Study on Magnetic Materials Used in Power Transformer and Inductor

H. L. Chan, K. W. E. Cheng, T. K. Cheung and C. K. Cheung

Digipower Technology Limited, Hong Kong
Department of Electrical Engineering, The Hong Kong Polytechnic University

ABSTRACT: Power electronics system is generally comprised of electrical and magnetic circuits. Nowadays, there were a lot of research works on circuit topologies ranging from single switch converter to soft-switching topologies, but the most difficult problems encountered by many design engineers were magnetic issues, such as construction of transformer or inductor, application of air-gap, under- or over-estimated power rating of the magnetic components, selection of magnetic core and so on.

The overall performance of any power converters depend on not only the circuit design, but also the application of magnetic components, this paper will address some common problems related to the applications of magnetic components, and some critical factors involved into development of such components for power converters.

A brief summary of some major magnetic materials, such as soft ferrites, powder iron and alloys will be mentioned in this paper too.

INTRODUCTION

Besides the circuit design issues, the most frequently-encountered problems for many power electronics engineers includes the following aspects:

(a) Under- or Over-estimated Power Rating of Magnetic Components
(b) Construction of Transformers and Inductors
(c) Use of Air-Gap
(d) Selection of Magnetic Cores

(a) Under- or Over-Estimated Power Rating of Magnetic Components

The first step to design a power transformer or an inductor is the determination of component size which is directly proportional to the power handling capacity. However, it happened quite frequently for the design of transformer (or inductor) being either under-estimated or over-estimated.

A transformer being under-estimated will insufficiently handle the power transfer for converters, and the outcome is over-heat due to increase in core loss and/or cupper loss. If the power rating of the transformer is designed far beyond the minimum requirement, the over-heat of transformer will cause the saturation flux density, B_{sat} (ferrite is assumed to be used in the transformer), to shift to a lower limit [2] as showed in Figure 1. It is therefore quite easy for the transformer to saturate itself, and leads to a larger magnetizing current. Short-circuit occurred in the winding as a result of diminishing inductance and thermal runaway.
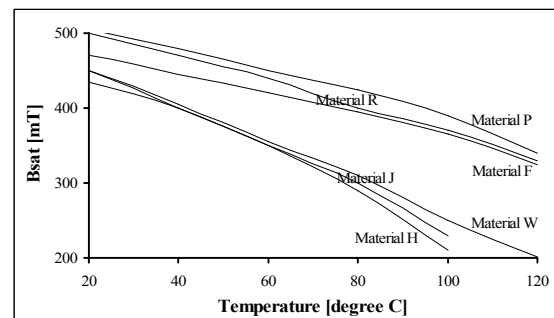

Figure 1: Flux Density vs. Temperature

Power losses in transformers or inductors come from core losses and copper losses. Core losses include hysteresis loss and eddy current loss in the magnetic cores. Copper losses are due to skin effect and proximity effect which increases the equivalent ac resistance, R_{ac}, of magnetic wires [4,5], or I^2R loss where $R = R_{ac} + R_{dc}$.

To reduce the temperature rise, we can then reduce either the core loss by lowering the flux density and/or switching frequency as showed in the following equation [3]:

$$P_{Hysteresis} = k \cdot f^a \cdot (B_{ac})^d$$

Where: $P_{Hysteresis}$ is hysteresis loss of ferrite materials, k, a and d are constants, f is switching frequency of transformer/inductor, and B_{ac} is ac flux density. Soft ferrites have the highest resistivity among the other magnetic materials, and the eddy current loss is thus usually not a severe issue. This makes it prominent in high switching frequency application.

Use of stranded wires, foil or Litz wires is a practical solution to minimize copper losses, and decreasing the switching frequency can also relieve the skin effect.

The outcome of under-estimated power rating of inductor is diminishing inductance; it results in a larger ripple current flowing through the inductor. The mechanism of decrease in inductance is similar to that happens in transformer.

On the other hand, if transformers or inductors are designed with excessive margin, it is obvious to incur some waste of resource as well as money. The worse case may lead to a design failure, as the power density of

converter is usually a moderate criteria in design specification.

(b) Construction of Transformers and Inductors

Because the transformer has both primary and secondary windings, which have opposite current flowing, therefore, the mmf induced in primary winding can be reduced by that induced in secondary winding. Based on such concept, sectioning transformer windings can be used to reduce the eddy current loss that incurred from the mmf. Eddy current loss is proportional to the square of ac flux, which is a function of mmf, so the more section the transformer, the lower the mmf or the eddy current loss. Figure 2 demonstrated both sectioning and non-sectioning techniques.
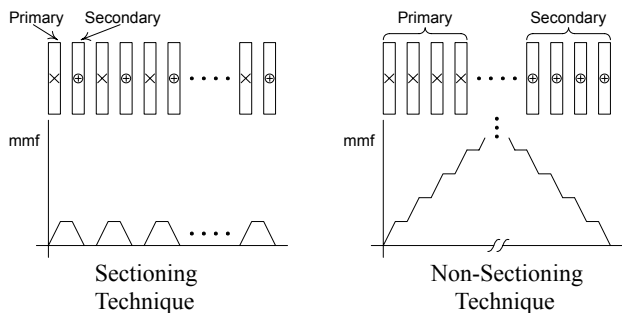

Figure 2: Leakage Fields in Transformer Windings

However, there exists some parasitic capacitances between primary and secondary windings, and these capacitances provide coupling for spreading paths for interference, which may deteriorate EMI profile or reduce the signal-to-noise ratio of wanted signals.
To reduce such interference, the capacitive coupling between primary and secondary should be minimized. Shielding of transformer windings is an effective way to reduce the interference, and it is usually done by winding one foil on the primary and seconding winding and then connecting to the input or output.

(c) Air-gap in Transformers and Inductors

Insertion of air-gap is a simple and effective way to alter the overall characteristics of magnetic circuit in such a way to optimize the performance of transformers and inductors.

It was a common misconception about air-gap that the insertion of air-gap could increase the saturation flux density, B_{sat}. Actually, B_{sat} will not change even though there is an air-gap introduced into a magnetic circuit, and it is determined by the material of core. The purpose of insertion of air-gap is to increase the total reluctance; it then decreases the inductance of transformers or inductors, such that a higher magnetic field H can be excited, or the saturation current will be increased.

Application of air-gap depends on type of converters and material of cores. For example: it is a must for flyback transformer, which serves 3 purposes in the converters, namely galvanic isolation, voltage amplification and energy storage. However, as it operates in only the first quadrant of B-H loop and the switching current is varying significantly (a flyback converter operating under discontinuous current mode has the largest swing of excitation current applied to the transformer winding), so it is a common practice to introduce an air-gap to prevent the core from saturation.

DC filter used in output stage of converters also require insertion of air-gap into the magnetic cores due to the same reason for flyback transformer.

Moreover, AC inductor, commonly found in resonant circuit such as phase-shifted converter [6], is carrying both directions of current that excites the core with positive and negative magnetic field H. This translates a large AC flux swing, it increases the core loss. To put in an air-gap into the core of inductor will reduce the saturation current, and minimize the core loss as area of B-H loop is flatten out as showed in Figure 3.
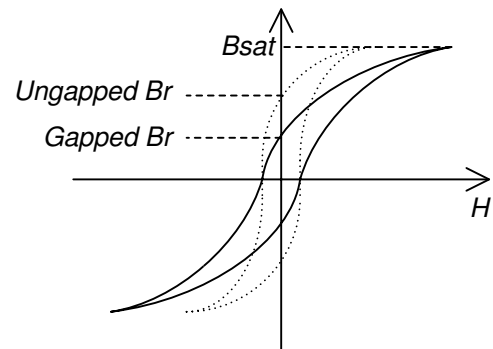

Figure 3: B-H Loop with and without Air-Gap

For push-pull, half bridge and full bridge transformers, it is usually not necessary to add air-gap in between the cores. These transformers are usually used in high power converters, and they operates within the first and third quadrants of B-H loop, so the materials chosen for the transformers should have high resistivity and saturation flux density B_{sat}, low residual magnetic flux density B_r and/or low coercive fore H_c, such that the core loss will be minimized. In addition, a core material with higher permeability is also beneficial to the reduction in core loss as energy stored in the core can be smaller. Nevertheless, a small air-gap might be needed to eliminate the DC bias that will lower the relative permeability μ_r [1].

In short, the insertion of air-gap is to take advantage of it high reluctance, which reduces the effective permeability μ_e, and it prevents the core from saturation.

(d) Selection of Magnetic Cores

There is a variety of core sizes and shapes available in the market; they all are designed to best suit for certain application. Some of the most popular devices found in commercial converters were summarized as follows:

Pot core and RM core
Pot core almost completely shield the winding wound on the bobbin, it does therefore exhibit a minimum electromagnetic interference (EMI) radiation. Low profile is another advantage, but the thermal dissipation of the entire device through air ventilation is poor. In addition, it is expensive and the core sizes in the market are only available for low power application.

E, EC and ETD Cores

E core has the most attractive feature for the commercial market, it is low cost, and besides, the simple bobbin structure having a wide windows are is quite easy for winding. Heat dissipation is very well compared to the other candidates. Furthermore, a variety of sizes is available for choice to suit almost any application. All these features make it the most popular core used in power circuits.

The shapes of EC and ETD cores are similar to E core, but the centre of core is round, such that the effective cross-sectional area is larger. This is particularly welcome in high power application.

PQ Core

The design of PQ core is mainly for high power application. Compared with other cores having similar sizes and shapes, the PQ cores have the largest windows areas. It is thus more feasible to obtain a higher inductance for use in high power density application. As the shape is also similar to E core, so the heat dissipation is fairly good.

Toroid

The key feature of toroid is bobbin-less, and it does also have the simplest structure – a round ring in shape – of magnetic core. Cost of device is cheaper due to a cut-down in bobbin cost, but the labor cost for winding is costly or it requires some sort of sophisticated winding machine. Leakage flux is almost not a problem for toroid, so shielding is usually not necessary, however the heat dissipation is poor as ventilation for core is blocked by the winding.

COMPARISON OF MAGNETIC MATERIALS

In this section of paper, a great effort was put in studying the materials of different magnetic cores including their characteristics and performances.

Elements used to make magnetic cores include mainly manganese [Mn], zinc [Zn], iron [Fe], aluminum [Al], nickel [Ni], magnesium [Mg], cobalt [Co] and some of their oxides. The magnetic materials are then further classified into three categories:
 (a) soft ferrites
 (b) alloy cores
 (c) powder iron cores

Soft Ferrites

Soft ferrites are metal oxides, while powder iron cores are made of metals and/or alloy. Metal oxides have a much higher resistivity than metal or alloys, the higher the resistivity, the lower the eddy current or the core loss. In addition, the low coercive force H_c is also a merit of ferrite core, because the enclosed area of hysteresis loop is smaller for a low H_c material, which does therefore have a lower core loss. This is why the ferrite cores are mainly utilized in high frequency applications. Table 1 listed some ferrite materials [2,10,11,12] that can be used high frequency application.

Table 1: Core Loss of Soft Ferrites

Operation Frequency [kHz]	Materials	Core Loss [mW/cm^3] under 100°C					
		at 160mT	at 140mT	at 120mT	at 100mT	at 80mT	at 60mT
20	Ferroxcube 3C85	82	25	18	13	10	
	Ferroxcube 3F3	28	20	12	9	5	
	Magnetics R	20	12	7	5	3	
	Magnetics P	40	18	13	8	5	
	TDK H7C1	60	40	30	20	10	
	TDK H7C4	45	29	18	10		
	Siemens N27	50			24		
50	Ferroxcube 3C85	80	65	40	30	18	9
	Ferroxcube 3F3	70	50	30	22	12	5
	Magnetics R	75	55	28	20	11	5
	Magnetics P	147	85	57	40	20	9
	TDK H7C1	160	90	60	45	25	20
	TDK H7C4	100	65	40	28	20	
	Siemens N27	144			96		
100	Ferroxcube 3C85	260	160	100	80	48	
	Ferroxcube 3F3	180	120	70	55	30	30
	Magnetics R	250	150	85	70	35	14
	Magnetics P	340	181	136	96	57	16
	TDK H7C1	500	300	200	140	75	23
	TDK H7C4	300	180	100	70	50	35
	Siemens N27	480			200		
	Siemens N47				190		
200	Ferroxcube 3C85	700	500	350	300	180	75
	Ferroxcube 3F3	600	360	250	180	85	40
	Magnetics R	650	450	280	200	100	45
	Magnetics P	850	567	340	227	136	68
	TDK H7C1	1400	900	500	400	200	100
	TDK H7C4	800	500	300	200	100	45
	Siements N27	960			480		
	Siemens N47				480		
500	Ferroxcube 3C85				1800	950	500
	Ferroxcube 3F3		1800	1200	900	500	280
	Magnetics R		2200	1300	1100	700	400
	Magnetics P		4500	3200	1800	1100	570
	TDK H7F						100
	TDK H7C4		2800	1800	1200	980	320
1000	Ferroxcube 3C85						2000
	Ferroxcube 3F3				3500	2500	1200
	Magnetics R				5000	3000	1500
	Magnetics P						6200

Powder Iron Cores

Powder irons have a lower value of permeability but a higher saturation flux density, whereas soft ferrites provide a higher permeability but a low saturation for flux density. There are 3 common materials in the market, namely Carbonyl Iron, Sendust (or Kool Mµ®) and Molypermalloy Powder (MPP).

Alloy Cores

Alloy type materials except amorphous have the highest saturation flux density and permeability among ferrites and powder irons, however, their low resistivity limits the applications with switching frequency to 30kHz. Common alloy cores include silicon steel, permalloy, supermalloy, permendur and amorphous.

Although, all of the materials suffer from high frequency core loss, the ferrites are most preferable to be used in high frequency operation. Figure 4 showed the relationship between frequency and relative permeability for different magnetic materials.
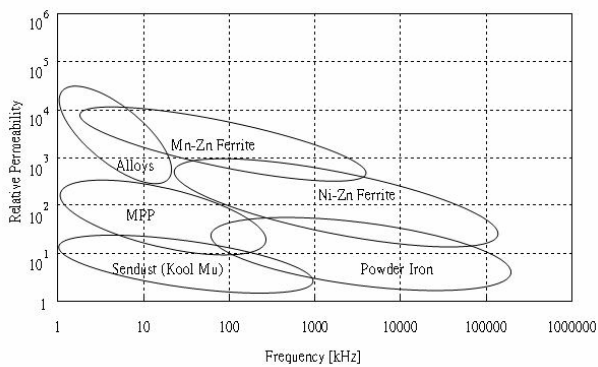
Figure 4: Relative Permeability vs. Frequency

PERFORMANCE TESTS

To evaluate the performance of different magnetic materials used in filtering, energy storage or power transfer, a 1400kW phase-shifted full-bridge converter was built and the resonant inductor, output filter and power transformer were tested with some different devices. The results were summarized as follows:
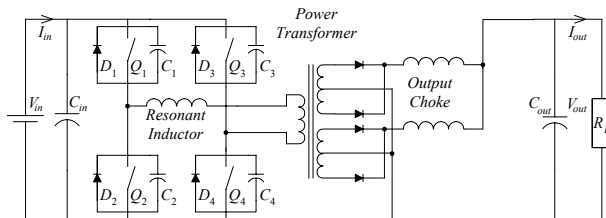

Figure 5: 1400W PS FB Converter

Resonant Inductor
The resonant inductor [7,8,9] was used for MOSFETs of lagging leg to achieve zero voltage switching (ZVS), while the MOSFETs of leading leg can easily switch under zero-voltage condition as the output choke with large inductance plays the role of resonant inductor at that moment. Some tests were carried out by using different materials and cores used in the converter, and then observation of performance was reported here.

(1) 18 turns of 12 threads of AWG25 wires were wound on a powder iron core with outer diameter of 33mm, the inductance was 28μH and Q was 6.1 at 1kHz. The temperature was 140°C after 15 minutes.

(2) 19 turns of 14 threads of AWG25 wires were wound on a MPP core with outer diameter of 40mm, the inductance was 34.7μH. The temperature of inductor was 110°C.

(3) 16 turns of 14 threads of AWG25 wires were wound on a powder iron core with outer diameter of 47mm, the inductance was 10.5μH and Q was 4.7 at 1kHz. The temperature of inductor after 15 minutes was about 110°C.

(4) 9 turns of 15 threads of AWG25 wires were wound on an EE42-3C85 ferrite core with air-gap of 0.3mm, the inductance was 32.5μH and Q was 3.5. The temperature of inductor after 20 minutes was about 68°C.

The temperature measured on the inductor was a good indication for assessment of the inductor, because a higher temperature rise implied a larger core loss and/or a larger copper loss. Inductor no. 1 was obviously too small to fit the converter, and inductor no. 2 employing MPP which had a lower core loss than powder iron, but its performance was still not satisfied. Having increased its size, inductor no. 3 also failed to stabilize in terms of thermal dissipation. Finally, the use of ferrite core with air-gap could fulfill the thermal requirement.

Output Choke
4 different output inductors were constructed and tested with the converter. The results were showed as follows:

(1) Inductance of output choke made of MPP core with outer diameter of 47mm was 20μH, the temperature rose to above 100°C within 20 minutes.

(2) Inductance of output choke made of MPP core with outer diameter of 47mm was 55μH, the temperature rose to about 60°C.

(3) Inductance of output choke made of EE42 ferrite core without air-gap was 67μH, the temperature rose to above 60°C after 20 minutes.

(4) Inductance of output choke made of EE42 ferrite core with air-gap of 0.3mm was 77μH, the temperature rose to 48°C after 20 minutes.

The conclusion drawn from the above results was similar to that obtained in Resonant Inductor Test; where powder iron and ferrites were supposed to perform equally well in filtering function, however, in high power application, the ferrite was still prominent.

Power Transformer
The following experiment was to evaluate the effects of different construction method of transformer. The main transformer was designed with bobbin PQ50/50 and the material of ferrite was 3C85. However, three different methods were employed in assembling the transformer, and the performance of transformer and converter were then observed.

(1) 2-Section Wholly-Wrapped
<u>Primary winding:</u>
No. of Sections = 2
No. of turn per section = 14 turns
Stranded wire = 12 threads of AWG25
Total Inductance = 3.5mH at 10kHz, Q = 46
<u>Secondary winding:</u>
No. of Sections = 4
No. of turn per section = 5 turns
Stranded wire = 20 threads of AWG25
Leakage Inductance = 20μH at 10kHz
<u>Construction and Test Results:</u>
Primary windings were divided into 2 sections, wound on the most inner and outer of the bobbin to enclose the secondary windings completely. Secondary windings were divided into 4 sections wound inside the primary windings, and each two sections were connected to form a center tab for output grounding.
The temperature of transformer reached about 70°C and the converter operated steadily from light to full load.

(2) 3-Section Wholly-Wrapped
<u>Primary winding:</u>
No. of Sections = 3

No. of turn per section = 11 turns
Stranded wire = 12 threads of AWG25
Total Inductance = 4.1mH at 10kHz, Q = 52
<u>Secondary winding:</u>
No. of Sections = 4
No. of turn per section = 5 turns
Stranded wire = 20 threads of AWG25
Leakage Inductance = 17μH at 10kHz
<u>Construction and Test Results:</u>
   Primary windings were divided into 3 sections, wound on the most inner, middle and outer of the bobbin to enclose evenly the secondary windings. Secondary windings were divided into 4 sections and each two sections were connected to form a center tab winding, which was wound in between the inner and middle of primary windings, and in between the middle and outer of primary windings respectively.

   The temperature of transformer was around 72°C and the overall performance of converter was satisfied.

(3) <u>Primary winding:</u>
No. of Sections = 2
No. of turn per section = 15 turns
Stranded wire = 12 threads of AWG25
Total Inductance = 3.7mH at 10kHz, Q = 35
<u>Secondary winding:</u>
No. of Sections = 4
No. of turn per section = 5 turns
Stranded wire = 20 threads of AWG25
Leakage Inductance = 34μH at 10kHz
<u>Construction and Test Results:</u>
   Primary windings were divided into 2 sections, wound on the most inner and middle of the bobbin to enclose only 2 sections of secondary windings. The other 2 sections of secondary windings were wound on the outermost of bobbin. Each two sections were connected to form a center tab, which was connected to the output ground.

   The temperature of transformer rose rapidly to above 80°C after 10 minutes and the primary current exhibited a bit of fluctuation.

   All the winding methods made use of sandwich technique for the sake of minimizing the eddy current loss and mmf of winding. The transformer no. 3 using partially-wrapped technique did not operate steadily and the temperature rise seemed to be a potential problem. On the other hand, the other two transformers worked well. Although, the magnetizing and leakage inductances of transformer no. 2 were higher and lower than those of transformer no. 1 respectively, their performances were both satisfactory. However, the assembly procedures for transformer no. 2 was much more complicated than that for transformer no. 1, so the simple 2-section wholly-wrapped technique was recommended, and the results did also prove that the tighter the coupling between primary and secondary windings, the lower the leakage inductance, and the more stable the converter works.

CONCLUSIONS

This paper presented the general design method for magnetic components of industrial power converters. The design issues regarding the conduction loss and core loss are discussed. Different types of magnetic materials are studied for the characteristics and the frequency of operation. A test based on the phase-shifted converter was used to examine the operational performance for the magnetic devices and in general the ferrites outperforms the other materials in the resonant converter and transformer. All the cases, the low permeability are used for high frequency applications. It is intended that the polymer-bonded magnetic device will be replacing the conventional ferrite, power iron and other alloy core due to the performance of the polymer-bonded materials in cost, flexibility and magnetic characteristics.

ACKNOWLEDGMENT

REFERENCES

[1] Mark A. Swihart, Inductor Cores – Material and Shape Choices, Magnetics, Division of Spang & Co. Pittsburgh, Pennsylvania USA.

[2] Magnetics® Databook, 2004 Magnetics Catalog, www.mag-inc.com.

[3] Mohan, Undeland and Robbins, "Power Electronics – Converters, Applications and Design, 2nd Ed.", Chapter 30, John Wiley & Sons, Inc. New York.

[4] K. W. E. Cheng and P. D. Evans, "Calculation of Winding Losses in High Frequency Toroidal Inductors Using Single Strand Conductors", IEE Proc. Electr. Power Appl., Vol. 141, No. 2, March 1994.

[5] K. W. E. Cheng and P. D. Evans, "Calculation of Winding Losses in High Frequency Toroidal Inductors Using Multistrand Conductors", IEE Proc. Electr. Power Appl., Vol. 142, No. 5, September 1995.

[6] H.L. Chan, K.W.E. Cheng and D. Sutanto, "A Bidirectional phase-shifted control DC/DC Converter ", IEEE Midwest Symposium on Circuits and Systems, MWSCAS, Las Cruces, New Mexico, USA, August 1999.

[7] A. J. Forsyth, P. D. Evans, K. W. E. Cheng and M. R. D. AI-Mothafar, "Operation Limits of Power Converters for High Power Ion Engine Control", AIDAA/AIAA/DGLR/JSASS 22nd International Electric Propulsion Conference, October 14-17, 1991, Viareggio, Italy.

[8] A. J. Forsyth, P. D. Evans, M. R. D. AI-Mothafar and K. W. E. Cheng, "A Comparison of Phase-Shift Controlled Resonant and Square-Wave Converters For High Power Ion Engine Control", Proc. of the European Space Power Conf., September 2-6, 1991, Florence, Italy.

[9] J. A. Sabate, V. Vlatkovic, R. B. Ridley, F. C. Lee and B. H. Cho, "Design Consideration For High Voltage, High Power, Full Bridge, Zero Voltage Switched PWM Converter", Proceeding of the Applied Power Electronics Conference, APEC 1990, March 11-16, 1990, Los Angeles, CA.

[10] Ferroxcube® Databook, "Soft Ferrites and Accessories", www.ferroxcube.com.

[11] Siemens® Databook, "Ferrites and Accessories", www.epcos.com.

[12] TDK® Databook, "Ferrites for SMPS", www.tdk.com.