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Vector magnetic characteristic technology in Oita University for development of low loss and high efficiency machines

Abstract*. The national project concerning development of technology of next generation applied electromagnetic machinery was founded in Oita under the name of "Oita Prefecture Innovative JST (Japan Science and Technology Agency) Research Program". In this paper, outline of this project is introduced and the applied technology based on vector magnetic properties is described. Many kinds of measurement equipment and systems were newly developed for this project. Some of them are presented in the paper.*

Streszczenie. *Przedstawiono główne wyniki realizacji projektu badawczego dotyczącego nowej generacji urządzeń elektromagnetycznych realizowanego w Oita University. Szczególny nacisk położono na opis właściwości wektorowych materiałów magnetycznych. Opracowano i opisano szereg nowych urządzeń i systemów pomiarowych. (**Technologie bazujące na właściwościach wektorowych materiałów magnetycznych opracowane w Oita University**)*

Keywords: vector magnetic property, high efficiency, low loss, magnetic power loss, magnetic measurement,
Słowa kluczowe: wektorowe właściwości magnetyczne, straty mocy, pomiary magnetyczne.

Introduction

Applied electromagnetic technology might be called mature one but it is a new technology too. Until now, many electromagnetic machines such as motors and transformers have been developed. However, the main requirement was quantity rather than quality. Next generation of applied electromagnetic technology will be concentrated on development of high-power machines being small and light at the same time. Fig. 1 shows a concept of design guidelines of electrical machinery and apparatus. The new guideline is imaged by the dotted line, while the continuous line shows the conventional guideline. A small-size machine with a low loss and a high efficiency has to provide more output, as well as a large machine has to be smaller size. It is necessary to establish the technology, which effectively utilizes high quality magnetic materials in order to solve the problem. In other words, the target is to develop high performance machines by using high quality materials.

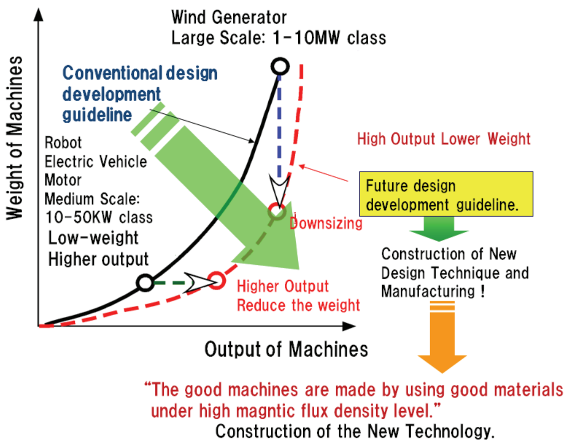


Fig. 1 Guideline of machine development

Fig. 2 shows a high torque density coefficient of motors offered by main manufacturers in Japan. This result was analyzed by the special investigation committee on the power magnetic material in JIEE. The high torque density factor is given by the following equation.

$$\eta = \frac{\text{Output Torque}}{\text{Net Weight of Core, Coil and Permanent Magnet}} \quad (1)$$

This factor is nearly proportional to the output torque. The applications of motors around 100-500Nm class are electric vehicles, hybrid cars and power machines. Only the effect of substituting secondary windings for permanent magnets can be considered as a factor in increasing torque density. The target for next generation motors is drawn by the dashed line in Fig. 2.

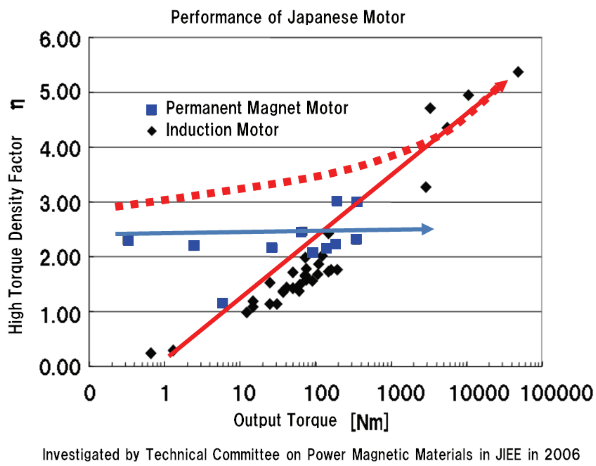


Fig. 2 High torque density factor of motors in Japan

Problems for Upgrading Efficiency of Machines

It is necessary to apply a high induction region to motor design in order to design a high density machine. However, it is not a straightforward task. In case of the high induction region, magnetic properties have strong nonlinearities and then it is difficult to use the magnetic properties measured by the conventional standard methods. The reason is that so far those are treated as a scalar quantity despite their vector nature.

Moreover, the standard measurements are subject to large errors in the high magnetic flux density region. By fixing the magnetic path length, the standard measurement methods overestimate the magnetic properties. Generally, the magnetic path length is changing with increasing magnetic flux density. Therefore, the measurements with the H-coil method, which does not use the magnetic path length in calculations, are desirable, as it is shown in Fig. 3. Furthermore, in arbitrary direction the magnetic field strength vector ***H*** is not always parallel to the magnetic flux density vector ***B***. Consideration of this complex vector behavior is very important for the design of high torque density machines.

There are three categories of the magnetic measurements.

(i) Standard measurement (based on the IEC standard)
In this measurement, the magnetizing current (CM) method based on the effective magnetic path length is used in evaluation of the magnetic field strength.

(ii) Evaluation Measurement
In this measurement, accurate evaluation of magnetic field strength is possible by means of the H-coil method.

(iii) Measurement Utilized for designing
This means measurement of vector magnetic properties for engineering design by suing the Vector Hysteresis (V-H) analyzer system.

The establishment of the measurement methods of category (ii) and (iii) is required now. Especially, (iii) is very important in preparing material recipes for technical design (Fig. 4).

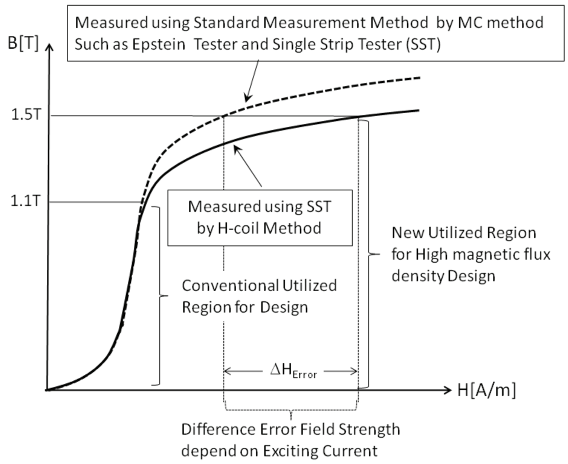


Fig. 3 Relation between standard measurement methods and the H-coil method

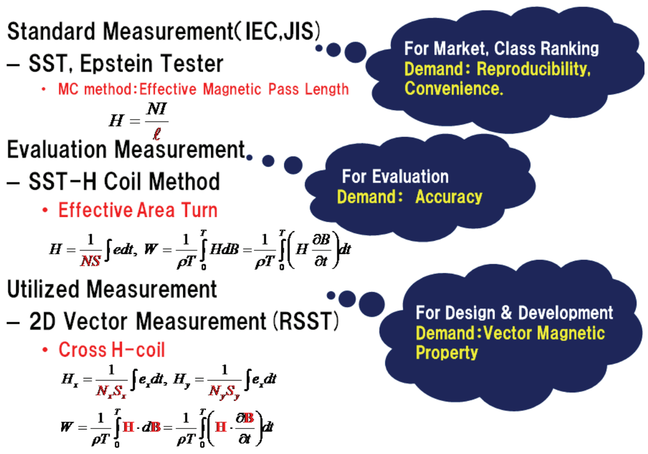


Fig. 4 Categories of magnetic measurements according to the purpose.

Vector Magnetic Property

In order to design high density machines having good efficiency in the high induction level, it is necessary to take into account the vector magnetic properties. It allows to use modern magnetic materials efficiently. Fig. 5 shows the two dimensional (2D) vector magnetic properties of a non-oriented electrical steel sheet. The locus of ***H*** for the alternating flux density in arbitrary direction (from 0.4 T to 1.8 T) are illustrated. In the low induction level, the rolling anisotropy can be seen, but this phenomenon changes and the crystal magnetic anisotropy appears over 1.3 T.

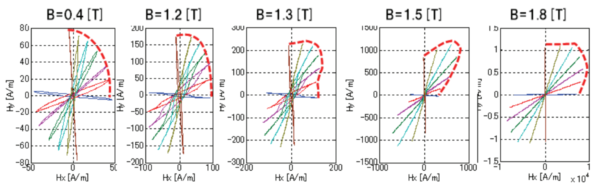


Fig. 5 Comparison of 2D vector magnetic property between low induction and high induction level.

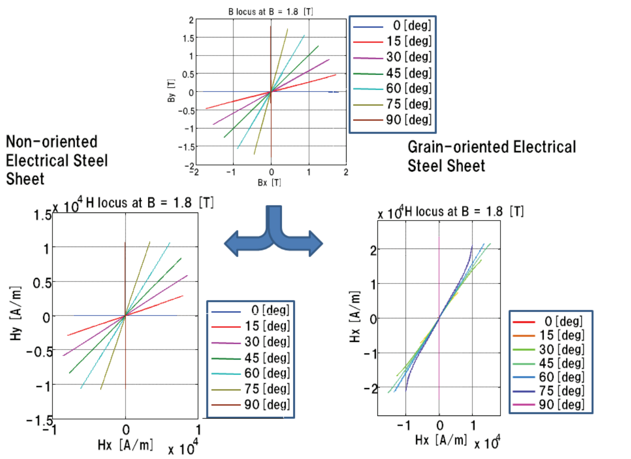


Fig. 6 Vector magnetic properties of non-oriented and grain-oriented electrical steel sheets under alternating flux condition.

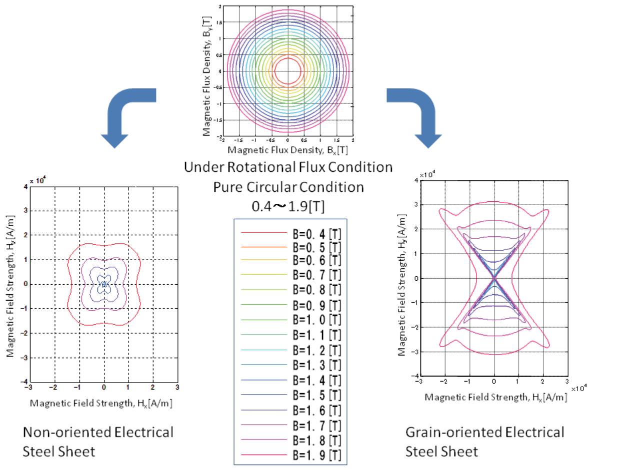


Fig. 7 Vector magnetic property of non-oriented and grain-oriented electrical steel sheet under rotating flux condition.

Figs. 6 and 7 show the vector magnetic properties in the high induction level of the non-oriented and grain-oriented electrical steel sheets under alternating and rotating flux conditions. The effect of the crystal magnetic anisotropy appears, when the magnetic flux density is larger than 1.3 T. This characteristic must be considered in designing high density machines at the high induction level. Also because ***H*** is not always parallel to ***B***, it is necessary to consider the vector magnetic properties in order to utilize the magnetic materials accordingly in a specific design.

Vector Magnetic Behavior in Transformer Core

In this section, we discuss measured distribution of the localized vector magnetic properties of the transformer model core (Fig. 8). Fig. 9 shows the V-H probe used in the measurement. Fig. 10 shows the locus distributions of ***B*** and ***H***. The distributions of the magnetic field strength vector trajectories in a practical model core is important as well as a current in machine designing. From the measured data, the magnetic power loss can be calculated by using the following equation.

$$(2) \qquad P = \frac{1}{\rho T}\int_0^T \left(H_x \frac{dB_x}{dt} + H_y \frac{dB_y}{dt} \right) dt$$

where, ρ is the mass density and T is the time period.

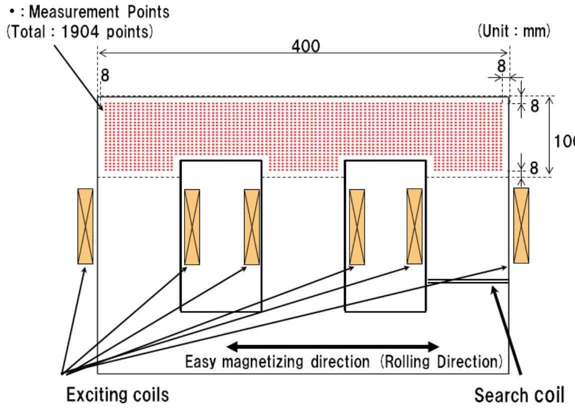


Fig. 8 Transformer model core.

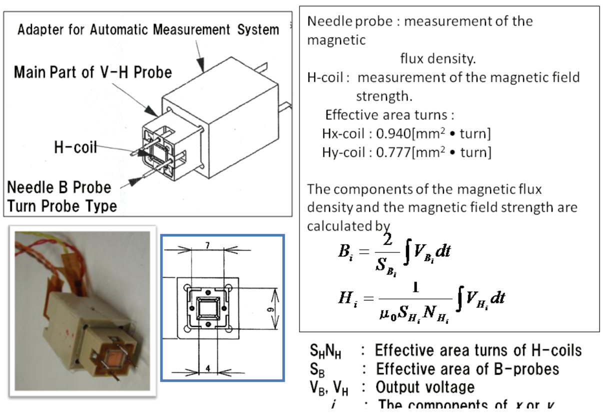


Fig. 9 Specification of V-H probe

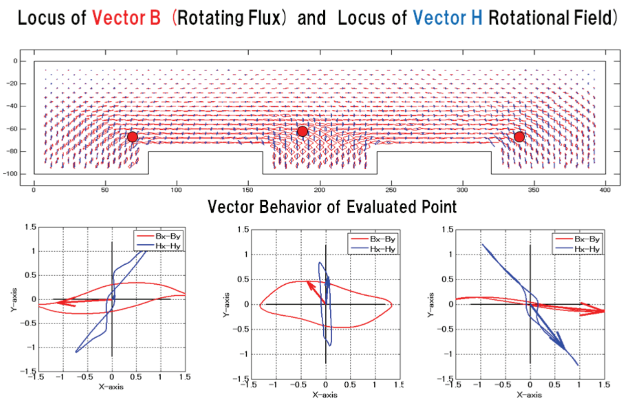


Fig. 10 Distribution of locus of ***B*** and ***H***.

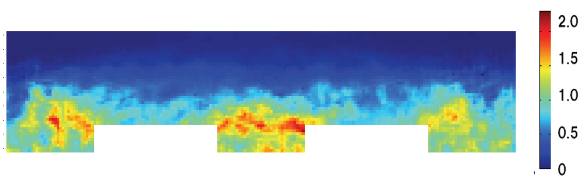


Fig. 11 Distribution of the magnetic power losses

Fig. 11 shows the measured magnetic power loess distribution. We must pay attention to asymmetry of distribution depending on not only the phase unbalance of U-V-W three-phase current but also the vector magnetic properties.

Utilization of Vector Magnetic Property [1]-[5]

In the conventional method, the magnetic properties have been expressed by scalar quantities. Similar situation exists in hysteresis loops. This approach has an impact on the adoption of decisively different strategy for the power losses minimization. In the former the loss reduction was simple because of the assumption that the power losses are a function of the magnetic flux density. You could say that the power losses can be reduced if the magnetic flux density decreases. However, lowering the magnetic flux level increases the weight of machines. Increasing the weight of machines does not allow for the construction of high density machines.

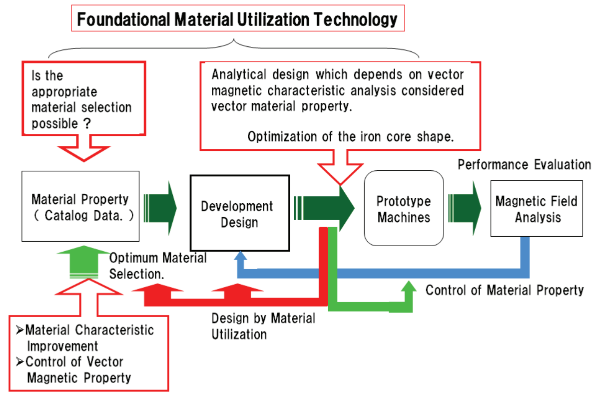


Fig. 12 Guideline of vector magnetic technology.

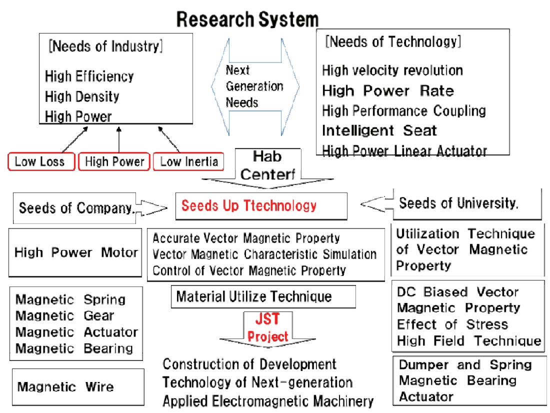


Fig. 13 Research system of Oita Project in JST.

Use of the vector magnetic properties in technical designing has a new possibility, because the magnetic power losses are obtained by taking into account the phase angle between ***H*** and t ***B*** as well as their amplitudes. Fig. 12 shows the guideline for the vector magnetic technology.

Fig. 13 shows the research system organization of the JST project. Thirteen companies and eight universities have been involved in the project. The research and development work involved about 80 scientists. The advantage of the project is the collaboration of electrical and mechanical engineers. In addition, medical doctors and physicists also took part in it. The project runs from January 2008 to December 2012 and will further continue (phase 3).

This project is composed of three sub-themes as shown in Fig. 14. The role of the sub-theme 3 is very large for the development of the next generation technology. 80% of various measuring systems are introduced in the sub-theme 3. The main measuring systems introduced or developed so far are a stress vector magnetic characteristic measuring system, a dynamic magnetic domain observation system by SEM, and a 40T pulsed field generator. The basic measurement systems and equipment are introduced during first 2 years (phase 1), and research fund is mainly spent after it (phase 2) for controlling the vector magnetic properties. The sub-theme 1 includes development of high power and high efficiency motors: one is a low speed high torque motor for direct drive and another is a high speed motor which uses the amorphous core. The sub-theme 2 includes development of high performance drive and transfer elements, which are a magnetic spring, a magnetic dumper, a magnetic coupling, a magnetic gear, a magnetic bearing and various magnetic actuators.

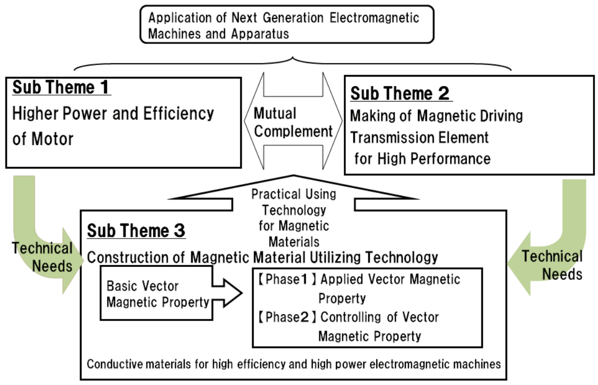


Fig. 14 Research system organization.

The systems developed during this project are as follows;

(i) Measurement System of Vector Magnetic Property (Vector Hysteresis Analyzer)

Using this system, it is possible to measure the vector magnetic properties up to 1.9T. A high speed V-H analyzer with a large-capacity power amplifier was also developed; the power amplifier delivers 800V, 2.4kW, up to 10kHz.

(ii) Measurement System of Stress Vector Magnetic Property [6]

This V-H analyzer is equipped with 8-channel A/D converter. The four channels are for measurements of H_x, H_y, B_x and B_y component. The three channels are for measurements of two-dimensional strain and stress with a three-axial strain gauge. Stress can be applied up to 70 MPa in arbitrary direction.

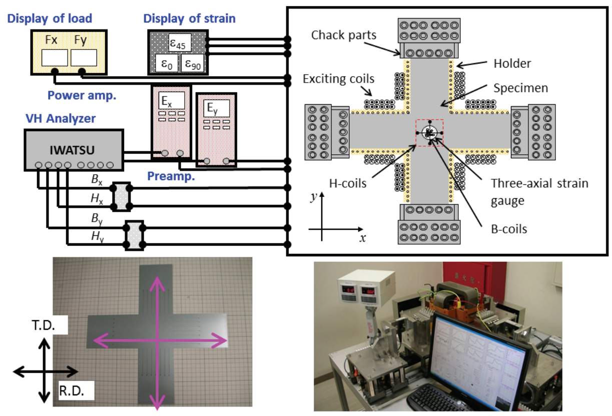


Fig. 15 Vector hysteresis analyzer system considering effect of stress and construction of specimen.

(iii) Measurement System of Two-Dimensional Magnetostriction [7]

This system can accurately and simultaneously measure a two-dimensional magnetostriction (by tensor formulation) and the vector magnetic properties.

(iv) Dynamic Domain Observation System by SEM

This system can observe the dynamic domain moving with frequency up to 500Hz under measuring the vector magnetic properties.

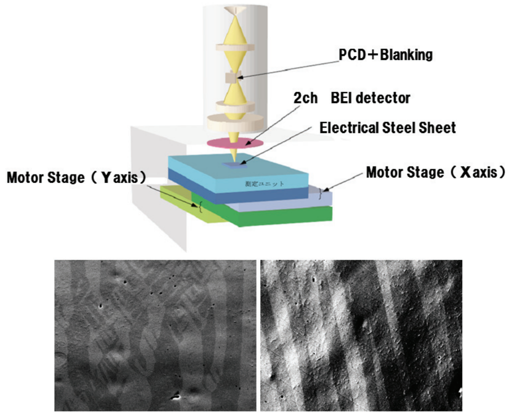


Fig. 16 Dynamic magnetic domain observation system under vector magnetic behavior.

(v) Loss Visualization System by Thermography [8]

This system can directly observe magnetic power loss distributions by using a thermography system.

(vi) Stress Effect Estimable typed SST

This system can evaluate the electrical steel sheets and amorphous sheets under tensile and compressive stress, by the MC method and the H-coil method.

(vii) Measurement System of Residual Stress by X-ray

This system can measure the distribution of residual stress such as tension, compression, and shear force in an electrical machine core by a X-ray diffraction technique [9].

(viii) Measurement System of Hard Magnetic Material by Long Pulse Excitation

This system can measure a saturated M-H hysteresis loop in easy and hard direction for anisotropic rare earth hard materials. It has a time constant of 0.1~0.5Hz and can excite up to 40T. Perfect major M-H hysteresis loops can be obtained as shown in Fig. 23.

(ix) Measurement System of Three-Dimensional Magnetic Field Distribution

It can measure a three-dimensional magnetic field distribution by using a three-axial hall element, which has size of 0.2mm.

(x) Measurement System of DC-biased Vector Magnetic Property (in Gifu University) [10]

It can measure the DC-biased vector magnetic property, and is equipped with 8-channel A/D converter and four sensitive flux meters.

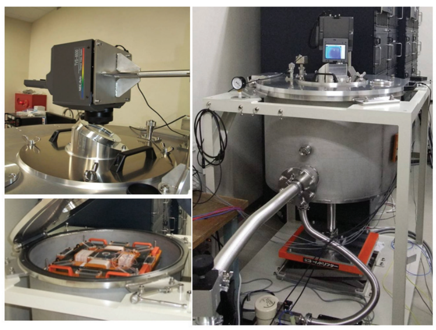


Fig. 17 Loss visualization system.

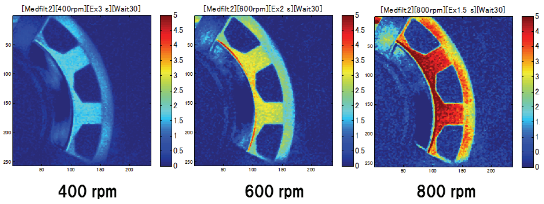
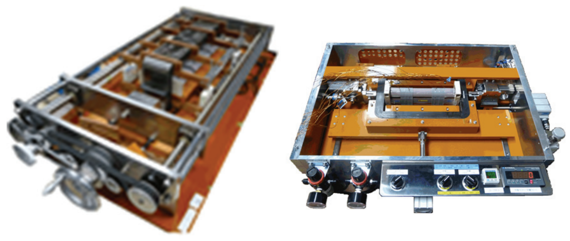


Fig. 18 Measured examples.



(a) 100mm width sheet (b) 30mm width sheet

Fig. 19 SSTs considering effect of stress.

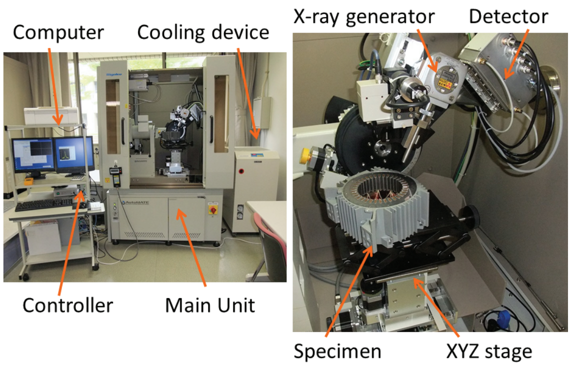


Fig. 20 Residual stress measuring system.

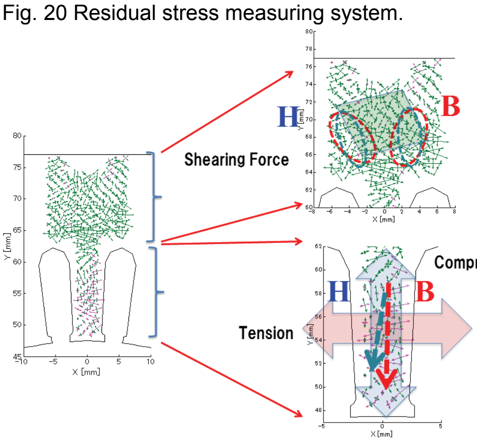


Fig. 21 Relationship between stress distribution and vector magnetic property.

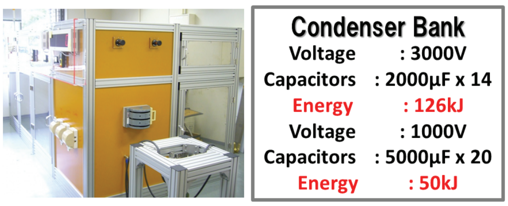


Fig. 22 Long pulse source for magnetizing.

(xi) Computer System for Vector Magnetic Characteristic Analysis by E&S Model

This system is for the simulation considering vector magnetic properties with a 25-computer integrated system through intranet.

(xii) Calibration System of H-coil

It can calibrate the crossing type H-coil sensitivity, which depends on an effective area turn and crossing angle.

(xiii) Controlling System of Vector Magnetic Property

It is for controlling vector magnetic properties by a laser and plasma jet treatment in order to reduce the magnetic power loss.

(xiv) Dielectric Breakdown Evaluation System for High Voltage PWM

This system consists of 1kV, 10kHz high frequency voltage source and an isolated measurement system.

(xv) Automatic Measurement System of Localized Distribution of Vector Magnetic Properties [11]

It can measure automatically localized distribution of the vector magnetic properties. It uses a special small V-H sensor, which has the H-coil (2mm x 2mm ~ 5mm x 5mm) and a needle type B-prove.

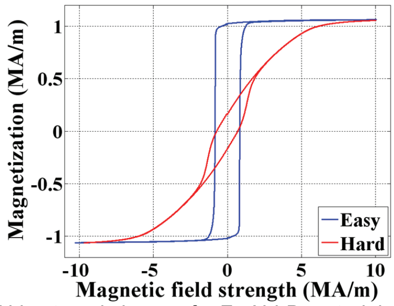


Fig. 23 M-H hysteresis loops of a Fe-Nd-B material.

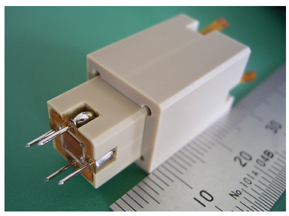


Fig. 24 V-H probe (4mmx4mm size)

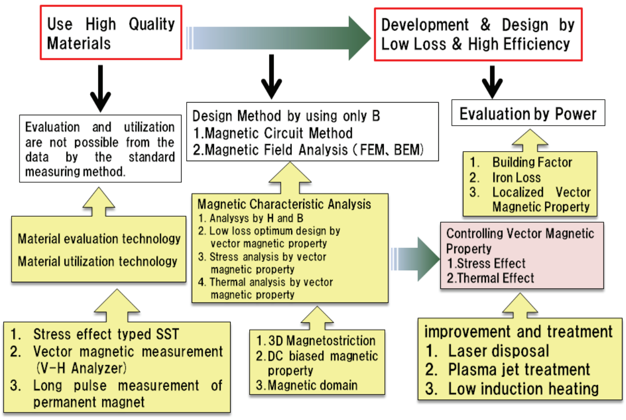


Fig. 25 Contents of vector magnetic characteristic technology

Fig. 25 shows problems to be solved and a breakthrough technology to be used in developing the high-performance machines with high-quality magnetic materials. Fig. 26 shows the block scheme of the vector magnetic characteristic technology system.

Conclusion

Our country covered unprecedentedly the nuclear hazard in March 11th, 2011. At present, almost nuclear power plants are not operating. Therefore, our aim is to establish the technology which will suppress electricity consumption.

The technology as the core enables low-loss and efficiency upgrading of electrical machinery and apparatus. The vector magnetic characteristic technology has a possibility to innovate the conventional technology. Figs. 25 and 26 show the engineering outline of the vector magnetic characteristic technology system. Furthermore, as a future problem, we propose the development of aiding systems for producing high-quality electrical machinery and apparatus based on vector magnetic characteristic technology as shown in Fig. 27.

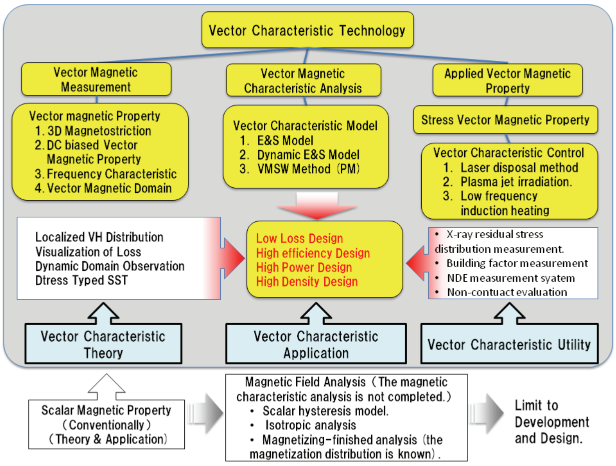


Fig. 26 Block diagram of vector magnetic characteristic technology.

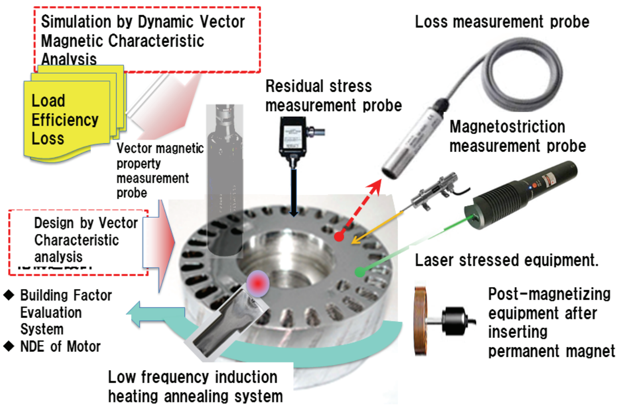


Fig. 27 High-functional non-contact manufacture-aiding systems utilizing vector magnetic characteristic technology (conceptual scheme).

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