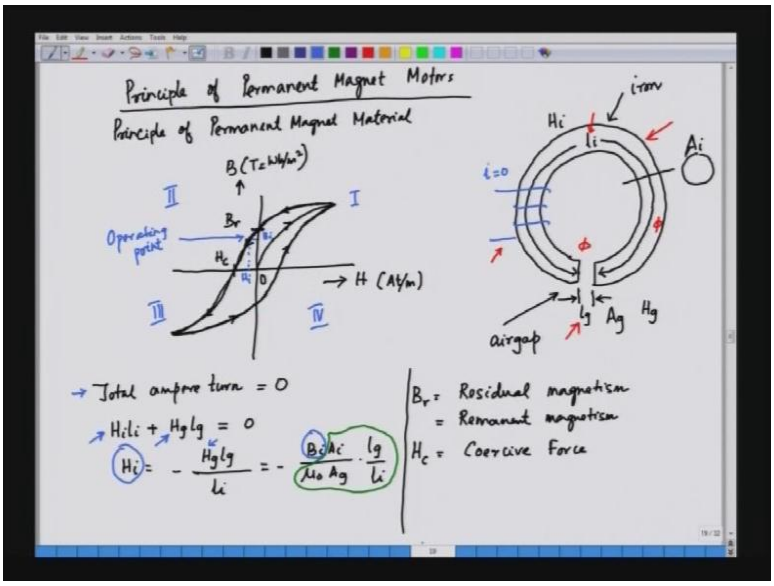
Advanced Electric Drives
Prof. S. P. Das
Department of Electrical Engineering
Indian Institute of Technology Kanpur

Lecture - 21

Hello and welcome to this lecture on advanced electric drives. In the last lecture, we are discussing about the principle of permanent magnet motors. And we have seen that in a permanent magnet motor the cadestic is basically in the second quadrant. It means the motor operates in the second quadrant of the B H characteristics.

(Refer Slide Time: 00:41)



So, just to recapitulate what we have studied in the last lecture; we have circular permanent magnet material, this is the material and this is something like ring structure. The cross section of this ring is a circle. And what we have done here, we have caught an air gap and the air gap is of length l g. And the cross section of this ring is A, and we have this iron path and iron path length is l i and air gap length is l g.

And, the common flux is passing throughout this magnetic material. Now, seems we do not have external current although we have the coil here in this case i is equal to 0. So, that is no external current. So, seems we do not have any external current that is no external m m f. So, we can say that the m m f dropped in the magnetic material is equal to 0. So, what is m m f? m m f is the product of H and l.

So, we can we can say that the total ampere turns is equal to 0. And the ampere turn consist of, the ampere turn in the iron that is H i l i and ampere turn in the air that is H g into l g. now, if we find out what is H I, H i will be equal to minus of H g l g by l i. So, we are seeing that the magnetic field in the at the field strength in the air gap and in the iron are opposite to each other. So, H i equal to minus of H g. So, what we will do right now is that; we will be replacing this H g by B i A i by H g. Because we know since; we have the common flux, we can say that the flux is equal to flux density into a d f.

So, we can say that phi is equal to B i A i the same flux is also passing through the air gap. So, that is equal to B g into A g or we can also say that B g is equal to B i A i by A g. And from this we can find out what is H g, H g is given by this expression; that is B i A i by mu naught. Mu naught is the permeability of free space, because; we are talking about the air gap it is mu naught by A g. So, what we will do here in the previous equation; we have this H g term in this case. The H g we can replace by B i A i by mu naught A g into l g by l i. So, this is basically, a very important derivation now, what does it give us? Now, this gives us that the direction of H i and the direction of B i are opposite to each other.

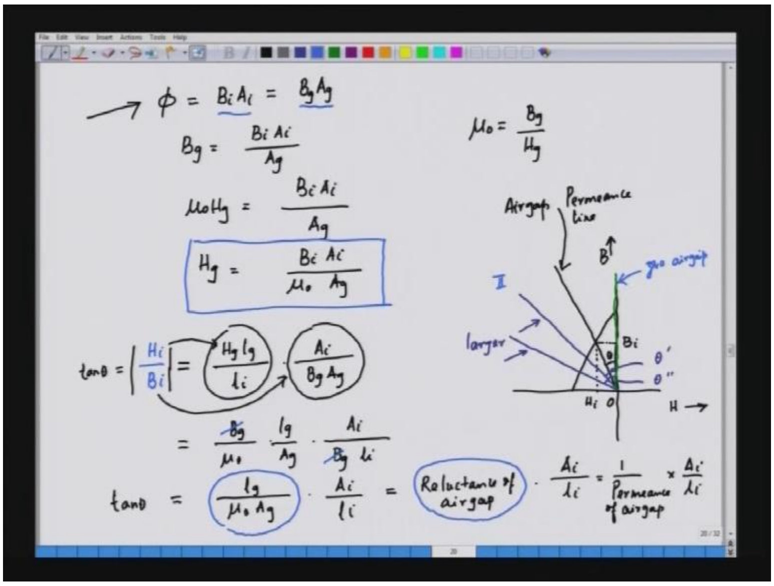
We have a negative sign here, and in the right hand side we will see that we have area the cross sectional areas A i and A A g and then we have the length of the air gap and the length of iron that is l g and l i respectively. Mu naught is a constant. So, this quantity is basically positive. So, what we have seen in this case is that H i is equal to minus of B i into some constant. That is say for example; k. So, it means the sin of B i and the sin of H i are opposite to each other all right. So, this can happen only in the second quadrant and in the 4th quadrant. So, what is the second quadrant, this is the quadrant number 1, this is quadrant 2, this is quadrant 3 and this is quadrant 4.

And, now in the first quadrant of the B H curve; B is positive this is a B, B is in the y axis and H is in the x axis. So, we see that in the first quadrant both B and H are positive. In the second quadrant B is positive, but; H is negative, it means 1 quantity is positive other quantity is negative. So, signs are opposite to each other. Than in the third quadrant we see that B is negative H is also negative, all right. And in the 4th quadrant; we see that H is positive and B is negative. So, it means the operating point here, when we caught an air gap in a in a permanent magnet the operating point can occur in the second quadrant or in the 4th quadrant.

Now, we see that the graph is symmetrical now, if you see this B H curve; B H curve is exactly symmetrical, you can see that we are returning like this and again, we are going from this back. So, the graph in the second quadrant and forth quadrant are something similar. So, we can say that the characteristic occurs in the second quadrant. So, if you say that it is occurring in the second quadrant, it can lie somewhere in the B H curve, may be somewhere here. We can say that this is the characteristic, this is the operating point.

So, the operating point here means a combination of B i and H i. B i is the magnetic flux density in iron, H i is a magnetic field strength in iron. So, what we can say here is the following that this is our B i and the corresponding value in the x axis is H i. So, this is our operating point. So, for discussing about the characteristic of permanent magnetic motor will only talk about the second quadrant of the B H characteristic.

(Refer Slide Time: 07:55)



Now, let us try to see little more detail way. Now, we have already seen that H i is given by this expression now, we will try to derive; what is H i by B i? Now, if I redraw this characteristic here, what i am trying to do? I am only drawing the second quadrant characteristics, this is the y axis B this is x axis that is H and this is the second quadrant. Now, suppose the operating point here is B i this is the flux density and the corresponding H is here in the x axis that is H i. So, if this is B i and H I, I can draw a line through the origin passing through this particular point. Now, will try to see the significance of this line; now, let us assume that this angle between this y axis and this line is theta.

Now, if we are, if i am trying to find out what is tan theta, tan theta is given has H i by B i. So, what is H i? H i is the field strength and B i is the flux density, all right. So, this is what is tan theta? So, this I will write down this equation that is equal to H g l g by l i into B i by B g A g. So, we are trying to replace here H i and B i, what is H i? H i is replaced by this quantity. I am talking about the magnitude only. So, we will be only interested in the magnitude. So, we will forget the angle. So, i will say that the magnitude of this. So, it is H g l g by l i is H i. What is B i? B i is replaced by this expression; because we know that the flux is a same flux is passing through the iron and the air gap. So, according to this equation I can say that B i A i equal to B g A g. So, i can replace this B i by B g A g by A i.

So, we will further do some simplification. So, what will do here, we will again replace this H i by B by mu naught H i is the magnetic field strength in air and B g is the flux density in air. So, B g by H g is equal to mu naught, mu naught is the constant of permeability. So, we can say here that this is B g by mu naught into l g, I will separate this out, l g by A g i will bring A g here into A i by l i by B g. So, this above equation can be rewritten in the following fashion. The right hand side B g by mu naught into l g by A g into A i by B g into l i and now this B g and B g will be cancelled we can cancel this quantity with this. So, ultimately what we have is the following that is equal to l g by mu naught A g into A i by l i.

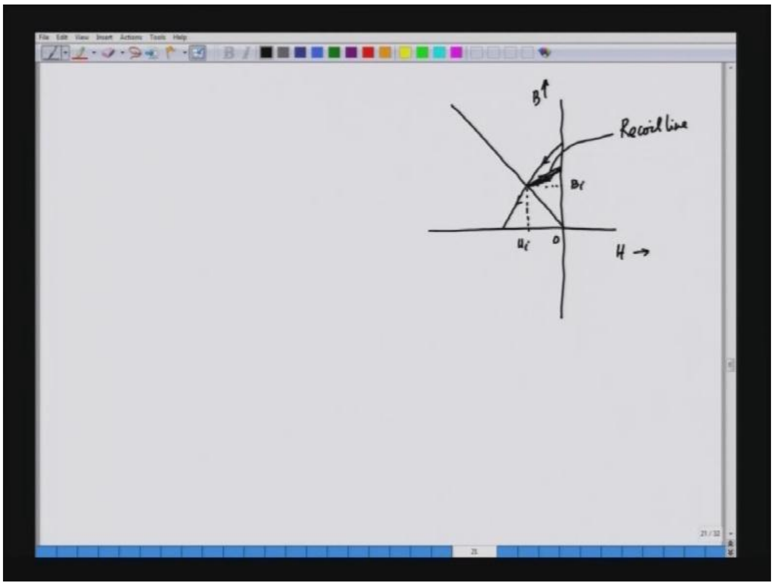
So, this is what we have here now what is this is basically tan theta. Now, if we see the right hand side of this equation which is given by this expression l g by mu naught A g into A i by l i. Now, we see that this quantity is basically the reluctance of the air gap. So, we can say here that is equal to the reluctance of the air gap into A i by l i. So, this is the reluctance of air gap into A i by l i. And that is also equal to 1 by permeance, we can say that is equal to 1 by permeance of air gap into A i by l i. So, this is equal to tan theta. So, we call it means theta is a major of the reluctant, if reluctant is more theta is more, if reluctance is less theta is less. So, we call this to be the permeance line or reluctance line, we can call this to be permeance line. So, we can call air gap permeance line. So, this is the significance of this line, this line gives a measure of the permanence or reluctance. Permeance is the inverse of the reluctance.

So, tan theta is given by this, we can say that this A i by l i is constant quantity, A i is the cross section area of iron, l i is the length of the iron those are constant quantities. So, this tan theta gives a measure of the permeance or reluctance of the air gap. Now, we can just go little further. So, if the reluctance is more, suppose; we can say that the reluctance is more, if the reluctance is more the air gap is more, if the air gap is more theta will be equal to a larger value. So, it means if you want to have a larger air gap this is the reluctance in this case and tan theta is proportional to reluctance.

So, i can draw another line for a larger air gap. So, this line will be for a larger air gap. So, this is for a larger air gap. So, if I increase the air gap, I will have a line which is having larger theta larger air gap means larger theta, tan theta value will be more. So, here theta will be here this is this is theta. So, I can say this is theta prime I will have still larger air gap. So, I will have still larger value of theta, I can say this to be theta double prime. So, if I increase the air gap, this line will shift in such a fashion theta will be more and more.

Now, if the air gap is made 0, this theta will also be equal to 0, air gap is made 0 means reluctance is 0. So, the reluctance is zero the right hand side of this equation will be equal to 0. So, left hand side is tan theta, theta is equal to 0. So, it means for 0 air gap I will have the line which is along the y axis. So, this line will correspond to 0 air gap all right. So, it means the varying these air gaps the line can shift from a vertical position to somewhere, were the air gap is maximum all right. So, when we vary this line interesting thing happens.

(Refer Slide Time: 16:48)

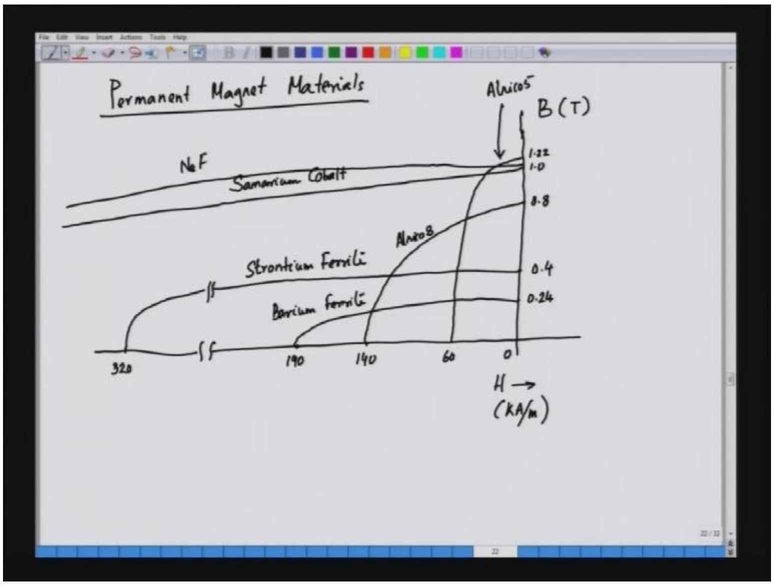


Let us see what really happens; now, we have already seen that we are talking about the B H characteristic of a magnetic material. And we are only confining our self to the second quadrant of the B H characteristic. This is B and this is H. So, this is our permeance line and this is operating point B i and this is H i and this is 0 the origin. Now, this point B is positive and H i is negative now, suppose we increase the value of current here. So, what we have here? We have winding in this case, in the winding we can pass some current and when the current become positive H i was negative, H i will gradually increase. So, if H i increases by increasing this current; what happens here? So, we will see that if H i increases the original curve is not traced. So, this will trace a different curve.

So, it will come somewhere here, again you decrease A i this will come somewhere here. So, the original curve is not traced, because; we have air gap this is the path in which we are travelling and here if you increase this current it will take a different path. Now, this line after something, if you again decrease this it will come back here, and after a few cycles this line will be stabilized and this line is called the Recoil line.

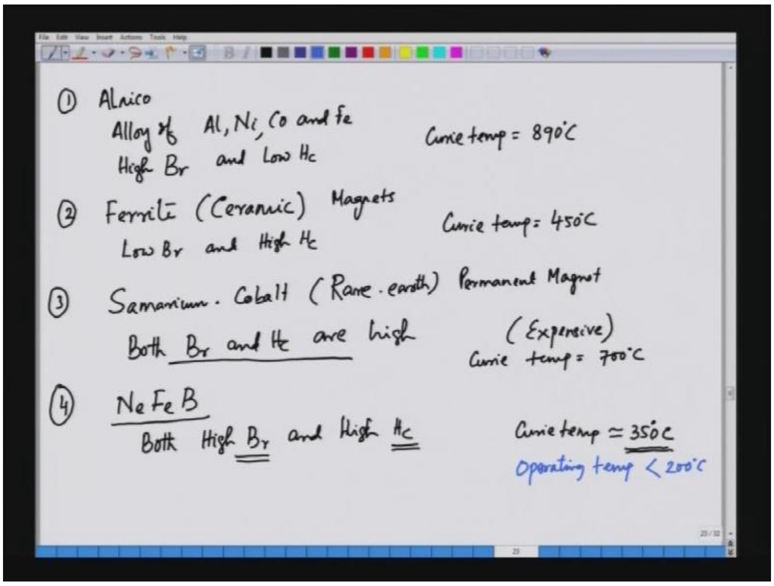
So, this recoil line is a line in which the characteristics move which is different from the original B H curve. This is the original B H curve and the recoil line is a line in which the characteristic actually moves when we increase or decrease the current, it departs the original B H curve. So, with this back ground let us go forward; now, what about the magnetic material? We have already seen the B H curve, and this B H curve is ultimately given by a magnetic material. So, we have various types of the magnetic material. So, we will try to discuss various types of magnetic material.

(Refer Slide Time: 19:35)



So, we will see that permanent magnet material and we can understand their behavior from the second quadrant of the B H characteristic. So, we have B in the y axis and H in the x axis we have the origin. So, this is the flux density and the unit of B is Tesla and unit of k in this case is H is kilo ampere per meter. So, we can plot the B H curve of typical magnetic material. Those are available for application in electric machines 1 type of magnetic material is called an alnico magnetic material. So, we will start with alnico.

(Refer Slide Time: 20:37)



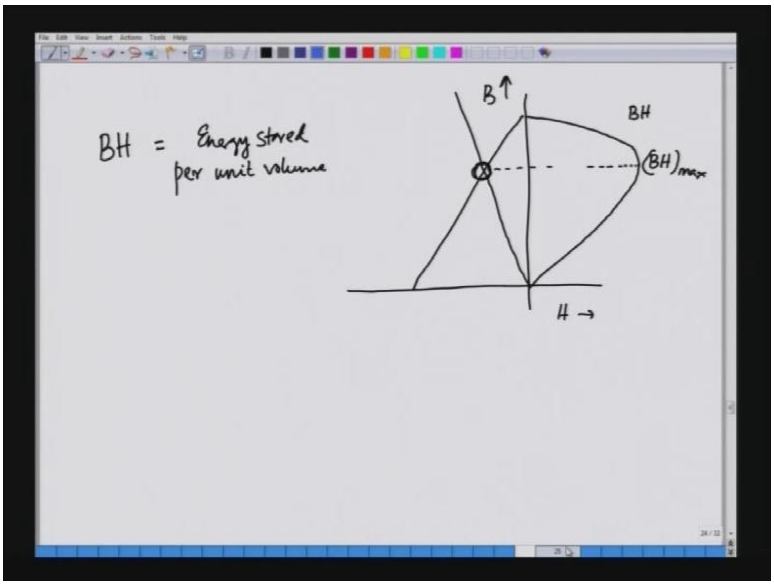
Alnico is basically, an alloy of aluminum nickel cobalt and iron. And this alnico material are classified by various number; alnico 5, alnico 7, alnico 9 and so on. Now, higher is the number better is the material. So, these classes of materials, permanent magnetic materials are characterized by a high B r and a low H C. So, we have high B r here, high B r means the residual flux or the residual magnetism. And low H c. So, we have a high B r or low H c. So, a typical material will be something like alnico 5 an alnico 5 will have a nature of B H curve which is something like this. This is approximately 1.22 and this is about 60 and this curve is drawn for alnico 5.

What about the other materials? So, we have alnico 8, and alnico 8 is having the following behavior or the following characteristics. This about 140 in the x axis so high B and low H c this is alnico 8. So, we have drawn this 2 graphs; 1 is for alnico 5 and other is for alnico 8 and alloy of aluminum nickel and cobalt. Now, let us say will have a different material called ferrite. So, ferrite we have say here 0.4, and then we will go up to 320 in this case. So, this ferrite are also used for permanent magnet electric motors and this is strontium ferrite. So, this strontium ferrite and now, what is the characteristic of ferrite.

Number 1 is alnico, number 2 is ferrite or they are also called ceramic magnets. They are characterized by a low B r and high H c, low residual flux and high cohesive force. As you are seeing here that in this case we have low B r, B r is very low here, this value is basically correspond to the flux density that is the residual flux is only 0.4 tesla. But H is 320 kilo ampere per meter, this is strontium ferrite. Similarly, we can have barium ferrite; barium ferrite is something like this 0.24 here, and will have something like 190. So, this is a curve for barium ferrite. And then we have another class of permanent magnet material called rare r permanent magnet material.

And they are something like samarium cobalt. So, this is the B H carve for samarium cobalt it goes like this. Samarium is a rare earth material and the allays of samarium cobalt and iron is called samarium cobalt permanent magnet materials. And samarium cobalt is also called rare earth permanent magnet and these are characterized by very high H c and B r. Both B r and H c high, So, we can say that both B r and H c are high here and there also be expensive, they are very expensive. So, we can also mention this they are expensive and they are used it those machines where you got to have very compact value. Because they have large energy density you will be discussing about energy density also. Energy density is a product of B and H.

(Refer Slide Time: 26:41)



So, if we have a material having this B H curve; B is in the y axis, H is in the x axis and this is second quadrant B H curve. We can also plot the product of B and H, the product of B and H will be something like this. So, this is B H product, B into H we are plotting this against H, against B here. So, here we have the maximum B H. So, this is B H max and B H gives the energy stored, the product of B and H give the energy stored per unit value. So, if you want to have very compact size, we have to in impact maximize B H, it means; the objective is that we have to operate this motor at this operating point. So, the operating here will be chosen that the B H product is maximum. And that is why we have to have very high B c B r and very H c also.

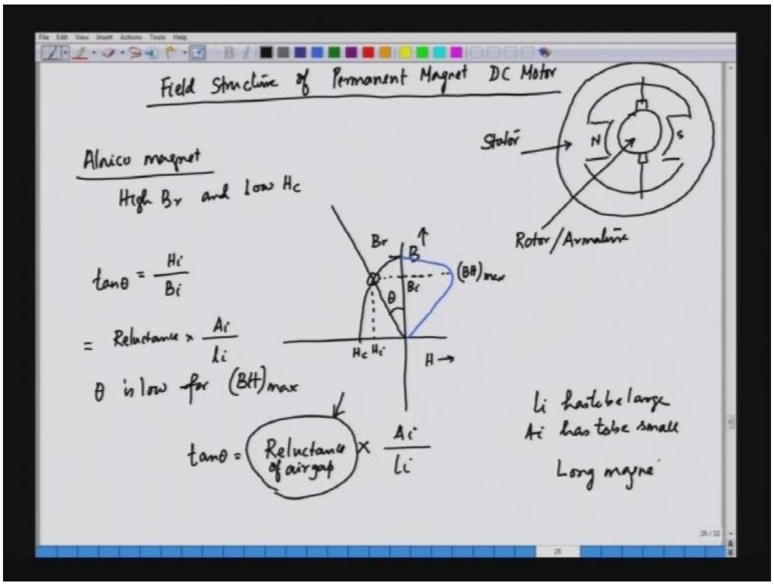
So, we can have material with very high B r and very H c and that material is basically in ideal material and samarium cobalt will be gives high B r and high H c. So, this is for rare earth material are samarium cobalt are both B r and H c are high. So, this is the graph for samarium cobalt. So, we can have very large energy density having samarium cobalt although this material is highly expensive. We also have another cross material called neodymium iron boron. So, we have another cross material called neodymium iron boron. So, this particular graph is for neodymium iron boron.

So, this is another cross material; N e F e B which is basically an alloy of neodymium iron and boron. This is the banished material we have, but; this material have some draw back we will try to see that. So, this has got both high B r and high H c. So, we have high residual flux as well as high cohesive force. This material have in fact, if you see the B H curve looks like this base material, but; unfortunately this material has got a low curie point. Curie point is a temperature beyond which the magnet material looses the magnetism. So, this are called a very low curie point. So, the curie point in this case is about, if you compare this, the curie temperature we can say that curie temperature in the this case is approximately 350 degree centigrade.

On the curie temperature of samarium cobalt is approximately equal 700 degree Celsius and about ferrite magnet the curie temperature is equal to 450 degree Celsius and for alnico the curie temperature is equal to 890 degree celcious. So, when we are operating the magnet material we should understand that the temperature of this material should be the below curie part, if it goes beyond that the material will use magnetism. So, although in neodymium iron boron the curie point is 200 or 350 degree Celsius the operation is restricted to 200 degree celsius, because; beyond 200 degree Celsius the metallurgical changes take place. So, we restrict the operating temperature here, in case of neodymium iron boron.

We can say that the operating temperature is less than 200 degree Celsius. So, although we have very high B r and very high H c, we have a very low curie temperature and hence; these are preference those application where, we know that the temperature is will not be high. So, with this back ground let us go forward. Now, if you see already that we have classified this motor into 2 categories the conventional d c motor having permanent magnet and then brass less d c motor and synchronous motor with permanent magnet.

(Refer Slide Time: 32:31)



So, we will try to see; the field structure of permanent magnet d c motor. Now, first a fall let us the field structure; the field is actually the stator. In this case; the motor is a d c motor, and in case of dc motor we know the armature is the rotor and field winding, field is a stator. Now, instead of field winding we have permanent magnet in the stator. So, the structure should be something like this. We have the armature, this is the rotor and we have the field which is the stator. So, here we have stator in this case, and this is the field we can have north pole and south pole. And here we have rotor, rotor is usually the armature.

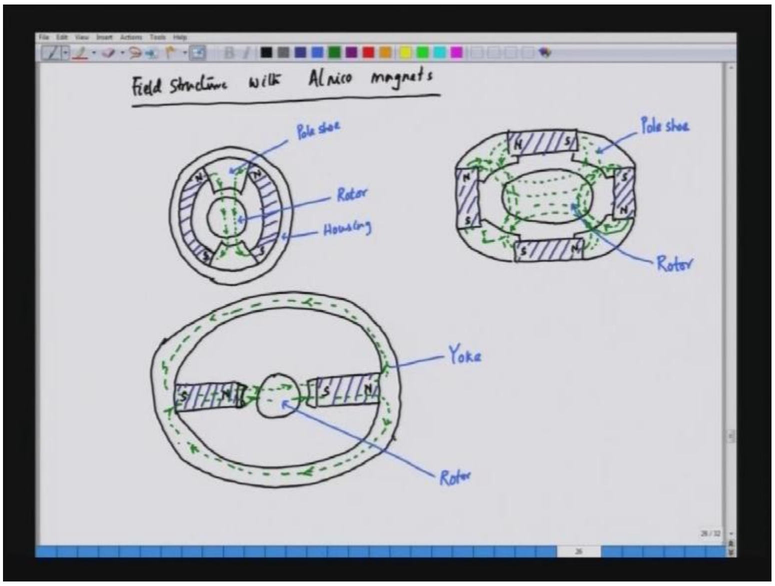
Now, let us talk over the alnico magnets; alnico magnets and ferrite magnets are less expensive. So, they are widely used, now if we see alnico magnets; we have already seen that in alnico magnets, we have high B r and lowest H c. So, let us write down in this case; we have high B r and low H c, high residual flux and very low cohesive force. So, in this case we have a structure like this, we have high B r and very low H c, these the B r and this is H c. Now, if we plot the B H product; the product B H product in this case will be something like this. Now, the product of B H gives energy density energy per unit volume. So, we should operate the material and its maximum B H value.

So, if we caught an air gap, the air gap should been such a way that B i and H i should be leading to the maximum B H product. So, this is the B H maximum and this should be naturally our operating point. So, this is the operating point, this angle is theta as we have all ready seen. So, we can say that tan theta here is equal to H i by B i that we have all ready seen. This is this is B i and this is H i and that is equal to the reluctance in to A i by l i. We already had seen this derivation little before. Reluctance of the air gap in to A i by l i. So, A i with the cross section area of iron, l i is the length of iron. So, tan theta is equal to reluctance of air gap into A i by l i. Now, if we are having ferrite magnet, the ferrite magnet has got high B r and low H c. B r is fairly high and H c is low very low in fact.

So, the maximum B H product occurs in such a way the theta is a low value; it occurs somewhere towards this B r top. So, theta is a low value here, usually theta is low in this case, for B H maximum. So, for maximum B H product theta has to be a low value. Now, if theta is low, what about A i and l i? Let us see we have this expression tan theta is reluctance into A i by l i. Now, the reluctance of air gap is a constant parameter, we cannot change this air gap length, air gap length is almost constant. So, this air gap length is almost constant. So, we cannot tamper with a change this air gap length. So, that is almost constant. So, what we can do here we can play with the magnet size, A i is the cross section area and l i is a length of the magnet. So, in this case we can choose A i and l i in such a way theta is a low value, it means l i has to be large has to be large and A i has to be small.

So, the ratio of A i by l i should be small and hence in alnico magnet we are going for long magnets. As you have seen that the alnico magnets should be long magnets, because; theta should be small tan theta should be small and air gap length cannot be tampered with, because; in a machine the air gap is fixed almost fixed. So, we can vary only the magnet size. So, to operate near this maximum B H product point, we have to have a long magnet which means l i have to be long and A i is the area has to be small. So, let us see some of the field structure using alnico magnets. And you see they are basically long magnets.

(Refer Slide Time: 39:05)



So, we have a structure like this field structure with alnico magnets. This is the stator structure. And what we do here; we put the magnets. And the magnet are long magnets. And we have the poles choose like this is the north pole and the south pole; we have the rotor. So, this portion is a magnet. And this is the pole shoe; which is made up of the soft iron.

And, this part is the rotor. This is the housing of the stator. And what about the flux lines? The flux lines will pass like this; the flux lines will start from the north pole will pass through the air gap and the rotor core; and will enter the south pole. This is the direction of the flux lines. Similarly, for this case this is the north pole the flux line will come out of the north pole; will enter the come from the pole shoe enter the rotor core. And then return through the south pole. So, these are the flux lines; in this motor were the magnets are basically long magnets.

Now, in all permanent magnets we should remember that the permanent magnet materials are very brittle. And they cannot be easily machined gives this kind of the long magnets; which can be fitted in the soft iron. So, the pole shoes are basically soft iron. And the magnet is long and little carbed and the magnet is fitted in the armature the starter housing with the pole shoe. So, that ultimately it creates north pole and south pole as we have seen. And another structure can be like this. So, we have again long magnets and this magnets are rectangular magnets.

So, what can we have here; we can have rectangular magnets. So, this magnets are like this. And here we have again north pole, south pole, south pole, north pole, north, south south and north. And this is the machine structure. So, this is the pole shoe here. This is the these are the magnets; these also the magnets long magnet with long large l i and small A i. So, the poles with basically a soft iron material and this facilitates the flow of the flux the rotor is in side. This is the rotor, rotor core.

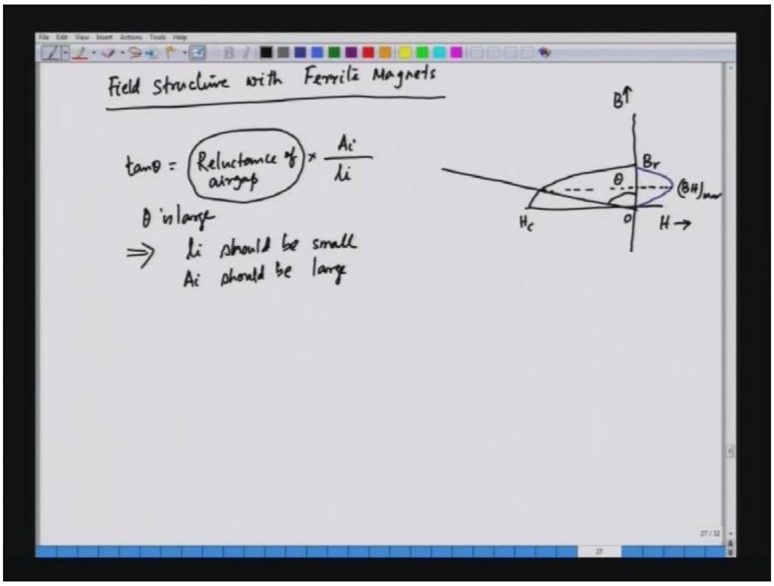
And what about the flux lines? The flux lines would be coming out of the south pole north pole and entering the south pole. So, this is one of the flux lines coming out of the north pole through the pole shoe and entering the south pole and again through the pole shoe. Similarly, here we have another flux lines from this coming out of the north pole and entering the south pole. And from this also and here also we have the flux lines coming out of the north pole and entering the south pole.

So, in this case we have a 4 pole structure and this is realized using 4 alnico magnets. And these magnets are long magnets. Now, we can we can have another structure also in which we have the rotor. And we have again long magnets; this is the magnet in this case and then we have stator core.

So, we have in this case the north pole here and the south pole here; we have south pole and north pole. In this case what we have here; we have the pole shoes here, and the pole shoes are made up of soft iron. So, this is the magnet we have; and here we have the rotor. This is the stator yoke; the flux lines will pass through the yoke here.

So, this starts from the north pole goes to the south pole compose a path through the yoke in the following fashion. This is the direction of the flux lines coming out of the north pole and entering the south pole. Similarly, on the other side we have the flux lines coming out of the north pole and entering the south pole. So, this is these are the structures of the field for alnico magnets. Alnico magnets are basically long magnets whenever they are used in electrical machines they are used as long magnets.

(Refer Slide Time: 48:59)

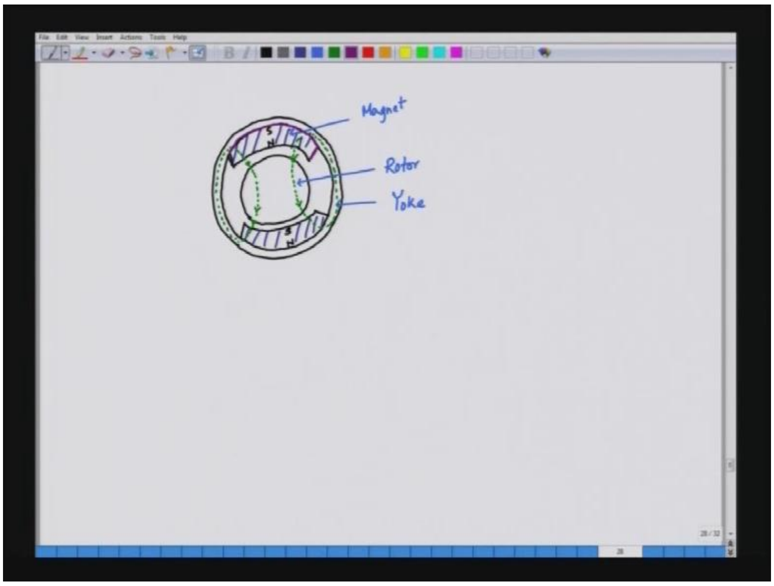


Now, let us see the ferrite magnets. Now, we will see the field structure with ferrite magnets. In ferrite magnets what we have low B r and high H c. If we have low B r and high H c theta will be large. If we draw the B H property at the B H characteristic of a ferrite magnet we will see we have low B r and high H c something like this. So, this is the flux density in the y axis and in the x axis we have H. And this is B r; and this one is H c. Now, if we flat the B H product the B H product would be something like this.

So, it means the B H product is maximum at a angle theta which is appreciably high, appreciably large. So, this is the B H maximum we have and this correspond to on operating point which is here. So, it means theta in this case is large. So, this angle is theta. So, it means if we are having a motor out of a ferrite magnet. Ferrite magnets are also very widely used we can we can use this magnets, but this magnet will result in high theta high value of theta. So, if high value of theta is achieved here. So, what is the theta; tan theta is reluctance of air gap into A i by l i.

So, if we want to have a high theta tan, theta will be large. So, to have large tan theta we will have low or small value of l i. So, it means theta is large here; which implies l i should be small and A i should be large. So, it means the reluctances of the air gaps is almost constant. So, we can have small l i and large area that is a i. So, this magnets are small magnets not large magnets small magnets, but having high width the cross section area is large. So, we will try to see some of this structure.

(Refer Slide Time: 52:03)



Using ferrite magnets we can say that this magnets will be sort magnets, but having large width. So, this is the magnet here; something like this. So, this magnet is with north pole here, south pole here, south pole here and north pole here and the rotor is here. So, this is the magnetic material we have this also the magnetic material.

And, then this is the rotor structure and this is yoke, this is the magnet, and what about the flux lines? The flux lines will be coming out of the north pole entering the rotor core going to the south pole and competing the path through the yoke. Similarly, we can have another flux line here. So, it is coming out of the north pole and entering the south pole. So, these are basically typical field structure using ferrite magnets. And in ferrite magnets the magnets are basically short, but the width is large. Here, this is the width of the magnet, the width is large.

So, the cross section area is large here, but the length this length is l I; l i is small here. And this is to maximize the B H product we are having this magnet. In the next lecture will be discussing about the field structure with the rare earth magnetic material like samarium, cobalt. And we will also see the structure of the machine when the magnetic materials are used for permanent magnet, synchronous machine and also for brass less d c motor.