Soft Magnetic Materials for High Frequency High Power Density Transformers in Power Electronic Systems

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Abstract—**Along with the trends of higher and higher frequency operations and smaller and smaller physical volumes of power electronic systems, the transformers and inductors used in the power electronic systems are facing challenge to operate at high frequencies. This paper presents a survey on the soft magnetic materials used in the high frequency high power density (HFHPD) transformers and inductors in the power electronic systems. Various types of magnetic material, such as electrical sheets, soft ferrites and amorphous magnetic alloys, are reviewed. It is revealed that soft ferrites seem the most suitable for the core materials of HFHPD transformers.**

Index Terms—**Soft magnetic material; High frequency high power density transformer; Power electronic system; Electrical sheet; Soft ferrite; Amorphous magnetic alloy.**

I. INTRODUCTION

With the rapid advance of power electronic technology, the operational switching frequencies in power electronic systems, such as the switch mode power supply (SMPS), have been extended to the megahertz region, and the power range commanded by converters extends from a few micro-VA to some hundreds of MVA [1-2].

Transformers have remained an indispensable part of modern power electronic circuits. Distinguished from those in power utility fields, the transformers in power electronic systems are normally required to have high reliability and small volumes. According to the theory of electromagnetics, the electromotive force (*emf*) induced in a transformer winding is proportional to the operating frequency and the magnetic flux linking the winding, smaller magnetic flux is required if the operating frequency is higher. Therefore, increasing switching frequencies of power electronic systems can lead to a dramatic reduction of the volume and weight of transformers used in the systems compared with those operated at low frequencies for a given power rating.

However, at high frequencies, a number of new factors, such as magnetic core loss, thermal effects on magnetic hysteresis of core materials, skin/proximity effects in both magnetic cores and windings, and the effects of stray capacitances and leakage inductances, become significant and cannot be ignored. These factors should be considered for proper design and numerical simulation of high frequency high power density (HFHPD) transformers and inductors [3].

Soft magnetic materials are commonly used as the core materials of the transformers and inductors due to their superior magnetic properties. They play a key role in designing high performance power electronic systems. This paper presents a literature survey on the soft magnetic materials used in the HFHPD transformers and inductors, including electrical sheets, soft ferrites and amorphous magnetic alloys, in terms of their magnetic properties at high frequency operations. Comparing the various materials reveals that the low power loss soft ferrites seem to be the most suitable for HFHPD applications.

II. GENERAL SOFT MAGNETIC MATERIALS

Magnetic materials are traditionally classified as diamagnets, paramagnets and ferromagnets according to their bulk susceptibility χ. Diamagnets have small and negative χ. Their magnetic response opposes the applied magnetic field. Paramagnets are materials having small and positive χ. The magnetization of paramagnets is weak but aligned in parallel with the direction of the applied magnetic field. Ferromagnets are most widely recognized magnetic materials for which the χ is positive and much greater than 1 [4].

The ferromagnets can be further classified as soft and hard magnetic materials according to their coercivities. Typically, “soft” magnetic materials have coercivities of below 1 kA/m [4]. They are regarded as magnetically “soft” since they can be easily magnetized or de-magnetized. Ferromagnetic materials can also be classified as either grain oriented or non-oriented according to their microstructures. The former has large magnetic domains (recognizable under proper conditions) and the latter has smaller domains, or not easily discernible domain structures [5].

Soft magnetic materials can find their applications as the core materials in power transformers, electronic transformers (those used in power electronic systems), magnetic components in microwave systems, and the stator and rotor cores for rotating electric machines. Soft iron and electrical sheet steels are two typical soft magnetic materials. Although high permeability and low coercivity of magnetic materials are needed for transformer cores, the low conductivity is also very important to reduce the eddy current losses since they operate under AC conditions.

The electrical sheet steels are mainly used in AC applications. For high power applications silicon-iron is widely used. Non-oriented silicon-iron is the material of choice in motors and generators while grain-oriented silicon-iron is used for transformers.

A. Non-oriented electrical steels

The technology of electrical steels actually began in 1900 when the work of Barrett *et al.* was published [6]. The addition of small amount of silicon or aluminum to iron was demonstrated to reduce magnetic losses significantly. A gradual improvement in magnetic properties was made because of the realization of the harmful effect of impurities in the steel. Since 1950s, non-oriented electrical steels have been developed along two paths: one is towards low cost for use in cheap devices, and the other is towards high magnetic efficiency. In normal non-oriented steels, the loss is mainly dominated by hysteresis loss, which is around 60-70% of the total loss in the best grades and considerably higher in poor grades. In the special case of larger grains, anomalous eddy current loss predominates and the loss increases. In general, the higher the resistivity becomes, the lower the permeability will be because the additions increase the resistivity and reduce the saturation magnetization. At present, wide range of alloyed and non-alloyed non-oriented electrical steels are available, based on low anisotropy, no aging, and good magnetic properties, particularly at high flux density [7-8].

B. Grain-oriented electrical steels

The grain-oriented silicon-iron is exclusively used as the core materials in power transformers [4] since the permeability of the material is the highest along the easy axis. The first grain-oriented electrical steel strip was produced in 1939 based on Goss's process, in which a careful combination of heat treatment and cold rolling is used to produce a texture giving a silicon-strip good magnetic properties when magnetized along its rolling direction. In 1965, a revolutionary electrical steel that is a high permeability grain-oriented silicon iron, was reported by Nippon Steel Corporation [8]. This material contains about 3-4% by weight silicon to reduce the conductivity. Power losses in general decrease with increasing silicon contents but the material will become brittle.

III. DEVELOPMENT OF LOW-LOSS AND HIGH-PERMEABILITY SOFT MAGNETIC MATERIALS FOR HFHPD APPLICATIONS

The trends of high frequency operation and miniaturization of power electronic systems greatly stimulate the development of low power loss high permeability magnetic materials. The group of low power loss soft magnetic materials, which is especially suitable for HFHPD applications, is permanently growing, depending on the progress in loss control and the operational frequency range. A number of soft magnetic materials, such as soft ferrites, special electrical sheet materials, amorphous materials and nickel-alloys fall into this group.

A. Soft Ferrites

Soft ferrites are ceramic magnetic solids that first appeared commercially in 1945 and for many years were thought to be ferromagnets [4]. They have attractive characteristics of high electrical resistivity and high magnetic permeability. By pressing a mixture of powders containing the constituent raw materials to obtain the required shape and then converting it into a ceramic component by sintering, a ferrite core can be made. The manganese zinc ferrite (MnZn ferrite) and nickel zinc ferrite (NiZn ferrite) are two main types of soft ferrite for a wide range of applications where high permeability and low loss are the main requirements. Soft magnetic ferrites are commonly recognized as very suitable core materials for transformers and inductors in power electronic systems operated at high frequencies [9].

For the lowest frequency range (less than 30 kHz sinusoidal), the use of the ferrites is more limited by the maximum applicable flux density level than by the power losses. For the mostly used frequency range (up to 100 kHz) and the most growing one (up to 1 MHz), the influence of power losses becomes gradually dominant. Up to approximate 200 kHz (sinusoidal excitation), MnZn ferrites are not influenced by eddy current losses, if the grain boundaries are enriched by suitable dopants, which can provide a high enough effective resistivity [10].

Since the chemical composition and the microstructure strongly affect the properties of ferrites, the initial permeability, electrical conductivity and the Curie temperature can be controlled by improvement of raw material quality, a highly sophisticated additive set for chemical composition, and better controlled production process [11]. A new highest permeability ferrite T56 with an initial permeability of μ_i = 20,000 has been developed recently and it is definitely possible to transfer this product into manufacturing scale [10, 12]. Another attractive feature of soft ferrites compared to alloys (Permalloy) is their lower price basis for the raw materials [10]. MnZn ferrites are the common choice for transformer cores in switch mode power supplies.

The magnetic properties of soft ferrites, however, are sensitive to operational temperature to certain extend [13-17]. The saturation flux density at 100^{o}C, for example, can be only about half of the value at 20^{o}C depending on the type of soft ferrite. Furthermore, the saturation magnetisation of soft ferrites is typically 0.5 T, which is much lower compared with other types of magnetic materials.

B. Electrical Sheet Materials

Some efforts have been made to develop electrical sheet steels for high frequency applications. For example, the thin anisotropy electrical sheets, which are manufactured by cold rolling of low carbon steel containing 3.5% Si, exhibit relatively low magnetic power losses and high permeability in their easiest direction of magnetization which are the beneficial magnetic properties at high frequency or at impulse conditions. The crystalline structure of such a sheet, however, causes an orientation dependence of magnetic parameters. Usually, their best magnetic properties are displayed in the rolling direction while the worst occurs at 55^{o} with reference to the rolling direction. Also the sheet thickness has significant influence on the anisotropy phenomena in such a sheet, for example, the anisotropy of coercive force intensity generally increases with a decrease in sheet thickness. The possible reason for this seems to be its strong texture and the domain structure [18]. Nickel-iron alloys (Permalloy) with above 30% nickels are widely used for electromagnetic applications as the most versatile of all soft magnetic materials. They have found their applications in inductors and transformers of different frequency ranges, such as power transformers, audio frequency transformers and high switching frequency transformers in power electronic converters. High quality transformers are often made of this material [4].

C. Amorphous Magnetic Alloys (Metallic Glasses)

The amorphous magnetic alloys or metallic glasses are an exciting group of alloys, perhaps the most important soft magnetic materials discovered since the ferrites. They are produced by rapid cooling (quenching) of magnetic alloys consisting of iron (Fe), nickel (Ni) and/or cobalt (Co) with one or more the following elements as additions, boron (B), phosphorus (P), silicon (Si) and sometimes carbon (C). They have very good magnetic properties for soft magnetic material applications [4]. The magnetic importance of amorphous materials was not commonly realized until the first work on them started in 1971 by Allied Signal Inc., Metglas Products [8].

In the long term, metallic glass development may lead to higher permeability and lower losses. The best commercial material has power losses as low as around 15% of the best silicon-iron grades. Stress sensitivity of amorphous materials is a major problem which must be overcome by possibly major changes in core design and building techniques, combined with attempts to reduce the basic stress sensitivity of the materials [8]. Replacing a variety of magnetic materials, they have found commercial applications in some areas, such as transducers, sensors, high frequency devices, electronic power supplies and magnetic recording heads. The major advantage of amorphous materials is the low power losses while they have the following disadvantages: (a) The operating temperature is limited to around 120^{o}C owing to the low Curie and recrystallization temperatures; (b) The saturation magnetisation is low; and (c) Their core losses begin to increase rapidly at higher flux densities.

Although metallic glass is the only commercially available magnetic material, which can replace the electrical sheet steels, its full potential in power industry is still unclear [8]. It does not seem to be a real likelihood of large-scale adoption of this material as transformer cores [4]. Recently, some researchers investigated the application of metallic glasses in MEMS [19-20]

IV. CONCLUSION

This paper presents a review on the soft magnetic materials used for the high frequency high power density (HFHPD) transformers and inductors in power electronic systems. The characteristics of soft ferrites, particularly the high permeability and low conductivity, give soft ferrite cores an undisputed superiority over electrical steels or transformer steels. These characteristics of soft ferrites become more and more attractive with the urge to increase switching frequencies for reducing dramatically the physical size of transformers and inductors in power electronic systems. Compared to other soft magnetic materials, low-loss soft ferrites seem more suitable for the core materials of HFHPD transformers and inductors.

REFERENCES

[1] J. D. Van Wyk and F. C. Lee, "Power electronics technology at the dawn of the new millennium – status and future (invite paper)," in *Record of the 30th IEEE Power Electronics Specialist Conference*, Charleston, South Carolina, USA, June 27 – July 1, 1999. pp. 3-12.

[2] B. K. Bose, "Power electronics and motion drives – technology advances, trends and applications," in *Proceedings of the IEEE International Conference on Industrial Technology*, Dec. 14-17, 2005, pp. 20-64.

[3] H. Y. Lu, "Numerical simulation of high frequency transformers in power electronic systems," *Ph.D. Thesis*, University of Technology, Sydney, Australia, Aug. 2001.

[4] David Jiles, *Introduction to Magnetism and Magnetic Materials*, Chapman & Hall, 1998, Second Edition.

[5] R. M. Del Vecchio, "Computation of losses in nonoriented electrical steels from a classical viewpoint," *Journal of Applied Physics*, vol. 53, no. 11, pp. 8281-8286, November 1982.

[6] W. F. Barrett, W. Brown, and R. A. Hadfield, "Electrical conductivity and magnetic permeability of various alloys of iron," *Proc. Roy. Dublin Soc.*, no. 7, pp. 67-126, 1900.

[7] C. K. Hou, "Effect of hot band temper rolling strain on the magnetic properties of low-carbon electrical steels," *Journal of Magnetism and Magnetic Materials*, vol. 162, pp. 291-300, 1996.

[8] A. J. Moses, "Electrical steels: past, present and future developments," *IEE Proceedings: Part-A*, vol. 137, no. 5, pp. 233-245, Sept.1990.

[9] B. P. Rao, C. O. Kim, C. G. Kim, I. Dumitru, L. Spinu, and O. F. Caltun, "Structural and magnetic characterizations of coprecipitated Ni-Zn and Mn-Zn ferrite nanoparticles," *IEEE Transactions on Magnetics*, vol. 42, no. 10, pp. 2858-2860, Oct. 2006.

[10] M. Zenger, "New developments in the field of soft magnetic ferrites," *Journal of Magnetism and Magnetic Materials*, vol. 112, pp. 372-376, 1992.

[11] S. Otobe, Y. Yachi, T. Hashimoto, T. Tanimori, T. Shigenaga, H. Takei and K. Hontani, "Development of low loss Mn-Zn ferrites having the fine microstructure," *IEEE Transactions on Magnetics*, vol. 35, no. 5, pp. 3409-3411, Sept. 1999.

[12] A. Znidarsic, M. Limpel and M. Drofenik, "Effect of dopants on the magnetic properties of MnZn ferrites for high frequency power supplies," *IEEE Transactions on Magnetics*, vol. 31, no. 2, pp. 950-953, Mar. 1995.

[13] SIEMENS, *Ferrites and Accessories*, Data Book 1990/1991.

[14] *Philips, Soft Ferrite Data Book 1996*.

[15] H. Y. Lu, J. G. Zhu, V. S. Ramsden, and K. Tran, "Measurement and modeling of magnetic hysteresis of soft ferrites at different temperatures," in *Proceedings of Australian Universities Power Engineering Conference*, Sydney, Australia, Sept. 29 – Oct. 1, 1997, pp. 477-482.

[16] H. Y. Lu, J. G. Zhu, and V. S. Ramsden, “An improved prediction of thermal effects on magnetic hysteresis of soft ferrites”, in *Proceedings of Australasian Universities Power Engineering Conference*, Darwin, Australia, Sept. 26-29, 1999, pp. 382-387.

[17] L. Zegadi, J. J. Rousseau, B. Allard, P. Tenant, and D. Renault, “Model of power soft MnZn ferrites, including temperature effects,” *IEEE Transactions on Magnetics*, vol. 36, no. 4, pp. 2022-2032, July 2000.

[18] M. Soinski, Z. Bak, and P. Bragiel, “Anisotropy of magnetic properties in thin electrical sheets,” *IEEE Transactions on Magnetics*, vol. 26, no. 6, pp. 3076-3079, Nov. 1990.

[19] S. Hata, J. Sakurai, A. Shimokohbe, “Thin film metallic glasses as new MEMS materials,” in *Proceedings of IEEE International Conference on Micro Electro Mechanical Systems*, Jan. 30 – Feb. 3, 2005, pp. 479-482.

[20] H. W. Lu, J. G. Zhu, and Y. G. Guo, “Development of a slotless tubular linear interior permanent magnet micro motor for robotic applications,” *IEEE Transactions on Magnetics,* vol. 41, no. 10, pp. 3988-3990, Oct. 2005.

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