**Course Name: Design of Electric Motors**

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**Title: Magnetic Materials and Concepts of BH Curves**

Greetings to all. In the last class, we have discussed about the basic principles of magnetic fields and magnetic field sources, Faraday's law, Ampere's law, Fleming's left hand and right hand rules, Thumb's rule, all those things we have discussed. In this class, we will discuss about the magnetic materials. What kind of magnetic materials we will utilize it for designing the magnetic circuits or our electrical motors and also we will discuss about the B-H curves. If we will see the periodic table of elements, there are 118 elements are exist as of now. This periodic table of elements all are exhibits the magnetic properties, whether it may be diamagnetic material or whether it is paramagnetic, whether it is ferromagnetic or anti-ferromagnetic.

From this periodic table, we can observe that all blue color one represents the diamagnetic materials and green color one represents the paramagnetic materials and red color we can see here few elements that elements exhibits the ferromagnetic materials and few other materials at different temperatures will exhibit different type of magnetic properties. Now, we will see how these materials will behave and what kind of materials from these 118 elements we will select for designing of magnetic circuits. First, I will discuss about the magnetic material, not only the diamagnetic, any type of material. We will discuss with respect to the basic terms magnetic domain, magnetic dipole and magnetic susceptibility.

These three terms I will utilize it for explaining the different types of magnetic materials. If we will consider the magnetic material here showing, this material is a combination of huge number of atoms. Let us consider a set of atoms whose magnetic fields are aligned in one particular direction that group of atoms we can call it as a magnetic domain. The definition if we will see, it is a region within the magnetic material in which the magnetization is in a uniform direction and magnetic dipole. It is a small or tiny magnet.

It is a combination of few magnetic domains, but if we will talk about the magnetic material, it consists of huge number of magnetic domains. Now, magnetic susceptibility is a measure with respect to this particular magnetic material. Let us assume that we are applying a magnetic field from this direction. How much this magnetic material is magnetized? How to measure that thing? That quantity is nothing but magnetic susceptibility. It gives a measure how much a material will become magnetized and it is a ratio of magnetization and magnetic field intensity.

Now, we will discuss about the different type of magnetic materials. First, I will start with diamagnetic materials. We can see the different type of diamagnetic materials as per the periodic table at right hand side as shown. Let us consider the diamagnetic material. If we will place in a magnetic field or let us apply a magnetic field to this diamagnetic material, the induced fields in this magnetic material are exactly opposite direction to the applied magnetic field.

Because of this reason, this magnetic diamagnetic materials will repels the applied magnetic fields and there is no movement in magnetic domains. magnetic susceptibility is negative and it is very small value. The susceptibility will not depend upon the temperature. If we will see the relative permeability of the material is less than 1, in the last lecture, we have discussed about the ampere's law. If the mu r value is very small or negligible, then there is no use of it.

Even though if we are utilizing the core, we are not at all increasing the magnetic flux density. This material will not enhance the magnetic fields. The examples for this diamagnetic materials are copper, silver, gold, zinc, silicon, bismuth, mercury, nitrogen and etcetera. We can see from this periodic table, all elements exhibits the diamagnetic materials. Next we will discuss about the paramagnetic materials.

Here also, if we place the paramagnetic material in a magnetic field, the induced magnetic field magnitude is very small and the direction is in the same as the applied magnetic field, but the magnitudes are very small. The magnetic domains are still randomly oriented because of the lesser magnitude of induced magnetic field and the susceptibility value is positive, but very small, almost negligible. For a diamagnetic materials, it is negative, but small value. For paramagnetic, positive and small value, there is no use of it. If we will utilize the core with respect to the paramagnetic materials, we cannot enhance the permanent or flux density.

The relative permeability of the paramagnetic materials also we will see here, it is very less even though it is greater than the permeability of the free space, but the value is very less. The examples for the paramagnetic materials are lithium, sodium, magnesium, potassium, calcium and all other elements which are green colored and highlighted in the periodic table. We can see at the right side corner. All this material exhibits the paramagnetic material properties. Now, we will see the ferromagnetic materials.

Similarly, here also, if we will apply a magnetic field, we can see in this figure. If there is no magnetic field, all domains are randomly oriented. If we will apply a magnetic field B to this particular type of magnetic material, all magnetic domains are aligned in one direction and induced magnetic fields also in the same direction of applied magnetic field. The simplest example I can give, how ferromagnetic materials will behave like consider a magnet, either it is a permanent magnet or electromagnet. I am showing with the electromagnet and take the simple iron piece.

If you will bring the iron piece into the magnetic field, all magnetic domains of iron are aligned in one direction and it will be attracted by the magnet. That is what we can see in this figure. All domains are directed or oriented towards the applied magnetic field, but the pole formation with respect to the iron piece and with respect to the source side are opposite. Here north is there and here south is there. Because of the attraction, opposite poles will induce in the iron piece.

The susceptibility value is large and positive and it will depend upon the temperature. If the temperature varies, susceptibility value also will vary. I am not giving the exact equation for the susceptibility, but it depends upon the temperature. The relative permeability value is very high. We can see the relative permeability for different materials like iron, cobalt, nickel.

Like for iron, it is 5000. For cobalt, 250. For nickel, 600. For cobalt, iron like alloys I am discussing with respect to the three materials, their respective alloys. For cobalt, iron with pure form 99.95 percent, 2 lakhs relative permeability and silicon plus iron, steels. We are utilizing steels in everywhere in all magnetic circuits. That permeability is 4000. The relative permeability is the unit less quantity because the mu value has the units and mu naught value also units and relative permeability does not have any units. The examples for the ferromagnetic materials are these things only, iron, cobalt, nickel and their alloys.

Anti-ferromagnetic materials, when there is no magnetic field, all domains are unaligned or oriented in different directions. If we will apply a magnetic field, there is a induced magnetic field in the same direction of applied magnetic field, but the magnetic domains are aligned in anti-parallel manner with respect to the neighbouring magnetic domain. The induced magnetic field magnitude is less or very less. So, susceptibility value is small and positive and mu r value is greater than 0, but almost negligible. The examples for this type of magnetic materials are manganese, chromium and many of their compounds like manganese oxide, manganese sulphide, chromium oxide and nickel oxide, etcetera.

And ferrimagnetic materials, this is the last type. Here the magnetic domains are aligned exactly opposite and parallel to each other. Here one line is in the same direction of applied magnetic field and other line or other fields are exactly opposite to the applied magnetic field. Similarly, other things. The magnetic domains are aligned with the induced or applied magnetic fields, but opposite and parallel in nature.

Because of the different magnitudes of these domains, parallel domains, there is a resultant magnetic field. The susceptibility value is large and positive. The relative permeability value also higher as compared to the anti-ferromagnetic materials, but slightly lesser as compared to the ferromagnetic materials. The examples are all ferrites like ferrous ferrite and nickel ferrite, etcetera. From this analysis, we have seen that ferromagnetic materials and ferrimagnetic materials are giving higher permeability values and higher susceptibility values.

Along with that, these materials are easy to magnetize as well as demagnetize. Because of these properties for designing the magnetic circuits, we will utilize only ferromagnetic materials as well as ferrimagnetic materials. Can we use the iron, cobalt, nickel, ferromagnetic materials directly or we have to utilize the alloys? Depending upon the application and depending upon the type of equipment, we can utilize the iron, cobalt, nickel directly also pure form, but the cost may be higher. Alloys will give the better performance with respect to the pure materials. I will consider a simple example of pure iron.

What are the characteristics of the pure iron? We will see here, it is soft and rust can happen or corrosion will happen and it is easy to melt, malleable, lower resistivity. Because of the lower resistivity, higher eddy current losses may happen in the pure iron material. In order to enhance these properties, we can add the iron plus some other materials, silicon, carbon, manganese, etcetera. Alloy is nothing but a combination of different materials. The properties of alloys, we can attain whatever the property we want.

Let us assume that we want the hard material. So, pure iron is soft, but if you want the hard, then we have to add some other element to iron. So, hard, rust free, higher strength, lower weight and lesser losses because of the higher resistivity. This higher resistivity is attained because of the addition of other element to the iron and at the end cost, design complex ability and life time, we have to check. Generally used iron alloys are in the magnetic systems.

We will see now carbon steel where iron plus carbon, we are utilizing the applications. We can see here construct the buildings, bridges, pipes, fittings, etcetera. Similarly alloy steel, iron plus carbon plus aluminum and other materials depends upon the application and depends upon what is the property we require. Based upon that, we will mix the composition of different materials and stainless steels. For example, 18 and 8 steel, here some typo mistake is there.

So, it is just 8, 18 and 8, 18 percent of chromium and 8 percent of nickel, we will utilize it for designing 18 steel and applications. We can see medicals, kitchen, mission bearings and etcetera. Magnetic cast iron where iron plus carbon plus steel and other materials are utilized for designing this carbon cast iron alloy. What are the magnetic materials used in the electrical missions? We can find in this IEEE papers by Andries Krinks. Different magnetic materials we can find in this table cobalt iron, nickel iron with respect to different material composition here, 49 percent cobalt and 49 percent iron and 2 percent of others, we will utilize it in the cobalt iron.

Similarly other materials like some non oriented SIFE, silicon steel where 1 to 3 percent of silicon and iron is the remaining portion. The flux density values we can see here for cobalt iron 2.1 tesla, for SIFE steel it is 1.15 and material densities also we can see. More details we can find in this IEEE paper.

These are the materials generally we will utilize it in the electrical missions. Now, we will discuss about the BH curves. When there is no magnetic field, let us consider the magnetic material and if you are not applying any magnetic field to that particular material, then all domains are randomly oriented. If you will apply a magnetic field B equals to 0 and finite value we are applying, then during that particular condition, all magnetic domains are aligned in one particular direction with respect to the applied magnetic field. Example also we have discussed with respect to the ferromagnetic material.

Now, the question is if you will remove this applied magnetic field, may be I am pointing out with the laser pointer, if you will remove this applied magnetic field, can we retain the same phenomena with respect to case 1? All domains will be randomly oriented. The answer is no, because of the magnetic fields that are applied at the previous stage and magnetic properties of the magnetic domains. So, if you will remove the magnetic field also, still some domains are aligned in the direction of applied magnetic field in the previous state. This is called as a magnetic memory or residual flux or retentivity, different names we can call it. In order to bring to its original state, where the magnetic domains are randomly oriented, in order to bring this situation, we have to reverse the magnetic fields.

If we will reverse the magnetic field, here at the left side corner, case 4 we can see, where the magnetic fields are reversed. If we will reverse the magnetic fields, we can attain the case 1, not exactly, but all magnetic domains are randomly oriented. If we will change the magnetic field like initially 0, then one direction and then we are reversing the direction of magnetic field. So, if we will vary the magnetic field in a AC manner, alternating manner, then we can see a loop formed by the magnetization curves.

That loop is called as a hysteresis. We will see in detail about the hysteresis loop in the coming slides. So, if we will vary the magnetic field in a AC manner, then we can see a hysteresis loop. Before going to the BH curves hysteresis loop, we will discuss the basic principles. The magnetic Ohm's law, where flux is equals to magneto motive force and divided by reluctance. It is the analogy with respect to the electrical circuits V by I and flux equals to B into A.

The flux lines are B fields in a particular area and Ampere's law gives the relation between the MMF and magnetic fields created by the current. In these two equations, we can see that flux is directly relation to the current and B is indirectly proportional to the current and H also is in the direct relation with the current. In electrical circuits, if we will consider the linear characteristics of VI, generally the resistance will not change. If the temperature is varying, then we may not see the linear characteristics. So, assume that here the resistance is not varying, then linear characteristics we will see.

So, similarly for magnetic circuits also flux versus MMF or B versus H, we will see the linear characteristics that is 1 by reluctance. Here also 1 by resistance IV characteristics, 1 by reluctance is nothing but permeability. If the magnetic circuit is ideal and if you are assuming it as a linear circuit, then there is no saturation and reluctance is assumed as a constant value, but most of the magnetic circuits with respect to the practical applications which will not use the linear characteristics. So, we will see the non-linear characteristics between the flux versus MMF or B versus H. So, here we can see that red color line is the saturation.

Even though if you will increase the current or if you will increase the MMF, there is no change in B value. If you will increase the current, H will change, but B will not change because at this point already all magnetic domains are aligned in one particular direction. The magnetic material will be saturated and the permeability during the saturation condition is 0. Now, we will discuss about the exact B-H curve or hysteresis loop. Consider a point at the origin where the magnetic domains of a material are randomly aligned.

Here current equals to 0 with respect to the excitation circuit and B fields as well as H fields equals to 0. If you will increase the current or if you will increase the MMF, so B fields will be increased and the magnetic domains will be aligned with respect to the applied magnetic fields. The magnetic fields are applied in this direction in a positive manner. So, few domains which are blue colored in this figure are aligned with respect to the applied magnetic field because of the lesser MMF and lesser B fields.

We can see here a line with respect to the B and H curve. Then we can observe that the magnitude of applied B field is less because of this thing, the less magnetization is happened here. If you will increase the current and if you will increase the MMF as well as B fields, then all domains will aligned in one particular direction. We can see here in this plot at point C where current B fields and H fields are reached to the maximum. If you will increase further the current or MMF, what will happen? If you will increase the current or MMF further with respect to the point D, there is no change in magnetization because all magnetic domains are aligned in one particular direction that is with respect to the applied magnetic fields. If any change in H or any change in current, there is no change in B fields that means, core is saturated.

Here permeability is equals to 0. If we take the slope with respect to this line, slope is 0. It is parallel to x axis. Now, if you want to bring back the magnetic material to its original state, what we can do is we will remove the applied magnetic field. If we remove the applied magnetic field, current will become 0 and MMF becomes 0, but the magnetic domains still in the direction of applied magnetic field in the earlier state that is D or C. So, we will see some magnetization in the material or we can call it, this state as a memory, magnetic memory or retentivity or remnants.

The definition for retentivity is it is a measure of magnetization left in the electromagnetic material after an external magnetic field is removed. The units are Weber per meter square or Tesla same as the B fields. If we want to bring back the material to its original state of A like where the all magnetic domains are randomly oriented, we have to apply the negative or opposite direction of B fields. So, from point E to F in order to attain the characteristics, we are reversing the applied magnetic field. Now, we are reversing in this direction, right to left and here left to right.

At the point F, the B fields equals to 0, but H is not equals to 0. This is called it as a cohesivity. The cohesivity definition is it is a measure of ability of a ferromagnetic material to withstand external magnetic field without the becoming demagnetized or simply we can say that the material reached to its original state where the magnetic domains are randomly oriented B fields equals to 0, but H is not equals to 0 magnetic field or intensity or MMF is there. Now, from F to G, still we are applying a magnetic fields in a opposite direction or current in a opposite direction. Then the material will reach to its maximum state where the magnetic domains are aligned in a reverse direction with respect to the applied magnetic field.

We are applying a magnetic field in this direction, right. So, all domains are arranged or oriented in the same direction. Similarly, it will be same if you will apply, if you will increase the B fields further or MMF further, then it will go into the saturation where there is no permeability. Permeability is equals to 0 and there is no change in B value, but the change in H may happen if you will increase the current. Similarly, retentivity we will see at the current, sorry, I point, we will see the retentivity again or magnetic memory and then if you will from the point I in order to bring the material to its original state that is J. So, we have to reverse the magnetic fields again at point I, we are reversing the magnetic fields direction.

So, then the magnetic material will retain its original state where all magnetic domains are in random direction. So, if you want to magnetize the material again, then we have to increase the B fields as well as H fields, then it will reach again to the point C. So, if you will see the B-H loop for an alternating quantity, we can see with the blue color dot point which is varying with respect to the from point J, C, E, F, G, I and J. So, that loop we can see that is the actual B-H loop for a material, if the alternating type of B fields are there. Next for soft magnetic materials and hard magnetic materials, how the B-H curves look like? We can see in this slide for hard magnetic material, wider B-H loops we can observe for soft magnetic materials, narrow B-H loops we can see.

So, the area under the curve B-H curve is represents the hysteresis loss, the energy dissipation or energy loss happening in every cycle we can say. The maximum flux densities or saturated flux densities we can see in this table, where ferrite has saturation flux density 0.3. Generally, we will utilize the ferrites for high frequency applications, SI steel and powder diurene, amorphous glass and MU metal, all these materials we can utilize it for designing the magnetic circuits. Generally, SI steels we will utilize it for designing the electrical missions, 1.2 for CRGO steel and 1 for CRNGO steel depends upon the composition, this value may be higher. Here CRGO is nothing but cold rolled grain oriented steel. Generally, we will utilize it this type of material in transformers, where the magnetic domain properties are aligned in one particular direction, whereas in CN or GBO cold rolled non grain oriented, the magnetic domains or magnetic properties are aligned in all directions. We will utilize it CN or GBO steel in electrical missions and generators. So, we will see the examples of soft magnetic materials and hard magnetic materials.

Here materials iron, cobalt, nickel and their alloys, all ferromagnetic materials will exhibit the narrow BH curve, comes under soft magnetic materials. Hard magnetic materials are used in designing of permanent magnets or permanent magnets by default has the wider BH loops. The example samarium, cobalt, alnico and neo dynamic magnets and strontium ferrites, all these materials consist of wider BH loops. So, with this I am concluding this class. In this class, we have discussed about the different type of magnetic materials, which type of magnetic materials we will utilize it for designing the magnetic circuits. Also, we have seen that how BH curves looks like. Thank you.