Electromagnetic Transient Analysis *and* Novel Protective Relaying Techniques *for* Power Transformers

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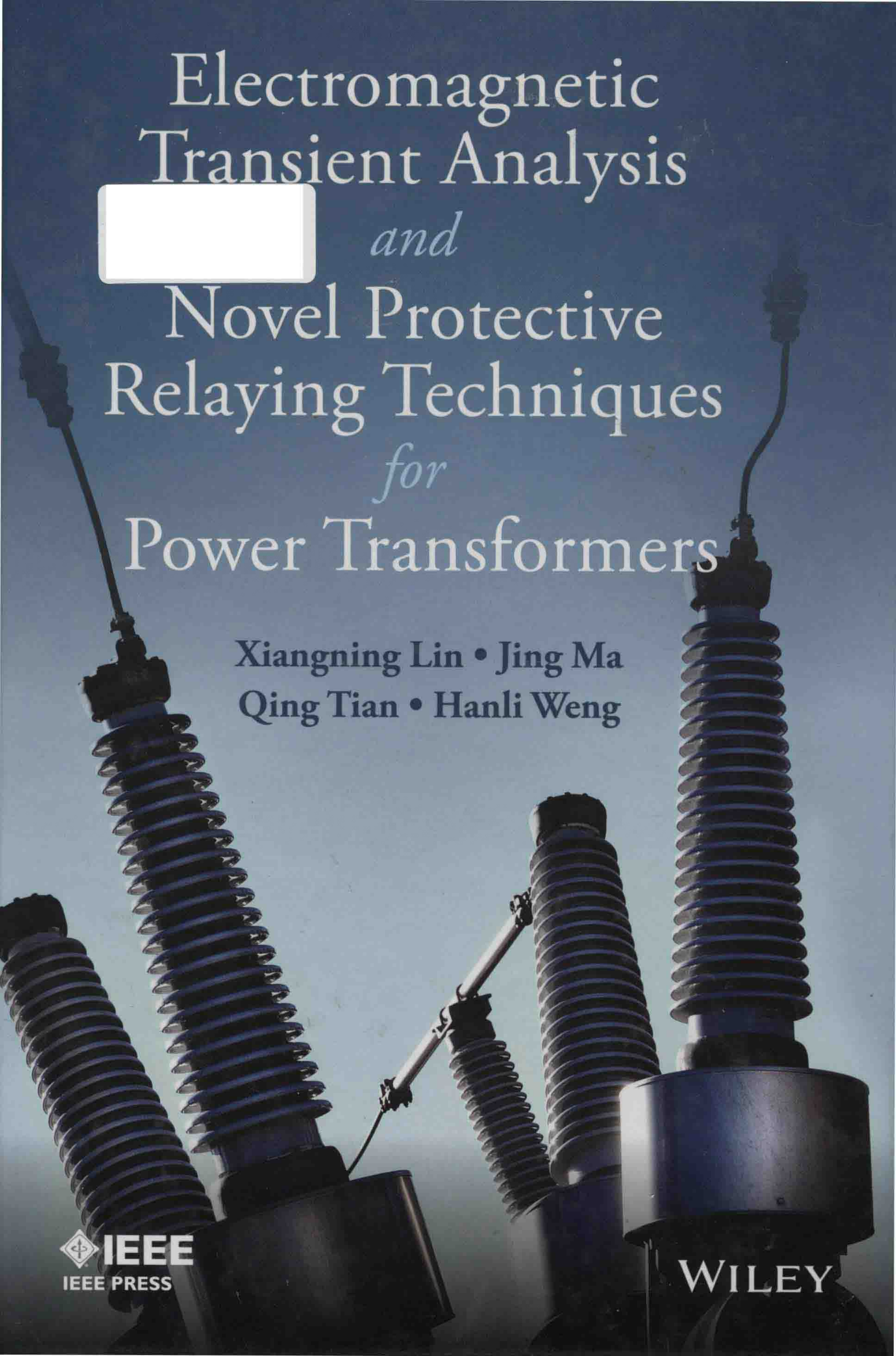

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ELECTROMAGNETIC TRANSIENT ANALYSIS *AND* NOVEL PROTECTIVE RELAYING TECHNIQUES *FOR* POWER TRANSFORMERS

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ELECTROMAGNETIC TRANSIENT ANALYSIS *AND* NOVEL PROTECTIVE RELAYING TECHNIQUES *FOR* POWER TRANSFORMERS

About the Authors

Professor Xiangning Lin has been working in this area since 1996. His research is mainly concentrated in the areas of power system protection/operation/control/modelling/simulation/analysis and smart grids. He has carried out very systematic research and practiced on power transformer electromagnetic transient simulation and protective relaying, especially approaches on operating characteristic analysis and studies on the novel principle of the transformer differential protection, for more than 18 years. He was the first to discover the ultra-saturation phenomenon of the power transformer and then designed appropriate operating characteristics analysis planes to make clear the advantages and disadvantages of the existing differential protection of power transformers. On the basis of this, he invented a variety of novel protection algorithms for the main protection of the power transformer. A series of papers were published in authoritative journals such as the *IEEE Transactions on Power Systems* and *IEEE Transactions on Power Delivery*. The work has been widely acknowledged and cited by international peers. Part of his research results have been used in many practical engineering projects. He is also a pioneer to the introduction of modern signal processing techniques to the design of the protection criteria for power transformers.

In recent years, Professor Lin has undertaken many major projects in China. For example, he guided a project of the National Natural Science Foundation of China to study the abnormal operation behaviour analysis and appropriate countermeasures of power transformers. Then he set up an advanced simulation and protection laboratory for the main equipment of power systems and pioneered the design and implementation of the corresponding protection techniques. He was also responsible for several projects from governments and enterprises on the study of the power transformer protection and monitoring. In addition, Professor Lin is a major member of the National Basic Research Program of China (973 Program) on the study of the interaction between large-scale electric power equipment characteristics and power system operation. He cooperated with the China Electric Power Research Institute to guide the study on the main protection for wind farms, including different types of power transformer. He has been teaching courses on *Power system protective relaying* and *Power system analysis* for many years. Much of the material covered in this book has been taught to students and other professionals.

Professor Jing Ma has been working in this area since 2003. His research is mainly concentrated in the areas of power system protection/control, modelling/simulation/analysis and smart grids. He has carried out very systematic research and practiced on power system protection, especially approaches concerning power transformer protection, for more than 10 years. He was the first to apply the two-terminal network algorithm to the areas of power system protection. A series of papers were published in authoritative journals such as the *IEEE Transactions on Power Delivery*. The work has been widely acknowledged and cited by international peers. He also proposed an approach based on the grille fractal to solve the Transient Analysis saturation problem, and the related paper has been published in the *IEEE Transactions on Power Delivery*. His research results have been used in many practical engineering projects.

In recent years, Dr Ma has undertaken many major projects in China. For instance, he participated in a key project of the National Natural Science Foundation of China to study the wide-area protection. He was also responsible for a project of the National Science Foundation project on the study of the power system smart protection and control. He is a major member of the National Basic Research Program of China (873 Program) on the study of the utilization of large-scale renewable energy with high security and efficiency, and was responsible for the design of the Power System Protection and Control Simulation Platform. Professor Ma has been teaching courses of *Power System Protection Theory* and *Power System Automation* for many years. He is also a key member of National Prime Course – *Power System Protection Theory*. Much of the material covered in this book has been taught to students and other professionals.

Dr Qing Tian is a senior engineer with the Chief dispatching centre, Southern Power grid, Guangzhou, China. He has been working in this area since 1998. His main research fields include power system protection, operation and control, together with the operation and maintenance technologies in HVDC and UHV AC transmission projects. He has published some well cited papers in authoritative international and Chinese journals. In particular, he has many experiences in solving practical engineering problems concerning UHVAC and UHVDC protections.

Dr Hanli Weng is a senior engineer with College of Electrical Engineering & New Energy, China Three Gorges University. She has been working in this area since 2004. Her main research fields include protective relaying of power transformer. She has published some well cited papers in the authoritative international and Chinese journals. In particular, she has many experiences in solving practical engineering problems concerning main equipment protection of large-scale hydro power station.

Preface

As the heart of the power system, the power transformer is crucial for the safety and stability of the power system, and the reliability of the protection arranged for the power transformer becomes a critical factor in guaranteeing the security of the system. Nevertheless, according to existing fault reports in the power industry, it is accidental event for the differential protection to mal-operate under some operating conditions. With the growing complexity of the power system structure and its components, the differential protection mal-operation events revealed have become an area of intense investigation in order to eliminate potential uncertainty and danger. Moreover, the electric circuit and the magnetic circuit, coupling in conjunction with each other, make the above phenomena even more intricate, as transformer switching events may cause electromagnetic transients. These phenomena remain an open issue and comprehensive studies are needed. However, while it is clearly essential to find out the origin of the abnormal operational behaviour in the power transformer, basic theory about electromagnetic transients in the power transformer is currently lacking. This book is published to address this problem directly.

The content of this book is arranged as follows: Chapter 1 defines the fundamental principle of the power transformer differential protection and some problems in this background. Second harmonic restraint based differential protection of Ultra High Voltage (UHV) power transformers is also investigated in this chapter. Chapter 2 attempts to study the unusual mal-operation of the differential protection of the transformer caused by ultra-saturation phenomena. In Chapter 3, appropriate theoretical bases for the existing protection method are discussed, preliminary comparative studies between phase current based and superimposed current based differential criteria are conducted and the results are compared. The main focus of Chapter 4 is on inrush identification by means of several novel schemes. Chapter 5 deals with the problems revealed in Chapter 4, with new methods put forward to eliminate the magnetizing inrush. Simulation verifications for the methods are also proposed.

The book is intended for graduate students in electric power engineering, for researchers in correlative fields or for anyone who wishes to keep an eye on the power transformer and the power system. We also gratefully acknowledge the technical assistance of *State Key Laboratory of Electromagnetic Engineering, School of Electrical and Electronic Engineering, Huazhong University of Science and Technology*. The work was also partly supported by the *National Natural Science Foundation of China (project numbers 50177011, 50407010, and 50777024)*. The authors are continuing their research in this field and would welcome contact with new ideas or if there is any confusion generated.

Xiangning Lin
Wuhan, China
2014

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Principles of Transformer Differential Protection and Existing Problem Analysis

1.1 Introduction

With the development of the electric power industry, large capacity power transformers are more and more widely applied in power systems. As the heart of the whole power system, the performance of the transformer directly affects the continuous and stable operation of the whole power system. In particular, once a modern transformer of large capacity, high voltage, high cost and complicated structure is destroyed by a fault, a series of problems will emerge, such as wide-ranging impact, difficult and lengthy maintenance, and great economic loss. Statistics show that during the years 2001–2005, the average correct operating rate of transformers 220 kV and above is only up to 79.97%, far below the correct operating rate of line protection (more than 99%).

Differential protection is one of the foremost protection schemes used in the power transformer. The theoretical foundation of differential protection is Kirchhoff's current law (KCL), which is applied successfully in the protection of transmission lines and generators. However, there are many problems when it is necessary to identify transformer internal faults under various complicated operation conditions [1]. From the perspective of an electric circuit, the transformer's primary and secondary windings cannot be treated as the same node, with the voltage on each side being unequal. Besides, the two sides are not physically linked. In terms of basic principle, transformer differential protection is based on the balance of the steady magnetic circuit. However, this balance will be destroyed during the transient process and can only be rebuilt after the transient process is finished. Therefore, many unfavourable factors need to be taken into account in the implementation of transformer differential protection:

- Matching and error of the current transformer (CT) ratio.
- Transformer tap change.
- Transfer error of the CT increases during the transient process of the external fault current.
- Single-phase earth fault on the transformer's high voltage side via high resistance.
- Inter-turn short circuit with outgoing current.
- The magnetizing inrush.

With respect to the scenarios listed above, solutions to the first five mainly rely on the features of the differential protection. The tripping resulting from the inrush current needs to be blocked for the purpose

Electromagnetic Transient Analysis and Novel Protective Relaying Techniques for Power Transformers, First Edition. Xiangning Lin, Jing Ma, Qing Tian and Hanli Weng.

of preventing mal-operation. In this section, various problems in current differential protection principles and inrush current blocking schemes are firstly studied and discussed. Then, some novel principles for transformer main protection are proposed and analyzed. Simulation and dynamic tests are carried out to verify the validity and feasibility of the novel principles. By comparative research, the development route of the transformer main protection technology is given.

Compared with EHV (Extra High Voltage) power systems, the electromagnetic environment of UHV (Ultra High Voltage) systems is more complex. Meanwhile, the configuration and parameters of an UHV transformer differ from an EHV transformer. In this case, the preconditions of applying transformer differential protection correctly rest with the modelling of the UHV power transformer reasonably and appropriate analysis of corresponding electromagnetic transients. The autotransformer is the main type of UHV transformer. However, the model of the autotransformer is not available in most simulation software. An ordinary countermeasure is to replace the autotransformer by the common transformer when executing electromagnetic transient simulations. In this case, the effect of magnetic coupling can be included but the electric relationship between the primary side and the secondary side cannot be involved. One of the existing models adopts the flux linkage as the state variable and includes the nonlinearity of the transformer core. It is clear in terms of concept but too complex to perform in many cases. In contrast, a new transient simulation model of the three-phase autotransformer is described, in which the controlled voltage and current sources are developed with the modified damping trapezoidal method, which is engaged to form the synthetic simulation model. In this case, both the efficiency and the precision of simulations are improved. However, this type of model will be more reasonable if it takes into account the nonlinearity of magnetizing impedance. Furthermore, the electromagnetic transient simulations in the UHV electromagnetic environment are new challenges, especially when including the UHV transmission line with distributed parameters.

Differential protection is usually the main protection of most power transformers. The key problem for the differential protection is how to distinguish between the inrush caused by unwanted tripping or clearing the external fault and fault currents rapidly [2–4]. The traditional methods of identifying the inrush are based on the theories of second harmonic restraint and dead angle. The flux saturation point becomes lower with the improvement of iron materials. The percentage of the second harmonic in the three-phase inrush current is probably lower than 15% in the case of higher residual magnetism and initial fault current satisfying certain constrains; the lowest might be under 7% with the relative dead angle smaller than 30°. The transformer differential protection cannot avoid the mal-operation regardless of whether second harmonic restraint and dead angle based blocking schemes are adopted. The theory of identifying the inrush using currents and voltages faces the problem of low sensitivity because of the difficulty of acquiring precisely the parameters of transformers. On the other hand, if the percentage of the second harmonic within the fault current is greater than 15%, this will cause a time delay in tripping of the protection based on the second harmonic criterion. This is due to the long-distance distributed capacitance and series compensation capacitance resonance in the high voltage power systems. The percentage of the harmonic will be larger if the characteristic of CT is not good (easy to saturate) and the differential protection cannot operate with the restraint ratio of 15%. Therefore, it is necessary to find a new criterion to identify the inrush for optimizing the characteristic of the differential protection of the power transformers.

1.2 Fundamentals of Transformer Differential Protection

1.2.1 Transformer Faults

Transformers are used widely in a variety of applications, from small-size distribution transformers serving one or more users to very large units that are the essential parts of the bulk power system. Moreover, a power transformer has a variety of features, including tap changers, phase shifters, and multiple windings, which requires special consideration in the protective system design.

Transformer faults are categorized into two classes: external faults and internal faults.

External faults are those that occur outside the transformer. These hazards present stresses on the transformer that may be of concern and may shorten the transformer life. These faults include: overloads; overvoltage; underfrequency; and external system short circuits. Most of the foregoing conditions are often ignored in specifying transformer relay protection, depending on how critical the transformer is and its importance in the system. The exception is protection against overfluxing, which may be provided by devices called 'volts per hertz' relays that detect either high voltage or underfrequency, or both, and will disconnect the transformer if these quantities exceed a given limit, which is usually 1.1 per unit.

Internal faults are those that occur within the transformer protection zone. This classification includes not only faults within the transformer enclosure but also external faults that occur inside the current transformer (CT) locations. Transformer internal faults are divided into two classifications for discussion; incipient faults and active faults.

Incipient faults are those that develop slowly but which may develop into major faults if the cause is not detected and corrected. They are of three kinds – transformer overheating, overfluxing, or overpressure – and usually develop slowly, often in the form of a gradual deterioration of insulation due to some causes. This deterioration may eventually become serious enough to cause a major arcing fault that will be detected by protective relays. If the condition can be detected before major damage occurs, the needed repairs can often be made more quickly and the unit placed back into service without a prolonged outage. Major damage may require shipping the unit to a manufacturing site for extensive repair, which results in an extended outage period.

Active faults are caused by the breakdown in insulation or other components that create a sudden stress situation that requires prompt action to limit the damage and prevent further destructive action. They occur suddenly and usually require fast action by protective relays to disconnect the transformer from the power system and limit the damage to the unit. For the most part, these faults are short circuits in the transformer, but other difficulties can also be cited that require prompt action of some kind. The following classifications of active faults are considered:

1. Short circuits in Y-connected windings
   (a) Grounded through a resistance
   (b) Solidly grounded
   (c) Ungrounded.
2. Short circuits in Δ-connected windings.
3. Phase-to-phase short circuits (in three-phase transformers).
4. Turn-to-turn short circuits.
5. Core faults.
6. Tank faults.

1.2.2 Differential Protection of Transformers

The most common method of transformer protection uses the percentage differential relay as the primary protection, especially where speed of fault clearing is considered important. The trend in standards for reduced fault-withstand time in power transformers requires that fast clearing of transformer faults be emphasized.

As shown in Figure 1.1, $\dot{I}_1, \dot{I}_2$ represent the transformer primary currents and $\dot{I}'_1, \dot{I}'_2$ represent the corresponding secondary currents. Differential current in the relay KD can be given by:

$$\dot{I}_r = \dot{I}'_1 + \dot{I}'_2 \tag{1.1}$$

The operating criterion is as follows:

$$I_r \geq I_{set} \tag{1.2}$$

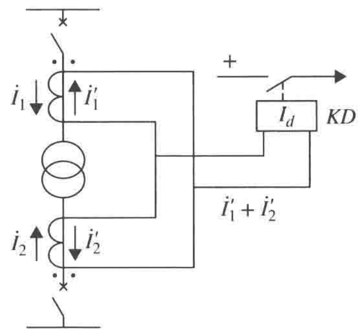

Figure 1.1 The wiring diagram of differential protection for a double winding transformer

I_{set} means the operation current and $I_r = |\dot{I}_1' + \dot{I}_2'|$ represents the root mean square (RMS) value of the differential current.

If setting transformer ratio $n_T = U_1/U_2$, Equation (1.1) can be rewritten as:

$$\dot{I}_r = \frac{\dot{I}_2}{n_{TA2}} + \frac{\dot{I}_1}{n_{TA1}} \tag{1.3}$$

$$\dot{I}_r = \frac{n_T\dot{I}_1 + \dot{I}_2}{n_{TA2}} + \left(1 - \frac{n_{TA2}n_T}{n_{TA2}}\right)\frac{\dot{I}_1}{n_{TA1}} \tag{1.4}$$

If $\frac{n_{TA2}}{n_{TA1}} = n_T$, we can know that $\dot{I}_r = \frac{n_T\dot{I}_1+\dot{I}_2}{n_{TA2}}$. Having ignored the transformer loss, the differential current $\dot{I}_r$ will be zero during normal operation or when experiencing transformer external faults. In this case, the protection will not activate. When an internal fault exists, it will produce an additional fault current, which makes the differential protection operate.

We always use three-winding transformers in the real power system, usually with Y/Δ-11 connection (Figure 1.2).

In Figure 1.2, i_a, i_b, i_c represent the currents on the windings and i_A, i_B, i_C represent the currents on the Y-windings; u_a, u_b, u_c represent the voltages of the windings and u_A, u_B, u_C represent the voltages of the Y windings; i_{La}, i_{Lb}, i_{Lc} represent line currents of phase A, B, C on the windings.

For the winding differential protection principle, the differential current between the two sides can be calculated according to Figure 1.2:

$$\begin{bmatrix} I_{da} \\ I_{db} \\ I_{dc} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} + K\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} \tag{1.5}$$

In Equation (1.5), $K = \frac{U_Y}{\sqrt{3}U_D} = \frac{w_Y}{w_D}$.

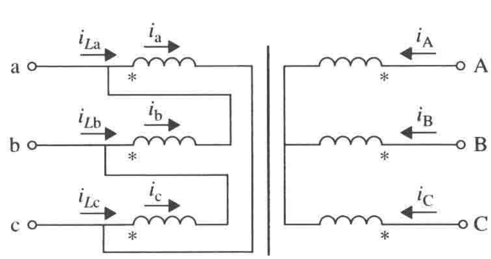

Figure 1.2 Three-phase transformer with Y/Δ-11 connection