Collaboration and Invisible Gap between Magnetics & Power Electronics Researchers

－ Toward Better Magnetic Design of Inverter-Driven Equipment -

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Many of the manufacturing industries meet revolutionary change in high-power electronics, controls, and communication links. Everyone in this scientific/technological field believes that magnetic and power electronic co-design/analysis greatly improve the equipment performance and extensively the quality of life. Nevertheless everyone also feels invisible gap between magnetic and power electronic approaches to solve the problems. In particular, design of non-linear magnetic core losses under non-sinusoidal wave excitation is a matter of common concern but differently approached by the two communities.

This talk firstly reviews the magnetic approach to analyze the core losses, which is featured by physical and material-scientific interests. Then power-system approach from the power electronics community will be introduced. The author suggests magnetic researchers to try finding physical/material meaning of behavior models suggested by power electronics side, and power electronics researchers to develop tools to apply non-sinusoidal magnetic field source to magnetics side.

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パワーエレクトロニクス技術から見た磁気・磁性材料への期待

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SiC や GaN 等の次世代パワーデバイスの出現によって、パワーエレクトロニクス装置の小型・高性能化、低コスト化の進展が期待されている。とりわけ、高速・高周波スイッチングによって変圧器・リアクトル、および電力用コンデンサなどの受動デバイスの小型化が期待されているが、受動デバイスの発熱に伴う温度上昇、および電磁ノイズの増加などの課題が明らかになってきた。
本稿では、パワーエレクトロニクスのスイッチング回路に使用される磁気デバイスの損失計測手法を紹介すると共に、各種磁性体の損失評価手法、およびこれらを用いた変圧器・リアクトルの低損失設計手法について解説する。さらに、今後のパワーエレクトロニクス技術の進展に対応した磁性材料への期待について紹介する。

Recent progress in Fe-based amorphous and nano-crystalline alloys for use in motor cores

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One of the most effective methods to reduce core loss in motor cores is to use superior soft magnetic materials. Non-oriented electrical steel (NO) is generally used for motor cores and core loss is reduced by decreasing its thickness to suppress eddy current loss. The thickness of currently commercial NOs ranges from 0.35 mm to 0.15 mm. However, from the standpoint of core loss reduction, it is much more effective to change core material from NO to Fe-based amorphous (Fe-based AM) or Fe-based nano-crystalline alloys (Fe-based NANO).

Table 1 lists magnetic properties of Fe-based AM Metglas® 2605SA1 (2605SA1), Fe-based NANO and NO. Core losses of 2605SA1 and Fe-based NANO are approximately 1/10 or less than that of a conventional NO (35H300). On the other hand, these materials have some disadvantages in manufacturing motor cores.

Fe-based AM is obtained in the form of thin strip by solidifying molten metal at cooling rates of more than 10^6 K/s which is faster than the growth rate of crystalline nuclei with single-roll rapid-solidification method. As-cast Fe-based AM has large internal stresses introduced by rapid solidification. Therefore, the stress relief annealing is essential to obtain better magnetic properties as indicated on “Non-field annealing” line in Table 1. However, the annealed Fe-based AM becomes slightly brittle. When the as cast Fe-based AM on “Non-annealing” in Table 1 is mainly considered in AM motor core, the core loss of the motor core is still much lower than that of NO. The thickness of an Fe-based AM strip is much smaller at approximately 0.025 mm, which is less than 1/10 of that of a conventional NO. And its Vickers hardness is 900, which is approximately 5 times that of NO. Therefore it is difficult to apply the conventional punching technique to Fe-based AM core manufacturing. Therefore IE5 efficiency class axial gap motors using Fe-based AM laminated stator cores manufactured with slitting and shearing methods, which are widely used for manufacturing Fe-based AM transformer cores, have been developed and commercialized.

Fe-based Nano is also cast by single-roll rapid-solidification method. Therefore the as-cast state has almost the same physical properties, such as thickness and hardness, as those of Fe-based AM. And Fe-based NANO requires high temperature annealing comparable with Fe-based AM in order to create nanocrystalline structure. Therefore Fe-based NANO is much more brittle than annealed Fe-based AM. In order to commercialize an Fe-based NANO motor, it is necessary to develop a core manufacturing method that is applicable to brittle alloy thin strips.

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Table 1 Magnetic properties comparison between nanocrystalline alloys and conventional materials

Material		B_s (T)	$P_{15/50}$ (W/kg)	$P_{10/400}$ (W/kg)	$P_{10/1k}$ (W/kg)
Fe-based AM 2605SA1	Non-field annealing	1.56	0.22 typ.	0.81 typ.	3.0 typ.
	Non-annealing		—	2.2 typ.	7.4 typ.
Fe-based NANO	FINEMET® FT-3M	1.23	—	0.12 typ.	0.57 typ.
	$Fe_{82}Cu_1Nb_1Si_4B_{12}$ (1)	1.78	0.20	1.3	4.4
	$Fe_{80.8}Cu_{1.2}Si_4B_{11}P_2$ (1)	1.79	0.18	1.8	6.8
	$Fe_{80.5}Cu_{1.5}Si_4B_{14}$ (1)	1.80	0.27	1.6	5.8
	$Fe_{81.8}Cu_{1.0}Mo_{0.2}Si_4B_{14}$ (2)	1.75	0.28	1.5	5.0
NO	35H300 (t=0.35 mm)	2.0	2.4 typ.	18 typ.	78 typ.
	15HX1000 (t=0.15 mm)	2.0	2.0 typ.	9.3 typ.	33 typ.
	6.5% Si-Fe 10JNEX900 (t=0.1 mm)	1.8	—	5.7 typ.	18.7 typ.

Soft Ferrite Materials in Power Electronics

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Magnetic materials are roughly classified into metallic magnetic materials and oxide magnetic materials by their composition. And, by their magnetic properties, magnetic materials are also classified into soft magnetic materials having the smaller coercive force (Hc) and hard magnetic materials having the large Hc. (figure 1)
Ferrites are well known as typical oxide magnetic materials. Since OP magnet and CuZn ferrite core were invented by Kato and Takei at 1930's, various kinds of hard/soft ferrites have been developed and used in many applications.
Soft ferrites are one of the important materials for power electronics, even today. Generally, the saturation magnetic flux densities of ferrite materials are smaller than that of metallic soft magnetic materials such as permalloy and silicon steel. However, because of their higher electrical resistivity, ferrites have superior magnetic properties at high-frequency. Therefore, soft ferrites have been widely used as the core of inductor and transformer for high-frequency.
MnZn ferrites and NiCuZn ferrites are well known as representative materials of soft ferrite.
Since these ferrites have different magnetic characteristics, suitable applications are different. For example, as shown in figure 2, appropriate operating frequency range is different by their different permeability range.
There are various magnetic materials, and even for only MnZn ferrite used as the core of transformer, there are many kinds of materials with different magnetic properties such as permeability, coreloss and saturation magnetic flux density. Therefore, it is important to understand magnetic features of various magnetic materials to select suitable materials for applications.
On the other hand, it is becoming more and more important to consider actual operating condition and usage on recent development of magnetic materials.
In the presentation, the recent topic on the development of ferrite materials and its application examples in power electronics will be reported.

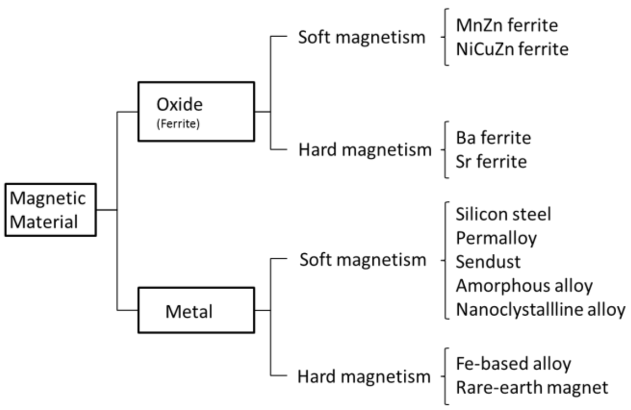

Figure 1. The classification of magnetic materials, and representative materials

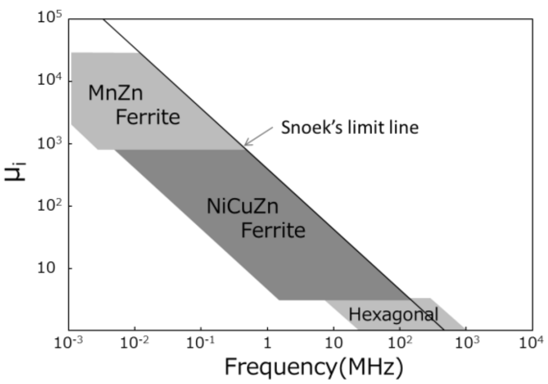

Figure 2. Schematic image of relationship between initial permeability range of ferrites and its appropriate operating frequency range.[1)]

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Magnetic material and magnetic measurement of the traction electric motor for high efficiency and miniaturization

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Compared to other types of electric motors used in vehicles, traction electric motors, which are used in hybrid vehicles (HVs), plug-in hybrid vehicles (PHVs), and electric vehicles (EVs), have a long operation time and a large output. In order to drive a vehicle, a motor must have a wide operation area. Motors are most frequently used under light- to medium-load conditions, and are driven by an inverter. Based on the above characteristics, traction electrical motors must be highly efficient and compact. In order for motors to satisfy these demands, high performance is also expected for magnetic materials.

Miniaturization of motors can provide an increase in the output power with the same volume, or in other words an increase in the output density. Increasing the rotation speed and torque are effective means for increasing the output density. It is desirable for the rotor to be constructed of a high-strength core material in order to increase the rotation speed. High torque density can be achieved by improving the saturation magnetic flux density and the space factor in the core material. In order to realize a high-efficiency motor, it is necessary to lower the iron and copper losses. Iron loss is caused by magnetic flux fluctuations. Therefore, reducing unnecessary magnetic flux, which does not contribute to the torque, and selecting an appropriate core material according to the flux fluctuation, are effective strategies for improving the efficiency.

Magnetic flux in the motor exhibits various behavior. Alternating flux is dominant in the stator teeth and the stator back yoke, while rotating flux is dominant in the tips of the stator teeth and in the joint of the stator teeth and back yoke. On a rotor, a DC flux is generated by a permanent magnet and a fundamental waveform of stator currents. At the area near the air gap, the magnetic flux fluctuates due to a change in the magnetic resistance. Moreover, an inverter superimposes high-frequency magnetic flux having a switching frequency on the above-mentioned magnetic fluxes. On the other hand, various mechanical situations occur in the motor. For example, for the case in which the stator is fixed by shrink fitting, a large stress is applied to the stator back yoke. In addition, when the coil end is compressed in order to miniaturize the height of the coil end, the stator core is subjected to stress in the direction of the rotation axis. As described above, the manner in which the magnetic flux flows and the manner in which the stress is applied are different for each portion. In motor design, it is important to know in detail the types of phenomena that occur for each portion. Understanding each phenomenon makes it possible to choose the appropriate materials in a suitable shape. Magnetic measurement is important in order to determine the characteristics of the materials. The next paragraph describes two important measurement examples.

First, we show the apparatus for measuring the rotational magnetic flux[1)]. In this apparatus, the number of teeth of the excitation yoke is increased from four (in the conventional apparatus) to eight. The eight teeth are divided into two groups, a main-pole and a sub-pole, and different currents flow in the exciting coil on the main-pole and the exciting coil on the sub-pole. This makes generating a rotating magnetic field in the measurement part in the center of the specimen easy at high magnetic flux density. By setting the ratio of the magnetomotive force distribution of the sub-pole to the main pole to 30:70, this apparatus made it possible to measure the iron loss under the condition that there is a rotating magnetic flux up to 1.9 T, as shown in Fig. 1. Figure 2 shows the thin needle probes on a steel sheet used to measure a magnetic property under out-of-plane stress[2)]. Measurement is performed while pressurizing the measurement part from the normal direction of the plate. Therefore, the wire diameter of conventional search coils is too thick to generate uniform pressure. Therefore, thin-film probes were fabricated on the surface of the sheet by sputtering, and the magnetic flux was measured using the principle of the probe method. Since the probe formed by sputtering is as thin as 20 μm, it is possible to perform measurement while applying pressure. The measurement results revealed that the iron loss increased or decreased depending on the direction of the magnetic flux by pressurization.

By measuring the magnetic characteristics, we can design an electric motor that considers these properties in detail, allowing the design of highly efficient and high power density motors.

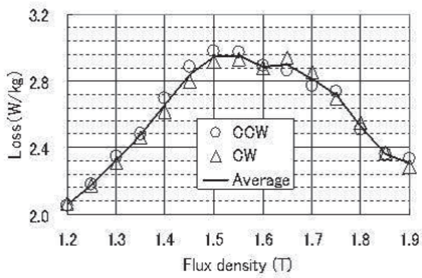

Fig. 1 Measurement results for the rotational flux.[1)]

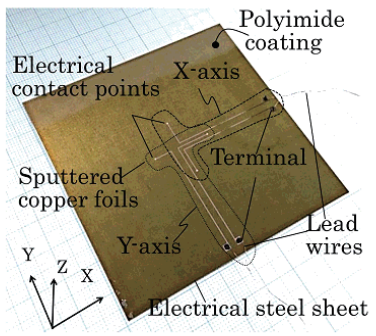

Fig. 2 Thin needle probe on a steel sheet.[2)]

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Required Magnetic Material Excited by Power Electronics Equipment

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Energy magnetic material of soft one as well as hard one is used in electrical energy circumstance in order to obtain high magnetic flux density in small external magnetic field. Electrical motor, transformer and inductor are its application. Because of power semiconductor development, power electronics technology is widely applied to electrical energy. So power magnetic material is said to be excited by and used in power electronics equipment.

One of the most important key technologies in power electronics is a switching operation. By using it, the energy consumption in the power semiconductor becomes small, and then the electrical energy conversion such as AC to DC or DC to AC in any voltage and any frequency can be realized in high efficient and in high responsibility. So an electrical motor excited by inverter, a kind of power electronics equipment, makes it possible to rotate in variable velocity. Now the motor drive system can be applied to all the transportation vehicle such as automobile, ship and airplane.

However, this tendency of power electronics excitation makes energy magnetic material in a new operated condition. Usually, it is excited in commercial frequency without harmonics components basically as far as it is used in connection with electrical energy network directly. In power electronics circumstance, an operating frequency becomes high and electrical current and voltage has harmonics components. High frequency operation is required to make the electrical components small, and harmonics components always generates because of the switching operation of power semiconductors.

This tendency has been already realized in small electrical energy equipment such as mobile phone or notebook personal computer. The operating condition is MHz to GHz frequency in mW to W electrical power. However, the new tendency as transportation revolution and new material of SiC and GaN requires a new operation condition as kHz to MHz in kW to MW, which can be realized by power electronics research. New magnetic material is strongly expected.

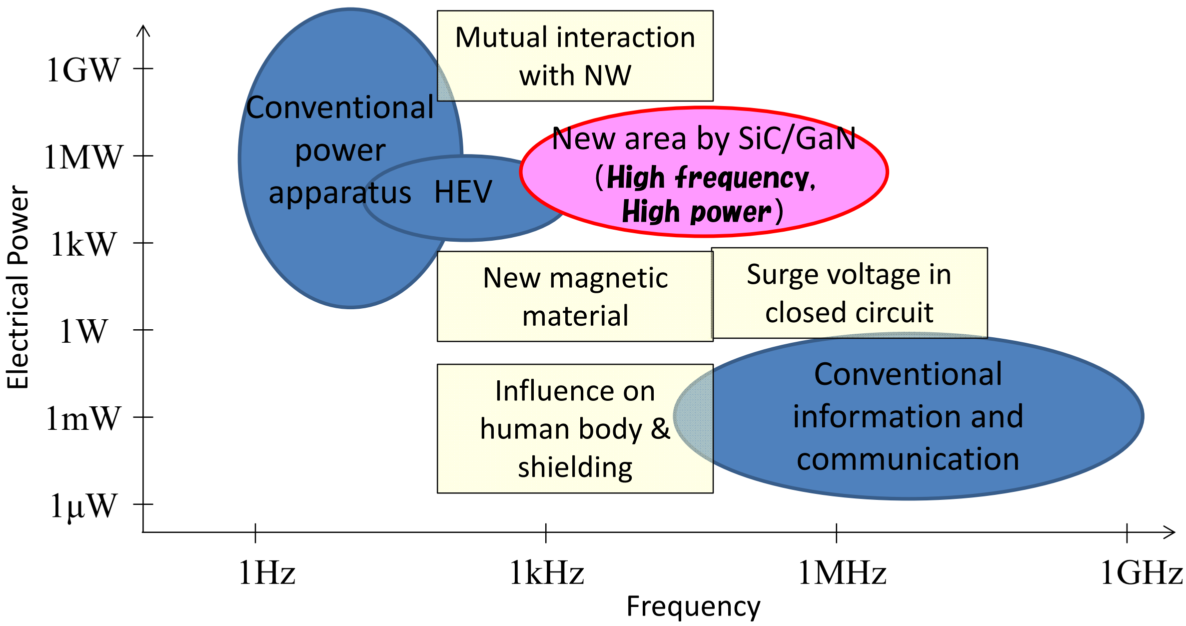

Fig. 1. Required magnetic material by power electronics development for new transportation system.

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