Chapter 6: Magnetic Materials

Ferromagnetism

Because you will use ferromagnetic materials in virtually every power supply it is important that you know their advantages and how to avoid potential shortcomings that may crop up unexpectedly. When used correctly, such components save space, improve performance and increase power transfer efficiency at very little cost.

We will cover magnetic materials in this chapter, building on the foundations of magnetic theory we started in Chapter 5. You may want to review these important areas of study because it demonstrated several relationships of air-core design that we can now improve on by insertion of iron-based cores. We started off in the last chapter by reviewing the basic history and progression of magnetic field concepts and in this chapter we will do the same. It goes without saying that the use of iron compounds in power transmission has helped increase our quality of life on Earth probably like no other material.

When we calculated the inductance for the plastic toroid in Chapter 5, Example 5, we used the value of the local permeability, μ_0 - the permeability of free space (in a vacuum) and this yielded the proper values of magnetic B field for the various configurations we examined. It was discovered by early experimenters in the 1800's that incorporation of an iron core increased the inductance of a winding by large amounts and definitely to the benefit of the device that was being constructed. For example, all early telegraphs used iron as a core material because it not only constrained the field to regions where it was centrally utilized making the Morse Code sounder more sensitive but it allowed increased distance of telegraph lines as well as saving battery life due to reduced magnetizing currents. The experimenter's spark coil of the 1870's is another example where higher and higher voltages could be realized by incorporating an iron core on which to wind the step-up transformer. History shows from such devices came the discoveries of X-Rays, sub-atomic particles and of course the basics of radio.

Certainly to the early experimenters this seemed like magic and the ability to get something for nothing was widely employed. It's one of those little things in physics where freebies do happen (another example is the increase in breakdown voltage of a transistor with temperature), so let's examine this benefit a little further knowing that as you proceed, all of the inductors and transformers you will design someday will have magnetic material in their construction.

Calculating the B field requires a modification

Because the use of a magnetic material within a core increases the B field in the material, the original Ampere's law equation that we used in Chapter 5 simply does not hold true anymore. This must have embarrassed many a physicist to see a law go astray but they soon got things under control by modifying the original equation as we will soon do. Here is Amperes Law as we learned from the last chapter:

$\int B \cdot d\boldsymbol{\ell} = \mu_o\, i$ Ampere's Lawdoes not work when magnetic material are present (6-1)

It has a problem because if the toroidal plastic piece of Chapter 5 were replaced with an iron ring of the same dimensions the B field created within would jump from 188 microTesla to over 500,000 microTesla, a three thousand fold increase. Likewise, the inductance of this device would increase this factor as well. The first question we should ask is: How does this happen?

The short answer for the increase in magnetic field is simple. Atoms that make up iron are really themselves tiny magnets and simply line up when asked to do so – all adding their collective magnetism to produce a substantially larger value. Several elements have this unique ability to do this: iron, nickel cobalt, gadolinium and dysprosium, the last two elements are from the lanthanide series of rare earths.

Normally in a piece of iron the atoms are randomly oriented and pointing in all directions due to the thermal vibrations present in the material. Because of this the net effect is zero and we say the iron is un-magnetized. When working on a car you have to admit that the iron used in its construction is un-magnetized. If it wasn't your tools would quickly stick to the fenders or engine (if cast iron) making work on a car very difficult. The iron is un-magnetized because that is how it is formed at the factory. But, add a small external magnetic field from, say, a permanent magnet placed near the engine block and the iron atoms within the block rapidly orient themselves and produce a corresponding magnetic field of opposite polarity. The regions in the iron just before the magnet sticks become reverse in pole orientation and attract the permanent magnet causing it to stick to the engine block. If the magnet is removed many of the atoms revert back to their scattered orientations but a small percentage still show local alignment. If you had a sensitive enough magnetic field detector you would see that the region where the magnet was touched shows an area of small magnetic field. This of course wears off after a while from temperature and vibration – the atoms of the iron rearranging themselves to a net zero after a certain time constant.

In 1907 The French scientist Pierre Weiss discovered that regions within magnetized iron were much larger than just separate atoms and the bulk piece of ferromagnetic material is really divided into tiny spots called magnetic domains. Within each domain, the spins are aligned, but in the un-magnetized state the spins of neighboring domains point in different directions and their collective magnetic fields cancel out. When the object has no net large scale magnetic field you can say this would be the lowest energy state. This is the iron you find in a junkyard. If you found a large magnet in a junkyard you would know and prize it highly. Iron metal where the domains are already oriented is quite rare and as you know, we call such items “permanent magnets”.

To be sure, these magnetic domains are very small, usually less than a micrometer in size making it impossible to see them with your unaided eye. Figure 6.1 shows a photomicrograph of neodymium iron boride, a magnetic material used to make the powerful rare earth magnets. Looking closely within the grain outlined you can see the regions of magnetic domains. They are the light and dark stripes where the magnetization of the neighboring regions are very different. If you put this specimen in a magnetic field these domains would quickly move around, aligning with the field and adding their own contribution. When such a ferromagnetic material is used in a power transformer the domains can grow and shrink very rapidly at rates over 1 MHz

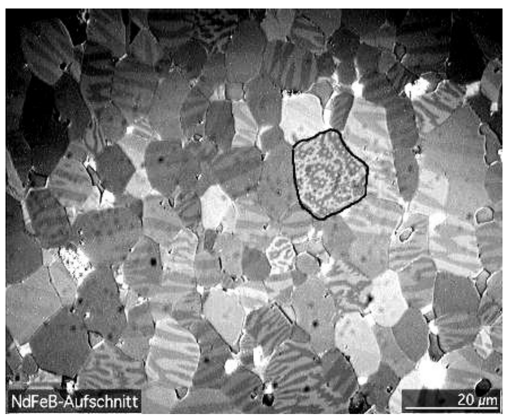

Figure 6.1: Domains in neodymium iron boride (Gorchy)

It is interesting to note that when a magnetic material is placed in an external magnetizing field the magnetization of the material adjusts in a series of discontinuous changes, causing “jumps” in the magnetic flux of the iron. Such surges can be detected by winding a coil of wire around the iron piece as a pickup, and place the signals produced into an audio amplifier and loudspeaker. Bringing a permanent magnet close produces current pulses in the coil, which when amplified produce clicking sound in the loudspeaker due to the sudden transitions of these domains. This strange crackling sound, which has been compared to candy being unwrapped, was first discovered by German physicist Heinrich Barkhausen in 1919 and is called *Barkhausen Noise*.

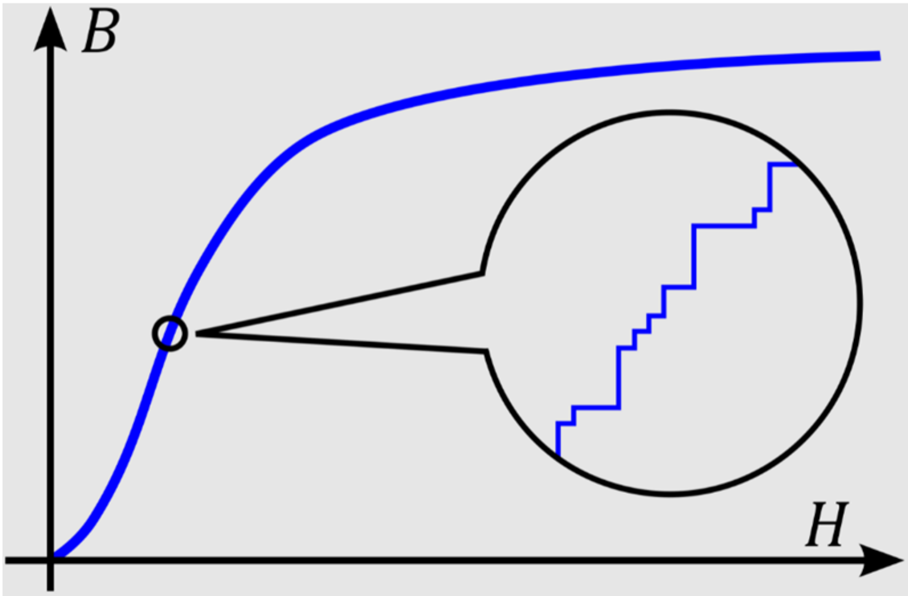

Figure 6.2: BH curve showing discrete Barkhausen steps (Stannered)

Figure 6.2 shows an increase in internal magnetic B field as the driving H field (more about this later on) increases. As you would expect, different ferromagnetic materials show different degrees of B field increase. This "gain" is usually not linear and quite sensitive to ambient temperatures. Since all freebies have a limit, the B field gain in a ferromagnetic material reaches a maximum value and cannot go any higher. This is called *magnetic saturation*. The value of the magnetic field at this point is called *Bsat* and has the units of Tesla (or gauss). When this happens all of the magnetic domains are pointed in the same direction.

To mathematically model this gain in both B field and inductance we have to introduce a term, μ_r, called the *relative permeability* of the material. This is the gain factor you get when a ferromagnetic material is inserted fully into the winding. The inductance of our plastic toroid will increase by an amount equal to the relative permeability of the core material as long as we don't drive the inductor too hard. To keep things consistent, we give relative permeability of air (really a vacuum) the value 1.0 because there is no gain in magnetic field or inductance of an air-core device. Table 6.1 lists the relative permeabilities of some common materials, and as you can see, several have very high values.

Table 6.1:
Magnetic relative permeability data for selected materials

Medium	Relative Permeability
Metglas 2714A (annealed)	1,000,000
Iron (99.95% pure Fe annealed in H)	200,000
Permalloy	100,000
Mu-metal	20,000
Electrical steel	4,000
Ferrite (manganese zinc)	350 – 20,000
Ferrite (nickel zinc)	10 – 2,300
Ferrite (magnesium manganese zinc)	350 – 500
Ferrite (cobalt nickel zinc)	40 – 125
Nickel	100
Aluminum	1.000022
Wood	1.00000043
Air	1.00000037
Vacuum	1.0
Copper	0.999994
Water	0.999992

You may recall in electrostatic theory the relative dielectric constant of a material is a number that shows a capacitors increase in value when that dielectric is used in a capacitor instead of air. Likewise the relative permeability of a material can be used to calculate the increase in B field or inductance when that particular material is used.

To make it easier to predict the B field in a winding, we need to start with an equation that remains invariant whether we place a ferromagnetic material inside a coil or not. This is called the H field whose magnitude only depends upon the current flowing through a winding and nothing else. Taking a cue from Amperes Law we define the *magnetic field strength* vector H as:

$$\int H \cdot d\boldsymbol{\ell} = i \qquad (6\text{-}2)$$

where i is the current flowing through the wire. Remember finding the magnetic field at a distance Ro from a wire carrying a current i ?

We can find the H field just as easy as we did the B field for a current carrying wire :

$$\int H \cdot d\boldsymbol{\ell} = i$$

$$H\,(2\pi)\,r = i$$

or

$$H = i / 2\,\pi\,Ro \qquad (6\text{-}3)$$

For a one inch distance from the wire (Ro = 0.0254 meters) carrying 20 Amperes the H value is:

$$H = (20) / 2\,\pi)(0.0254)$$

$$H = 125.31 \quad Ampere / meter$$

Notice the units that are used for this parameter.

Following the above process when dealing with inductors or transformers of more than one turn, the general relationship for the H field is, :

$$\int H \cdot d\boldsymbol{\ell} = N\,i \qquad (6\text{-}4)$$

where N is the number of turns. Because of this, the proper units for the H field are officially:

$$H = 125.31 \quad Ampere\text{-}turn / meter$$

Many times you will just see it simply listed as Amp/meter which does not take into account multi-turn windings. Also, you may have seen and used the older unit for the H field: Oersted. There is a conversion:

$$1\ Oersted = 80\ Ampere\text{-}turns\ /meter \qquad (6\text{-}5)$$

Magnetic material vendors often display a B-H curve in their data sheets. We will have to use one shortly.

What happens to the B field if we wind our inductor with a ferrite toroid ? Let’s go back to our plastic toroid and determine the H field magnitude first and put that into the BH curve of the ferrite:

Example 1: A plastic toroid of 5.08 cm outer diameter and 3.18 cm inner diameter having a height of 0.8 cm is wound with 125 turns of # 28 AWG magnet wire. As it passes a current of 0.2 Ampere, determine the H field within the plastic toroid at a radius of 2.065 cm from the center (halfway in the core – dotted line).

Solution:

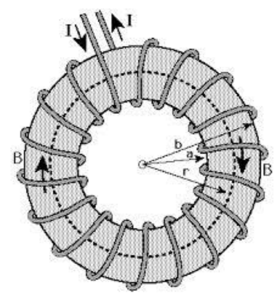

Figure 6.3: Toroidal inductor wound on plastic form

Using Ampere's law dealing with H field we can calculate the magnetic field within such a toroid:

$$\int H \cdot d\ell \;=\; N\,i$$

around a path of radius r gives:

$$H \quad = \quad N\,i\,/\,\ell$$

since the length is bent around on itself, $\ell = 2\,\pi\,r$

$$H \quad = \quad N\,i\,/\,2\,\pi\,r \qquad\qquad (6\text{-}6)$$

We want the B field at a radius of r = 2.065 cm, which is the center dotted line of the ring.

$$H(\text{at dotted line}) \quad = \quad (0.200)(125)\,/\,(2\pi)(0.0265)$$
$$H(\text{at dotted line}) \quad = \quad 150.1 \text{ Ampere – Turns / meter}$$

Almost 2 Oersted. Now, let's replace the plastic toroid with one made of 3C91 ferrite. All we have to do now is look up the BH curve for the ferrite material and check where 150.1 A-T/m would be on the X axis and read the magnitude of the B field on the ordinate or Y axis. This may sound like a roundabout way of finding the B field it has to be this complicated because the B field changes with excitation and temperature not to mention mechanical pressure. Figure 6.4 shows this for the popular ferrite material 3C92.

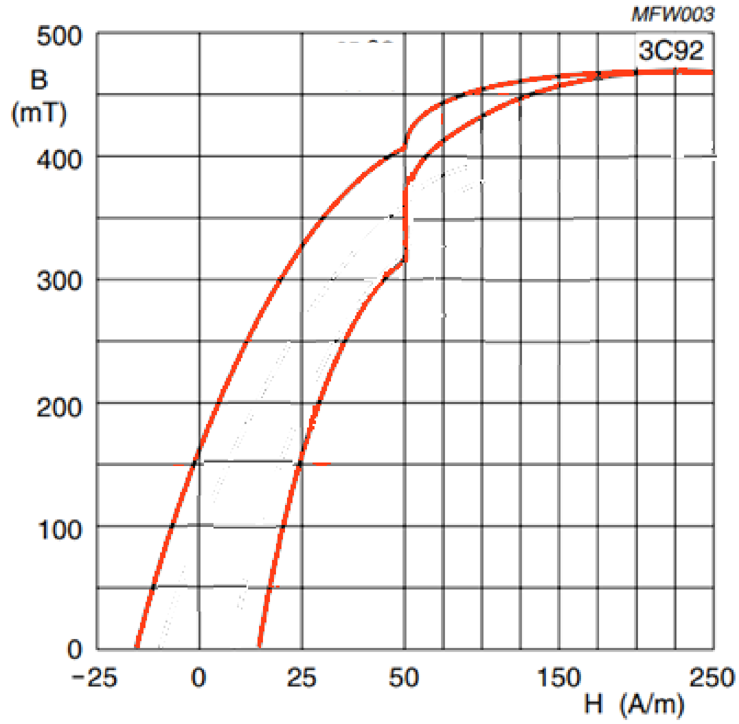

Figure 6.4: 3C92 BH curves

Because a BH curve can have two values for the B field due to hysteresis effects (the magnetic material retains some B field even as the H field is shut off), we can get an average of the B field range. Using the H field of 150.1 A-T/m shows that our B field is about 0.46 Tesla (4,600 gauss) at room temperature – the red curve. Notice too that the curve has significantly bent over meaning that any increase in H field would not produce much corresponding increase in B field. This is the saturation region. An old rule of thumb for ferrites was that anything larger than 1 Oersted would drive the ferrite into saturation. You can see this from our B-H chart for 3C92 when H = 80 Amp-Turn/meter (1 Oersted) the B field is in saturation. Almost all ferrites follow this rule of thumb.

Is saturation bad? It can be. Many engineers are bitten by the saturation problem because they designed their power transformer not taking into account all of the factors that a customer may subject their product to. High input line, elevated temperatures, and greater than usual loads can drive the converter transformer towards regions of higher B fields and possible saturation. When a magnetic core saturates, it's inductance drops – usually increasing the current flowing. When this occurs, the magnetic material usually rises in temperature due to more losses from higher current – driving the core further into saturation. A saturated core raises the risk of a thermal runaway and forcing the component, usually a transformer to seriously heat up – perhaps to the point of catching fire. Core saturation is an important danger to be concerned about.

On the other hand, there are some cases where a saturating core material is required for operation in power converters such as the Royer or Jensen oscillator. Magnetic amplifiers that control huge electric motors would not operate if it wasn't for the idea of saturation, but as you can see, this depends upon the utilization. If the H field is reduced and the core comes out of saturation no lingering ill-effect is seen.

In our toroid the maximum B field for 3C91 ferrite is about 4,600 gauss. What would happen if we used another ferromagnetic material? Figure 6.5 shows that if we used steel, we could pass 3 times the current before saturation begins at 14,000 gauss (1.4 Tesla).

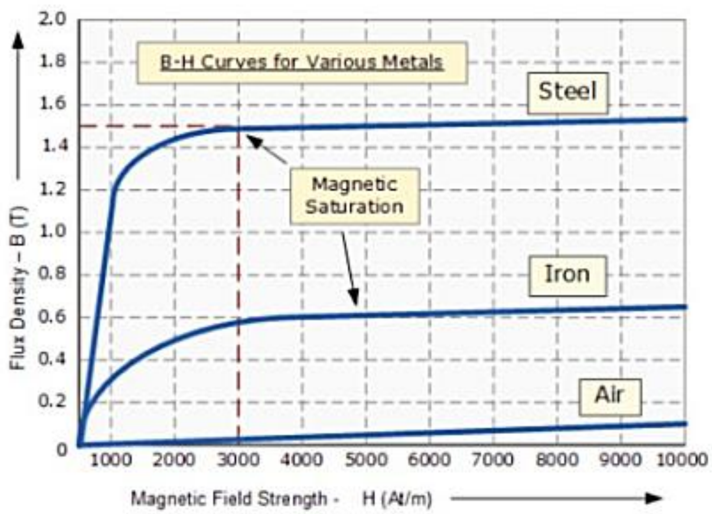

Figure 6.5 BH curve for iron

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Inductance with an magnetic material core

We have said that when a ferromagnetic core is placed inside a winding the increase in inductance is defined as being caused by the increase in relative permeability for that region. To utilize this value all we have to do is insert it into the equation for inductance. Consider the air-core solenoid where the inductance is given by:

$$L = \mu_o N^2 Ae / \ell e \qquad \text{(air core inductor R << } \ell\text{e)}$$

where Ae is the cross sectional area and ℓe the length of the inductor. Multiplying that equation by the relative permeability gives us the equation for the inductance a linear solenoid wound on a magnetic material:

$$L \quad = \quad \mu_r \mu_o N^2 Ae / \ell e \qquad \text{(ferromagnetic core inductor)} \qquad (6\text{-}7)$$

where μ_r is the *relative* permeability as discussed earlier. Normally the relative permeability can be obtained from the B-H curve of the material by looking at the slope of the line:

$$\mu_o \mu_r \quad = \quad dB/dH \qquad (6\text{-}8)$$

Figure 6.6 shows the relative permeability plotted as a function of H along with the corresponding B field. As you can see, the μ_r value varies widely and this makes it hard to determine exactly what value to use. Starting with the slope of the curve at small H values we get the initial permeability μ_i. When the material approaches saturation, μ_r drops rapidly after passing a point of maximum permeability μ_m. When you drive a transformer it travels through all of the regions shown.

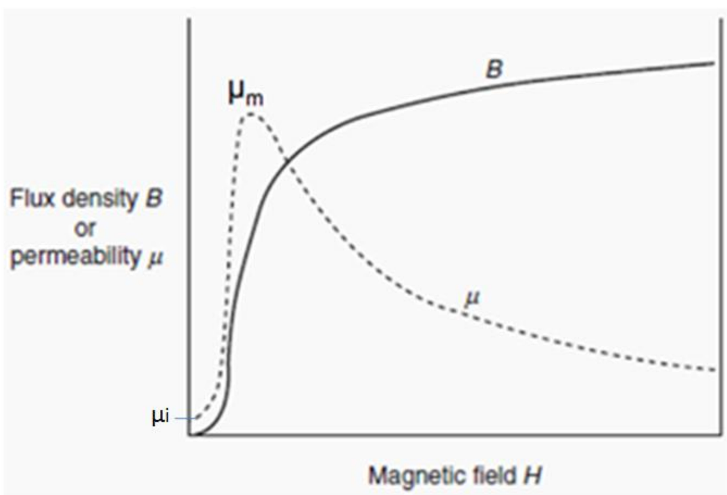


Figure 6.6: Permeability vs H field

Some vendor catalogs list μ_i because it is easy to measure where H is nearly zero. But that is a value that is usually much lower than the maximum permeability as Figure 6.6 indicates. It becomes a challenge to determine exactly what value of permeability to use in calculating the inductance of your device. Probably the best answer for what to use in the form of relative permeability is found in a vendor's information catalog on their material. For example, sometimes a vendor will publish the A_L values for a particular core. This gives the inductance value as a function of the number of turns. Old Ferroxcube catalogs would specify $A_L$in mH/100 turns while newer ones list nH/turn-squared. Whatever type of A_L is used, just remember that inductance is always based on the square of the number of turns.

Example 2: Figure 6.7 shows the data sheet for a 2616 ferrite pot core. How many turns are needed to fabricate a 1.5 Henry inductor from an up-gapped set of 2616 cores made of 3C91 material?

Solution: The datasheet shows the inductance factor for 3C91 material, the A_L value 6700 nH/turn^2. From this, finding the inductance is easy:

$$L = A_L N^2 \tag{6-9}$$

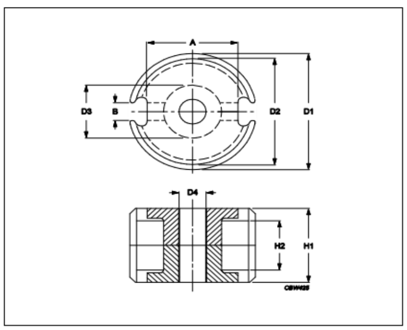
$$1.5 = (6700E\text{-}9)\, N^2$$

$$N = 473 \text{ turns}$$

Product specifications

FERROXCUBE
A YAGEO COMPANY

Core **P26/16**



Effective parameters			
	Parameter	Value	Unit
Σ(I/A)	*core factor (C1)*	0.4	mm^{-1}
Ve	*effective volume*	3530	mm^3
Le	*effective length*	37.6	mm
Ae	*effective area*	93.9	mm^2
Amin	*minimum area*	77.4	mm^2
m	*P26/16*	≈ 20	g/set

Dimensions for product: P26/16						
	Nom	Tol +	Tol -	Max	Min	Unit
A	18.00	0.40	0.40	18.40	17.60	mm
B	3.80	0.60	0.60	4.40	3.20	mm
D1	25.50	0.50	0.50	26.00	25.00	mm
D2	21.20	0.80	0.00	22.00	21.20	mm
D3	11.50	0.00	0.40	11.50	11.10	mm
D4	5.40			5.40	5.40	mm
H1	16.10	0.20	0.20	16.30	15.90	mm
H2	11.00	0.40	0.00	11.40	11.00	mm

Inductance factor				
Material	Value	Tol +	Tol -	Unit
3C91	6700	25%	25%	nH/turns²
3D3	2150	25%	25%	nH/turns²
3H3	5000	25%	25%	nH/turns²
4C65	386	25%	25%	nH/turns²

Power loss: 3C91				
Measuring conditions			Max	Unit
100 kHz	200 mT	60 ºC	1.800	W/set

Bsat					
Measuring conditions			Material	Min	Unit
25 kHz	250 A/m	100 ºC	3C91	320	mT

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Figure 6.7: Typical pot core ferrite catalog page

Common Ferromagnetic materials:
As mentioned earlier, it was found that ferromagnetism only occurs in a few elements. Over the years materials scientists have discovered many different compounds that show magnetic behavior that can be utilized for inductors or transformers. In addition to pure elements like iron and nickel that show this effect, there are many iron alloys that are ferromagnetic as well and some that are not. For example, some alloys such as the Heusler alloys oddly enough are ferromagnetic but don't contain any ferromagnetic elements at all! Discovered in 1903, the alloy Cu_2MnAl has a room-temperature saturation value of around 8,000 gauss, nearly twice that of 3C91 ferrite but low permeability (less than 100) and only stands out as a curiosity compound at the present. Conversely, there are some stainless steel alloys such type 304 that are composed of almost 70% iron yet show no signs of ferromagnetism. That is why screws made of 304 may be used with magnetic cores to hold the assembly together without any problem – iron screws will heat up as the core transcends its BH curve in operation.

The most popular ferromagnetic materials for the power conversion industry are silicon steel, permalloy, metglass, ferrites, MMP and powdered iron. We will look at each one separately because they come up constantly in electrical designs.

Silicon Steel
Silicon steel is by far the most common ferromagnetic used in the world. Nearly all power transmission systems build transformers made from silicon steel. All utility pole transformers as well as stators and rotors of electric motors have laminations made of this alloy. It is interesting to look at the record of silicon steel development. History records the advances made at the Budapest Ganz Electrical Works in 1878 as one of the first lighting systems in the world to use AC (Westinghouse-Tesla) for their customers instead DC (Edison). They were competing against Edison DC power and by using a crude type of transformer based on two copper windings wrapped around an iron ring were able to transmit energy at higher voltages with lower copper cost. Seven years later they began constructing transformers using flat steel laminations to reduce eddy currents further improving their system.

At about that time (1889), Robert Hadfield, a British metallurgist, in search of a formable steel alloy for train wheels, accidently discovered that silicon, when added to iron, could result in a much improved magnetic material. The silicon it turned out increases the resistivity of the alloy by a factor of four while maintaining the saturation field value at relatively high levels. Silicon also has the effect of reducing the magnetostriction of the material therefore decreasing the annoying hum found in early laminated transformers. By 1906 steel with 3% silicon became available in the United States for transformer use. The next area of improvement for silicon steel was to reduce hysteresis loss. This was done by Goss in 1934 using cold rolling of the laminations to orient the grain structure.

Silicon steel typically shows a relative permeability of 4,000 and a power loss between 1 to 5 watts per pound at 60 Hz. Because silicon steel has a high B field saturation level of nearly 15,000 gauss, (about 4 times that of ferrite), it is ideal for line operated transformers because fewer turns are needed of copper wire. Most silicon steel transformers operate with an efficiency of 98% - the highest value for any human-made machine. Unfortunately, because of the eddy current and hysteresis loss, silicon steel is not practical for high frequency (f > 400 Hz) power conversion.

Permalloy

Permalloy is a ferromagnetic alloy having a composition of 80% nickel and 20% iron. It was first developed in 1914 by Swedish physicist Gustav Elmen at Bell Telephone Laboratories who was looking for a magnetic core to be used in deep-sea telegraph cables. Needing a method to mitigate the large inherent line capacitance, Elmen found that he could apply the transmission equations of Oliver Heaviside by periodically placing magnetic cores along the way, speeding up the signal rise time by mitigating capacitive effects. Elmen improved the material in 1923 by incorporating several heat treating steps creating alloys with relative permeabilities up to 100,000.

A disadvantage of permalloy is that it is not very ductile or workable and applications requiring elaborate shapes cannot be easily made. Permalloy is available as transformer laminations and magnetic recording heads and is most often found as tape-would toroidal cores. Eddy currents within the metal limit the maximum useable frequency to about 100kHz.

In the late 1950's scientists H. L. B. Gould and D. H. Wenny, at Bell Laboratories discovered an even better alloy of made of vanadium, iron, and cobalt and having much lower core losses than normal permalloy. They called the material Supermendur. Current formulations add trace amounts of niobium, silicon and manganese and offer magnetic field saturation values over 22,000 gauss. Supermendur laminations are commercially available but are very costly. Usually this material is found in 400 Hz three-phase military airborne transformers where weight is a primary factor and cost on the bottom of the list.

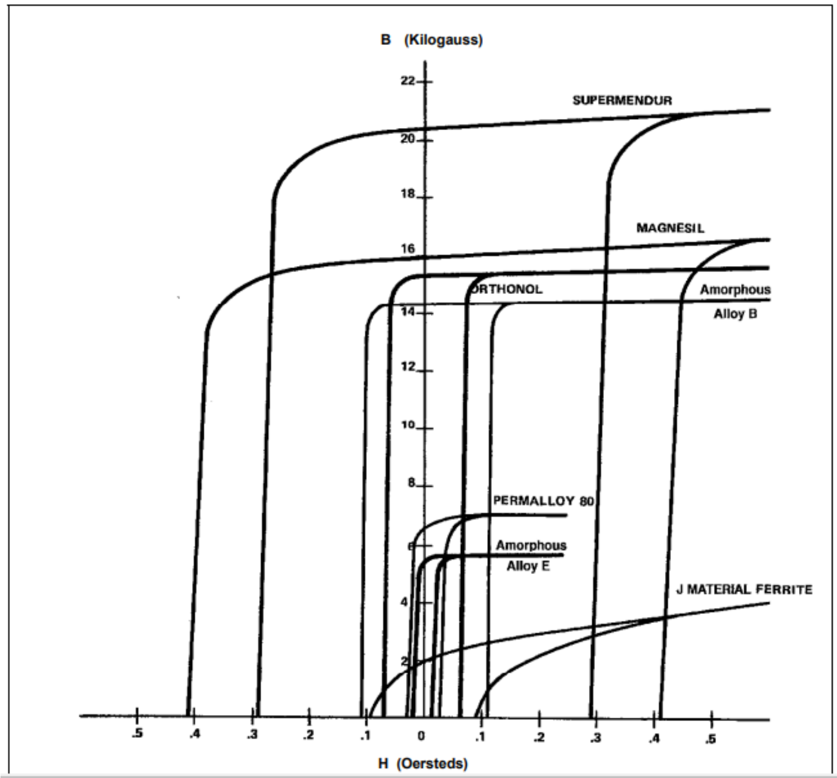

Figure 6.8: BH curves for various ferromagnetic materials (Magnetics)

Amorphous glass

This rather new material is really a glass prepared by pouring a molten metallic composition onto a rotating wheel, cooling the metal down at a rate of about one million degrees C per second. This is so drastic a drop that crystals really don't get a chance to grow. The composition is usually an alloy of iron with boron, silicon, and phosphorus and the films average about 25 µm thick. Transformers with amorphous glass cores show very low eddy current losses due to the high material resistivity. This technology was developed at AlliedSignal research facilities in Morristown, New Jersey back in the late 1970's and only now, fifty years later, are they gaining momentum as a green alternative for power transmission. Because an amorphous metal transformer can save energy, their use can lead to a reduction in CO_2 emissions from power generating plants. This technology has been widely adopted by large developing countries such as China and India in an effort to meet future global standards. Amorphous glass cores can be found in high end switching power supplies.

Ferrites

Small size power converters owe their existence to ferrites. The first country to develop ferrite material was Japan in the 1930's. There, Dr. Takeshi Takei, a professor at Tokyo Institute of Technology, discovered that oxides containing zinc and iron have distinguished magnetic properties such as low eddy current loss and can easily operate at high frequencies. Working in conjunction with Professor Yogoro Kato they perfected a hot powder sintering process that gave a ferrite with very high permeability and this was ideal for use as an inductor. Almost directly afterwards the founding of TDK Corporation resulted in the manufacture of iron-based magnetic material ferrite that was used to fabricate components for use in radio and telephone service. Since this was during the war years, not a lot of information came forth from Japan about this new material.

Figure 6.9: Dr. Takeshi Takei and Professor Yogoro Kato examine a ferrite core (https://ieeexplore.ieee.org/document/8535826)

It was not until 1945 that J. L. Snoek of the Phillips Research Laboratories in the Netherlands succeeded in producing a 'soft' ferrite for commercial applications that could be pressed and fired in a few select shapes and sizes, primarily for inductor and antenna applications. Snoek showed that by adjusting the zinc content he could influence the magnetic saturation level, the permeability, and the energy losses to desired values.

Basically, ferrites are ceramic materials that contain iron oxides combined with nickel, zinc, and sometimes manganese. They are called "soft ferrites" to distinguish them from "hard ferrites", that are used to make permanent magnets. Because they are a high resistivity material they show very low eddy current loss, an attractive attribute especially at frequencies above 1 MHz. The typical resistivity for 3C91 material is 5 Ohm-meter, seven orders of magnitude higher compared to silicon steel (4.72E-7 Ohm-meter).

Two different types of ferrites are available: Manganese–zinc and nickle-zinc. Mg-Zn formulations are used primarily for power conversion, running at frequencies below 2 MHz. Ni-Zn ferrites find use above 1MHz in communication work, but as a rule have lower permeability and saturation levels. But, with regards to maximum temperature operation, some NiZn ferrites, such as Fair-Rite material 67 can work to over 450 degrees Celsius while most MnZn materials have a maximum of about 200 degrees Celsius.

One of the distinctive features of ferrite cores is that they can be pressed in a multitude of shapes and dimensions. From cylindrical to flat rectangles, from pot cores to E cores, many hundreds of designs are available from manufacturers at power levels spanning from milliwatts to kilowatts.

MPP cores

A toroidal moly-permalloy powder core (MPP) is composed of powder from multiple ferromagnetic alloys held together by an epoxy binder. Because the metal is in powder form, it has particles surrounded by tiny air gaps that reduce the effect of bulk saturation. In addition, because the particles are tiny, eddy-current losses are minimized. Its composition is typically made from approximately 79% nickel, 17% iron, and 4% molybdenum. MPP was developed into cores by the Western Electric Company in the early 1940s for use in telephone circuits. MMP cores display the lowest losses of all the ferromagnetic materials. While not having a large permeability to boast of (because of the gaps between particles) its ability to operate in high H fields is very important for in-line filters and current carrying chokes. Figure 6-10 below shows one particular core material, Magnetics 60µ MMP material, can be operated at least up to 20 Oersteds before any significant roll-off in relative permeability is seen. This is compared to one Orested with similar sized ferrite cores.

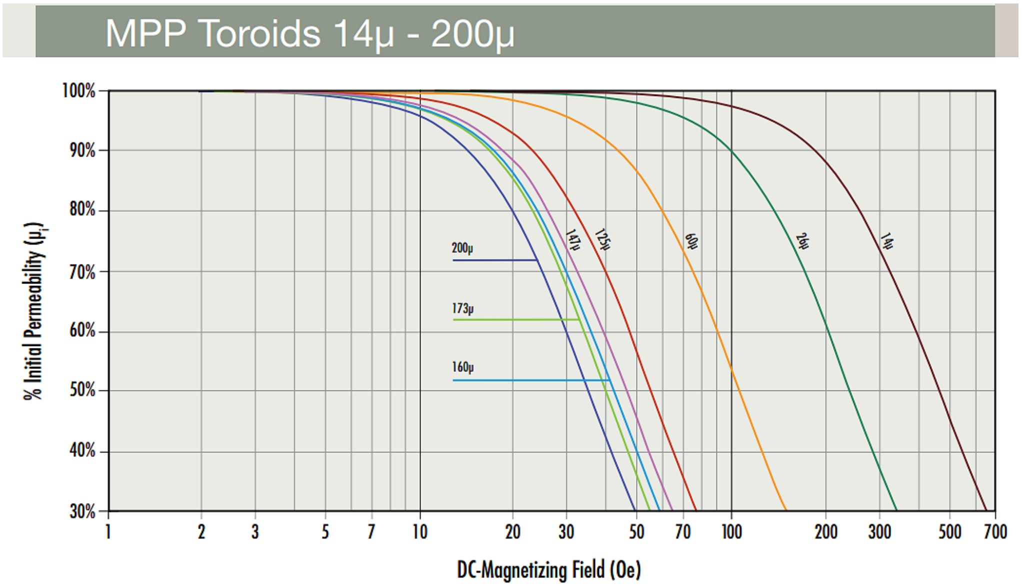

Figure 6.10: Permeability as a function of DC magnetizing field for MMP core material

Most MMP cores can operate at very high temperatures. The core displayed above can operate up to 430 degrees Celsius, much higher than any Mn-Zn ferrite. The powder is made by grinding hot-rolled ingots cast with the proper alloy ratios. Under proper temperature control the particles grow oxide coatings of a certain thickness allowing the powder to be screened to a certain fineness. Normally, 120 mesh is used in audio frequency applications, and 400 mesh for frequencies above 50kHz.

MPP cores are primarily used for inductors whenever DC current is flowing, for example in an input line filter choke where the goal is to block out conducted EMI radiation from appearing back on the input lines. They are also useful in output filtering as well. You will find MMP cores used in the making of: flyback transformers, resonant circuits, quartz filters, loading coils, choke coils, pulse transformers, and other industrial circuits. They are particularly useful in military electronics because of their high operating temperature ability.

One drawback is that as the frequency of operation increases the desired permeability decreases and along with that the resultant effective inductance. Thus, when using frequencies higher than 500 kHz MPP cores are often replaced by ferrite. Also, most MPP shapes are limited to a toroidal configuration – not a useful shape for high voltage transformers.

Iron Powder Cores

Many cores are made from powdered iron because it is the cheapest material available. All of the old high voltage flyback transformers found in black and white televisions utilized cores of compressed powdered iron because back in the 1950's that was about all one had in the form of C cores. This material unfortunately has higher core loss than ferrites but this can be compensated for by making the core bigger, an advantage where cost is more important than mass and size. As you know with iron, the saturation flux of about 15,000 gauss, four times that of ferrite, meaning you can use a lower amount of turns, decreasing not only cost but the copper loss as well. Powdered iron cores have both higher hysteresis and eddy current losses than other cores but if they are limited to less than 50 kHz, these dissipation constraints can be lived with. The binder used is usually an epoxy or other organic resin and unfortunately susceptible to thermal aging. Many iron powder cores are available as toroids but sometimes E, EI, and rods or blocks can be obtained for use in high-power and high-current inductors or transformers.

You will find powdered iron in DC output chokes (low voltage power supplies), chokes for power factor correction, resonant inductors, and pulse and low cost flyback transformers.

Sendust Powder Cores

Sendust is a magnetic metal powder that was invented by Hakaru Masumoto at Tohoku Imperial University in Sendai, Japan circa 1936 as an alternative to Permalloy in inductor applications for telephone networks. Sendust composition is typically 85% iron, 9% silicon and 6% aluminium. The powder is sintered into cores to manufacture inductors. Sendust cores have high magnetic permeability (up to 140 000)[clarification needed], low loss, low coercivity (5 A/m) good temperature stability and saturation flux density up to 1 T.

The Kool-Mu cores made by Magnetics utilize sendust material. Bourns also makes sendust cores.

Curie Point

In dealing with ferromagnetic materials, the parameter called the Curie Point will often come up. This is the temperature above which the ferro-magnetic material loses all of its magnetic properties due to thermal vibrations upsetting the domain structure. The Curie Point is named after the French scientist Pierre Curie, who studied magnetism in steel and who showed that magnetism was lost at a critical temperature.

Because higher temperatures make atoms vibrate with greater amplitudes, there comes a point where the gains observed by ferromagnetism suddenly drop to zero because the alignment process is unable to keep up with the disorder caused by thermal agitation. An air-core inductor having a value of 50 uH that increases to 0.15 Henries when a ferromagnetic material is placed inside, will see its inductance drop back to 50 uH if the material is heated past its Curie Point. The effect is reversible and once the material drops below the Curie Point again the high inductance of 0.15 Henries will return.

Some books say Curie Temperature when describing this effect but this is not correct. The Curie Temperature is a different parameter used to scale the Curie-Weiss law that predicts magnetic activity (susceptibility) in the paramagnetic region above the Curie point. You should always say *Curie Point* when discussing the temperature where the relative permeability drops to one.

Different ferromagnetic materials have different Curie points. Iron for example has a Curie Point of 770 ° C. An alnico permanent magnet (Al: 10%, Ni: 20%,Co: 20%, Cu:5%, Ti: 1%,Fe:44%) can be used until 700 ° C before the Curie Point renders it useless. Ferrites usually have much lower Curie Points because of the oxides within their structure. The popular 3C92 can only be used to 280 °C. Permalloy alloys are good to about 450 °C. Technically, a ferromagnetic material becomes paramagnetic at temperatures above the Curie Point and therefore only very weakly magnetic. Pressure on a sensitive magnetic material such as a soft ferrite will increase the Curie Point slightly. This is sometimes seen when hard potted transformers are elevated in temperature where the ferrites are compressed by thermal expansion.

B saturation as a function of temperature

It was mentioned earlier that the values of Bsat are sensitive to temperature. A transformer working close to saturation may suddenly find itself suddenly entering the saturating region because of an increase in losses raising the core temperature. This dangerous run-away situation should be avoided at all costs because it is usually catastrophic in nature. It is important therefore to know how the values of Bsat vary with respect to temperature.

From work done in the late 1970’s, A.P. Miodownik and F.C.Schwerer, showed that the B field saturation level is proportional to a sixth power equation involving temperature:

$$Bsat\,(T) \quad = \quad (Bsat_{25})\, a\, (1 - (T/T_C)^6) \qquad (6\text{-}10)$$

thus, it is possible to calculate the maximum B field allowed in a ferrite material like 3C92 if a few parameters are known. Here T_C is the Curie Point and degrees Kelvin is used. .

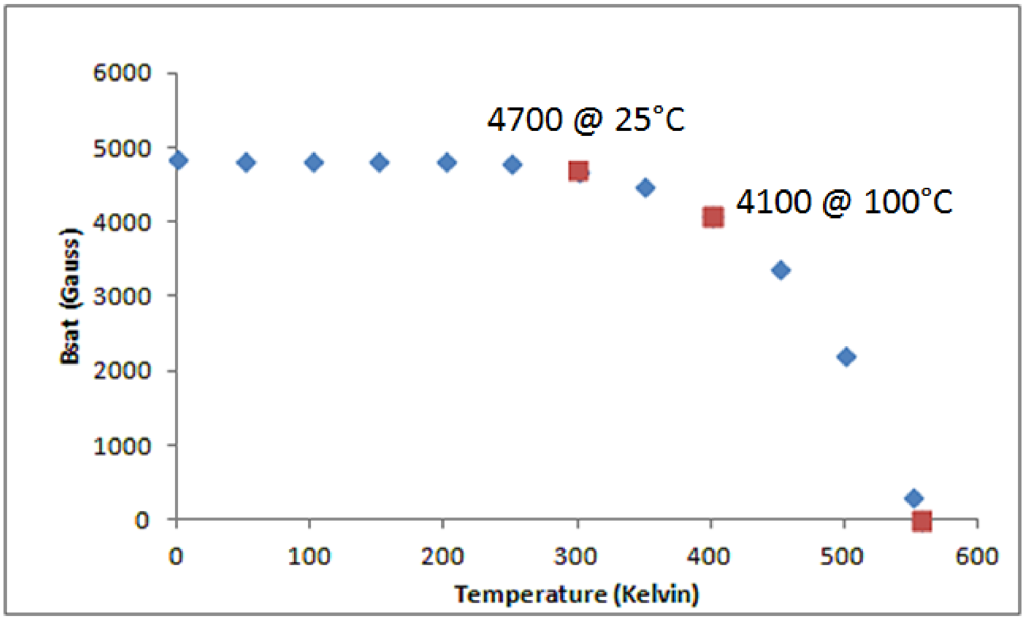

Fig: 6.11: Bsat for 3C92 ferrite material

Power Dissipation in Magnetic Materials:

There are two main areas where dissipation occurs within a magnetic core. One, eddy current loss is due to the resistance of the ferromagnetic material acting on internal current loops and the other is called hysteresis loss is due to the movement of the magnetic domains as the material cycles.

Eddy current losses come from AC circulating currents flowing through conductive paths in the ferromagnetic material. The general equation for this loss is dependent upon the square of the frequency and B field (where B is in Tesla):

$$P_{eddycurrent} \quad = \quad k_e f^2 B_m^2 V \qquad (6\text{-}11)$$

where values of Ke are:

Material	k_e loss factor (kW/ m^3 T^2 Hz^2)
Silicon steel:	9E-3
Ferrite:	8E-9
Permalloy:	1.03E-5

Hysteresis Loss in Magnetic material

As we said earlier, when the applied H field creates a resulting B field in a ferromagnetic material, the magnetization of the core material changes by expansion and contraction of the tiny magnetic domains it is composed of. These variations of domain take energy to accomplish and when this is done at a certain frequency, power is lost that results in heating of the material.

Look at the B-H loop of a typical silicon steel material as shown in Figure 6-12 below.

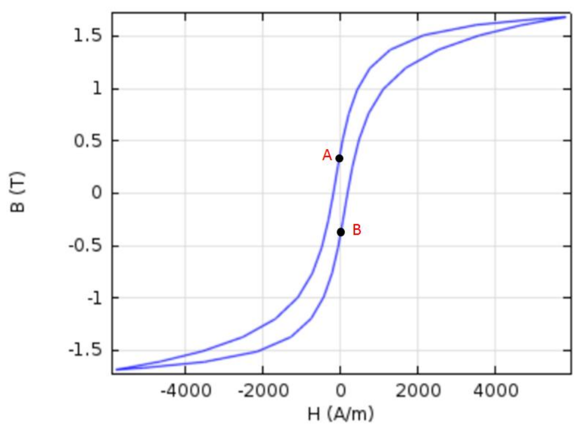

Figure 6.12: BH Loop silicon steel

Going slowly around the loop, starting from the origin (not shown), notice that it doesn't exactly retrace itself. The forward increasing BH curve does not correspond to the reducing BH curve. There is a distinct separation in curves. Looking at this in more detail, as we apply an H field using the external current, the material eventually saturates at about 16,000 gauss. But, as the current is slowly turned off, the B field does not slide back to zero but stays at about 3,500 gauss indicated by point A. We have made a slight permanent magnet in the silicon steel.

You have probably seen this effect when making an electromagnet with an iron nail and turns of copper wire powered from a dry cell battery. With the battery turned on you can pick up a pile of iron filings but if you shut off the current the electromagnet you made can still pick up a little bit of iron filings – it is still a somewhat magnetic even without any current flowing. Some of the magnetic domains that were fully pointing in one direction when saturated with the current on have not completely returned to zero. A small percentage of them are oriented in the same direction. This is called retentivity, the B field retains a value even though the H field is shut off. To get rid of this, we would have to reverse the current and apply an H field in the opposite direction. The amount of H field needed to counteract this effect and reduce it to zero is called the coercively. Hard magnetic materials such as alnico magnets have high retention and large values of coercively.

Driving this core with a high frequency AC sinewave requires that we get rid of the retained magnetic field twice every cycle and this wastes energy. A typical equation of the hysteresis loss, sometimes called the Steinmetz equation, named after German-American engineer who first characterized such loss for General Electric in 1890's, is:

$$P_{hysteresis} = k_h f B_m^{1.4} V \qquad (6\text{-}12)$$

where P is the power loss in Watts, k_h is the Steinmetz hysteresis coefficient for the material, f frequency, B_m the maximum value of B field in Tesla and V the volume of the ferromagnetic material in cubic meters. Silicon steel has a k_h value of 0.17 kW/m^3 T^2 Hz.

Ferrite such as 3C92 uses a slightly different exponent on the magnetic field:

$$P_{hysteresis} = k_h f B_m^{2} V \qquad (6\text{-}13)$$

and from the data sheet a k_h value of 0.05 kW/ m^3 T^2 Hz is calculated. Amorphous glass cores show lower values of 0.005 kW/ m^3 T^2 Hz using the same equation.

A typical 2616 ferrite transformer (volume 4.1 cm^3) operating at 100 kHz and 2,000 gauss (0.2 T) will show the following material losses:

$$P_{hysteresis} = k_h f B_m^2 V$$
$$P_{hysteresis} = (0.05)\,(100{,}000)(0.2)^2(4.1E\text{-}6) = \quad 0.82 \text{ Watts hysteresis loss}$$

$$P_{eddycurrent} = k_e f^2 B_m^2 V$$
$$P_{eddycurrent} = (8E\text{-}9)(100{,}000)^2(0.2)^2(4.1E\text{-}6) = \quad 0.013 \text{ Watts eddy current loss}$$

$$Total: = 0.833 \text{ Watts}$$

Because such a transformer can deliver 50 Watts of power, our transformer have a maximum efficiency of:

$$\eta = Pout / Pin = 50 / 50.833 = 98\%$$

which is quite reasonable. Of course this does not take into consideration any copper losses, which are usually of the same order of magnitude.

Losses vs Temperature

The hysteresis loss effect actually drops with respect to temperature as shown by Figure 6-12 taken from a Ferroxcube material catalog for 3C92 material. This is due to the lower friction present in domain wall movement at higher temperatures. Notice however, past a certain point the hysteresis effect rises again.

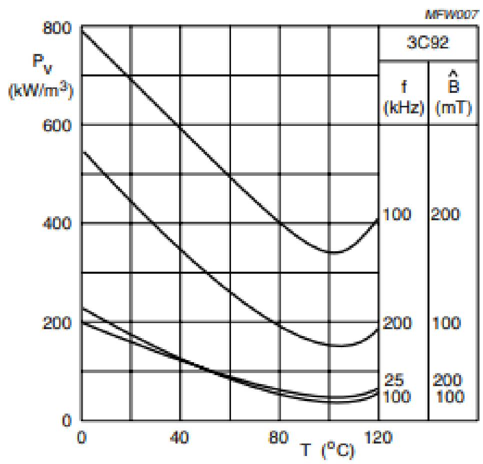

Figure 6.13: Hysteresis loss as a function of temperature.