I Design and Material Selection of Single-Phase Transformers

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Abstract. Transformers are indispensable appliances in our lives and play an essential role in the production, transport, and distribution of electricity for living and working purposes. An apparatus that uses electromagnetic induction to modify voltage is called a transformer. Therefore, this paper focuses on analyzing the basic working principle of a transformer, a detailed disassembly of the transformer, briefly analyzing the structure of the transformer, calculating the core parameters and coil parameters, selecting the appropriate model, and accounting for the results based on the rated power of the given conventional transformer. The goal is to successfully design a small single-phase transformer supplying power to resistive loads. Through a series of calibration calculations, it is finally determined that the selected iron core meets the operating standards and achieves the design purpose.

Keywords: Transformer; Winding; Iron core.

1. Introduction

1.1. Current status of transformer development

Currently, there are more than 1,000 registered transformer manufacturers in China, with no more than 10 companies capable of producing 500kV transformers. These include TBEA's Shenyang Transformer Factory, Hengyang Transformer Factory, Xi'an Transformer Factory, Baoding Tianwei Baochang Electric Company Limited, Changzhou Toshiba Transformer Co, Chongqing ABB Transformer Co, and Alstom Transformer Co., Ltd., among others. Companies that can produce 220kV transformers are not more than 30, and those producing 110kV transformers are about 100. Among them, enterprises with an annual production capacity of over a hundred units include TBEA Hengyang, Shen, Baobian, Qingdao Qingbo, Huapeng, and others. In the dry-type distribution transformer sector, there are about 100 enterprises, with Shunde, Jinxiang, Xuji, Huapeng, and others having a production capacity exceeding 1,000,000kVA. The production of box-type transformers involves 600 to 700 enterprises.

China's transformer industry is vast, but it is predominantly composed of small and medium-sized enterprises. According to statistics as of November 2008, there were a total of 1,589 enterprises in China's transformer industry, with only over 130 surpassing a total industrial output value of more than 100 million. Only 16 of these enterprises had more than 2,000 employees. The highest sales revenue, as per statistics, was reached by Baoding Tianwei at 10.79 billion yuan, constituting 5.86% of the industry, with the top 10 enterprises collectively holding a 20.6% share. In recent years, the production capacity of China's transformer products has significantly increased through technological transformation, mergers and acquisitions, and expansion. For instance, TBEA owns production plants in Shenyang, Hengyang, Xinjiang, and Tianjin. The Western Electric Company has production plants in Xi'an and Changzhou, while Baoding Tianwei has production plants in Baoding, Qinhuangdao, Hefei, and others. The production capacity of transformer products of these three groups is close to or exceeds 80,000MVA. Simultaneously, production enterprises such as Huapeng, Dachi, Qingdao, and Qianjiang are gradually expanding their production scale and improving their capacity, with an annual production capacity exceeding ten million kilowatt-hours.

1.2. Purpose and significance of transformer design

Safe use of electricity is paramount, with transformers serving as the heart of the power transmission and distribution system [1, 2]. The essential components of a transformer include an iron core (magnetic core), a secondary coil, and a primary coil. Operating on the principle of electromagnetic induction, the transformer adjusts the voltage of alternating current to facilitate safe electricity usage.

The design of the transformer holds great significance, focusing on ensuring the user's safety and personal well-being. There are inherent electrical hazards that prompt the automatic tripping of the transformer to mitigate risks. The transformer not only modifies the voltage of the alternating current and adjusts impedance but can also alter the current without surpassing the designated power limits. Transformers serve varied purposes in different environments; high-voltage transformers for regular use necessitate increased power, while household appliances in daily use require a shift from high voltage to low voltage.

To address these diverse needs, different transformers can be designed to enhance efficiency, maximize power utilization, and minimize wastage [3]. Simultaneously, transformers adhere to specific standard requirements [4] to ensure the safe utilization of electricity.

2. Working Principle and Structure of Transformer

2.1. Principle of operation of the transformer

Transformers operate on the principle of electromagnetic induction, where energy is supplied to the main coil to generate an alternating magnetic field in the transformer's core. This process induces an electromotive force in the secondary coil, resulting in a voltage shift. The operational principle of a single-phase transformer is illustrated in Fig. 1.

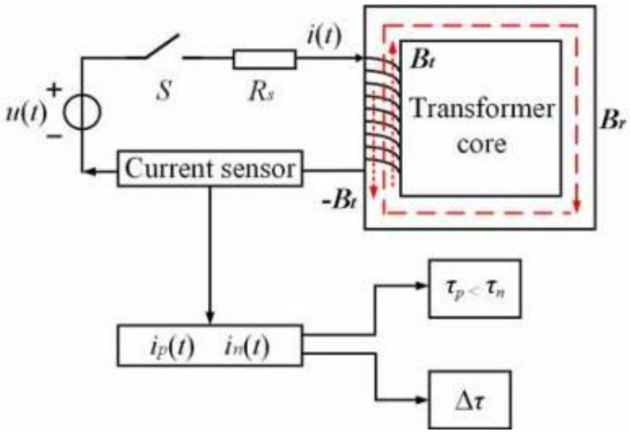

Fig 1. Single transformer working principles diagram [5].

The current in the core will create an alternating flux when the primary winding and secondary winding make electromagnetic contact when the transformer's primary side AC voltage U1 flows via the primary winding current I1. According to the principle of electromagnetic induction, alternating flux through the two windings will be induced electromotive force, the size of the number of turns and the number of turns of the windings and the maximum value of the main flux is proportional to the number of turns of the windings on the side of the voltage is high, the number of turns of the windings on the side of the low voltage, at this time, the secondary side of the transformer for the open-circuit, i.e., no-load transformer, one or two secondary coil voltage and one or two turns of the windings is proportional to the number of turns, that is i.e., $U1 / U2 = N1 / N2$ but the primary and secondary frequency remains constant, thus achieving the voltage change.

2.2. Transformer construction

Transformer consists of core, windings, insulation structure, tank, and other accessories.

2.2.1. Windings

An integral part of an electrical circuit, consisting of insulated flat or round wire wound on paper, yarn or lacquer. It induces electric potential, transfers current and realizes electromechanical energy conversion. In a single-phase transformer, the high-voltage and low-voltage windings are divided into two parts, which are wound on two core posts, and the two parts can be connected either in series or in parallel. Examples are shown in Fig. 2 and Fig. 3.

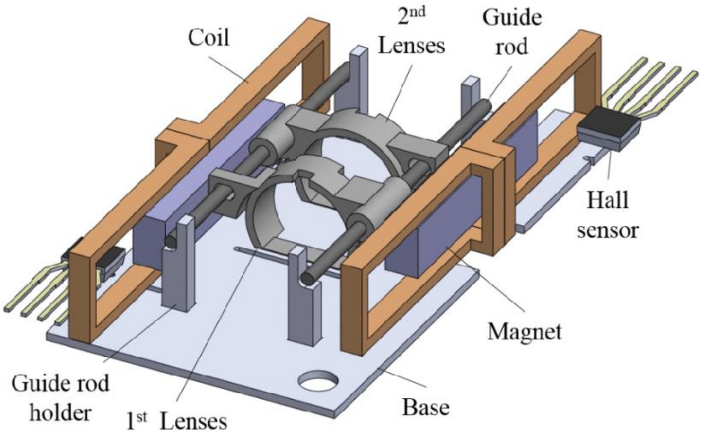

Fig 2. Structure of proposed VCM actuator [6].

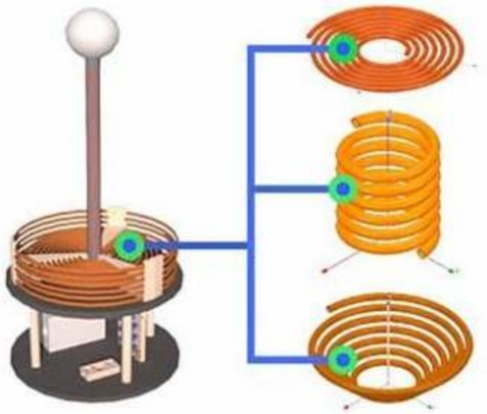

Fig 3. Concentric winding structure [7].

2.2.2. Iron core (of the heart)

The core is the magnetic circuit part of the transformer. In order to reduce the hysteresis and eddy current loss in the core, the core are stacked with hot-rolled or cold-rolled silicon steel sheets, and the inter-sheet is coated with lacquer film to avoid inter-sheet short circuit.

There are two basic forms of core construction: core and shell, as shown in Fig. 4.

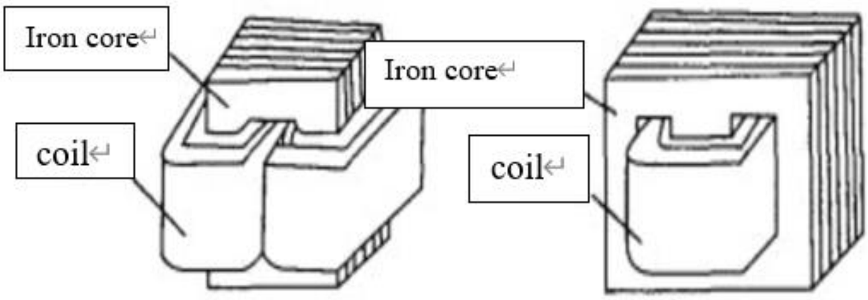

Fig 4. Core Structure.

2.2.3. Insulated structures

The realisation of transformer insulation includes external and internal insulation. External insulation refers to isolating the electrical parts of the transformer from the external environment to prevent electric shock accidents and ensure safety. Internal insulation refers to the insulation of various parts and windings inside the transformer to prevent electrical breakdown and ensure the normal operation of the transformer [2].

2.2.4. Fuel tanks and other accessories

Iron core and windings constitute the body of the transformer, the body is placed in the tank with transformer oil, in the oil-immersed transformer, transformer oil is both insulation medium, but also the cooling medium.

2.3. Classification of transformers

There are many types of transformers, according to different classification standards, can be divided into power transformers, distribution transformers, lightning transformers, dry-type transformers, oil-immersed transformers, single-phase transformers, three-phase transformers, autotransformers and so on.

2.3.1. Classification by use

Firstly, power transformers are one of the main equipment in power plants and substations, i.e. transformers of all levels before distribution. Secondly, the transformer that reduces the voltage to the working voltage of the power-using equipment is called a distribution transformer, which is used for daily lighting and factory power, and the general low voltage is 0.4KV and below.

2.3.2. Classification according to cooling method

First, dry-type transformers rely primarily on air convection for cooling [8]. Second, oil-immersed transformers, which are widely used in power supply and distribution systems, rely on the circulation of insulating oil inside the transformer to dissipate the heat generated by the coils to the transformer's heat sink [9].

2.3.3. Classified according to the number of power supply phases

There are single-phase transformers and three-phase transformers, which are widely used in life and research. The latter one uses multiple windings to accommodate different input voltages.

2.3.4. Classification according to the number of coils

First, autotransformer is a special type of transformer that has only one winding, where one portion doubles as turns for both circuits and the other portion only as turns for a separate circuit. An autotransformer performs the function of transforming voltage, current or impedance by sharing a portion of the coil. Second, double-winding transformer is a transformer with two separate coils. One of the coils is designed as the primary winding and is usually connected to the power supply, while the other coil is designed as the secondary winding and is usually connected to the load. The transformation of voltage and current is achieved by mutual inductance between the primary and secondary windings. Third, three-winding transformer is a transformer with three separate coils. Each coil has a different number of turns and is referred to as various of windings. This type of transformer is commonly used in power systems that require a number of different voltage levels for voltage step-up, step-down and isolation functions.

2.3.5. Classification according to conductive raw materials

First, copper wire transformer refers to the use of copper conductors as a conductor material in the coil of a transformer for transmitting electrical energy. Copper wire is one of the commonly used conductor materials for transformer coils and is widely used because of its good electrical and thermal conductivity. Second, aluminium wire transformer is a transformer that uses aluminium conductor wires as the conductor material in the coils of the transformer for transmitting electrical energy. Aluminium wire is less commonly used in transformers than copper wire, but is still employed in some specific applications.

2.3.6. Classification according to the form of iron core

First, core transformer is a common type of power transformer whose core structure consists of a number of iron chips stacked in a specific way. Second, Shell-type Transformer, also known as shell transformer, is a common type of power transformer. It is characterized by having a common core and separate high voltage and low voltage windings located on each side of the core.

3. Disassembly and Assembly of Transformers

The disassembly and assembly of the transformer was carried out to better understand the details. In this process, the structure of the transformer parts was understood and a clearer understanding of the working principle of the transformer was gained.

3.1. Transformer splitting process

To split the transformer, proceed is shown in Fig. 5, Fig. 6, Fig. 7 and Fig. 8.

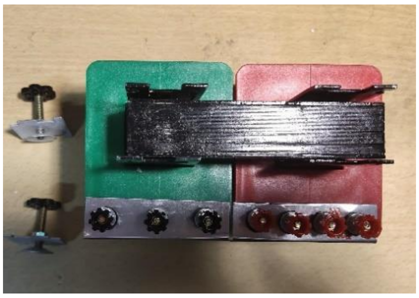

Fig 5. Transformer in Original Condition.

Fig 6. Removal of Top Device, Bar Yoke, and Both Side Coils.

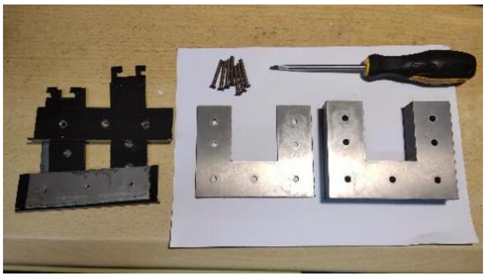

Fig 7. Screwdriver to screw out the screws of the U-core and separate the U-core.

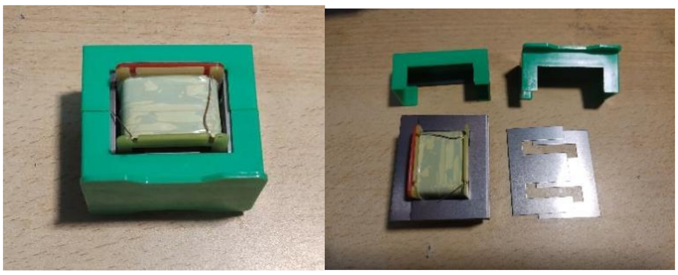

Fig 8. Detachable Transformer and Small Transformer Disassembly Results.

3.2. Transformer assembly process

To assemble the transformer, proceed is shown in Fig. 9 and Fig. 10.

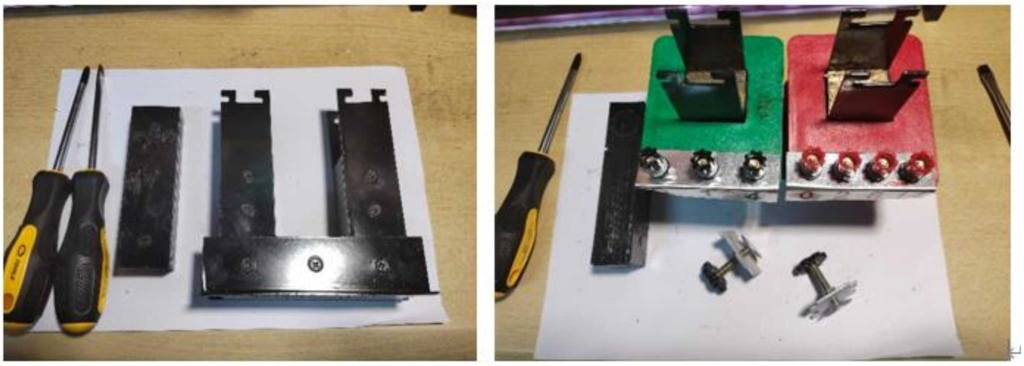

Fig 9. Assembling the U-Core, Screwing Back, and Assembling the Transformer.

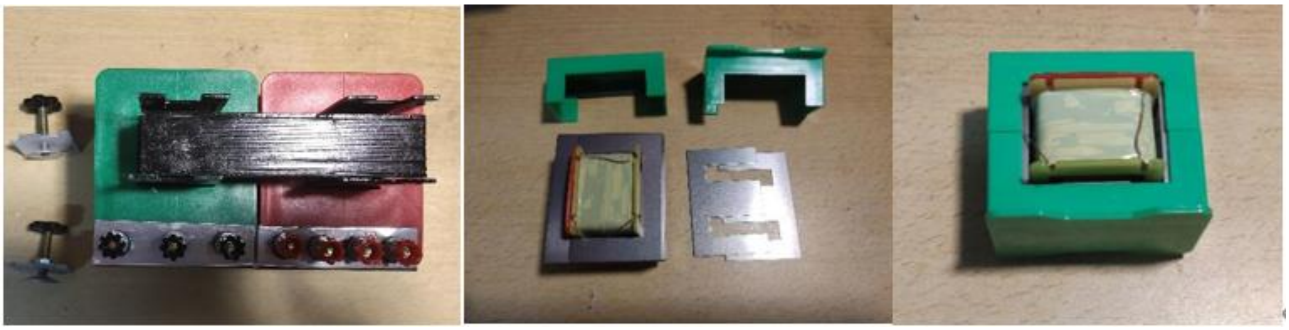

Fig 10. Removable Transformer and Small Transformer Restoration.

4. Calculation of transformer parameters

In order to have a practical object of study for calculation, it is assumed that the rated power of the load is 240W, the transformer primary voltage $U_1 = 220V$, and the voltage on the secondary side of the transformer is $U_2 = 36V$.

$$\mathrm{P} = \mathrm{U}_2\,\mathrm{I}_2 \quad \rightarrow \quad \mathrm{I}_2 = 6.67\mathrm{A} \tag{1}$$

4.1. Calculation of Primary Side Power

Vice-side power is given by $\mathrm{P2} = 240\mathrm{VA}$. The primary power, denoted as P1, is calculated as $\mathrm{P1} = \mathrm{P2} / \mathrm{K} = 267\mathrm{VA}$, with K representing the assumed efficiency of the transformer, set at 0.9.

4.2. Selection of core size

S is the effective cross section and is represented by [10]:

$$\mathrm{S} = 1.25\sqrt{\mathrm{P}_2} = 1984\mathrm{mm}^2 \tag{2}$$

Because the silicon steel hikes have insulating varnish and there are gaps between the stacks, S' is greater than S [9].

$$\mathrm{S}' = \mathrm{S}/\mathrm{Kc} = 2229\mathrm{mm} \tag{3}$$

Kc is the silicon steel sheet stacking factor, $\mathrm{Kc} = 0.89$.

According to S', for the table optional EIB-114 type iron core. The composition is presented in Fig. 11.

$$A = kab \tag{4}$$

k for the gap coefficient, its value and the thickness of the insulating varnish coated with silicon steel sheet and the gap between the sheet, the tighter the core stacking, the higher the k value [11].

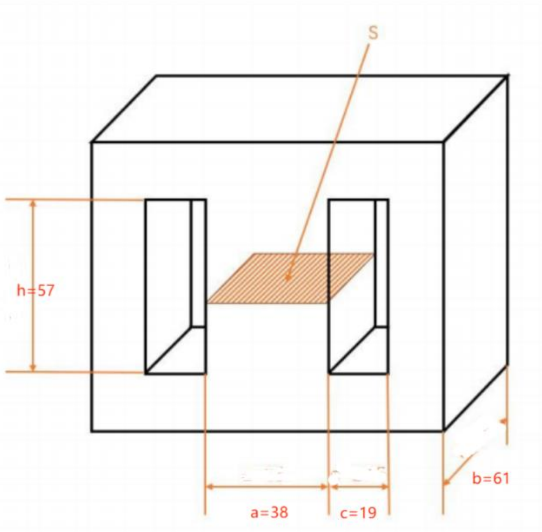

Fig 11. Core Dimensions.

Table 1 shows the various types of iron core coils to choose from. ELB-114 was selected for this design.

Table 1. Various types of iron core

Iron core type	Core size			
	Thickness of the stack	tongue width	window width	window height
EI-L	b	a	c	h
EI-28	8 10 13 16	8	6	17
EI-35	9.6 12.5 16 20	9.6	7.7	19.5
EI-41	13 16 21 26	13	8	21
EI-48	16 20 25 32	16	8	24
EI-54	18 22.5 29 36	18	9	27
EI-57	19 24 30 38	19	9.5	28.5
EI-60	20 25 32 40	20	10	30
EI-66	22 28 35 45	22	11	33
EI-76.2	25.4 31.5 40 50	25.4	12.7	38.1
EI-85.8	28.6 36 46 58	28.6	14.3	42.9
EIB-96	32 40 51 64	32	16	48
EIB-105	35 44 56 70	35	17.5	52.5

EIB-114	38 47.5 61 76	38	19	57
EIB-133.2	44.4 56 71 90	44.4	22.2	66.6

4.3. Calculation of winding turns

Under the known conditions, the core cross-sectional area S is specified as 1984 mm2. The number of turns in the primary winding N_1 is determined by the formula $N_1 = \frac{U_1}{4.44fBS} = 333$, where the supply frequency f is 50 Hz, and the flux density of the silicon steel sheet B is 1.6 T [12].

The number of turns in the secondary winding N_2 is given by:

$$N_2 = 1.05U2 / 4.44fBS = 6 \tag{5}$$

4.4. Calculation of cross-sectional area of winding conductor

The primary current $I1 = 1.1P1 / U1 = 1.33A$. 1.1 is the empirical coefficient of the transformer due to the presence of an excitation current component.

The secondary current is

$$I_2 = P_2/U_2 = 6.67A \ [12]. \tag{6}$$

The cross-sectional area of the primary side conductor $S1 = I1 / J = 0.534$ mm2. Under the condition that the load current is basically unchanged and its own heat dissipation condition is good, the current density of enamelled wire J=2.5A/mm2 is selected [10].

Cross-sectional area of the secondary conductor S2 can be calculated as:

$$S_2 = I_2/J = 2.67mm2 \tag{7}$$

Enamelled wire with a diameter of d1 = 0.83mm and an outer diameter of D1 = 0.92mm is used for the primary side conductor.

Enamelled wire with a diameter of d2 = 1.90 mm and an outer diameter of D2 = 2.02 mm is used for the secondary conductor.

4.5. Calculating core window size

The window area can be calculated by:

$$A_0 = k_{\text{windings}}(F_1N_1 + F_2N_2 + \cdots + F_NN_N) \ (mm^2) \tag{8}$$

where F_1、F_2 ... F_N are the cross-sectional area of each winding, respectively; N_1、N_2 ... N_N are the number of turns of each winding, respectively, and k is the filling factor. k_{windings} generally take1.2~1.8. In this design, take $k_{\text{windings}} = 1.4$ in this design [11].

If the window area is larger than the actual window area of the core, it indicates that the core window cannot fit the windings, as mentioned in 4.2 above. Therefore, the primary side cross-sectional area F_1 , cross sectional area of the secondary side conductorF_2 , the effective utilisation height of the core windowh' and window areaA_0 are calculated as follows:

Effective utilisation height of core windows $h' = 0.9h = 51.3(mm)$

Primary side turns per layer M1 $M_1 = H'/D_1 = 55.7$

Number of original borderline circles n_1 $n_1 = N_1 / M_1 = 6$

Primary edge coil thickness $H_1 H_{n1=1} (D_1 + \partial) = 8.32mm$

Sub-edge turns per layer $M_2 M_2 = h'/D_2 = 25$

Number of Submarginal Wire Loop Layers $n_2 n_2 = N_2/M_2 = 1$

Sub-edge coil thickness H2 $H_2 = n_2(D_2 + \partial) = 2.14mm$

Where ∂ interlayer insulation thickness take 0.12mm

Total coil thickness $E = 1.5(H_0 + H_1 + H_2) = 18.69mm$ 1.5 is the safety factor, H_0 is the thickness of the coil frame, take $H_0 = 2mm$ because 19mm>18.69mm, indicating that the actual window of the core can accommodate the winding. The overall design is reasonable [13].

5. Conclusion

The core material of a transformer affects the performance and stability of the transformer. Therefore, when designing a transformer, it is necessary to select a suitable core material to ensure performance and reliability. Currently the commonly used core materials are silicon steel plate, zinc oxide ferrite and so on. Calculating the number of turns is a very important aspect. Generally, when designing a transformer, the input and output voltages need to be selected and the ratio determined. The number of turns of the transformer can then be calculated from the above parameters. If there is a need to achieve a more accurate ratio, a tapped or multi-turn design can be used.

It is worth noting that the number of turns of a transformer not only determines the input and output voltages, but also has an impact on the temperature rise and losses of the transformer. Therefore, a reasonable calculation of the number of turns is required in the design. In the design of the transformer, if the parameters are wrong, the transformer will not work or even have an accident.

With the continuous progress of science and technology, driven by the trend of energy saving and emission reduction, green energy and other trends, transformers are expected to usher in a new development peak in the next few years. In the future, the development of transformers I think will be energy efficient, intelligent, diversified applications as the trend. In addition to the traditional power, communication and other fields, transformers will also be widely used in new energy, electric vehicles and other fields. Diversified applications will bring more opportunities and challenges for the development of the industry. This is the direction of our learning.

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