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# Magnetic Properties of Two-Phase Composite Magnetic Material and Its Application to Electrical Equipment

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A detailed research on the magnetic properties, preparation, and application of two-phase composite magnetic material was conducted in this paper. Firstly, in order to obtain the characteristics of high remanence and low coercivity, a micro field mathematical model of hysteresis was established and the magnetization model of this material was determined on the basis of micro magnetic theory. Secondly, the relationship between remanence and coercivity was analyzed and the preparation technology of the material was proposed from the perspective of the elemental composition, the heat treatment, and the other steps. Finally, after mastering the magnetization characteristic, conversion and control mechanism of the material, a new power transformer with function of DC bias compensation based on the two-phase composite magnetic material was proposed. The simulation and experimental results showed that the transformer could achieve a good compensation for the DC bias problem by using material remanence, which provides intelligent and energy-saving electrical equipment for the electric network safe operation.

*Keywords:* two-phase composite magnetic material, magnetic properties, heat treatment, preparation of material, power transformer, electrical equipment.

## 1. INTRODUCTION

Recently, some new types of magnetic materials have been developed. Especially the application of the composite technology has created a kind of new two-phase composite magnetic material with magnetic conductive characteristic, non-magnetic conductive characteristic, excitation and the other magnetic stage characteristics, The hard and the soft magnetic phases of this material could be realized the functional conversion under certain external magnetic field conditions [1–2].

Philips, a 20$^{th}$ century scientist from the Netherlands, and with his colleagues discovered the remanence enhancement effect in the Stoner Wohlfarth model in low-$N_d$ alloy [2], which the remanence ratio was much greater than 0.5. Further research showed that this was due to a new strong exchange coupling between hard magnetic phase grains and soft magnetic phase grains in the alloy. The exchange coupling leads to a new product with a high remanence and high-energy. This kind of alloy would be a new generation of low-cost composite materials with the advantages of high magnetocrystalline anisotropy of the hard magnetic phase and high saturation magnetization of the soft magnetic phase [3–4].

This paper studies the magnetization characteristics, the conversion mechanism, and the control method of this material under the action of complex magnetic fields. A new power transformer with the function of DC bias compensation based on the two-phase composite magnetic material was designed for the safe operation of the smart grid [5–6].

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## 2. CHARACTERISTIC OF THE TWO-PHASE COMPOSITE MAGNETIC MATERIAL

Two-phase composite magnetic material is a kind of multi-functional material. Fig. 1 shows its schematic diagram of the hard and soft magnetic material exchange coupling effect [7]. After a exchange coupling, a new material hysteresis loop can be got. As can be seen in Fig. 1, it can be used as a general transformer core because of the soft magnetic characteristics; it can also be used as a kind of permanent magnet excitation source because of its hard magnetic characteristics. The magnetic characteristics could be converted between each other under the certain condition of external magnetic field and the magnetic potential direction can be controlled.

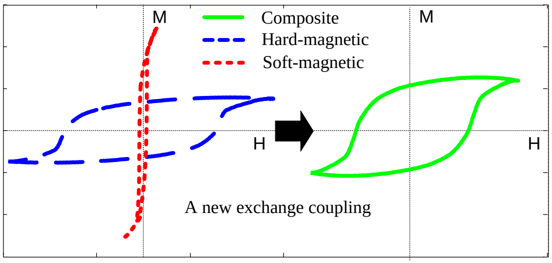
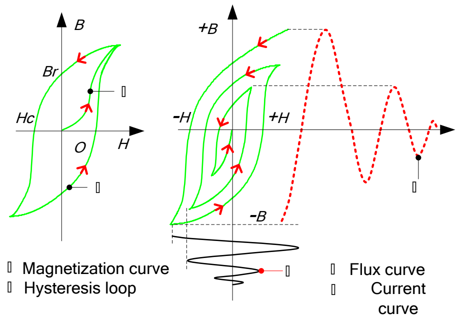



**Fig. 1.** Schematic diagram of the hard and soft magnetic material exchange coupling effect

After the exchange coupling, it can be observed that there is strong exchange coupling effect between the magnetically hard phase and the soft phase. The material coercivity is far lower than that of the hard magnetic materials. However, it is far higher than that of the soft magnetic materials, thus this material inherits magnetic properties of the hard and the soft magnet materials.

Conversion of the magnetic properties can be achieved through a smaller direct current. In the aspect of magnetization, the material messy magnetic domain could be changed by the external current, which the magnetization can be realized. Fig. 2 a shows the relationship between the magnetic flux density ($B$) and the magnetic field strength ($H$).




a b

**Fig. 2.** Schematic diagram of magnetization and demagnetization: a – magnetization curve and hysteresis loop; b – hysteresis loop of demagnetization

In the aspect of demagnetization, the material ferromagnetic properties can be removed by the method of disordering magnetic domain structure. The two-phase composite magnetic material is put into an external magnetic field with a decaying strength and a variable direction. There is no obvious magnetization direction in the magnetic domain when the current curve drops to 0 A, as shown in Fig. 2 b. Finally, the two-phase composite magnetic material returns to the state of no magnetization. The demagnetization can be completed [7].

In order to obtain suitable properties of the magnetic material, there are two main composite methods. One method is the coaxial drawing method, and the other is the heat treatment method. The first one processes two kinds of alloys with different coercivities into a cylinder and round rods, then embeds round rods into cylinder rods and finally draws them into fiaments after the heat treatment. The magnetic characteristics of the composite material obtained by the method can be expressed as:

$$B_e(H) = \frac{B_{big}(H)_{small} \cdot S_{small} + B_{small}(H) \cdot S_{big}}{S_{small} + S_{big}}, \tag{1}$$

where $B_e(H)$ is the magnetic induction intensity when the magnetic field is $H$. $B_{big}(H)$ is magnetic induction intensity when the coercivity is high and $B_{small}(H)$ is the magnetic induction intensity when the coercivity is low. $S_{big}$ and $S_{small}$ are the cross sectional areas of the two kinds of the material.

The residual magnetic induction intensity of the magnetic material is:

$$\mathrm{Br} = \frac{B_{rbig} \cdot S + B_{\mathrm{rsmall}}}{\left(1 + S_{big} / S_{small}\right)}. \tag{2}$$

Zero magnetic induction intensity of the magnetic material is:

$$B_{\mathrm{g}} = \frac{B_{rbig} \cdot S - B_{\mathrm{rsmall}}}{\left(1 + S_{big} / S_{small}\right)}. \tag{3}$$

It is known that the magnetic characteristics depend on the ratio of the cross sectional areas of the materials with two different coercivities. According to this method, proper composite materials can be prepared by using the two materials with different coercivities. And in this method, the mechanical processing is simple and suitable for mass production with low costs.

The main process consists of thermo-forming the alloys followed by the repeated cold treatments and the annealing treatment. The characteristics of the composite materials are acquired gradually. At present, because the processing of the first method mechanical is complex and the production of materials are restricted. The second method is usually adopted.

## 3. INFLUENCE FACTORS OF THE TWO-PHASE COMPOSITE MAGNETIC MATERIAL PREPARATION

### 3. 1. The effects of elemental composition on two-phase composite magnetic materials

In order to obtain a suitable magnetic material for this new power transformer, the relationship between elemental composition and magnetic properties is kept as follows:

**Table 1.** Elemental composition of two-phase composite magnetic material (element contents: %)

| Elements | Co | S | Cr | Si |
|---|---|---|---|---|
| Nominal value | 11.5-13.0 | 0.02 | 23.5-25.0 | 0.8-1.1 |
| Experiment value | 12 | 0.015 | 24.0 | 1.0 |
| Elements | P | Mn | Fe and C, Ni, Cu, V | |
| Nominal value | 0.02 | 0.2 | Else | |
| Experiment value | 0.03 | 0.16 | Else | |

The molecular formula of the two-phase composite magnetic material is Fe-12Co-24Cr. The elemental contents have a great influence on magnetic properties [8].

(1) The higher content of Co, the better magnetic properties, but the poorer machinability. However, the lower-Co alloy has a good workability, but the preparation process of this alloy is much more complex and difficult to control, thus there is a narrower adjustable range of magnetic adjustable parameters.

(2) Fluctuations of the contents of Cr have a direct effect on the coercivity of the magnetic materials. Results shown a Cr volatility of 3 %, and the coercive force can be fluctuated by 40 %.

### 3. 2. The effects of heat treatment process on the magnetic properties

Heat treating is mainly used to deal with material properties. The control of temperature greatly affects the hard and the soft magnetic phases. A four-time annealing technique on the two-phase composite magnetic material was adopted in this paper [9].

The two-phase composite magnetic material was prepared. Table 2 shows the magnetic properties of the magnetic material measured in the experiments.

**Table 2.** Magnetic properties of two-phase composite magnetic material

| Tempering process | Remanence, T | Coercivity, Oe |
|---|---|---|
| 1st | 1.0-1.2 | 75 |
| 2nd | 1.3-1.5 | 100 |
| 3rd | 1.3-1.5 | 137 |
| 4th | 1.3-1.5 | 200 |

Fig. 3 illustrates the size and sample of the two-phase magnetic material used to design the new power transformer. The direction in material is the direction of magnetization.

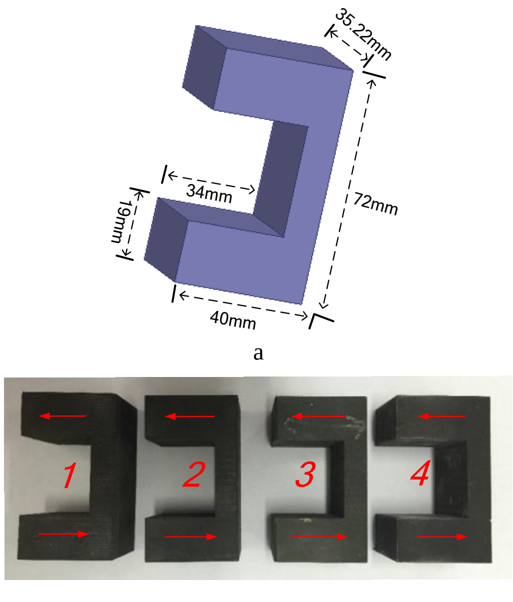
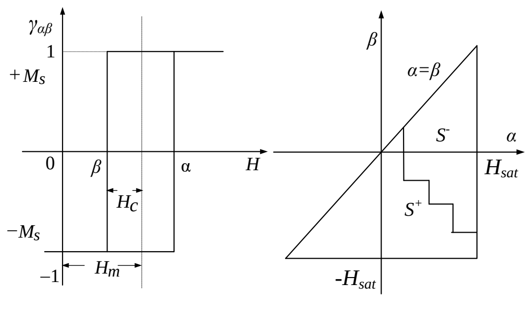



**Fig. 3.** Two-phase composite magnetic material: a – material size; b – material sample

## 4. ESTABLISHMENT OF THE HYSTERESIS MODEL BASED ON PREISACH THEOTY




a b

**Fig. 4.** Preisach theory: a – reactanglur hysteresis characteristics; b – Preisach model

Magnetization characteristics of this material is very important for designing transformer. Under the complex magnetic field, the magnetic characteristics are hard to catch. Preisach considers that magnetic characteristics of ferromagnetic material are a gather of magnetic dipoles which has rectangular hysteresis characteristics. The macro magnetic characteristics of the material can be described by each of dipole field [10 – 11]. Fig. 4 a to b illustrates the theory and the figure of Preisach.

When an external magnetic field is bigger than $H_c + H_m$, the dipole is in state of $+ M_S$, when the external magnetic field is smaller than the $H_c - H_m$, the dipole is in state of $- M_S$, when the external magnetic field is in the middle of $H_c \pm H_m$, the state of the dipole is depend on the variation of the external magnetic field, as shown in Fig. 4.

Expression of the external effects of the material based on the Preisach theory is shown in Eq. 4 [7]:

$$B = \iint_S \mu(\alpha,\beta)\gamma_{\alpha\beta}(H)d\alpha d\beta = \iint_{S^+} \mu(\alpha,\beta)d\alpha d\beta - \iint_{S^-} \mu(\alpha,\beta)d\alpha d\beta, \quad (4)$$

where $\mu$ ($\alpha$, $\beta$) is the non-negative weighting function of Preisach theory. $\gamma_{\alpha\beta}$ is the hysteresis operator. $\mu$ ($\alpha$, $\beta$) and $\gamma_{\alpha\beta}$ have the following characteristics:

$$(a)\ \mu(\alpha,\beta) = \mu(-\beta,-\alpha) \qquad (\alpha,\beta) \in S$$
$$(b)\ \mu(\alpha,\beta) = 0 \qquad (\alpha,\beta) \notin S$$
$$(c)\ \gamma_{\alpha\beta}(H) = 1 \qquad (\alpha,\beta) \in S^+$$
$$(d)\ \gamma_{\alpha\beta}(H) = -1 \qquad (\alpha,\beta) \in S^-$$

When the ferromagnetic material is not magnetized, the number of the forward and the reverse magnetic dipole is the same. The material has no magnetism. As shown in Fig. 4 a:

$$B = \iint_{S^+} \mu(\alpha,\beta)d\alpha d\beta - \iint_{S^-} \mu(\alpha,\beta)d\alpha d\beta = 0\,. \quad (5)$$

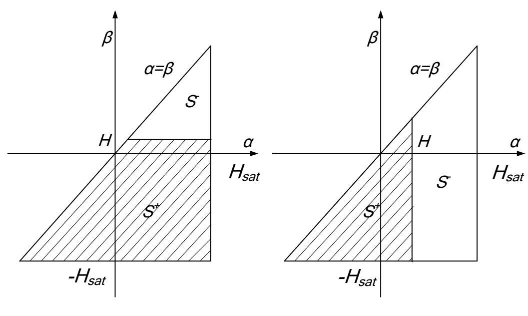
When the material starts to be magnetized, the magnetic flux density can be expressed as:

$$B_i = \iint_{S^+} \mu(\alpha,\beta)d\alpha d\beta - \iint_{S^-} \mu(\alpha,\beta)d\alpha d\beta = T(H,-H)\,. \quad (6)$$

$$T(\alpha,\beta) = \int_\beta^\alpha \int_y^\alpha \mu(\alpha,\beta)dxdy = \int_\beta^\alpha \int_\beta^x \mu(\alpha,\beta)dxdy\,, \quad (7)$$

where $T$ ($\alpha$, $\beta$) is the area of the triangle, which the vertex is ($\alpha$, $\beta$). As $\mu$ ($\alpha$, $\beta$) = $\mu$ (-$\alpha$, -$\beta$), so $T$ ($\alpha$, $\beta$) = $T$ (-$\alpha$, -$\beta$), $T$ ($\alpha$, $\alpha$) =0, $B_i$ is the magnetic flux density of the initial magnetic curve.

When the material is magnetized to saturation, with the decrease of the magnetic field strength; the magnetic flux density changes along with the declining branch of the limited hysteresis loop curve, as shown in Fig. 5 a.




a b

**Fig. 5.** Two magnetization states: a – declining branch; b – rising branch

The whole process can be expressed as:

$$B_d = B_i(H_{sat}) - 2T\cdot(H_{sat},H)\,. \quad (8)$$

When the material is reverse magnetized to saturation, with the rise of the magnetic field strength, the magnetic flux density changes along with the rising branch of the limited hysteresis loop curve, as shown in Fig. 5 b. The magnetic flux can be expressed as:

$$B_r = -B_i(H_{sat}) + 2T \cdot (H, -H_{sat}) . \quad (9)$$

Fig. 6 shows the hysteresis loop of the two-phase composite magnetic material. Where, $M_S$ is the saturation magnetization and $H_{ci}$ is the coercivity [12 – 13].

From the figures, it can be seen that the simulation effect was good. Fig. 7 a shows the distribution of the magnetic line in normal work and Fig. 7 b shows the magnetic line distribution under DC bias. It can be seen that the magnetic flux density increased and the transformer divorced from the normal work. Fig. 7 c shows the magnetic line trend of the material working independently, and the direction of the magnetic line trend was opposite to that of the DC bias, which the purpose of DC bias compensation could be realized. Fig. 7d shows the distribution of the magnetic line after the compensation. The flux density of the transformer core decreased and the transformer returned to the normal working conditions.

Based on the theoretical study, this paper designs an experiment system. Fig. 8 shows the prototype of the new power transformer and the position of the magnetic material. Fig. 9 shows the excitation current waveform and the harmonic wave before and after the compensation in the experiment.

## 5. RESULTS OF IMPLANTATION TWO-PHASE COMPOSITE MAGNETIC MATERIAL

The flow of DC in the transformer winding can cause half-cycle saturation of the core. This saturation can cause distorted exciting current, overheat, and additional power system problems. Measures should be taken to suppress the transformer DC bias. A 2D finite-element transformer model was built in this paper, and the compensation of DC bias was studied based on the model [14-16].

In this paper, the two-phase composite magnetic material was magnetized to counteract the DC bias in the transformer core when the DC bias occurred. The magnetic material was demagnetized when the DC bias disappeared, and the transformer resumed to normal work. Simulation on the designed transformer was conducted using ANSOFT software. Fig. 7 shows the distribution of magnetic line of the transformer at different states.

From Fig. 9, it can be seen that the excitation current dropped significantly compared to the current under DC bias. The harmonic in transformer winding is greatly reduced after the compensation. The transformer returns to normal working conditions after the compensation.

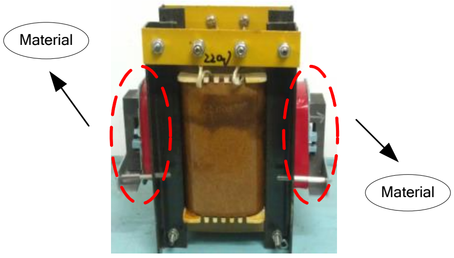
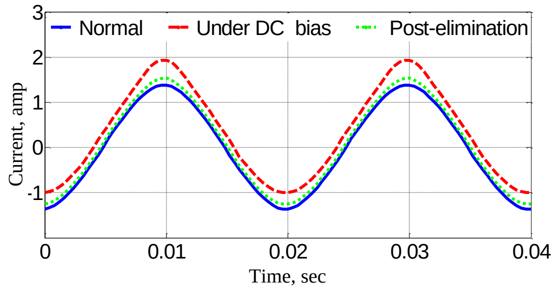
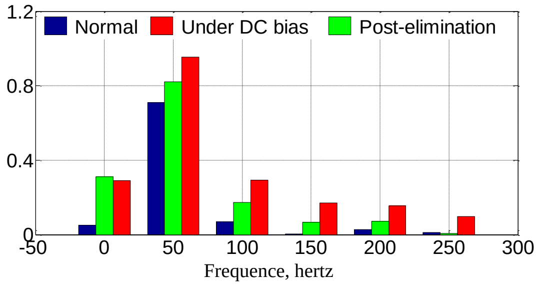



**Fig. 8.** Prototype of the new power transformer and the position of the material




a



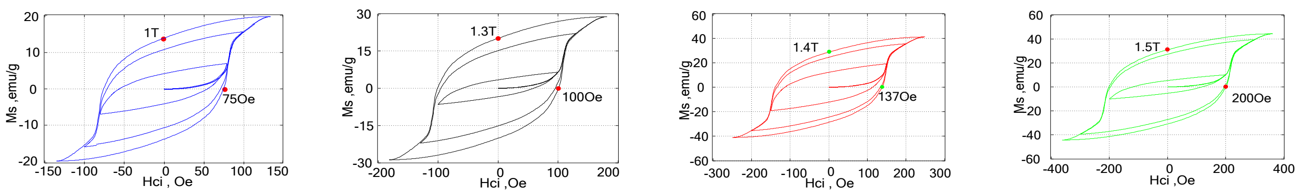

b

**Fig. 9.** The excitation current waveform and harmonic wave before and after compensation: a – current waveform; b – harmonic wave

## 6. CONCLUSIONS

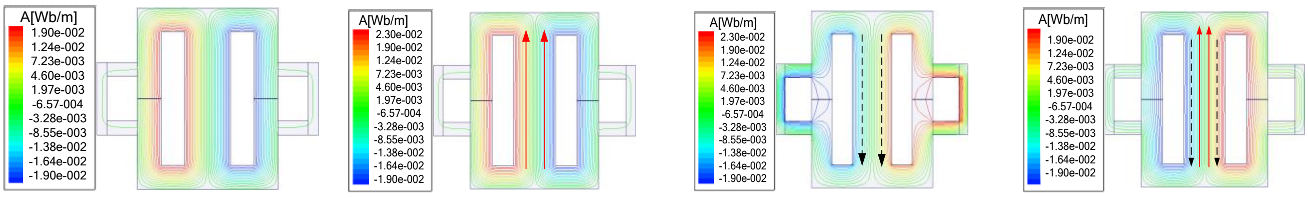
In this paper, the relationship between the remanence and coercivity of two-phase composite magnetic material was determined, and a hysteresis mathematical model was established. A preparation technology was achieved for the composite material, and it was found that this material could be magnetized and demagnetized easily under an external current field.

Different elemental compositions, elemental contents, and heat treatment processes had great influences on the magnetic properties.




a b c d

**Fig. 6.** Hysteresis loop at different coercivities: a – 75 Oe; b – 100 Oe; c – 137 Oe; d – 200 Oe




a b c d

**Fig. 7.** Distribution of the magnetic line at different states: a – transformer normal work; b – under DC bias; c – material work; d – after the compensation

The characteristic of high remanence and low coercivity was obtained after a large of experiments. It can be known from the experiments:

1. The higher content of Co, the better magnetic properties, and the poorer its machinability; however, the lower-Co alloy has a good workability.
2. Fluctuations of the contents of Cr have a direct effect on the coercivity of magnetic materials, especially for the coercive force.

New transformer with function of DC bias compensation was designed based on this two-phase composite magnetic material. The simulation and experimental results showed that the compensation effect was evident. All indicators satisfied the actual needs of the project.

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