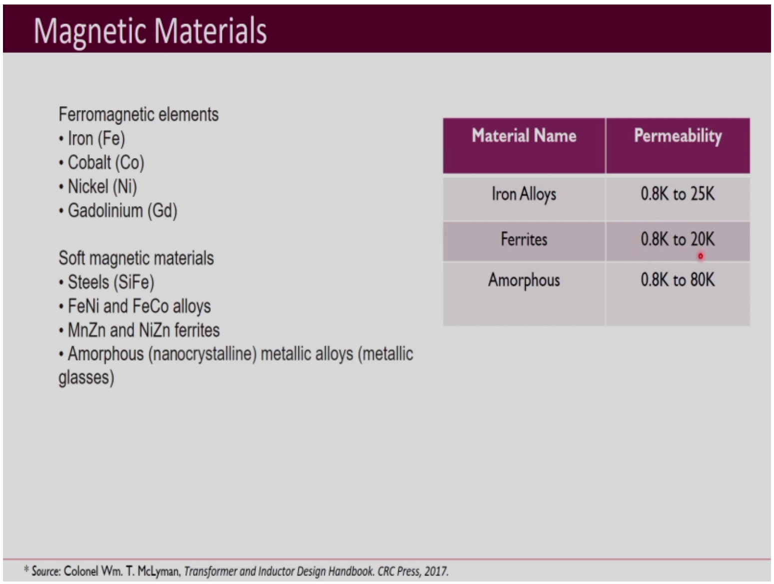
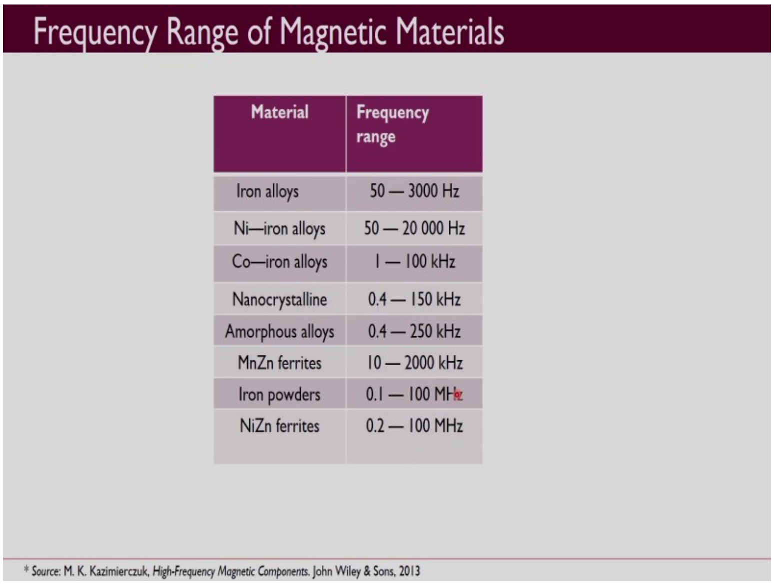
Design of Power Electronic Converters
Professor Shabari Nath
Department of Electronic and Electrical Engineering
Indian Institute of Technology, Guwahati
Module: Magnetics Design
Lecture: 47
Magnetic Materials

Welcome to the course on Design of Power Electronic Converters. We were discussing magnetics design. So, let us now look into the different magnetic materials that are used for making the magnetic cores.



So, the materials which are used for making magnetic cores are basically a ferromagnetic element and these are the main ferromagnetic element, such as Iron, Cobalt, Nickel and Gadolinium and their combinations are many times used to make the soft magnetic materials. So, soft magnetic materials mainly are of four types, one is steel based and second is iron alloys.

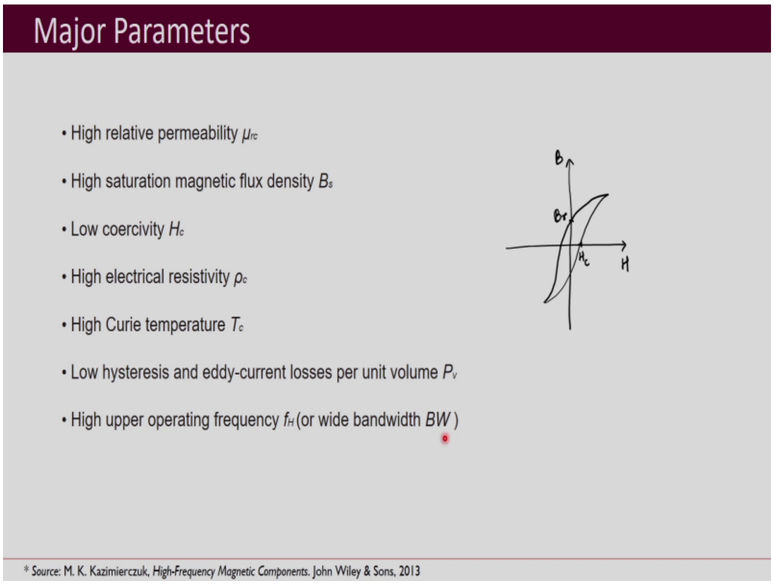
Apart from that there are ferrites and then there is amorphous material, which can be of metallic glass type or nanocrystalline type. So, permeability range is shown here. For iron alloys this is the permeability range and then for ferrites amorphous it is shown here. So, you can see that the amorphous materials have relatively much higher permeability range as compared to the Iron alloys and ferrites.



Material	Frequency range
Iron alloys	50 — 3000 Hz
Ni—iron alloys	50 — 20 000 Hz
Co—iron alloys	1 — 100 kHz
Nanocrystalline	0.4 — 150 kHz
Amorphous alloys	0.4 — 250 kHz
MnZn ferrites	10 — 2000 kHz
Iron powders	0.1 — 100 MHz
NiZn ferrites	0.2 — 100 MHz

Then we want to select a magnetic material for a particular Power Electronic Application. Then we have to see whether the chosen material is suitable for the frequency of operation or not. Now, this table shows the frequency range of magnetic materials. You can see here that the frequency ranges of Iron alloys are relatively lesser (*50 to 3000 Hz*). That means *3 kHz* is the frequency range in which the iron alloys can be used.

For example, you might have heard about CRGO (cold-rolled-grain-oriented steel). It is used in *50 Hz* power transformers. Then the other is nickel iron alloy or cobalt iron alloys, and their frequency ranges are relatively higher. Further as you go to nanocrystalline and amorphous alloys, their frequency range is also good. It is the nanocrystalline materials, which can be used up to *150 kHz*, and amorphous alloys can be used to about *250 kHz*. Then the ferrites come, and the frequency range of magnezinc ferrites is also good. Up till about *2 MHz* they can be used. Then, the Iron powders and nickel zinc based ferrites come, and their frequency ranges is even higher. They can be used about *100 MHz*.



So, you should be looking into the important parameters, when you select a magnetic material those are given here. One is this high relative permeability of the material and it should be as very high as possible. Then the saturation flux density comes and it is desirable to have high saturation flux density.

Then low coercivity H_c is there because coercivity is something what is required to make the magnetic flux density equal to 0. So, this gives H_c. So, this is the BH curve. So, this part is the coercivity and this part is the residual flux. You can call it as B_r. So, this should be as low as possible, which is the H_c value. Then, high electrical resistivity ρ_c comes.

Now, why electrical resistivity is important? We have discussed before about eddy currents. So, whenever we choose a magnetic core then there will be eddy currents in it and they should be as less as possible. So, one of the ways of reducing eddy current is by laminations. But, not all materials may support formation of laminations because they will be brittle material laminations, and that cannot be formed. Apart from that, stacking of the lamination is also a problem.

So, it is better to have solid cores, but then for that resistivity of the material should be high. So, the eddy currents that are produced would be less. Then high curie temperature comes. What is this curie temperature? It is the temperature at which the magnetism is lost. This is a very rough definition, and there are more precise definition, but for our purpose and for simplicity, just understand that curie temperature should be very high. If it is very higher, then it will be more ability of the material to withstand the temperature. Low hysteresis and eddy current losses per unit volume (P_v) should be there. So, the loss that is going to take place, that is the core loss and it should be low and per unit volume loss is provided by the manufacturer of these magnetic materials.

So, you should look into it that this P_v value, the core loss value per unit volume should be as low as possible. Then upper operating frequency range should be high. So, if it has very high frequency range up to which this material can be used, then that is very good. You can use it for wider frequency ranges. But however, depending on the particular requirement of frequency you should be looking into whether the material can be used for those ranges of frequencies or not.

Magnetic Materials (cont..)

Magnetic and Operating Properties of Some Iron-Based Soft Magnetic Materials

Material	FeSi, laminated	NiFe, nickel Steel, laminated			Powdered iron	Carbonyl iron
Contents	3-6% Si	Permaloy 80% Ni	Isoperm 50% Ni	Invar 30%-40% Ni	95% Fe bulk	92.5% Fe bulk
Permeability, μ_i	1000-10000	10000	3000	2000	1-500	1-50
B_{peak}, T	1.9	1	1.6	0.6	1-1.3	1-6-1.9
ρ, $\mu\Omega m$	0.4-0.7	0.15	0.35	0.75		$>10^6$
P_{loss}, W/kg	0.3-3 at 1.5 T/50 Hz	24 at 0.2 T/5 kHz	22 at 0.2 T/5 kHz	21 at 0.2 T/5 kHz		60 at 0.02 T/1 MHz
Curie temp. T_c, °C	720	500	500	500	700	750

* Source: Alex Van den Bossche and Vencislav Cekov Valchev, *Inductors and Transformers for Power Electronics*. Taylor & Francis Group, 2005.

This is a table which shows the properties of these iron based soft magnetic materials and those are mainly *FeSi*, then *NiFe*, powdered iron and carbonyl iron and they have their own composition. Here it is given for *3 to 6% of Si* and this *NiFe* again can be made in different compositions.

So, that is given for *3* compositions over here in this table. Then powdered iron composition and then carbonyl iron are there. So, first is the permeability which is very important. It should be as high as possible. So, here carbonyl iron's permeability is much lesser and as we go to powdered iron, then it increases. Then for *NiFe* it is further high and it depends on the composition of the material that is being used. Then further *FeSi*, this material has this very good permeability range of *1000 to 10,000*. Then it is B_p that means the saturation flux density. If you see B_p here, it is *1.9* and for *NiFe* isoperm *50% Ni* also you see that the saturation flux density is quite good and it is about *1.6*. Carbonyl iron also has good saturation flux density. Then further the resistivity should be as high as possible. Now, here you see all of these have lower resistivities whereas, this one carbonyl iron has got very good resistivity and P_{loss} should be as low as possible.

Here if you compare it, you can see here that this *Fesi* has very low P_{loss}. Of course, this is measured at a particular flux density, which is *1.5 T* for a particular frequency which is *50 Hz*. This material is FeSi which is specially used for *50 Hz* power transformer applications and curie temperature should be as high as possible. So, here you can see that, that *FeSi* and carbonyl iron have got very good curie temperature. The powdered iron also has very high curie temperature.

Magnetic Materials (cont..)

Magnetic and Operating Properties of Ferrites, Amorphous, and Nanocrystalline Soft Magnetic Materials

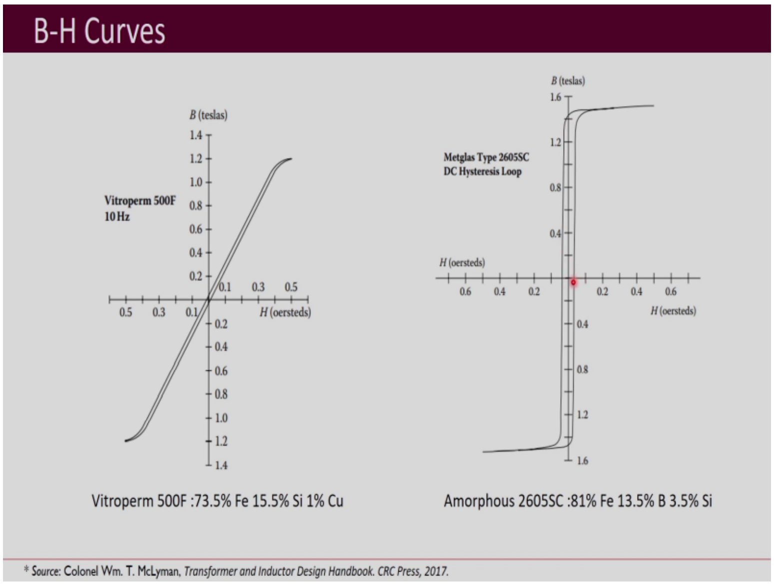
Material	Ferrites	Amorphous		Nanocrystalline
Contents	MnZn, NiZn bulk	73.5% Fe, ribbon thickness-5-25 μm	70-73% Co, ribbon thickness-5-25 μm	73.5-90% Fe, ribbon thickness-20 μm
Permeability, μ_i	1000-20000	10000-150000	10000-150000	15000-20000
B_{peak}, T	0.3-0.45	0.7-1.8	0.5-0.8	1.2-1.5
ρ, $\mu\Omega m$	$10^2 - 10^4$ MnZi $10^7 - 10^9$ NiZn	1.2-2	1.4-1.6	0.4-1.2
P_{loss}, W/kg	12 at 0.2 T/20 kHz 60 mW/cm^3	18 at 0.2 T/ 20 kHz	7-8 at 0.2 T/ 20 kHz	5 at 0.2 T/20 kHz
Curie temp. T_c, °C	125-450	350-450	400	600

* Source: Alex Van den Bossche and Vencislav Cekov Valchev, *Inductors and Transformers for Power Electronics*. Taylor & Francis Group, 2005.

Now, similar data is given here for ferrite, amorphous and nanocrystalline material. So, ferrites come in different composition like *MnZn*, different elements may be used here and amorphous again can also be manufactured using different elements and different composition. So, this is given here for this composition *73.5%* of *Fe*, then this one is for *70 -73%* of *Co* and for the nanocrystalline material, the composition there is used, which consists of *73.5-90%* of *Fe*. So, in permeability range all of these have very good permeability. Nanocrystalline has very high permeability.

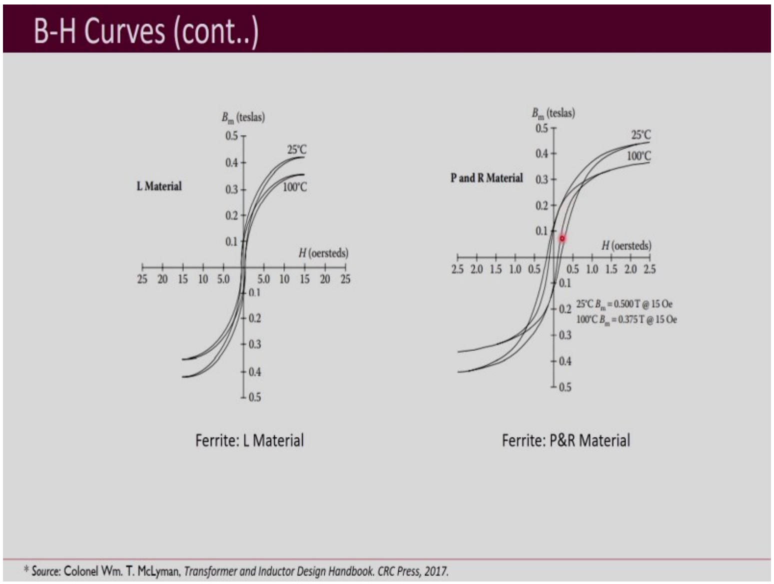
Then saturation flux density density of the ferrites is relatively less. So, although it can be used for very high frequencies, but the problem is that, you cannot push lot of flux density trades. You cannot use it for very high-power applications. Whereas, if you see here nanocrystalline material, it can be used for relatively higher switching frequencies in the range of *100 kHz* and the flux density is also good. It is about *1.2-1.5* which is close to *FeSi* material, then for resistivity if you see here, ferrites have very good resistivity and these other materials have relatively have much smaller resistivities.

Then P_{loss}, the core loss is going to take place per unit. I mean in terms of per kg this P_{loss} data is given. So, here you see that nanocrystalline has relatively lesser P_{loss} as compared to others. Nanocrystalline has got the highest curie temperature. So, these are the important parameters that you should be looking for and then you can compare the material which is going to be more suitable for design of inductors and transformers.



Now, depending on the material, BH curves can be very different, and there are different manufacturers of magnetic materials. They make the magnetic materials from different composition of different elements and based on it, obtained BH curve also is different. Now, here this is this material vitroperm 500 F. This is the name of that material and this has the composition, which is *73.5% Fe*, *15.5% Si* and *1% Cu*.

So, the obtained BH curve is like this. Then here this is expressed in oersteds and this is actually the CGS unit of H, magnetic field intensity and then amorphous 2605SC is another magnetic material and here this BH curve is given and you can see here that this BH curve is appeard to be very different as compared to this one. Here, residual flux is much higher of flux density, although the coercivity is lesser. Whereas, in this case both the residual flux and coercivity are very small.



Then, these are BH curves for L material and P and R material. You can see that the BH curve shape is again very different. So, here these are given for *2* temperatures, which are *25°C* and *100°C*. This is for L material. You can see that the BH curve is very thin. The width of it is very thin. Whereas, here you can see that for P and R material, this BH curve is thicker, and the width of it is higher. So, this is just to give you an idea that different materials will have different BH curves and so, you can look into them for your knowledge.

Ferrites Material Properties

*Magnetics Material Name	Initial Permeability, μ_i	Flux Density B_s @15 Oe	Residual Flux, B_r	Curie Temperature °C	Coercive Force, Hc Oe	Density Grams/cm³ δ
L	900	0.42 T	0.15 T	>300	0.94	4.8
R	2300	0.50 T	0.12 T	>230	0.18	4.8
P	2500	0.50 T	0.12 T	>230	0.18	4.8
T	2300	0.47 T	0.16 T	>215	0.25	4.8
F	5000	0.49 T	0.10 T	>250	0.2	4.8
W	10,000	0.43 T	0.07 T	>125	0.15	4.8

* Source: Colonel Wm. T. McLyman, *Transformer and Inductor Design Handbook*. CRC Press, 2017.

This is the data that is shown for the different ferrite materials and there is a manufacturer named by magnetics of the soft magnetic materials and they develop these ferrite materials. They have given different names to the different ferrite materials and these have slightly different compositions in them. There are differences among them.

So, that is the data, which is shown and named as L, R, P, T, F and W. That is the notation that is given to identify the material. So, you can see here the permeability, and the best permeability is obtained for this ferrite material W and then the saturation flux density is more or less the same, but relatively is higher for P and R materials.

For residual flux you can see here, that it is the lowest for W, and curie temperature again also vary. This L material has got the highest curie temperature, then for coercivity again you can see here that lesser coercivity is for this W and density is also provided, density is the same for all of them, but density is also something you should be paying attention to that because, it is the density which decides how much volume you will be needing for a particular amount of weight of that material. So, we do not want very heavy and at the same time, we do not want the size to increase.

Core Loss Coefficients for Magnetics' Ferrite Materials

$P_v = K f^m B_m^n$

k, m, n

Material	Frequency Range	K	m	n
R	f < 100kHz	5.597(10^-4)	1.43	2.85
R	100kHz <= f < 500kHz	4.316(10^-5)	1.64	2.68
R	f => 500kHz	1.678(10^-6)	1.84	2.28
p	f < 100kHz	1.983(10^-3)	1.36	2.86
P	100kHz <=f < 500kHz	4.855(10^-5)	1.63	2.62
P	f => 500kHz	2.086(10^-15)	3.47	2.54
F	f =< 10kHz	7.698(10^-2)	1.06	2.85
F	10kHz < f < 100kHz	4.724(10^-5)	1.72	2,66
F	100kHz<=f<500kHz	5.983(10^-5)	1.66	2.68
F	f=>500kHz	1.173(10^-6)	1.88	2.29
J	f=<20kHz	1.091(10^-3)	1.39	2.50
J	f>20kHz	1.658(10^-8)	2.42	2.50
W	f=<20kHz	4.194(10^-3)	1.26	2.60
W	f>20kHz	3.638(10^-8)	2.32	2.62

* Source: Colonel Wm. T. McLyman, *Transformer and Inductor Design Handbook*. CRC Press, 2017.

Then when we discussed the core loss calculations, at that time I told you that these coefficients are important. So, you may recall that this core loss per unit volume was given as

$$P_v = k\, f^m\, B_m^n$$

So, these *k*, *m* and *n* are empirical coefficients, which you have to note down to do the calculation of core loss. So, those data are provided by the manufacturer of the materials. You can see here this is for the same ferrite materials which are manufactured by magnetics. So, their frequency ranges are given and also the values of *k*, *m* and *n*, those three coefficients are provided by them, there are different manufacturers of these magnetic materials.

Similar Ferrite Materials

Manufactures	Material Designation						
Magnetics	L	R	P	F	J	W	
μ_i	900	2300	2500	3000	5000	10000	
Ferroxcube	3F45	3F3	3C94	3C91	3E27	3E5	3E7
μ_i	900	2000	2300	3000	6000	10000	15000
Fair-Rite		77	78		75	76	
μ_i		2000	2300		5000	10000	
EPCOS		N97	N72	T41	T65	T38	T46
μ_i		2300	2500	2800	5200	10000	15000
TDK Corp.		PC40	PC44	H5A	HP5	H5C2	H5C3
μ_i		2300	2400	3300	5000	10000	15000
MMG		F44	F45	F5A	F-10	FTA	FTF
μ_i		1800	2000	2300	6000	10000	15000
Ceramic Mag			MN80C	MN8CX	MN60	MN100	
μ_i			2050	3100	6500	9000	
TSC Ferrite Int.		TSF-7099	TSF-7070	TSF-8040	TSF-5000	TSF-010K	
μ_i		2000	2200	3100	5000	10000	

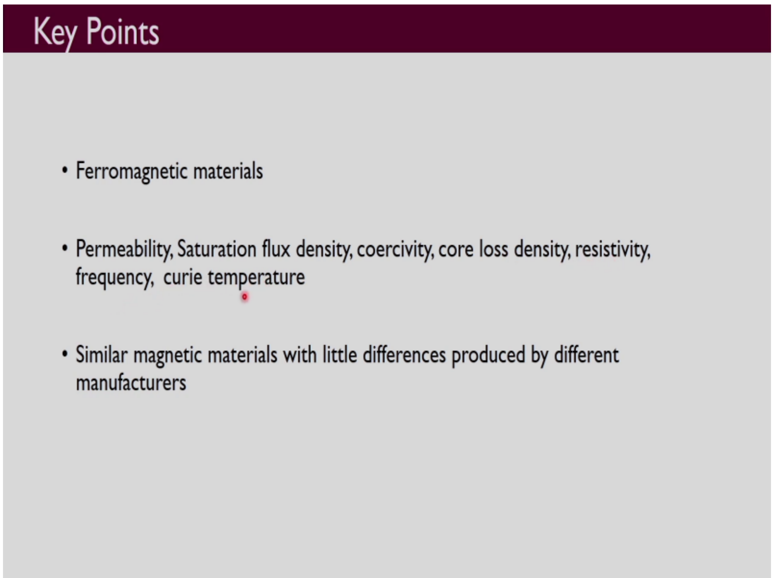
* Source: Colonel Wm. T. McLyman, *Transformer and Inductor Design Handbook*. CRC Press, 2017.

The well-known manufacturers here it is listed such as Magnetics, Ferroxcube, Fair-rite, EPCOS, TDK Corp and so forth, and they all make different magnetic materials, but there are some similarities among them. I mean, you can categorize them as the similar magnetic materials.

So, that is easy for you to choose. If suppose you are not able to get the magnetic material of one manufacturer, you can obtain similar magnetic material from other manufacture. So, this table is showing that. But note that the material may be similar, but their part numbers or their designation, the way in which they are denoted, are different or identified.

Now, here you can see this by magnetic. Magnetics ferrite materials are denoted like this L, R, P, F, J, W and so forth. This Ferroxcube like to give this number *3* before that and then for 3F45, 3F3, 3C94 and so forth, these permeabilities are given. So, for L and 3F45 the permeability is same. Similarly, these are the magnetic materials with different names, but, similar permeabilities are given here in this column.

Similarly, for other similar materials also by different manufacturers are listed here for different permeabilities. So, this is for the information that you can choose a magnetic material from any manufacturer and if you do not get that you can use another manufacturer. The part number will be different, but they have similar materials available.



So, what are the key points of this lecture? So, in ferromagnetic materials what are used for magnetic design and the important parameters are, such as permeability, saturation flux density, coercivity, core loss density, resistivity, frequency and curie temperature. Similar magnetic materials with little differences are produced by different manufacturers. So, looking on the parameters you can select the magnetic material which is going to be suitable for the application. Thank you.