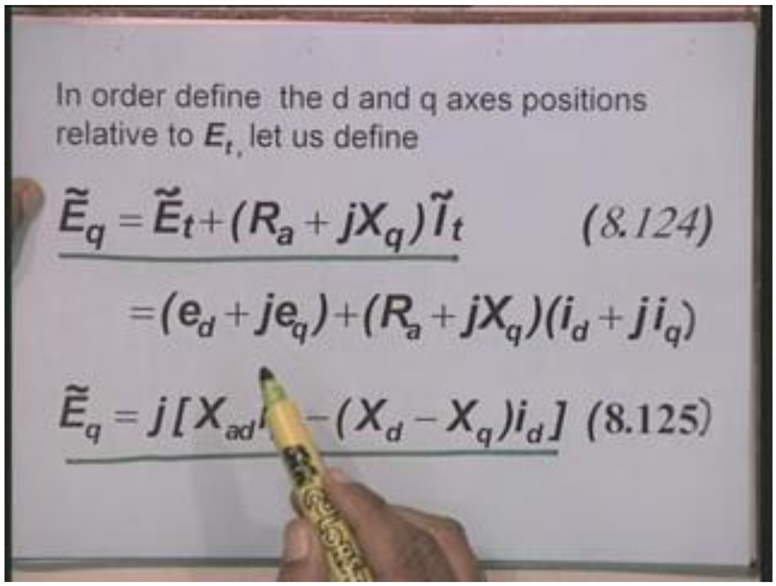


Once we establish the location of q axis we are in a position to obtain the d and q components of voltage and currents which are required, okay.

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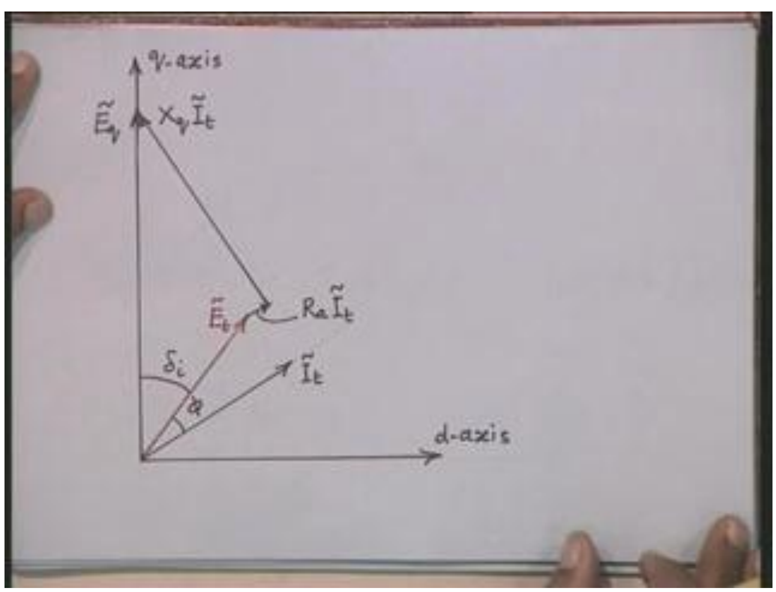

Now here this is the phasor diagram which shows the that voltage $E_q$ bar or $E_q$ is along the q axis what we have done is that this is the terminal voltage, this is the load current or terminal current, the phase difference between the terminal voltage and the current is phi to this we are adding this voltage drop $R_a$ $I_t$ and adding the voltage drop $X_q$ $I_t$ this gives you $E_q$.

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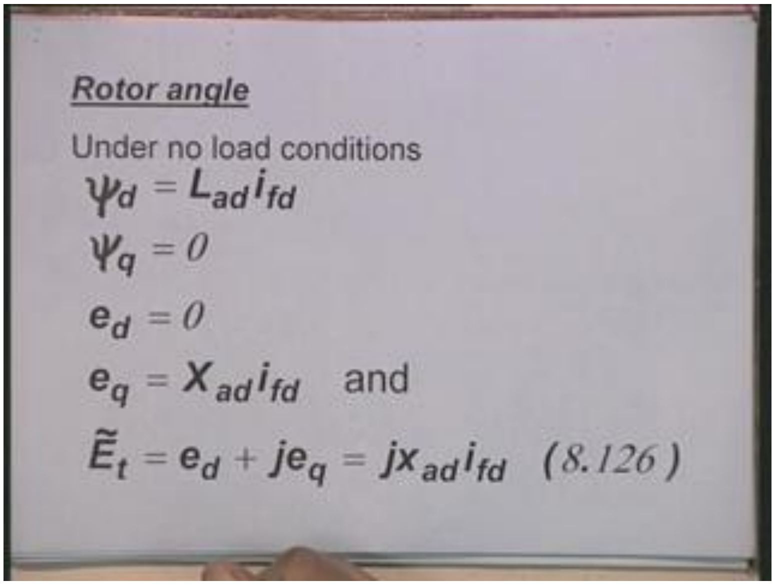


Now this voltage $E_q$ is along the q axis and the angle between $E_t$ terminal voltage and this $E_q$ that is the q axis right this is denoted by the angle delta i. Now we will establish a term which is a rotor angle or the power angle, although we have mentioned right now that the power angle is the angle between the q axis and the terminal voltage.

Now we will establish actually that in case there is no load on the machine that is machine is under no load condition right then the terminal voltage, terminal voltage $E_t$ is along the q axis and therefore when the machine is loaded right $E_t$ falls back with respect to the q axis right now to establish this we start with our original equations they are the stator voltage equations that is $e_d$ equal to minus omega r psi q minus $R_a$ $i_d$ $e_q$ equal to omega r psi d minus $R_a$ $i_q$ and the field voltage $e_{fd}$ is equal to $R_{fd}$ $i_{fd}$ while the flux linkages are minus $L_d$ $i_d$ plus $L_{ad}$ $i_{fd}$ psi q equal to minus $L_q$ $i_q$ and the flux linkages in the field winding is psi $f_d$ is equal to $L_{ffd}$ $i_{fd}$ minus $L_{ad}$ $i_d$.

In the amortisseur on the d axis psi 1d equal to minus $L_{f1d}$, now we are putting amortisseurs is identified as 1, K equal to 1 $i_{fd}$ minus $L_{ad}$ $i_d$ psi 1q equal to psi 2q. I have we have assumed here that they are 2 amortisseurs on the q axis minus $L_{aq}$ $i_q$. Now when you consider the system under no load condition right under no load condition there is the $i_d$ and $i_q$ will be 0. Okay now once $i_d$ and $i_q$ are 0, you can see here psi q will be 0. Okay and once psi q is 0 and id is 0 therefore what you see here is that $e_d$ become 0.

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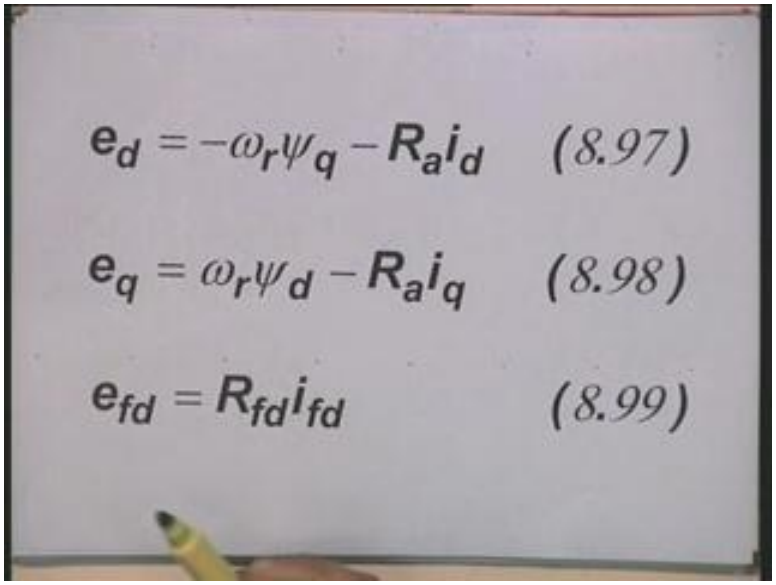


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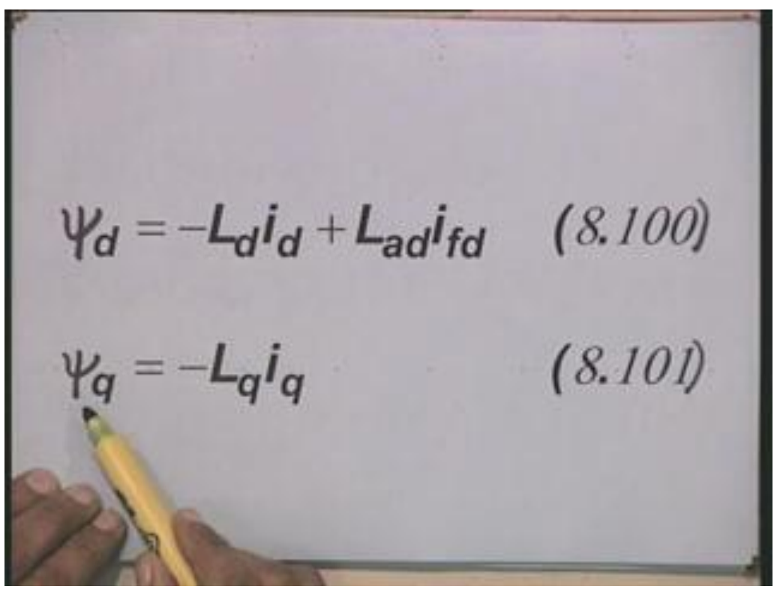


Okay now with this substitution we write here the under no load condition the d axis flux linkage is equal to $L_{ad}$ $i_{fd}$ that is in these equations you substitute $i_d$, $i_q$ and $e_d$ equal to 0 and psi q is also 0 therefore, we when we make the substitution we find here that psi d is equal to $L_{ad}$ $i_{fd}$ that is the direct axis flux linkage is directly proportional to field current this is very important relationship under no load conditions psi q is 0 $e_d$ is 0 $e_q$ is equal to Xad ifd that is the q axis component of the terminal voltage is directly proportional to the field current. Okay now we know the terminal voltage $E_t$ is equal to $e_d$ plus j times eq right that is what we established earlier. Now since ed is 0 $e_d$ is 0 and eq equal to $X_{ad}$ $i_{fd}$.

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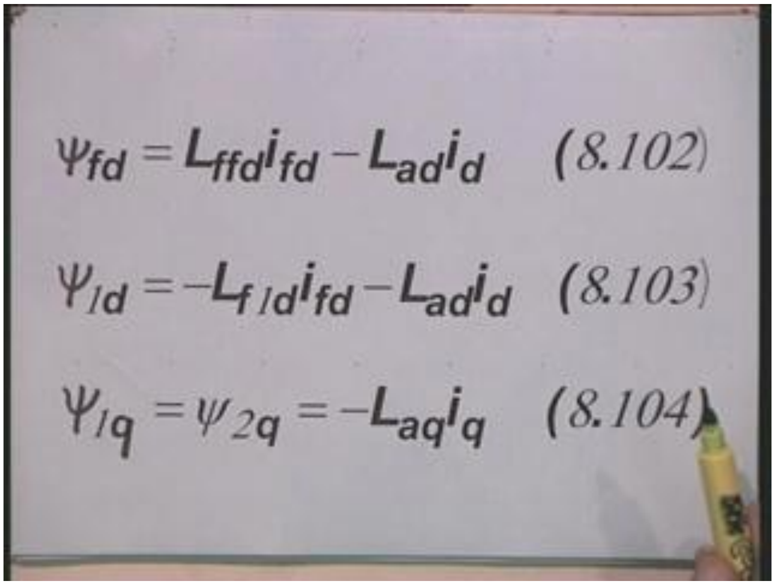


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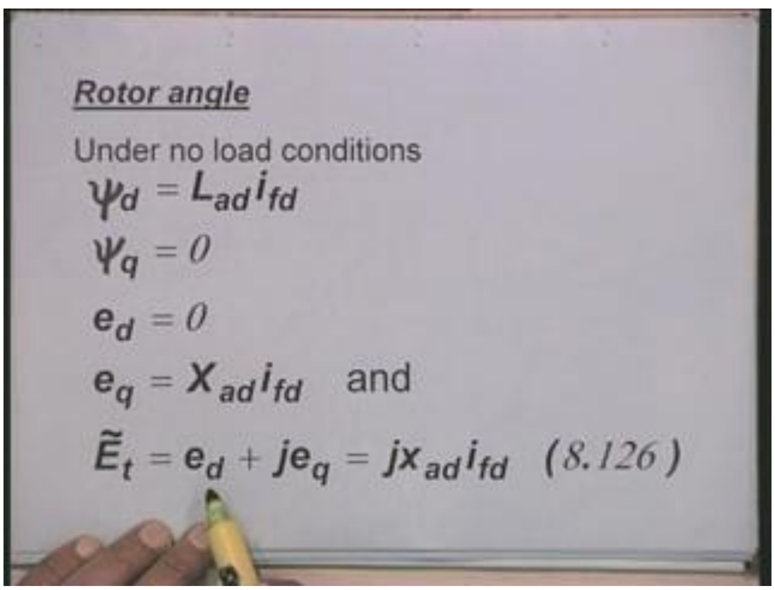


So that $E_t$ comes out to be equal to j times $X_{ad}$ $i_{fd}$ that is in the no load condition the terminal voltage is in quadrature with the direct axis that is j is here and is proportional to the field current $i_{fd}$ right.

Now this is all known to all of you because under no load condition the terminal voltage is directly proportional to the field current excitation and this voltage is called excitation voltage under no load condition the terminal voltage is the excitation voltage. Now we can establish a very simple equivalent circuit under steady state operating conditions for a round rotor synchronous generator that if you consider the round rotor synchronous generator then $X_d$ and $X_q$ are equal and this we will denote as $X_s$ synchronous reactance, $X_d$ equal to $X_q$ equal to $X_s$ for a round rotor right.

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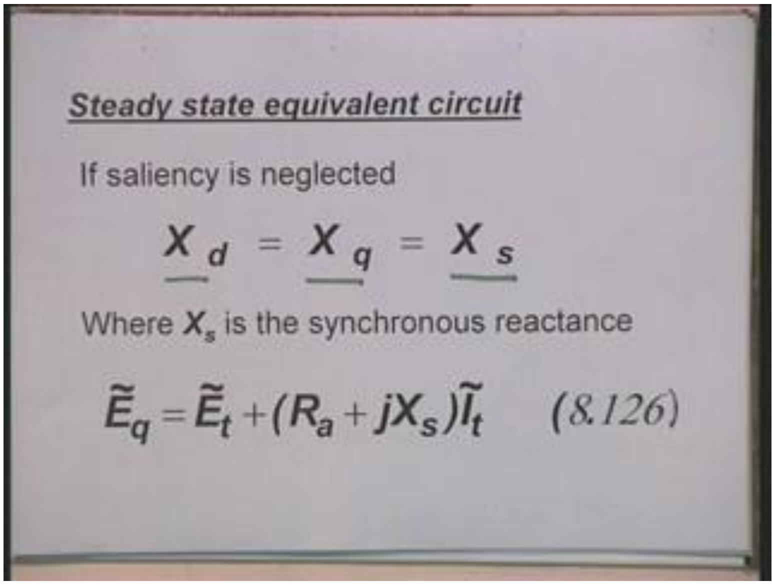


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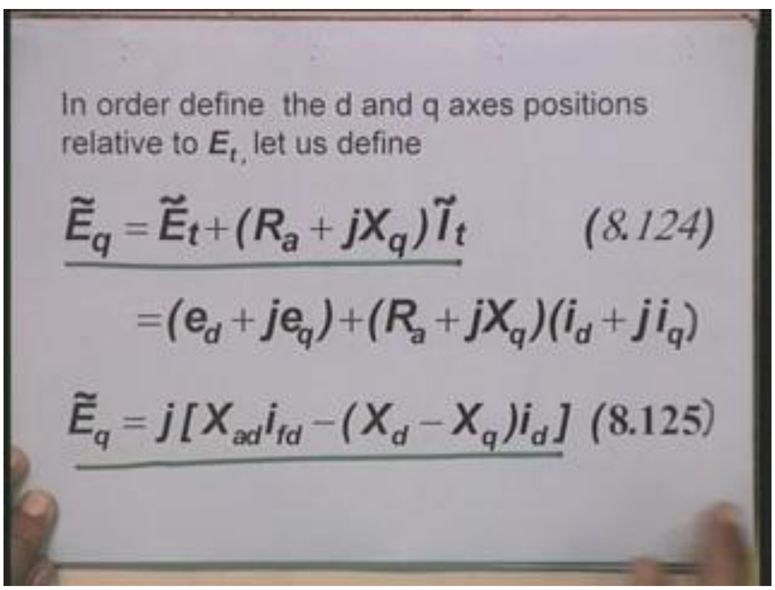


Now when you substitute the value of substitute the value of $X_d$ equal to $X_q$ equal to $X_s$ in the equation for $E_q$ because $E_q$ is now becomes $E_t$ plus $R_a$ plus j times $X_s$ $I_t$, we have seen earlier that $E_q$ is equal to j times $X_{ad}$ $i_{fd}$ minus $X_d$ minus $X_q$ $i_d$ now the moment the moment the $i_d$ is 0 id is 0 $E_q$ is equal to j times $X_{ad}$ $i_{fd}$ right. Now this is what we are trying to establish here that if you do not neglect the armature resistance $R_a$ will come right and $X_d$ $X_q$ neglecting the leakage reactance right $X_{ad}$ becomes $X_s$ right. Otherwise, $X_d$ is equal to $X_q$ equal to $X_s$ while $X_{ad}$ is the mutual reactance okay.

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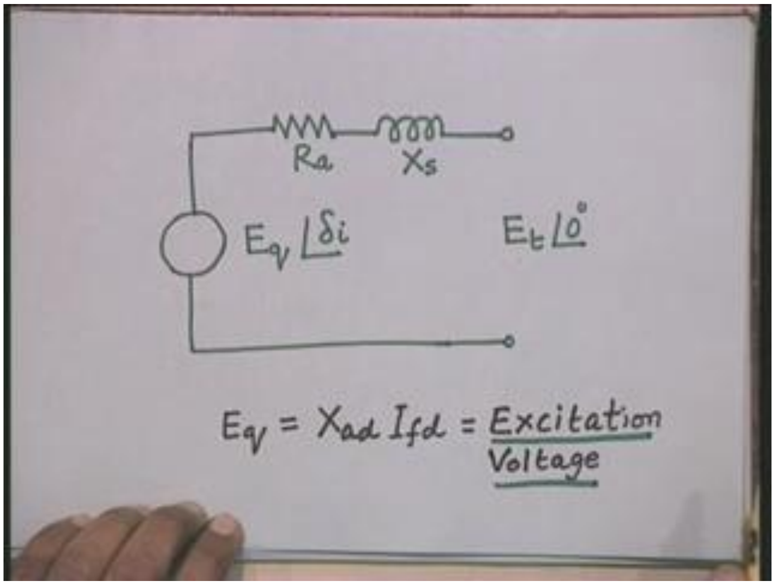


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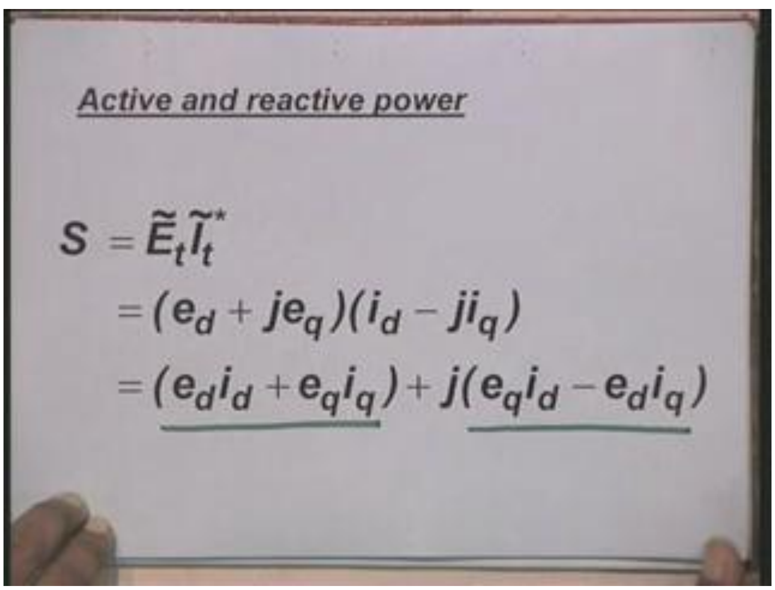


Therefore, we can write draw a simple a simple equivalent circuit of the synchronous generator where terminal voltage is denoted as $E_t$ angle 0 and the excitation voltage as $E_q$ angle delta i and we put an impedance $R_a$ plus $R_a$ and $X_s$ that is impedance is $R_a$ plus j times $X_s$ that is a very simple equivalent circuit which is obtained and where this we have establish that this $E_q$ the magnitude of the $E_q$ is equal to $X_{ad}$ $I_{fd}$ that is called excitation voltage, a very simple expression. Now we can derive the expression for the complex power in terms of d and q axis components okay, complex power S is equal to $E_t$ into $I_t$ star $I_t$ star that is I star stands for conjugate now when we substitute the expression for $E_t$ and $I_t$ right in this expression, we get S equal to $e_d$ $i_d$ plus j times $e_q$ $i_q$ plus j times $e_q$ $i_d$ minus $e_d$ $i_q$. Therefore, this term is identified as the real power and this term is the reactive power.

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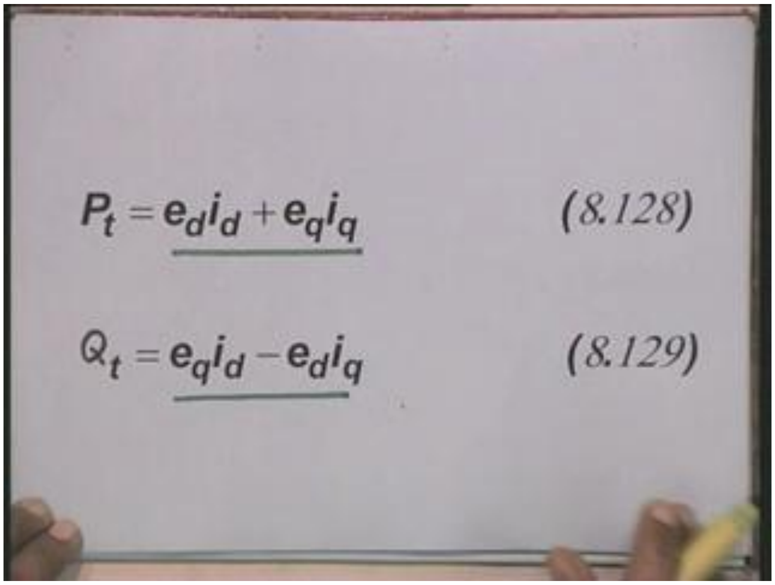


So that we can write down here that the real power at the terminal of the machine is $e_d$ $i_d$ plus $e_q$ $i_q$ that is you know the dx is component of voltage the dx is component of the current $q_s$ is component of the voltage $q_s$ is component of the current right you multiply the corresponding voltage and currents and add them you get $P_t$. Similarly, you obtain the expression for $Q_t$ as $e_q$ $i_d$ minus $e_d$ $i_q$. Okay now we will establish one very interesting expression for torque because we have seen that the expression for torque is psi d $i_q$ minus psi q $i_d$, this expression is the very general expression which we have established.

Now in these expressions we substitute the expression for psi d and psi q from the previous relationships established relationships and then simplifies this equation. You will find that this torque $T_e$ that is a air gap torque will come out to be equal to the terminal power plus $R_a$ into $I_t$ square or we can say that I square R loss what we what do we understand here.

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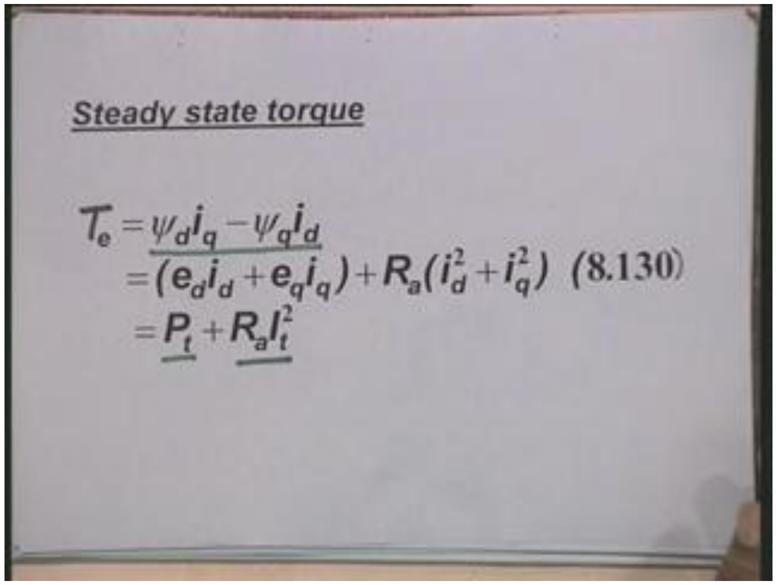


Now since in per unit quantities power and torque are equal when we use the per unit quantities then the torque is same as the power. Now this torque is the air gap torque or we can and this air gap torque can be obtained as the terminal power plus the armature resistance loss right and therefore whenever you performed stability steady analysis this is one computation which is required to be performed that first we find out what is the terminal power then to that terminal power we add the armature resistance loss okay and that gives us the electro magnetic torque and that is what we will be substituting in the expression for swing equations that is in the swing equation.

We have to substitute $T_e$ the $T_e$ is computed using these expressions and and under steady state conditions right the mechanical torque is equal to the electrical torque therefore mechanical torque is computed by this expression right while electrical torque will be will continue to be computed by this expression because under dynamic conditions this is the expression for electromagnetic torque under dynamic conditions for under steady state condition we can say that the steady state torque is equal to terminal power plus losses. This is a very important step in case you neglect the armature resistance then terminal power is same as the electromagnetic torque but today with the availability of computing facility right and the capability of the digital computers there is no need to neglect the armature resistance because armature resistance losses are substantial okay and they have bearing on the stability results.

Now, we come to the very important aspect of modeling of the system. So for, so for we have neglected the saturation in the magnetic circuit. This was neglected to simplify the mathematical model. However, however the magnetic saturation need to be accounted and if we neglect it then the errors in the results are sometimes substantial and therefore there is a necessity to understand how do we account for the saturation in the magnetic circuit. Now to understand how do we account for a saturation in the magnetic circuit, we will look into the open and short circuit characteristic of the synchronous generator all of you are aware of open circuit characteristic of the synchronous generator short circuit characteristic of the synchronous generator and we will see that the open circuit characteristic is very useful in determining the saturation characteristic of the machine okay.

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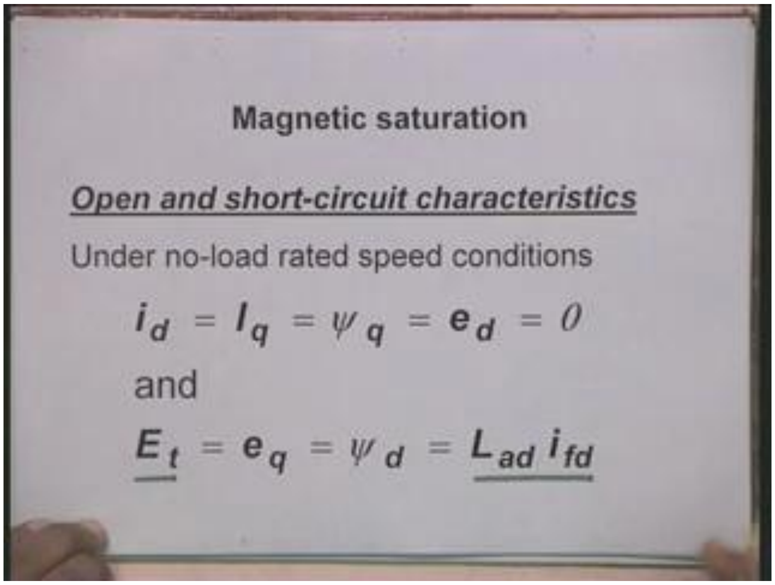


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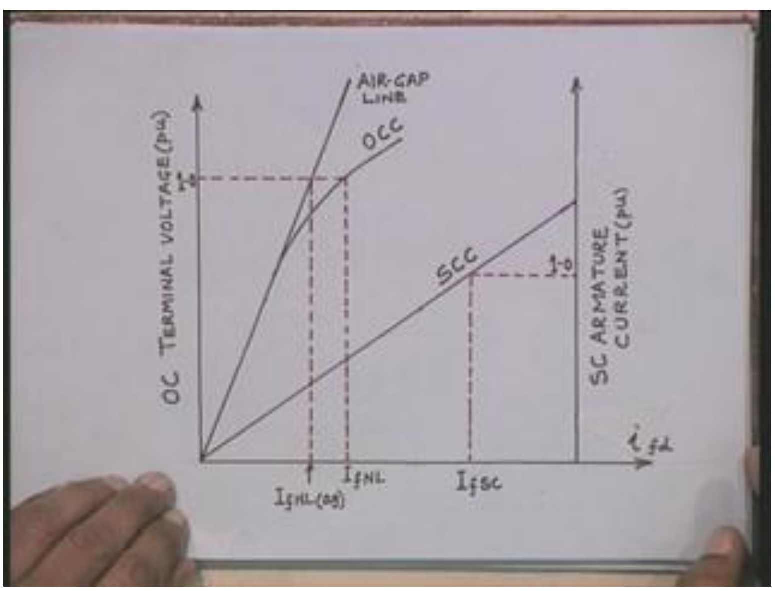


Now we write under no load conditions we established earlier also $i_d$ $i_q$ psi q and $e_d$ these four terms where 0 when the machine is not loaded right the $i_d$ and $i_q$ components of the current are 0 psi q is 0 and $e_d$ is also 0 this is what we have established in our previous discussion. Then the terminal voltage $E_t$ came out to be equal to $L_{ad}$ $i_{fd}$ that is this terminal voltage is directly proportional to the field current. Okay and this terminal voltage is also called excitation voltage under no load conditions under no load condition this is also the excitation voltage now let us look at the at this characteristic.

On this axis I am I have shown the field current $i_{fd}$ and on this axis we are showing the open circuit terminal voltage in per unit. Okay when you perform the open circuit characteristic or perform the experiment to obtain the open circuit characteristic what we do is we run the machine at rated speed okay and note down the terminal voltage for different values of the field current.

Now here while plotting this characteristic I have neglected the residual flux, okay otherwise there is some residual flux and you will get that even if the field current is 0 there will be some that is that has been neglected here. Now the the open circuit characteristic will look like this. Okay that is it remains straight line and then starts getting saturation, now if you draw a tangent to the open circuit characteristic in the initial portion right then we get a straight line, we can draw a straight line which is tangent to the initial portion of the OCC, we call this air gap line.

Now here here we will define two field currents that is if the terminal voltage is one per unit, the field current required when you consider the saturation is IfNL. In case we ignore the saturation then the field current required is IfNL (ag), ag stands for that or the air gap line considering the air gap line. Okay now if we plot short circuit characteristic that is on this axis I am putting short circuit armature current in per unit there is again the same field current. This short circuit characteristic comes out to be a straight line while you perform the short circuit characteristic the machine is run at rated speed and the terminals of the machine are put short shorted okay.

Now there is no saturation when we are performing short circuit characteristic that is you consider actually the short circuit current right for different values of the field current even beyond the rated current, you will find there is hardly any saturation. The basic reason for for the short circuit characteristic comes coming out to be straight line can be attributed that under short circuit condition right the armature current is having the demagnetizing affect okay and because for the demagnetizing affect the resultant magnetic field which is produced in the air gap or in the iron core is very low and therefore saturation does not take place and this is very important point.

Now here we can now define unsaturated reactance of the machine and then we define saturated reactance of the machine. Now to define this that is what we do here is that when the synchronous machine, when the synchronous machine terminals are shorted and let us say it carries one per unit current right at that time whatsoever the induced emf due to this field current is used in overcoming the drop in the short circuited path.

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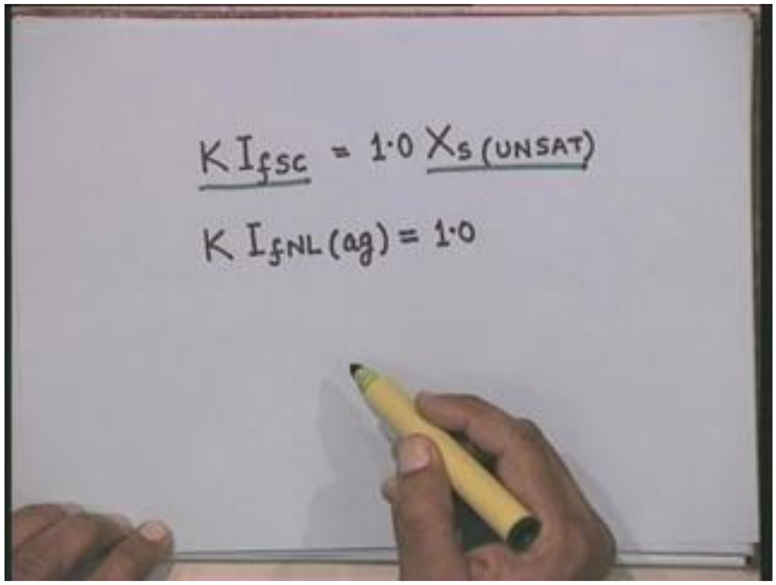


If we neglect the armature resistance armature resistance then we can say that the induced emf is a some constant times $I_{fsc}$ equal to 1 into $X_s$ unsaturated okay that is there under short circuit condition there is no saturation in the system right therefore the reactance which we talk about the unsaturated reactance and the voltage induced is some constant time in the field current okay, then if we see here the open circuit characteristic then one per unit voltage is produced when the current is equal to IfNL okay.

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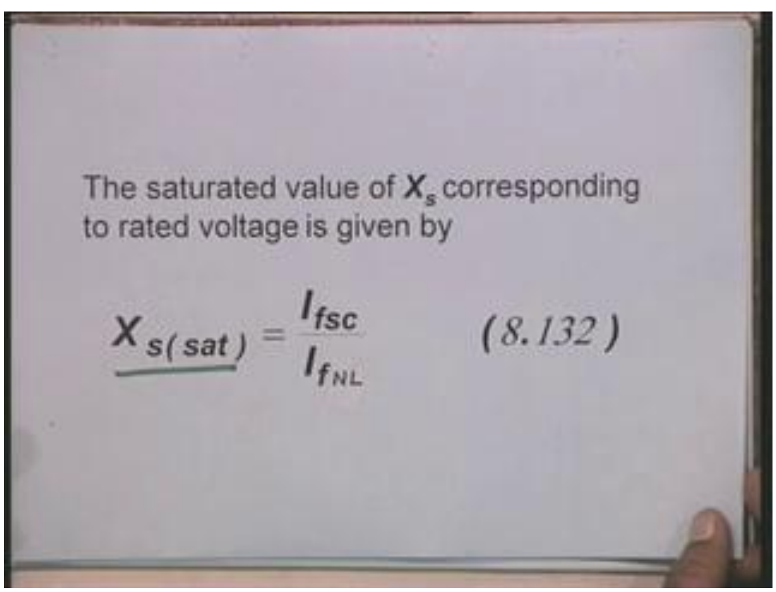


Now being the proportionality constant same that is K IfNL ag equal to one right therefore I using these 2 equations we can establish that the unsaturated value of synchronous reactance is equal to IfSC divided by IfNL (ag), this is a very important term that is what is the value of unsaturated synchronous reactance or unsaturated value of synchronous reactance that is $X_s$ unsaturated is obtained using the open circuit characteristic open circuit characteristic and short circuit characteristic that is on this short circuit characteristic we draw we find out what is the field current required to produced one per unit current in the armature under short circuit condition.

Similarly, we find out how much is the how much is the current which is required to produce one per unit voltage under on air gap line again this is I am putting a air gap line therefore this ratio of IfSC upon IfNL the ratio is of IfSC and IfNL (ag) gives you a saturated unsaturated value of synchronous reactance. Okay now when we look at the saturated value of the synchronous reactance.

Now we can find out the value of saturated synchronous reactance that to produce one per unit voltage under open circuit condition the field current required is IfNL, okay this IfNL ag was on air gap line while IfNL is on OCC right therefore, since open circuit characteristic there is some saturation taking place therefore the field current required is IfNL and following the same approach as we have done earlier now we can write down that saturated value of the synchronous reactance is IfSC divided by IfNL. Normally, we perform the open circuit and short circuit test to find out the synchronous reactance of the machine the synchronous reactance which we compute by doing open circuit and short circuit test are the will give you the saturated value of the synchronous reactance okay.

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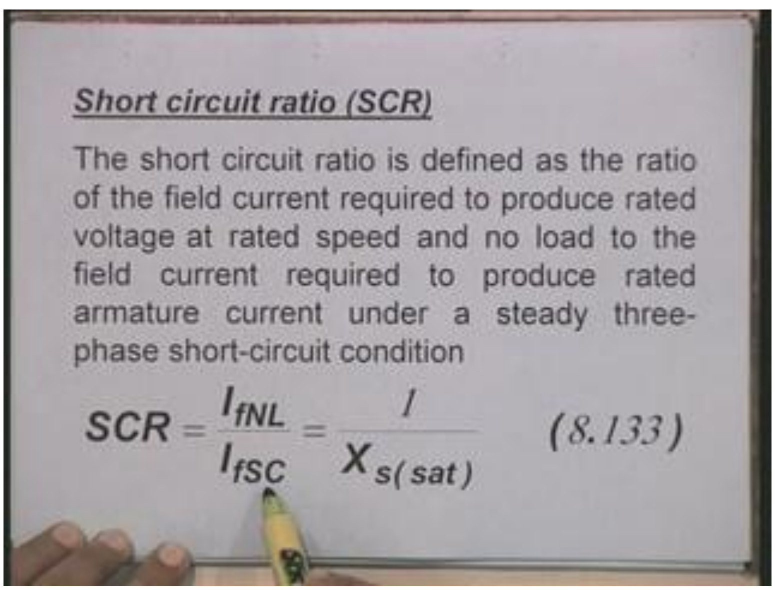


Now our task is that to relate to relate the unsaturated value of synchronous reactance to the saturated value of the synchronous reactance. Okay now to relate this before I relate this one more term which is very commonly used I am just introducing that is the short circuit ratio, the short circuit ratio is defined as IfNL divided by IfSC and it comes out to be the reciprocal of reciprocal of saturated synchronous reactance right the if the if the since short circuit ratio is low  that is what that synchronous reactance is high and in fact in industry we very very frequently used this term short circuit ratio and it also gives the information about the quality of the machine.

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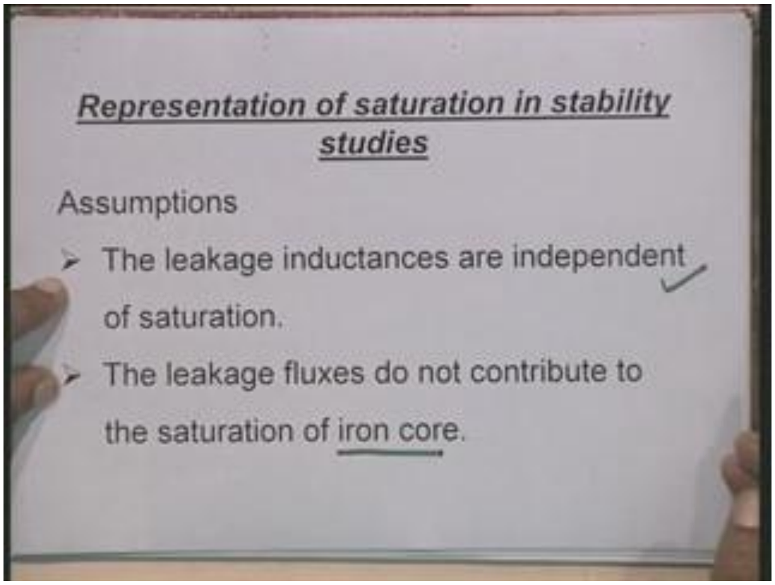


Now for representing the magnetic saturation for stability studies we make some realistic assumptions the assumptions made are that the leakage inductances are independent of saturation when we talked about a various inductances, we found mutual inductances as well as the leakage inductances right. For example, $L_d$ direct axis inductance $L_d$ is equal to $L_{ad}$ plus LL, LL is the leakage component okay and $L_{ad}$ is $L_a$ $e_d$ is due to the flux which which crosses air gap goes through the field winding and again return backs to the armature okay.

Now since this leakage flux is mostly takes path through the air right and it crosses the iron but but it is but it is it does not contribute toward the saturation of the iron right because the reluctance to the leakage flux path is mostly due to the air and therefore we make this realistic assumption that is the leakage inductances are independent of saturation, second is the leakage fluxes do not contribute to saturation of iron cores that is the same thing because leakage fluxes do pass through the iron core but we assume here that do not contribute to the saturation. This is an assumption the realistic assumption but not very very strictly they given but acceptable for stability studies.

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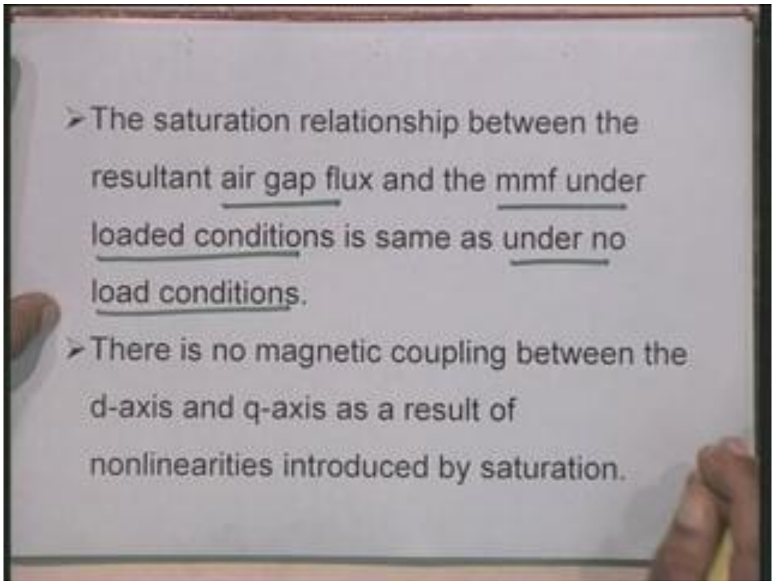


This is another very important is that saturation relationship between the resultant air gap flux and the mmf under loaded conditions the same as under no load conditions. Now this is very important assumption here that we will establish the saturation relationship using the open circuit characteristic right while while we assume here that that this relationship is also applicable under loaded conditions.

Okay that is the saturation relationship between the resultant air gap flux and mmf under loaded conditions is same as under no load conditions, okay that is why the open circuit characteristic is very useful and used for determining the saturation characteristic okay then another is the there is no magnetic coupling between d-axis and q-axis as a result of nonlinearities between the nonlinearities introduced by saturation because here here under linear conditions we assume that the d axis and q axis are magnetic circuit do not have any coupling okay and even if there is nonlinearities now in the magnetic circuit, we assume that that coupling does not exist even under nonlinearities this is what is the meaning of this. Now with this assumption we will now concentrate upon the these terms mutual inductance that is $L_{ad}$ and $L_{aq}$, this now this $L_{ad}$ is the mutual inductance considering saturation and we express $L_{ad}$ their mutual inductance with saturation is equal to $K_{sd}$ times mutual inductance unsaturated, u stands for unsaturated $L_{ad}$ u and this term $K_{ad}$ is called direct axis saturation coefficient $K_{sd}$.

Okay similarly for quadrature axis we can write down $L_{aq}$ is equal to $K_{sq}$ $L_{aq}$ $L_{aqu}$ that u again stands for unsaturated value of mutual inductance and this $K_{sd}$ and $K_{aq}$ are the saturation coefficients but our basic task is to obtain this coefficients. Okay now here again we look at the open circuit characteristic.

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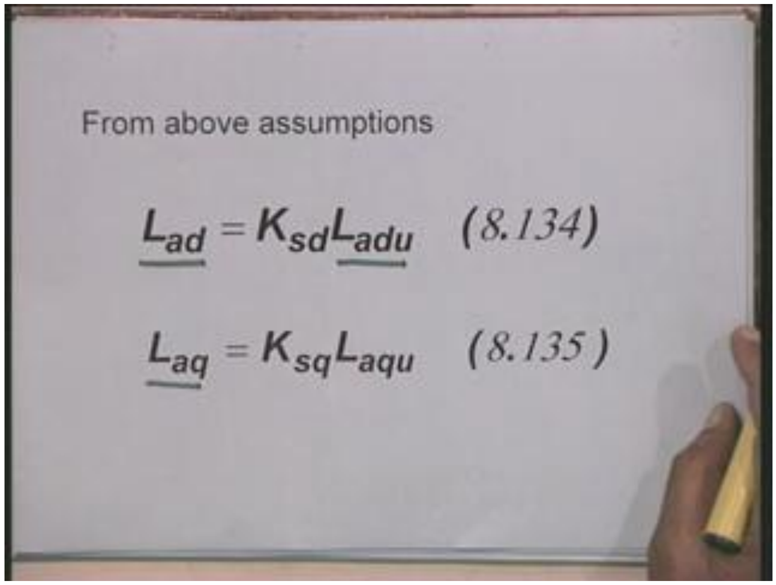


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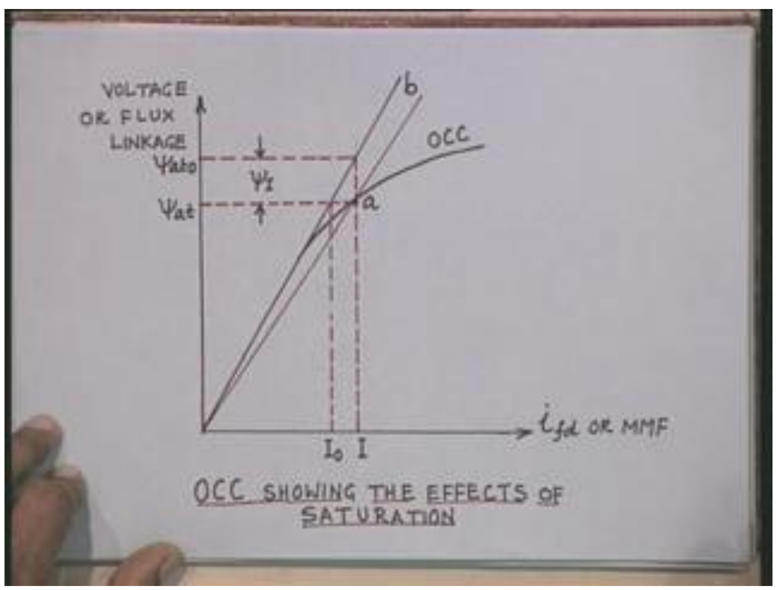


Now in this open circuit characteristic on this axis that is on y axis, we are putting the voltage open circuit voltage or flux linkages because we have established that the open circuit voltage is proportional to the flux linkage okay and on this axis you can put field current or the mmf. Okay, now we see two important things here that for a given field current I right, if I consider the saturated characteristic that is open circuit characteristic I find that the total air gap flux produced is psi at, okay if you neglect the saturation then the for the same field current the flux produced is psi ato is not because this is a line this is air gap line okay and we are operating at this point the field current is say I, okay for the same for this field current the flux produce is psi $a_t$ when you consider the OCC and the flux produced is equal to psi at O if I consider the air gap line right.

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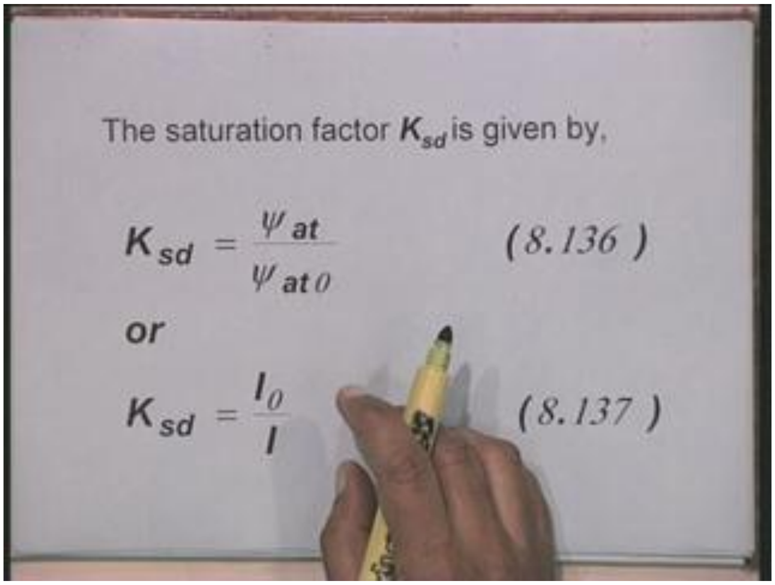


The saturation coefficient $K_{sd}$ is defined as psi at divided psi at O this this saturation coefficient on direct axis or direct axis saturation coefficient $K_{sd}$ is equal to psi at that is the flux linkage corresponding to current I on open circuit characteristic and psi at O is the flux linkage on air gap line for the same current and you can see here very carefully that this ratio is same as psi O, $I_o$ by I and it is going to be always less than 1.

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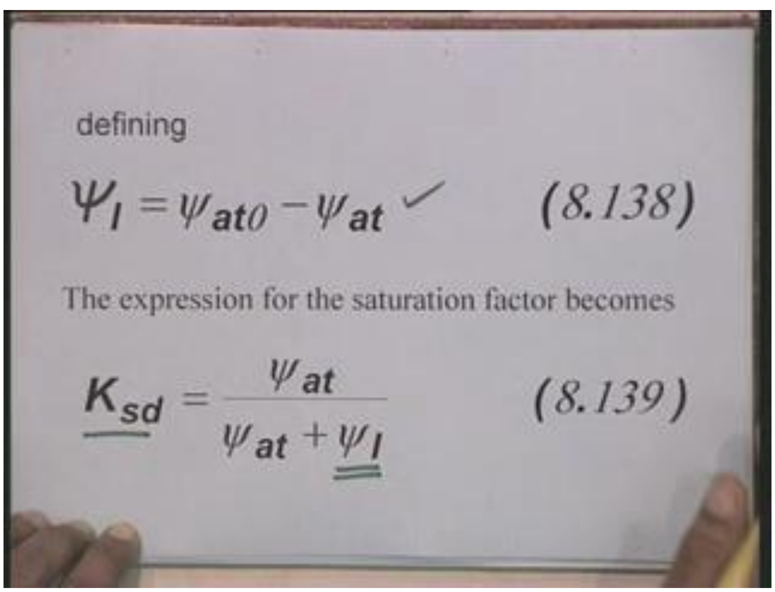

The saturated value of the inductance is going to be less than the unsaturated value of the inductance therefore we can see here actually that whether I take the ratio of psi atO to psi at or psi at to psi ato or I take ratio of $I_o$ to I they will give the same result okay. Now we define here difference that is psi atO minus psi at this difference flux linkage is designed by psi I and this psi I is very important to determine the saturation characteristic of the machine or we define psi I as psi atO minus psi at and $K_{sd}$ can now be written as psi at divided by psi at plus psi I that is i replace this psi at O by psi I plus psi at right therefore the major exercise will be that for a given value of psi at, we have to find out what is the value of this psi I.

So that we can compute the saturation coefficient $K_{sd}$ now here, now we have to basically model this OCC open circuit characteristics to be modeled that is we have to develop a model for the open circuit characteristic once we I know this this is the model of the open circuit characteristic I can always find out find out this psi I for a given value of psi at okay.

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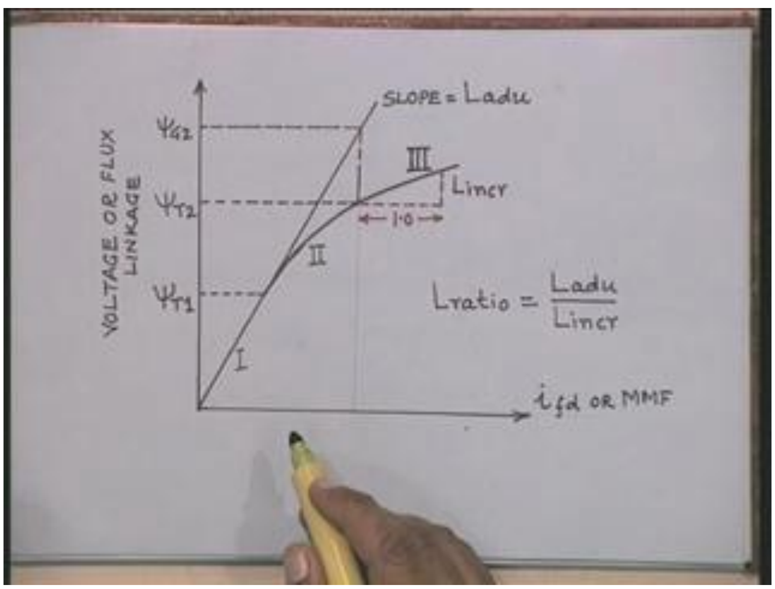


Now for modeling if you look at this characteristic the initially this characteristic is a straight line. Okay then we will find actually that from then this characteristic is practically following exponential shape and then once it gets fully saturated again it will it is going to become a straight line, if you carefully examine the open circuit characteristic right then you can divide this open circuit characteristic into 3 segments that is the first segment is one where the flux linkage is proportional to the field current that is in the unsaturated condition, second segment yes the the iron core starts getting saturated and the characteristic is a non-linear one.

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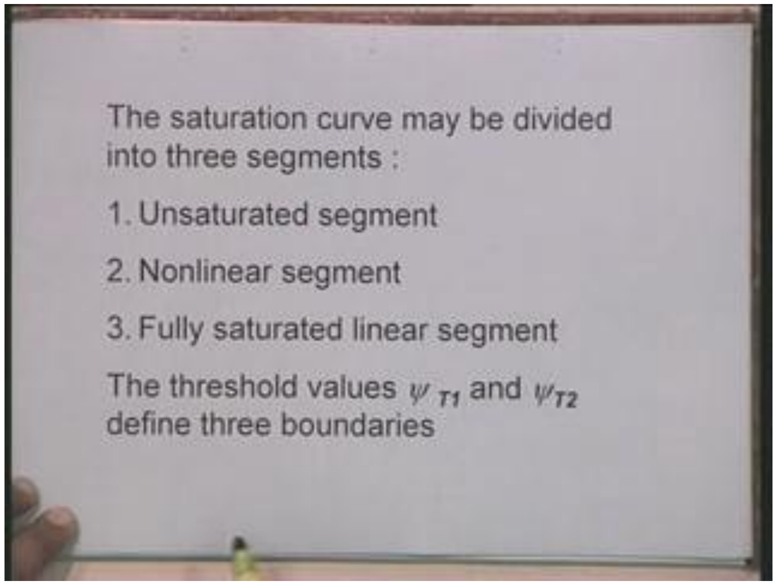


Okay, then in the third segment this characteristic becomes a straight line under saturated condition what happens is that when you increase the mmf the air gap flux is going to increase right but this increase is going to be linear relationship again therefore, for modeling the open circuit characteristic or magnetization characteristic of the machine we divide this characteristic into 3segments  and these 3 segments are unsaturated segment, non-linear segment and third is fully saturated linear segment.

This is the new thing which you have to very carefully understand okay now these 3 segments are shown here and psi T1 is the boundary value of flux linkage for the segment one psi T2 is the boundary value of the flux linkage for second segment psi T2 and beyond this it is the linear linear characteristic okay.

Therefore now what we do is that whenever you to try model right we this characteristic is available to us experimentally you obtain the characteristic whichever way you obtain it, this characteristic is known to you. Okay, now I can define here in this linear portion if I take one per unit value on the on the x axis that is I take this as a x axis and I call this vertical height as L i n e r incr incremental L incremental right then I can write down the slope equal to the slope of this characteristic can be written as iLncr that is this is the straight line characteristic with slope you have to obtain. Okay our the these 3 segments can be model  very easily.

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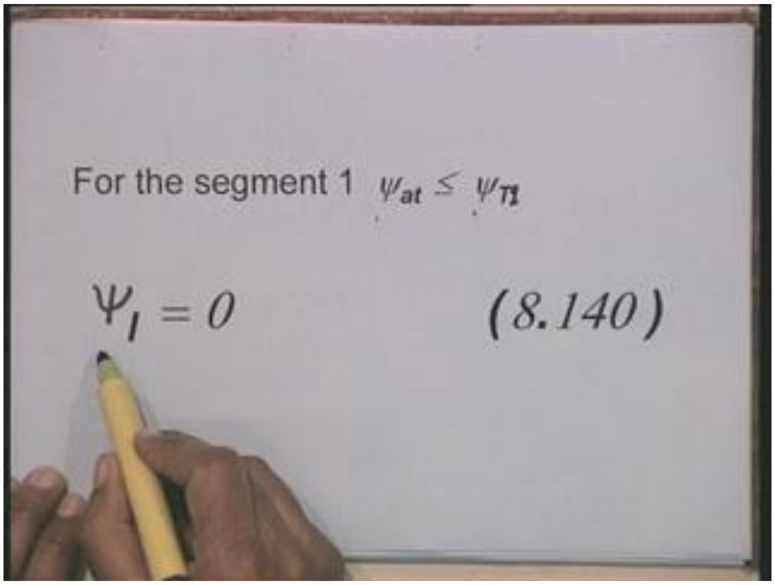


So for actually the segment one is concerned segment one is concerned the psi at is less than equal to psi T1 which is the boundary for segment one right and therefore the this psi I term is 0, now this the actual OCC and the air gap line they are coinciding right and therefore the psi I which is difference between psi at O and psi at is 0. The second segment is a non-linear segment okay.

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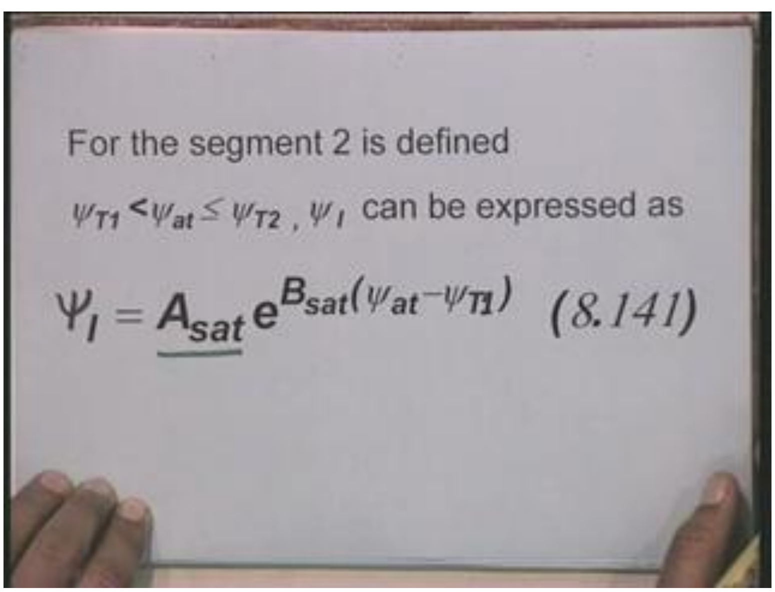

The boundary values are psi at should be greater than psi T1 and less than equal to psi T2, okay this is the range we have already established for the second segment that is the second segment is the psi at anywhere on this line right this is going to be in this range psi T1 and psi T2. Now this can be modeled by a the equation of this form the exponential form of equation the psi I can be written as psi I can be written as $A_{sat}$ that is A saturation this is a coefficient this the subscript sat is used to indicate that we are trying to model the saturation that is psi I equal to A saturation e to the power B saturation multiplied by psi at minus psi a T1 what is this psi I, this is the difference between the psi atO and psi at and this psi I can be model by this expression where you for any value of psi at psi at you find out this difference psi at1 psi T1 is known to you and these coefficients have to be obtained, these coefficients have to be obtained actually for a given machine okay.

Once these coefficients are known psi I can be computed. Now here if you see that if I put psi at equal to psi T1 right that is actually at the beginning of the segment psi at is equal to psi T1, you can again look here at this point right at this point psi I is 0 right but when I use this equation psi will come out to be equal to $A_{sat}$, this is a slight discrepancy at this boundary. However, in practice this term psi at is small right and therefore this discrepancy is not very significant because when I use this equation and try to put actually the initial value that is psi at equal to psi T1 right then psi I should come out to be 0 but it is not coming out to be 0 by this equation right.

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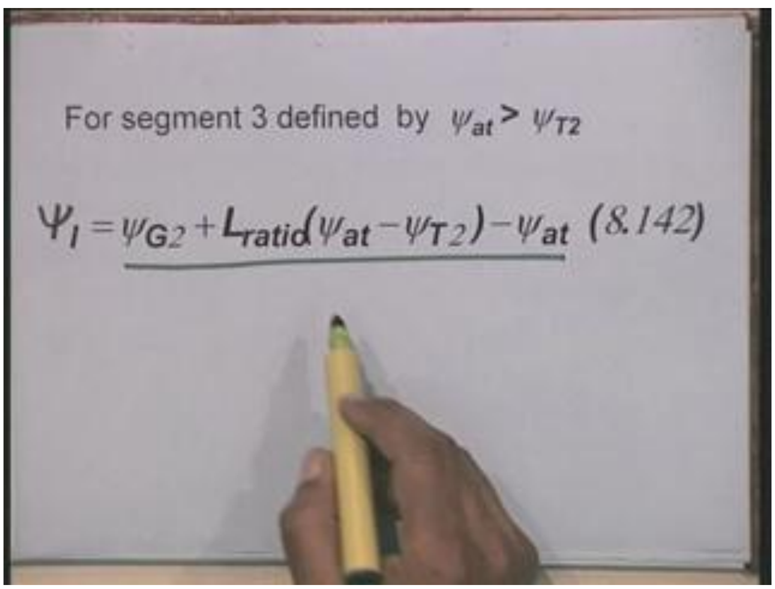


However since A sat this coefficient is generally very small and therefore this discrepancy is a negligible or can be ignored because again let me emphasize here that we trying to develop the model okay and for this developing the model we have to very carefully obtain these coefficients because when I said is exponential I have to do curve fitting okay and once these coefficients are obtained we obtain actually the model for psi I. Now the last segment which is again a straight line fully saturated segment third segment the fully saturated one okay.

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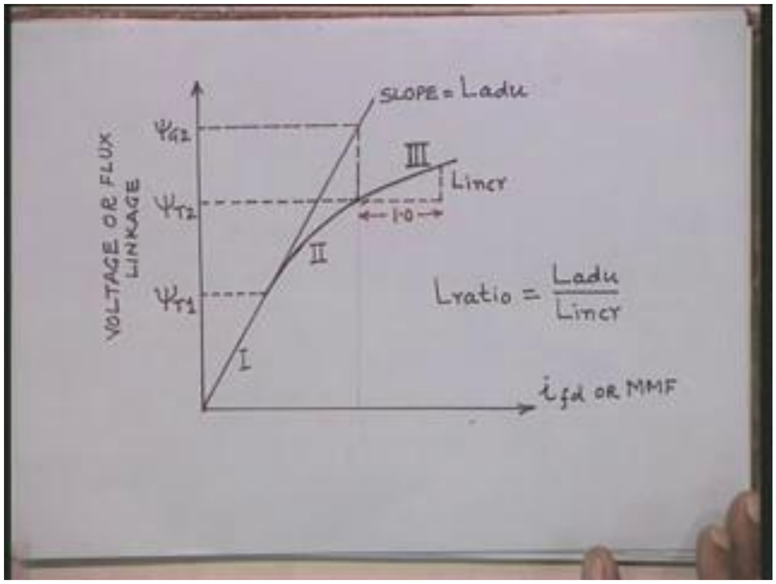


Now here we have to find out find out what is the value of psi I when psi at is beyond psi T2 right now to obtain this what we really do here is we may have to write down the equation for this segment is a straight line, you can write down the equation of the segment in the form of y equal to mx plus c a straight line okay and then you know this equation for this line what is the equation for this air gap line, you simply write down psi at equal to $L_{adu}$ into $i_{fd}$ because this is a path line passing through origin while this line is not going to pass through origin therefore, you have to make use of the initial conditions that is actually that our initial conditions are that when the flux is equal to psi T2 right psi T2 the field current is ifdo something, you can note it down that is because here this is the segment which we are trying to model right.

Now you do this exercise look this exercise you can do and obtain the expression for the psi I which is which is the difference between actual psi at and psi atO right. Now psi I has been obtained in this case as psi g2 plus L ratio into psi at minus psi T2 minus psi at. Now this I will suggest all of you to derive the expressions psi I equal to psi g2 plus L ratio psi at minus psi T2 minus psi at, I have already checked it, it comes out to be okay there is no discrepancy.

Now here what is done here is that when the flux linkage is psi T2 right we find out actually the value of flux linkage on air gap that is for the psi T2, you note down this current and for the same current you can find out a flux linkage which is on air gap line corresponding to the air gap line that is called psi g2 and using this information that for this particular current this point is lying on the third segment characteristic right and using this value that the flux linkage is psi g2 therefore basically at this point at this point psi I is equal to psi g2 right.

Therefore if I substitute here in this equation in this equation right if psi if I take this psi at if I take this psi at equal to psi T2 and this term become 0 right and psi I becomes psi g2 minus psi at, no no psi psi T2 is nothing but psi at right therefore this equation is satisfied. Okay and this can be derived now once you are in a position to obtain this quantity psi I the coefficient $K_{sd}$ is known okay now next point is how to obtain the saturation coefficient for q axis okay.

Now, so far actually d axis is concerned we have OCC for q axis we do not have similar open circuit characteristic we cannot plot it. Now here generally we made one assumption that in the q axis the saturation is 0, a very realistic assumption that you can make this assumption that on q axis that is the saturation coefficient $K_{sq}$ is equal to 1 because the magnetic the flux takes its path, so larger air gap when you talk about the q axis of the machine, okay.

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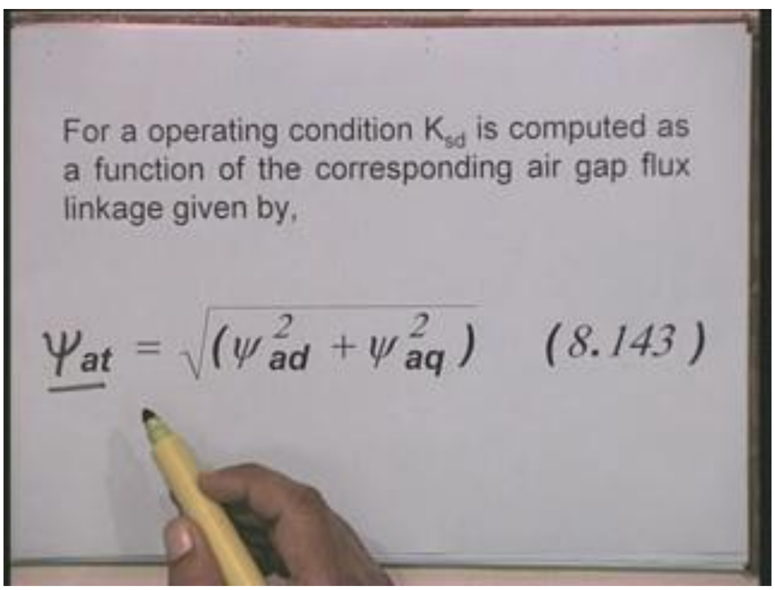


Now when we are talking about this the flux psi at is equal to psi ad square psi aq square that is the flux which we have been talking about right is the total flux in the air gap psi at equal to psi ad square plus psi aq square.

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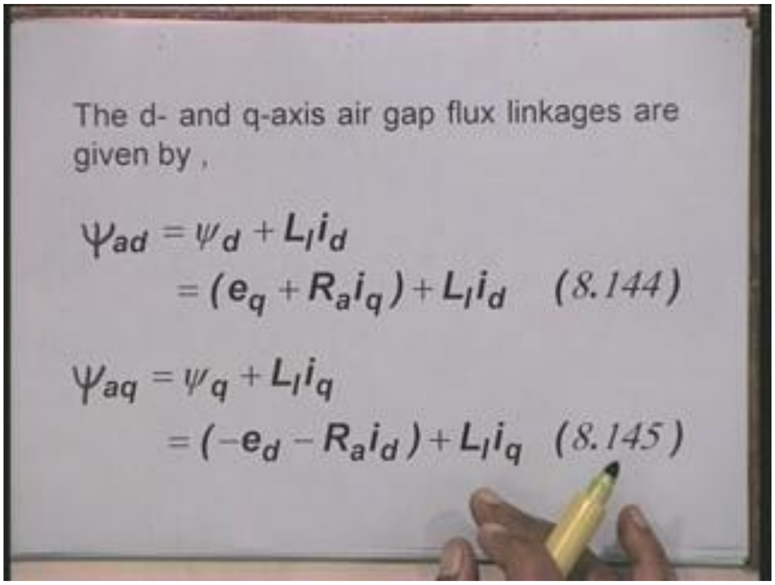


Now here we will just establish one very is simple relationship using our expressions for psi ad and psi aq, psi ad and psi aq these are the expressions which were known to you the relationships are that is you write down the expressions for psi at that is you write down the expressions for psi ad which is then psi plus $L_{lid}$ and psi aq as psi q plus $L_{liq}$.

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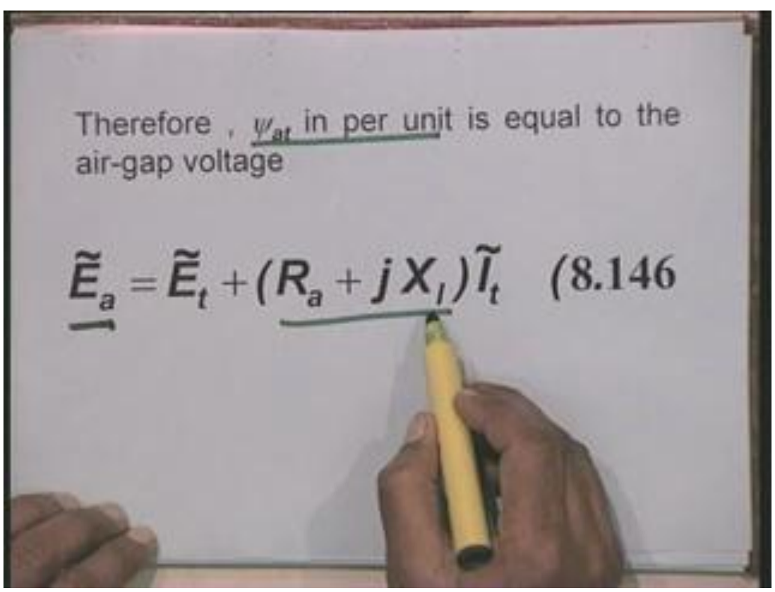


Okay and psi d can be written by this expression psi d psi ad is equal to $e_q$ plus $R_a$ $i_q$ psi q is written as minus $e_d$ minus $R_{aid}$ these are the equations which we have already developed earlier and now if you substitute this in the equation for psi at right, you will find actually that psi at when you express in per unit because we are all doing per unit calculations this psi at will come out to be simply as a voltage $E_a$ $E_t$ plus $R_a$ plus j times $X_l$ into $I_t$ that is this psi at is a voltage behind psi at is a voltage behind or is equal to the voltage behind behind this impedance that is $R_a$ plus j times $X_l$ that is $E_q$ when we are talking about that was the voltage behind $R_a$ plus j times $X_q$. Okay now here it is only talking about the leakage reactance this is this is established by substituting these expressions. Now with this we have established how do we obtain the saturated value of the reactance is required for calculations.

Now if you see it very carefully here then for each operating condition you know for each operating condition, you have to find out what is the saturated value it is not same for all operating condition this coefficient $K_{sd}$ is different for different operating condition you can easily see here that psi at when I say psi at is obtained corresponding to one particular operating condition. Okay and for that we have to find out psi atO, okay and this ratio psi at upon psi atO gives you saturation coefficient and this psi at is different and therefore we get the different value of saturation coefficient and that is why, when you perform the stability studies stability studies right the saturation has to be computed as the loading condition keeps on changes for different loading condition different value of saturation coefficient is to be used. With this I am concluding here the modeling of synchronous machines for stability studies. Today, we have talked about the method of modeling, modeling the saturation right.

How how it has been done basically we started with the basic definition of what we mean by saturation coefficient and then the OCC open circuit characteristic is divided into 3 segments and for each segment we have written the expression for the flux linkage psi I which is the difference between psi atO and psi at that is psi atO is the flux linkage for a given field current on air gap line right and then we compute the value of saturation coefficient. Further, we have assumed here the saturation coefficient on q axis as 1that is saturation is neglected and this can be considered with this.

Let me say that we have completed the synchronous machine modeling this modeling is complete in the next chapter we will study the synchronous machines model for stability studies. Okay when we talk about the actual model of the synchronous machine we are considering here now the stator circuit, rotor circuit transient while in the stator circuit we have we have made the assumption that the derivative terms are negligible as compared to the speed voltage terms therefore, this assumption will be carried over for a stability studies also that is when we have written the stator circuit equations we have ignored the transformer voltages and therefore this assumption will be carried over beyond for stability studies also.

However, there will be some more assumptions that can be made and simplified to obtain are made to obtain the simple synchronous machine model for stability studies. Now when we talk about the modeling the next step will be to model the excitation system and the models for turbines and governors that makes the complete model for the energy system that is turbine, governor, excitation system and synchronous generator that is the complete thing, we will devote few more terms to develop the models for the excitation system and this okay. Thank you very much.