Advanced Electric Drives
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Lecture - 20

Hello and welcome to this lecture on advanced electric drives. In the last lecture, we are discussing about are a cyclo converter feds synchronous motor drive with unity power factor action, as you know the synchronous machine as a field winding; in case of round synchronous machine we have a field winding. And synchronous motor can operate in leading the power factor, in unity power factor or magnate power factor. As a special case sometime it is beneficial to operate the machine under unity power factor condition. That is what we discussing in the last lecture.

The advantage of operating and induction the synchronous motor under unity perfect operation is that, it only takes active power; the power is only active there is no reacting power, hence the efficiency of the overall system is maximized. So, if we see the block diagram that way discussing in the last lecture.

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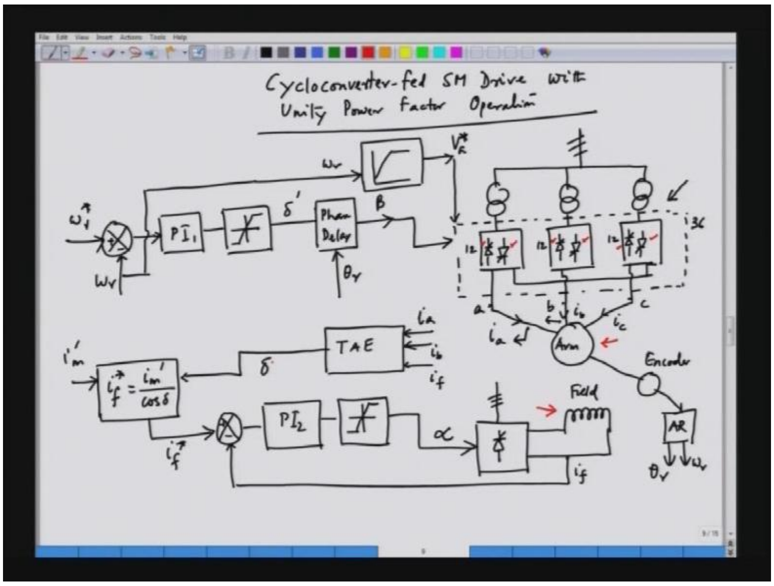

In the block diagram we have the cyclo converter this is the cyclo converter that we have. And cyclo converter is fielding the armature for the synchronous machine this is the armature of the synchronous machine. And the field winding is fed from different converter that is 6 power converters which is fielding to the field winding. And the cyclo converter if you see this has got 2 anti parallel phases of converter in each phase; phase a has got a positive is bridge and also a negative s c r bridge similarly, phase b have got positive s c r bridge and negative s c r bridge and phase c also have positive s c r and negative s c r bridge.

Now, in each phase the current is alternative and hence we need 2 converters one for the positive current and one for the negative current; in fact, we need 2 bridges. So, per phase we have 2 bridges one for priding the positive current, other for priding the negative current. And the field winding is separate 6 power converter that is we are talking about in this case. And the whole system is operated in such a way that the power factor is unity.

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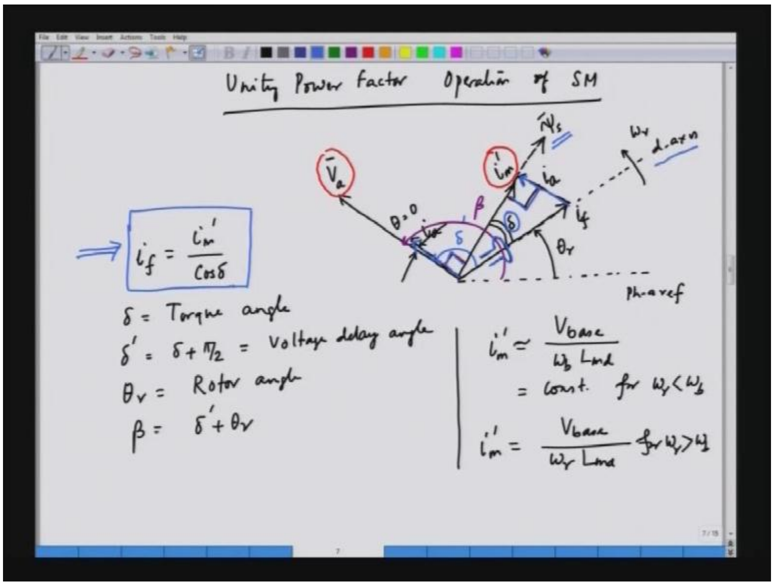

And, how the power factor is unity that we can see by referring to the phasor diagram that we have already seen in the last lecture. So, in this case you know that this is the magnetization current i m. And the magnetization current and the armature voltage V a perpendicular each other this angle is 90 degree. So, see this angle is 90 and V a which is also have been 90 degree with i m is in parallel with V a this is i a and this is also i a. So, in fact what we have; we have 2 lines which are parallel i a here and i a here; because this angle are 90 we have 90 degree here, also 90 degree here. So, as a result we can see that the current i a is in phase with the armature V a. So, which means the power factor is 1 power factor is unity or theta; power factor angle is equal to 0.

So, to impress this particular condition; we have to control the field current as per this equation the field current i f if you see this right angle triangle; this right angle triangle one side is i m prime the other side is i a the armature current and the third side is i a, i f is along the field axis. So, we have the field poles here this is the field pole. So, i f is along with the field axis or the d. So, this triangle 1 side is i f other side is i a and the third side is i m prime and i m prime is magnetization current. Now, to ensure that this right angle triangle exist we can find out i f by the relationship. So, i f is given as i m prime by cos delta.

Now, what is this delta; this delta is the torque angle. Delta is this angle which is the angle between the d axis and the stator flux; the stator flux is along the magnetation current the stator flux is psi s. And the stator flux linkage is along the magnetation current direction triangle between the phase and the d axis is the torque angle. Now, if you find out the reference field current it means when the synchronous machine is operating we have to adjust the field current. The field current has to be adjusted in such a way the power factor is maintained at unity.

So, in other words the field current i f is control as i m prime by cos delta. So, this delta has to be find out and to find out delta what we need; we need the torque angle is estimator. So, this is the torque angle estimator which is a block in this particular block diagram they it is a computational block. And out of this we get the torque angle that is delta and the torque angle is fed to this calculation block and we get the reference field current as i m prime by cos delta. So, what is this torque angle estimator? So, the torque angle estimator take input as the i a; the armature current i b the armature current is phase b. Since, we have let assume a torque connected machine if you know i a and i b we can find out i c? i c is equal minus of i a plus i b.

So, in fact we can calculate the third current by just having the knowledge of i a and i b. And the field current all current can measure by using hall sensors. So, we have the hall sensor to measure i a, i b and i f. So, with this information we need to find out what is the torque angle?

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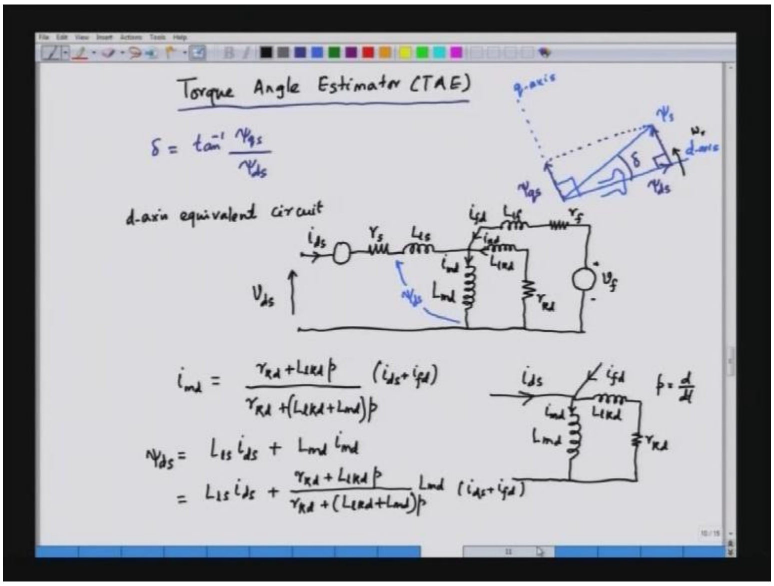

Now, we have seen that the torque angle is angle between the stator flux linkage and the d axis. Now, this is the d axis; d axis is the same as a pole axis we having the field in the rotor the field is moving away the d axis; of course not stationary it is also moving away it is moving at a speed of the rotor. So, this is the rotor speed. So, d axis is moving away with the speed of the rotor. So, what we do we find out the component of this flux linkage along the d axis. So, we can find out the component of this along the d axis. So, we can project this along the d axis. So, this component is called psi d s; the stator flux linkage in the d axis.

Similarly, we have a q axis and the q axis is orthogonal to d axis; this is the q axis which is having right angle or phi by 2 with the d axis. And again we can project the stator flux linkage along the q axis. So, if you project the stator flux linkage along with the q axis this flux is called psi q s for the flux linkage in the q axis. So, if we know the individual component psi d s and psi q s; psi d s is the flux linkage in the d axis, psi q s is the flux linkage in the q axis we can find out what is delta; delta is this angle right. So, if this is psi q s this is also psi q s, this angle is also 90 degree all right.

So, we can calculate delta provided we know psi d s and psi q s. So, delta is calculated by what is called a torque angle estimator block. And we can say that delta is equal to tan inverse of psi q s by psi d s. So, to find out delta is the information about the q axis stator flux that is psi q s and also about the d axis stator flux that is psi d s. So, how to find out this psi d s and psi q s and how to find out this; let us remember the equivalent circuit of the synchronous machine in the respective axis. So, we have already seen the equivalent circuit in d and q axis.

So, let us try to derive this equation or this psi d s and psi q s from the equivalent circuit. So, if you take d axis equivalent circuit. So, what will have here we have been a back e m f and resistance draw leakage induction then we have might age induction here in the d axis. And then we have the leakage induction of the dumper winding the resistance of the dumper winding.

And then we also have the field winding leakage and the field winding resistance and the field winding voltage. So, this is our with v d s have the voltage and this is the resistance the stator leakage induction that L s s in the d axis. And this is managing induction L m d in the d axis and this part is the dumper the dumper leakage induction in L k d, dumper resistance this r k d, the field leakage is L f, L l f. And the field resistance is r f and the field applied voltage is v f all right.

So, these are the variables that we have here the parameters. And we have the current in case this is the d axis stator current i d s; this is the dumper current in the d axis entering this junction that is i k d. And this one is the field winding current that is i f d. So, we have to find out what is the magnetation current and the magnetation current in this case in the d axis is i m d. So, we are talking about solid for machine. So, we are drawn d axis in flux circuit. Now, we have to find out stator flux linkage; the stator flux linkage is the flux linkage associate with the magnetizing branch and the stator linkage. So, this is psi d f psi d f is the flux linkage associate with the magnetizing branch and also the stator linkage stator linkage inductions.

Now, to find out this psi d s we have to find out what is i m d; i m d is produced by 3 currents i m d is magnetizing current in the d axis; which is produce by the stator d axis current, the dumper is current and also the d axis field current. So, in fact we can say that this i m d is basically produce by this currents. And of course we do not know the dumper current; the dumper current is the current which we cannot measure; we can measure the field current because field is the available the terminal are available. So, we can sensor to measure the field current, we can also measure the stator current we can also sensor in the stator to measure the stator current.

But unfortunately we cannot measure the damper currents; dumper currents is hidden inside the machine, dumper is part of the field the rotor and the dumper current are not available for measurement. So, we have to somehow get the magnetizing current in terms of the field current and in the stator current. So, what is i m d. So, if you find out what is i m d we can take this circuit we can take only this part of the circuit this is L m d. So, we have a current which is entering here is i d s; the current which is entering from this side from the field is i f d. And the current which is with coming from the dumper of course the dumper current is not known. So, if we just replace by the dumper parameters this is r k d and this is L k d and this current is i m d.

So, we need to find out what is i m d in terms of i d s and i f. So, we can apply this basically current divided circuit. So, we have the current which we have the 2 currents here and the currents are i d s and i f d; the stator current and the field current they are basically divided partly in the partition branch and partly in the dumper branch. So, we can find out i m d in the following way r k d plus L l k d p divided by r k d plus L l k d plus L l d into p; this is small p is the derivative operator this is d by d t. So, this dynamic equation will give us i m d by simple current division principle.

So, if we know what is i m d; we can find out the stator flux linkage in the d axis. So, what is psi d s? psi d s is taken as L l s into i d s plus L m d into i m d. So, if you want find out the flux linkage we have to 2 terms here; the leakage flux that is L l s into i d s and then plus L m d into i m d. So, this we can simplify and expand this that is L l s into i d s plus r k d plus L l k d p divided by r k d plus L l k d plus L m d p. And then we have got L m d here again we have multiply with L m d. And then the currents will be can be written here we can write the current and the currents are i d s plus i f d. So, this is the expression for psi d s.

Now, we can see here to find out psi d s we have to know i d s; i d s this can be measured by having hall sensor we can measure i a, i b, i c; if you know i a, i b, i c you can transform that into d and q component in the rotor. So, we can have i d s and i q s. So, in fact i d s and i q s are measureable. So, we have got information about i d s; the field current i d f can be measured having sensor in the field circuit. So, we know i d s and i f and the parameters have a machine are given; we know the stator parameters, stator inductions, we know the mighty age inductions, we know the dumper parameters. So, we can find out psi d s by the equation. And these equations all quantities are known, the parameters are known, the currents are also known.

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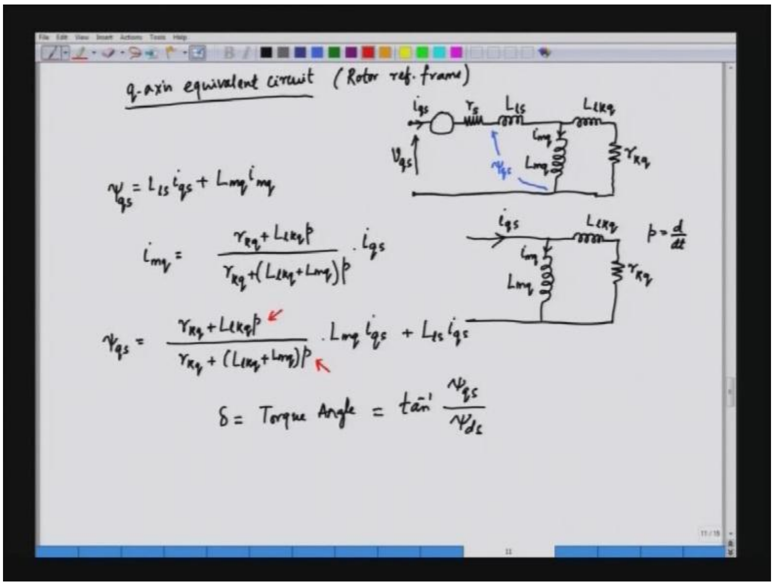

Now, similarly, we can calculate the stator flux in the q axis. So, I will just draw the q axis equivalent circuit. Now, this equivalent circuit is actually in the rotor reference frame given this one also is in the rotor reference frame. So, here exactly in the same way we have the back c m f in the q axis, the stator resistance in the q axis, the stator linkage inductions, then we have the mighty age induction and then we have the dumper parameter. In the q axis we do not have any field winding; the field winding present in the d axis. So, in the q axis in the rotor we only have the dumper winding.

So, we can have the dumper linkage inductions and will have dumper resistance. So, this is r k q and this is L l k q dumper linkage inductions and dumper resistance refers to the parameter, refer to the stator. Then here the mighty age induction is L m q in the q axis the stator linkage induction is in fact same because of the stator is a symmetrical stator having 3 windings which are symmetrical. So, we have same linkage induction in the stator that is L s; stator resistance will also be the same that this is r s and this is applied voltage in the stator v q s. Now, similarly the current entering here is i q s and this current is the magnetation current which is going in the magnetation branch that is and i m q.

So, if you want find out what is the q axis stator flux linkage; we can do that by this equation psi q s is equal to L l s into i q s the linkage flux plus the magnetation flux which is L m q into i m q. Now, again in the similar passion the stator flux linkage in the q axis in the flux linkage associated with the magnetation branch and the stator linkage. So, this is psi q s. So, this is basically given by this equation psi q s is the is equal to L f into i q s; that is the linkage flux in the q axis plus L m q into i m q that the magnetation flux in the q axis. The formation of the 2 gives us the q axis stator flux linkage.

Now, how to find out i m q similarly we can do that as we have done previously will draw only this part of circuit this is L m q. And this part is the dumper part in the current which is entering this particular branch is i q s. And this current get divided into 2 parts; one is in the magnetation branch other is in dumper circuit. So, we are only interested in i m q. Now, this is current divided circuit we have 2 parallel branches and other current will be divided into invert proportional to there in imputers. So, we can calculate what is i m q i m q in this case can be given us this is L l k q the linkage inductions the resistance r k q.

So, we have r k q plus L l k q; p is derivative operator divided by the total interiors of the circuit r k q plus L l k q plus L m q into p into i q s. So, this basically gives magnetation current in the q axis. So, once we get the magnetation current; we will be in a position to find out the total flux linkage in the q axis that is psi q s. So, psi q s in this case psi q s is given us r k q plus L l k q p divided by r k q plus L l k q plus L m q p. And we have to multiply with L n q because we are talking about flux linkage in to i q s plus leakage flux that is L l s in to i q s.

Now, if you see if we analyze this expression for psi q s; we see that is the psi q s expression in the right hand side all the variables are known; the currents i q s can be measured by having all sensor in the armature we can measure the various currents i a, i b, i c. And once we measure the 3 phase current; we can transform the 3 phase current in to the rotor reference frame in to i d s and i q s respectively. So, in fact i q s is measurable and the parameters of the machine like the damper parameter in the q axis the leakage inductions these are available to us. So, in the right hand side of this equation all the values are known. So, we can find out what is i q s. So, we have already seen the calculation of psi d s.

Now, we have in able to derive the expression for psi q s to; so this basically to a dynamic equation. So, giving the currents and the parameters we can find out the flux linkage. And from the flux linkage as we have already seen that we can calculate the value of delta; delta is the torque angle and that is equal to tan inverse of psi q by psi d s. So, this is how we implement the block torque angle estimator all this calculation are done in real time; of course if you see this expression for psi d s and psi q s we will see that ultimately we have to implement a few integrators p is the derivative terms; so we have p in the numerator and also t in the denominator.

So, ultimately this will lead to something like an integrating action finally. And then we have the summation in this case. So, that is no derivative term in the final implementation of psi d s psi q s. So, once we find out psi d s and psi q s; we can calculate the torque angle delta which can for control of synchronous motor. Now, we have also seen that in the synchronous motor control we also need theta r; theta r is the rotor position rotor is moving away; the d axis is moving away the rotor is continuously rotating member.

And, then also we need the expression for the speed. And this theta r and the speed are obtain using an angle resolver; angle resolver stand for A R; A R is the angle resolver. So, the angle resolvers give us information about theta r and omega r. Now, what is an angle resolver? Traditionally angle resolver actually gives us the cos and sign angle of the rotor. But now a days we have availability of incremental encoders and also absolute encoders to implement this angle resolver.

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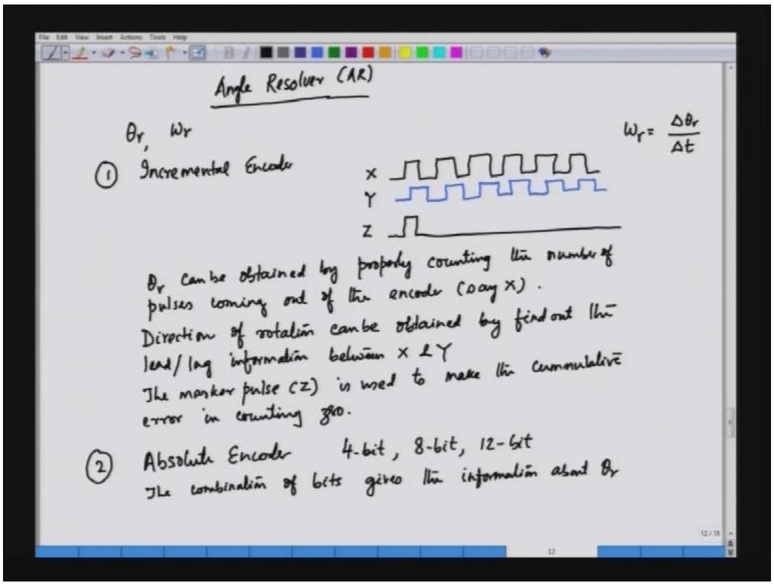

So, we have 2 types of encoders; the encoders are we are actually discussing about the angle resolver that is A R. So, this can be the objective is to find out theta r and omega r. And this can be obtained by using incremental encoder; the incremental encoder gives us pulses as a rotor rotates. So, it gives us tame up pulses like high and low signal like this. So, this is the output of an incremental encoder; in fact this incremental encoder actually gives us 2 signals which are in quadrature. So, this is one channel of the other channel of the encoder will basically gives us again a tame up of which is basically shifted from the other pulse by phi by 2.

So, this is maybe we can call this should be X pulse this will be Y pulses. So, this 2 are the output of the implemental in encoder; in addition to that encoder is also gives another signal marker pulses; marker pulses give once revolution. So, this pulse just gives one pulse in a revolution like this. So, this is may be the signal call Z. So, if we use implemental encoder which is not very expensive; which can be very easily mounted on the rotor will have 3 signals X, Y and Z and in this case X,Y are in quadrature. So, depending upon the rotation of the rotor the direction of the rotation X may lead Y for Y may lead X.

So, by counting this number of pulses; we can get information about theta r. So, theta r can be obtained by properly counting the number of pulses counting out of the encoder let us say X. So, if we take 1signal let say X; if we count number of pulses will be able to have information about theta r. Now, what about the direction; the direction can be obtained by seeing which pulse is leading which one. So, the direction information can be obtain by ((Refer Time: 31:56)) which can be used to find out with X is leading Y or Y is leading X. The direction of rotation can be obtained by finding out the phase angle or the lead lag information between X and Y.

And, what is the role of marker pulse; the marker pulse actually when we are continuously incrementing and trying to find out theta r; angle actually cannot be higher than 360 degrees; when you are talking about 1 revaluation this is 360 degree mechanical. So, 720 is same as 360. So, in fact this marker pulse actually synchronous the signal. So that the cumulative error is reduced. So, marker pulse gives the indication of a start of the counting and this s also use to synchronous; so that the cumulative error in the counting is made 0. So, the marker pulse Z is use to make the cumulative error in counting 0. So, this is about incremental encoder which is not very expensive.

Now, if you want to find out the exact theta r irrespective of the rotation; we can go for what is called an absolute encoder it is expensive; an absolute encoder are available either in the binary coded form or in the gray coded form; we can have the option to choose whether to go for a binary coded form or gray coded form. So, the absolute encoder will give us a unique combination of the pulses. So that we can find out the value of theta r. So, the second is to go for absolute encoder they can be get either 4 bit, 8 bit or 12 bit. So, what we are getting in this case we are getting 4 bit at a time or we are getting 8 bit at a time or we are getting 12 bit at a time.

So, when we are getting multiple bits at a time this combination of the bits will give us an information about the rotor position; since, we have large number of wires it is naturally expensive. So, they are actually preferred for those application were the absolute encodes are really necessary. So, in this case the combination of bits gives the information about theta r.

And once we signed out theta r we can differential this information at what rate theta r is changing. And d theta r by d t will give us omega r. So, after finding out that we can calculate this omega r by having this expression that delta theta r by delta t is a rotor speed that is omega r. So, this is all about angle resolver. So, the angle resolver is an essential part of synchronous machine. Because without this angle information a synchronous motor cannot be controlled; it can only be control provided we have some angle information.

So, we are discussing about the control of synchronous machine. So, we have seen how we can implement the torque angle estimator and also an angle resolver. And synchronous motors are usually controlled in close loop fashion with a rotor position feedback; we will go to a new topic that is on permanent magnet motors. So, this permanent magnet motors are very widely used for various applications; the reason of behind their popularity is the compactness.

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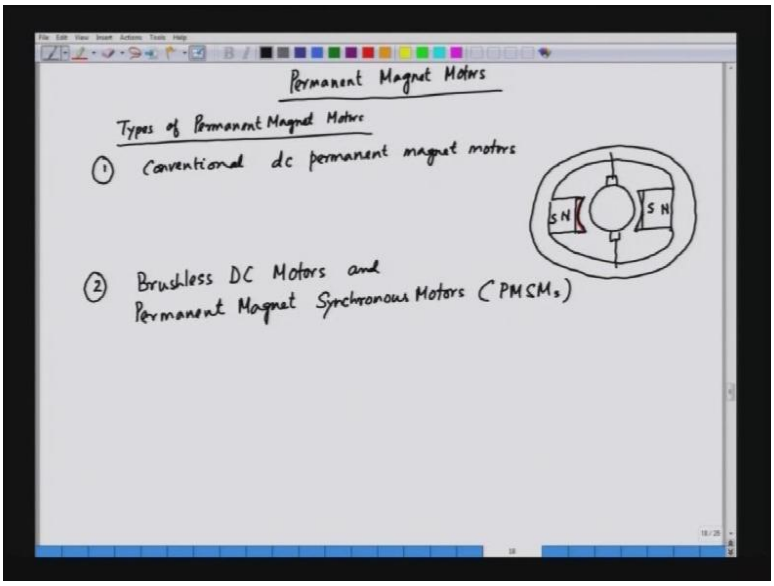

So, today will be discussing about permanent magnet motors; they are popular because of high torque to weight ratio the field winding is replaced by permanent magnet. And hence we do not have any field excitation; the permanent magnet keeps the flux and the armature is the conventional armature. And there is interaction between the permanent magnet flux and the armature current and hence a torque is produced. Now, if we see the classification of this permanent magnet motors essentially we have 2 types of permanent magnet motors. The first one is the conventional permanent magnet d c motors were the armature is a rotor and the field is a stator the field winding is replaced by a permanent magnet.

So, number 1; types of permanent magnet motors the first type is conventional d c permanent magnet motors. Now, in this case the armature and the commentators segments and the brushes are just like that of a normal d c motors. But the field windings which are in the stator are replaced by permanent magnets. So, we have the armature here, we are having the brush in this case. But instead of a vowed feel what we have here; we have a permanent magnet field. So, this is a structure of a permanent magnet d c motor the conventional one. And we have the armature and we have the field winding the field winding are having permanent magnets; these are the permanent magnets in the field winding.

And, when we mound this permanent magnet basically the magnet comes in peace and this is north, south. And this basically these are the poles shoe. And similarly here we have the pole shoe as a magnet is placed here we have south and north. So, we have 2 magnets. And one gives the North Pole other gives the south pole for the working of the d c motor. Now, these type of motors are also very popular for low power video per application; we also have another type of permanent magnet called brushless d c motor and also permanent magnet synchronous motor.

Second type of permanent magnet motors are brushless d c motors and permanent magnet synchronous motors and that is called P M S Ms. So, this 2 types of motor like brushless d c motor and permanent magnet synchronous motor; the construction is somewhat similar to that of a conventional synchronous machine. In the synchronous machine the field winding is on the rotor, the armature is on the stator as we already seen.

But the field winding is replaced by a permanent magnet field there is no winding in the rotor, there is no field winding in the rotor; instead of conventional field winding we have the magnets the permanent magnets in the field winding. Now, before we talk about the details of this permanent magnet motors; let us have some basic idea about the working of this permanent magnet motors, and something about the material the permanent magnet material.

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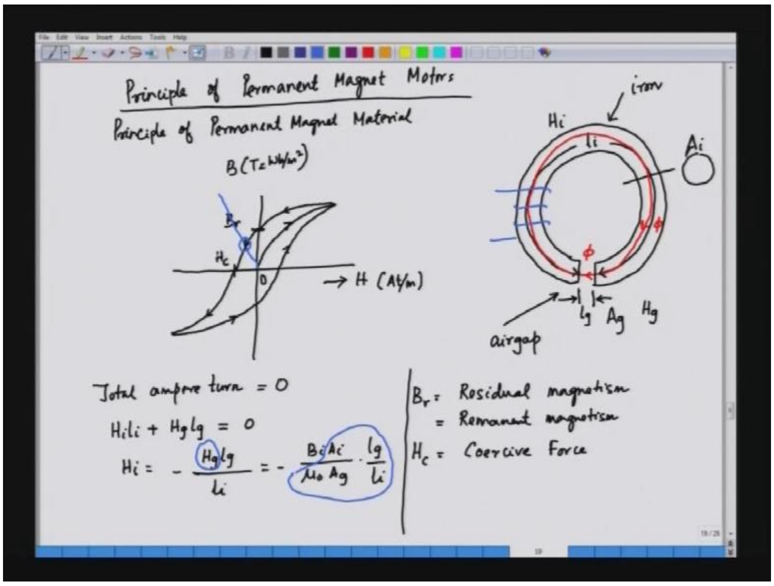

So, we will see the principle of permanent magnet motors; in fact we have to we can discuss about principle of permanent material. Let us take a permanent magnet material, let us take ring separate permanent magnet material and let us caught an air gap. So, we will take a ring in this case and then what will do here will caught a air gap. So, this is a permanent magnet may be an idiom material and then this is having an air gap which is of length L g and this is having a circular cross section. And the cross section this is iron part and this is the air gap and the length of the iron part is l i. So, this is the length of the iron part from this side we have a l i. And the cross section area here is A i similarly the length of the air gap is L g and the area of this air gap is A g.

So, usually when we talk about a magnetic material they follow what is called the B H characteristic. So, if see the B H characteristic of a typical material this is the H; H is the field strength which is usually the unit is ampere term per meter. And the first density is B and the unit is usually tesla or Weber per meter square; tesla is same as Weber per meter square. So, if we plot the B H characteristic we have various types of material; we can have a soft material, we can also have a hard material. So, if we plot the B H characteristic it starts like this as we increase the H or the field strength the flux density increases; then after some time it is saturates with the increase of the field strength age the flux density no more increases. And then if we decrease the field strength the flux density decreases but in a different path.

And, then if we make age negative flux density for the decreases and sometimes this becomes equals to 0. Then we further increase H in the negative direction if reverses. So, B becomes negative and then we increase H after that. So, H will reduce to increase to 0 and then H will become positive. So, this is how they path is stretched and this is what we call a B H characteristic; sometimes if we see there some of the material have got very small B H look. And in this case if you see that the reveres path and the forward path they do not coincide. And the lope inside this 2 paths enclosed is called the B H lope; in a soft magnate this B H lope is quite small in hard magnate material the B H lope is quite large.

So, in this B H lope we have got some important property this is called B r; B r is basically the flux density for H equal to 0; this is called residual magnetism or remanent magnetism. So, B r is called residual magnetism or remanent magnetism all right. And when we make H negative B becomes equals to 0 and the value of H for which B becomes equals to 0 is cold H C; H C stands for the coercive force. So, we have B r is the residual flux or the residual magnetism and H C is the coercive force. So, these are the important 2 important quantity is of magnate material. So, in this particular lope we have lope structure circular permanent magnet; in which we have caught air gap of length L g.

Now, in this case you know that we do not have been in a current. So, since we do not have been in a current; we can say that the total ampere turn is equal to 0; if you take this magnetic part we have partly iron and partly air gap there is no exciting current; even if we have the quail here the quail can we thought of we can half of quail like this and the quail is not carrying in the current.

Now, in the absence of an external current we can say the total ampere turn drop in this lope is equal to 0. So, we can say that total ampere turn is equal to 0. Now, that will give as this equation that the ampere turn in the iron is H i in to l I; H i is the field strength in the iron and l i is the length of iron plus H g l g; h g is the field strength in the air gap and l g is the length of the air gap that is equal to 0 or we can say that H i is equal to H g l g by l i with a minus sign.

So, we can say that h i is equal to minus H g l g by l i with a minus sign it is a negative quantity. So, now again we can say that when your we have a lope the flux will be the same we have the same common flux. Because the same flux is passing through this lope the flux lines or basically passing and they are crossing this and entering. So, the flux lines are basically closed line. So, whatever flux is in the iron the same flux is the also passing in the A R. So, we can say that we have a common flux here. So, what is flux is flux? Flux is flux density in to the cross external area.

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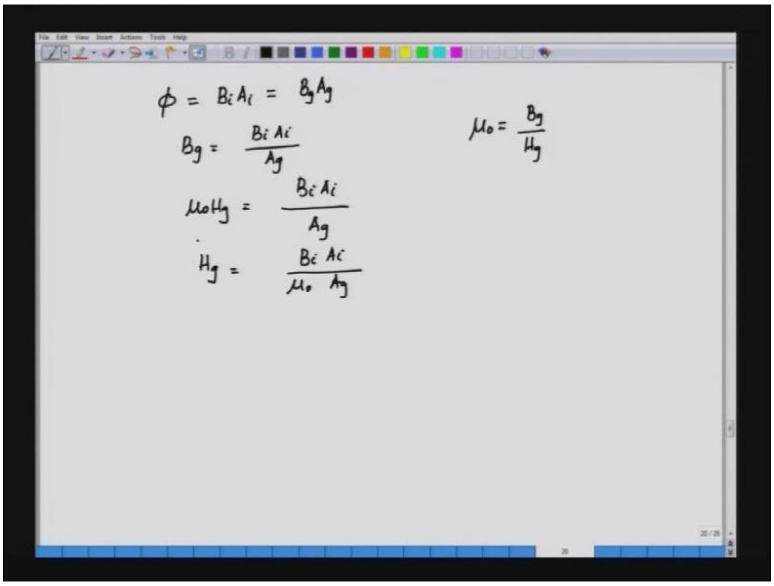

So, we can say here that phi is equal to B i in to A i in the flux in the iron is B i in to A i flux density of the iron in to cross external area of iron is equal to B g in to A g; the flux density of air gap into the cross external area of the air gap. So, this is the flux passing in the particular lope. Now, we can say that what is B g? Now, B g is equal to B i, A i by A g all right. So, B g is equal to B i, A i by A g.

Now, we know that mu naught is equal to B g by H g. H g is the field strength, B g is the flux density. And their related by a content of prop personality curve permeability constant. So, this is mu naught is the constant of permeability of free space; since, we have air gap they are it is mu naught. So, mu naught is equal to B g by H g.

So, we will replace this B g in the following fashion that mu naught in to H g is equal to B i, A i by Ag or we can say that H g is equal to B i, A i by A g by mu naught. So, this is what we have here. Now, this H g we can take from this equation or replace it is in the previous equation. In the previous equation we have H g term here. Now, this is our H g now this h g we can replace by what we have here is B i, A i by A g by mu naught. So, we can say that is equal to minus B i, A i by mu naught by A g in to l g by l i it is interesting equation; where we have H i equal to minus of B i, A i by mu naught A g in to l g by l i.

Now, if you see the right hand side in the right hand side; we have the flux density B i, Ai a i is the cross external area l g l i . So, these are all positive quantities the area is positive, the lengths are positive, the mu naught is positive. So, we are seeing that H i and B i are opposite side to each other. And hence in a material where we have caught air gap the casuistic operates in a second quadrant.

So, this is basically the second quadrant were B i and H i are of opposite side. So, in all permanent magnet motor they operate in the second quadrant were B i and H i are of opposite side. So, in the next lecture we will see how we can take a specific a permanent magnet material. And how we can construct the field winding or the field or the stator that will be discussing in the next lecture.