ELECTROMAGNETIC TRANSIENT ANALYSIS AND NOVEL PROTECTIVE RELAYING TECHNIQUES FOR POWER TRANSFORMER
ELECTROMAGNETIC TRANSIENT ANALYSIS AND NOVEL PROTECTIVE RELAYING TECHNIQUES FOR POWER TRANSFORMER

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Contents

About the Authors ix

Preface xi

1 Principles of Transformer Differential Protection and Existing Problem Analysis 1
1.1 Introduction 1
1.2 Fundamentals of Transformer Differential Protection 2
1.2.1 Transformer Faults 2
1.2.2 Differential Protection of Transformers 3
1.2.3 The Unbalanced Current and Measures to Eliminate Its Effect 5
1.3 Some Problems with Power Transformer Main Protection 7
1.3.1 Other Types of Power Transformer Differential Protections 7
1.3.2 Research on Novel Protection Principles 9
1.4 Analysis of Electromagnetic Transients and Adaptability of Second Harmonic Restraint Based Differential Protection of a UHV Power Transformer 17
1.4.1 Modelling of the UHV Power Transformer 18
1.4.2 Simulation and Analysis 20
1.5 Study on Comparisons among Some Waveform Symmetry Principle Based Transformer Differential Protection 27
1.5.1 The Comparison and Analysis of Several Kinds of Symmetrical Waveform Theories 27
1.5.2 The Theory of Waveform Symmetry of Derivatives of Current and Its Analysis 28
1.5.3 Principle and Analysis of the Waveform Correlation Method 32
1.5.4 Analysis of Reliability and Sensitivity of Several Criteria 33
1.6 Summary 36

2 Malfunction Mechanism Analysis due to Nonlinearity of Transformer Core 39
2.1 Introduction 39
2.2 The Ultra-Saturation Phenomenon of Loaded Transformer Energizing and its Impacts on Differential Protection 43
2.2.1 Loaded Transformer Energizing Model Based on Second Order Equivalent Circuit 43
2.2.2 Preliminary Simulation Studies 48
## Contents

2.3 Studies on the Unusual Mal-Operation of Transformer Differential Protection during the Nonlinear Load Switch-In

2.3.1 Simulation Model of the Nonlinear Load Switch-In 57

2.3.2 Simulation Results and Analysis of Mal-Operation Mechanism of Differential Protection 57

2.4 Analysis of a Sort of Unusual Mal-operation of Transformer Differential Protection due to Removal of External Fault

2.4.1 Modelling of the External Fault Inception and Removal and Current Transformer 70

2.4.2 Analysis of Low Current Mal-operation of Differential Protection 70

2.5 Analysis and Countermeasure of Abnormal Operation Behaviours of the Differential Protection of the Converter Transformer

2.5.1 Recurrence and Analysis of the Reported Abnormal Operation of the Differential Protection of the Converter Transformer 80

2.5.2 Time-Difference Criterion to Discriminate between Faults and Magnetizing Inrushes of the Converter Transformer 86

2.6 Summary 95

References 95

3 Novel Analysis Tools on Operating Characteristics of Transformer Differential Protection 97

3.1 Introduction 97

3.2 Studies on the Operation Behaviour of Differential Protection during a Loaded Transformer Energizing

3.2.1 Simulation Models of Loaded Transformer Switch-On and CT 99

3.2.2 Analysis of the Mal-operation Mechanism of Differential Protection 102

3.3 Comparative Investigation on Current Differential Criteria between One Using Phase Current and One Using Phase–Phase Current Difference for the Transformer using Y-Delta Connection

3.3.1 Analyses of Applying the Phase Current Differential to the Power Transformer with Y/Δ Connection and its Existing Bases 109

3.3.2 Rationality Analyses of Applying the Phase Current Differential Criterion to the Power Transformer with Y/Δ Connection 113

3.4 Comparative Analysis on Current Percentage Differential Protections Using a Novel Reliability Evaluation Criterion

3.4.1 Introduction to CPD and NPD 117

3.4.2 Performance Comparison between CPD and NPD in the Case of CT Saturation 118

3.4.3 Performance Comparison between CPD and NPD in the Case of Internal Fault 121

3.5 Comparative Studies on Percentage Differential Criteria Using Phase Current and Superimposed Phase Current

3.5.1 The Dynamic Locus of $\frac{\varphi_{-1}}{\varphi_{+1}}$ in the Case of CT Saturation 123

3.5.2 Sensitivity Comparison between the Phase Current Based and the Superimposed Current Based Differential Criteria 126

3.5.3 Security Comparison between the Phase Current Based and the Superimposed Current Based Differential Criteria 128

3.5.4 Simulation Analyses 130

3.6 A Novel Analysis Methodology of Differential Protection Operation Behaviour

3.6.1 The Relationship between Transforming Rate and the Angular Change Rate under CT Saturation 132
3.6.2  Principles of Novel Percentage Restraint Criteria 133
3.6.3  Analysis of Novel Percentage Differential Criteria 142
3.7  Summary 151
References 151

4  Novel Magnetizing Inrush Identification Schemes 153
4.1  Introduction 153
4.2  Studies for Identification of the Inrush Based on Improved Correlation Algorithm 155
   4.2.1  Basic Principle of Waveform Correlation Scheme 155
   4.2.2  Design and Test of the Improved Waveform Correlation Principle 159
4.3  A Novel Method for Discrimination of Internal Faults and Inrush Currents by Using Waveform Singularity Factor 163
   4.3.1  Waveform Singularity Factor Based Algorithm 163
   4.3.2  Testing Results and Analysis 164
4.4  A New Principle of Discrimination between Inrush Current and Internal Fault Current of Transformer Based on Self-Correlation Function 169
   4.4.1  Basic Principle of Correlation Function Applied to Random Single Analysis 169
   4.4.2  Theory and Analysis of Waveform Similarity Based on Self-Correlation Function 170
   4.4.3  EPDL Testing Results and Analysis 173
4.5  Identifying Inrush Current Using Sinusoidal Proximity Factor 174
   4.5.1  Sinusoidal Proximity Factor Based Algorithm 174
   4.5.2  Testing Results and Analysis 176
4.6  A Wavelet Transform Based Scheme for Power Transformer Inrush Identification 181
   4.6.1  Principle of Wavelet Transform 181
   4.6.2  Inrush Identification with WPT 185
   4.6.3  Results and Analysis 185
4.7  A Novel Adaptive Scheme of Discrimination between Internal Faults and Inrush Currents of Transformer Using Mathematical Morphology 190
   4.7.1  Mathematical Morphology 190
   4.7.2  Principle and Scheme Design 193
   4.7.3  Testing Results and Analysis 194
4.8  Identifying Transformer Inrush Current Based on Normalized Grille Curve 202
   4.8.1  Normalized Grille Curve 202
   4.8.2  Experimental System 205
   4.8.3  Testing Results and Analysis 207
4.9  A Novel Algorithm for Discrimination between Inrush Currents and Internal Faults Based on Equivalent Instantaneous Leakage Inductance 211
   4.9.1  Basic Principle 211
   4.9.2  EILI-Based Criterion 217
   4.9.3  Experimental Results and Analysis 218
4.10 A Two-Terminal Network-Based Method for Discrimination between Internal Faults and Inrush Currents 222
   4.10.1  Basic Principle 222
   4.10.2  Experimental System 230
   4.10.3  Testing Results and Analysis 230
4.11 Summary 234
References 234
5 Comprehensive Countermeasures for Improving the Performance of Transformer Differential Protection

5.1 Introduction 237

5.2 A Method to Eliminate the Magnetizing Inrush Current of Energized Transformers 242
5.2.1 Principles and Modelling of the Inrush Suppressor and Parameter Design 242
5.2.2 Simulation Validation and Results Analysis 249

5.3 Identification of the Cross-Country Fault of a Power Transformer for Fast Unblocking of Differential Protection 255
5.3.1 Criterion for Identifying Cross-Country Faults Using the Variation of the Saturated Secondary Current with Respect to the Differential Current 255
5.3.2 Simulation Analyses and Test Verification 257

5.4 Adaptive Scheme in the Transformer Main Protection 268
5.4.1 The Fundamental of the Time Difference Based Method to Discriminate between the Fault Current and the Inrush of the Transformer 268
5.4.2 Preset Filter 269
5.4.3 Comprehensive Protection Scheme 271
5.4.4 Simulation Tests and Analysis 274

5.5 A Series Multiresolution Morphological Gradient Based Criterion to Identify CT Saturation 294
5.5.1 Time Difference Extraction Criterion Using Mathematical Morphology 294
5.5.2 Simulation Study and Results Analysis 297
5.5.3 Performance Verification with On-site Data 302

5.6 A New Adaptive Method to Identify CT Saturation Using a Grille Fractal 304
5.6.1 Analysis of the Behaviour of CT Transient Saturation 304
5.6.2 The Basic Principle and Algorithm of Grille Fractal 308
5.6.3 Self-Adaptive Generalized Morphological Filter 312
5.6.4 The Design of Protection Program and the Verification of Results 313

5.7 Summary 317

References 317

Index 319
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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
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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.

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1

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...
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.
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, $I_1, I_2$ represent the transformer primary currents and $I'_1, I'_2$ represent the corresponding secondary currents. Differential current in the relay KD can be given by:

$$I_r = I'_1 + I'_2$$  \hspace{1cm} (1.1)

The operating criterion is as follows:

$$I_r \geq I_{set}$$  \hspace{1cm} (1.2)
Electromagnetic Transient Analysis and Novel Protective Relaying Techniques

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

$I_{set}$ means the operation current and $I_r = |I_1' + I_2'|$ 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:

$$I_r = \frac{I_2}{n_{TA2}} + \frac{I_1}{n_{TA1}}$$

(1.3)

$$I_r = \frac{n_T I_1 + I_2}{n_{TA2}} + \left(1 - \frac{n_{TA2} n_T}{n_{TA1}}\right) \frac{I_1}{n_{TA1}}$$

(1.4)

If $\frac{n_{TA1}}{n_{TA2}} = n_T$, we can know that $I_r = n_T I_1 + I_2$. Having ignored the transformer loss, the differential current $I_r$ 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:

$$\begin{bmatrix} I_{da} \\ I_{db} \\ I_{dc} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} + K \frac{U_T}{\sqrt{3} U_D} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix}$$

(1.5)

In Equation (1.5), $K = \frac{U_T}{\sqrt{3} U_D} = \frac{v_A}{u_D}$.

Figure 1.2 Three-phase transformer with Y/Δ-11 connection
1.2.3 The Unbalanced Current and Measures to Eliminate Its Effect

Due to differences in transformer ratios and CT accuracy, unbalanced current may exist in the CT secondary currents during external faults which could influence differential protection’s correct operation. There are three sources of error that tend to cause unbalanced currents:

1. Tap changing in the power transformer
2. Mismatch between CT currents and relay tap ratings.
3. Differences in accuracy of the CTs on either side of the transformer bank.

As illustrated, the unbalanced current produced by the difference of transformation ratio and transformer error is related to the through current caused by transformer external faults. With an increase in the through current, the unbalanced current also increases. This feature is the basis of the operating principle of the differential relay with restrained characteristics. When a restraint current, which can reflect the size of transformer, is introduced, the operating current of the relay will not be set to avoid the maximum through current ($I_{k_{\text{max}}}$) but will be automatically adjusted according to the restraint current.

For a two-winding transformer, since $I_2 = -I_1$ (when an external fault occurs), it can be concluded that $I_{\text{res}} = I_1$. Besides, we have $I_{\text{amb}} = f(I_{\text{res}})$, since the unbalanced current is related to the fault current. Hence, the operation equation of the differential relay with restrained characteristics is given by $I_r > K_{\text{rel}}f(I_{\text{res}})$, where $K_{\text{rel}}$ is the reliability coefficient.

The relationship between the differential current ($I_r$) and restraint current ($I_{\text{res}}$) is demonstrated in Figure 1.3. Obviously the differential relay will act only when the differential current is above the curve of $K_{\text{rel}}f(I_{\text{res}})$. So the curve of $K_{\text{rel}}f(I_{\text{res}})$ is defined as the restrained characteristic of the differential relay. The area above the curve is the action area while the area below is the restraint area.

Figure 1.3 shows that the curve $K_{\text{rel}}f(I_{\text{res}})$ is a monotonously rising function. When $I_{\text{res}}$ is small, the transformer is unsaturated, therefore the curve $K_{\text{rel}}f(I_{\text{res}})$ is in proportion to $I_{\text{res}}$. As $I_{\text{res}}$ increases and becomes large enough to set the transformer saturated, the changing rate of curve $K_{\text{rel}}f(I_{\text{res}})$ will increase, thus the curve becomes nonlinear.

Since the transformer saturation depends on many factors, the nonlinear part of the restrained characteristic is difficult to measure. Hence, the actual restrained characteristic must be simplified. Generally in differential protection, the ‘two broken line’ characteristic is widely used, with a straight line parallel to the coordinate axis and an oblique line represented by $I_{\text{set.r}}$. In Figure 1.3, the oblique line intersects with the horizontal line at point g and with the curve $K_{\text{rel}}f(I_{\text{res}})$ at point a. In correspondence to point g, the action current is the minimum action current; the restraint current corresponding to the action current is defined as the inflection point current. When $I_{\text{res}} < I_{\text{res,max}}$, $I_{\text{set.r}}$ is less than $K_{\text{rel}}f(I_{\text{res}})$ permanently, this ensures that the differential relay will not mal-operate under any external fault. However, this leads to decrease of the protection sensitivity under internal faults. The unbalanced current, such as the excitation current and noise caused by the restraint current in measurement circuit, also requires the setting

![Figure 1.3 The restrained characteristic of relay](image-url)
of a minimum action current. Otherwise mal-operation may result. The mathematical expression of the restrained characteristic is:

\[ I_{set, r} = \begin{cases} I_{set, \text{min}} & I_{res} < I_{res, g} \\ K (I_{res} - I_{res, g}) + I_{set, \text{min}} & I_{res} \geq I_{res, g} \end{cases} \]

where \( K \) represents the slope of the restrained characteristic:

\[ K = \frac{I_{set, \text{max}} - I_{set, \text{min}}}{I_{res, \text{max}} - I_{res, g}} \]

Apart from the restraint current, the transformer inrush current will also cause unbalanced current, which also calls for discussion.

When a transformer is first energized, there is a transient inrush of current that is required to establish the magnetic field of the transformer. The mechanism of inrush generation can be seen in Figure 1.4. The reason rests with the transient saturation of flux of the transformer core due to appropriate inception angle and residual flux. This is not a fault condition and should not cause protective relays to operate. However, under certain conditions, depending on the residual flux in the transformer core, the magnitude of inrush current can be as much as 8–10 times normal full load current and can be the cause of false tripping of protective relays. This is rather serious, since it is not clear that the transformer is not internally faulted. The sensible response is, therefore, to thoroughly test the transformer before making any further attempts at energizing. This will be expensive and frustrating, especially if the tests show that the transformer is perfectly normal. Since this is such an important concept, it will be examined in some detail in order to understand the reason for high inrush current and to learn what steps can be used in protective relays to prevent their tripping due to magnetizing inrush.

There are several factors that control the magnitude and duration of the magnetizing inrush current:

- Size of the transformer bank.
- Strength of the power system to which the bank is connected.
- Resistance in the system from the equivalent source to the bank.
- Type of iron used in the transformer core.
- Prior history of the bank and the existence of residual flux.
- Conditions surrounding the energizing of the bank, for example,
  - Initial energizing
  - Recovery energizing from protective action
  - Sympathetic inrush in parallel transformers.
There are several methods that have been used to prevent the tripping of a sound transformer due to large inrush currents that accompany initial energizing of the unit. The common methods used are:

1. Desensitize the relay during start-up.
2. Supervise the relay with voltage relays.
3. Add time delay.
4. Detect magnetizing inrush by observing the current harmonics.

These methods can be further described, as follows:

1. Methods have been devised to desensitize the differential relay and prevent tripping during start-up. One method parallels the operating coil with a resistor, with the resistor circuit being closed by an undervoltage relay contact. When the transformer bank is de-energized, the undervoltage relay resets, thereby closing the resistor bypass circuit. On start-up, the operating coil is bypassed until the undervoltage relay picks up, which is delayed for a suitable time.
2. Another method uses a fuse to parallel the differential relay operating coil. The fuse size is selected to withstand normal start-up currents, but internal fault currents are sufficient to blow the fuse and divert all current to the operating coil.
3. The voltage supervised relay measures the three-phase voltage as a means of differentiating between inrush current and a fault condition, a fault being detected by a depression in one of the three-phase voltages. This concept is usable for either fast or slow relays, it constitutes an improvement in the method.
4. Simply adding time delay to the differential relays during energizing the transformer is effective but must be accompanied by some method of overriding the time delay if an actual fault occurs during start-up. Usually, time delay is used in conjunction with other relay intelligence.
5. Harmonic current restraint is another method that is used. It was noted earlier that the second harmonic of the total current is almost ideal for determining whether a large inrush of current is due to initial energizing or to a sudden fault. Most differential relays use filters to detect the second, and sometimes the fifth, harmonic current and restrain tripping when this current is present.

### 1.3 Some Problems with Power Transformer Main Protection

#### 1.3.1 Other Types of Power Transformer Differential Protections

#### 1.3.1.1 Inter-Phase Differential Protection Principle

There are still some problems that exist in the winding differential protection:

- The winding current of transformers with Y/Δ-connection cannot be obtained.
- Cooperation with overcurrent protection is difficult, which will produce a protection dead zone.

Similar to the phase differential protection, the differential current of inter-phase current differential protection can be obtained:

\[
\begin{bmatrix}
I_{da} \\
I_{db} \\
I_{dc}
\end{bmatrix} =
\begin{bmatrix}
1 & -1 & 0 \\
0 & 1 & -1 \\
-1 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
I_a \\
I_b \\
I_c
\end{bmatrix} + K
\begin{bmatrix}
1 & -1 & 0 \\
0 & 1 & -1 \\
-1 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
I_A \\
I_B \\
I_C
\end{bmatrix}
\]

The disadvantage of inter-phase differential protection principle is as follows: for a three-phase transformer with Y/Δ-11 connection, when a Y-side single-phase grounding occurs, protection sensitivity will decrease. As a solution to this problem, a zero-sequence differential protection scheme is put forward in this section.
1.3.1.2 Zero-Sequence Differential Protection Principle

For single-phase high voltage large transformers, the main type of short-circuit fault is between winding to the iron core (when ground insulation is damaged), that is, single-phase grounding. Inter-phase short-circuit (in-box fault) seldom happens. Thus, single-phase grounding is carefully studied.

The constitution of zero-sequence differential protection is shown in Figure 1.5. On the Y-side of the transformer, the secondary sides of the CTs are connected to form a zero-sequence filter. Together with the secondary side of the neutral CT, the zero-sequence differential protection is formed.

Advantages of zero-sequence differential protection are:

- Relatively high sensitivity to single-phase grounding faults on the Y-side;
- The operation current is not affected by the transformer tap.
- Not directly influenced by the magnetizing inrush current.
- All CTs apply the same ratio, which is not related with the transformer ratio.

Disadvantages of zero-sequence differential protection are:

- Low (zero) sensitivity to inter-phase faults and faults on the low voltage side.
- Low sensitivity to high resistance grounding faults.
- Examination of wiring error on the secondary side is more complicated.

1.3.1.3 Split-Side Differential Protection

For phase differential protection schemes, the problem of mal-operation caused by inrush current or overexcitation always exists. Therefore, it is necessary to develop a novel transformer differential protection scheme that is not affected by either inrush current or overexcitation current. The new protection scheme is called transformer split-side differential protection in this section, the wiring diagram of which is shown in Figure 1.6.

For transport considerations, modern large capacity transformers are commonly made up of three single-phase transformers. The terminals of the windings are all led out of the shell, which facilitates the implementation of the proposed spilt-side differential protection. Advantages of this protection scheme are:

- Relatively high sensitivity to single-phase grounding faults.
- Not affected by the transformer tap.
- Not directly affected by the inrush current.

![Figure 1.5 Connecting diagram of zero-sequence current differential protection](image-url)
The spilt-side differential protection being applied to large power transformers can simplify the device.

Simple protection principle, reliable device, and convenient debugging.

Disadvantages of split-side differential protection are:

- Low (zero) sensitivity to common inter-turn faults.
- Applicable only when each winding has two terminals led out.
- The number of protection relays needed doubles.

From the above analysis, it is obvious that zero-sequence differential protection and split-side differential protection schemes are both superior to inter-phase differential protection in certain aspects. However, in view of the actual connection modes of transformers and the protective relaying characteristics, the inter-phase differential protection, especially longitudinal differential protection, is still most commonly used as the main protection for transformers. In longitudinal differential protection, the impact of inrush current has long been a problem that requires special measures to deal with it.

1.3.2 Research on Novel Protection Principles

With the rapid development of microcomputer technology and the wide application of the transformer main-backup-integrated protection scheme, it has become possible to conduct complex calculations within the transformer protection device using multiple electric variables. Since the transformer is a nonlinear and time-varying system, the voltage and current are two independent variables, not linearly correlated. Thus, by using both the voltage and current variables to describe the operation state of transformer, the information is more complete. Furthermore, it facilitates the search for new protection criteria of higher sensitivity and better reliability. Currently, transformer protection principles that use both the voltage and current variables mainly include: the magnetic flux characteristic principle, sequence impedance principle, loop equation principle, power differential principle and so on.

The magnetic flux characteristic principle is based on the nonlinearity of the excitation branch and has a promising application future. However, currently it is applicable only to single-phase transformer groups. For three-phase transformers with Y/Δ connection, since the internal circulation current on the Δ-side winding is difficult to measure, how the magnetic flux characteristic can be applied in this case to reflect the nonlinear characteristics of the excitation branch remains to be studied.

In the following sections, the advantages and disadvantages of the sequence impedance principle, loop equation principle and power differential principle are discussed, on the basis of which some novel principles of transformer main protection are put forward.
1.3.2.1 Sequence Impedance Principle

The sequence impedance principle is based on the changes of the transformer positive and negative sequence equivalent networks before and after the fault. With the variation of the positive and negative sequence voltage and current, the positive and negative sequence impedances felt by the relay points on both sides of the transformer can be calculated. Then, according to the direction of the calculated impedances, it can be decided whether the transformer fault is internal or external. For a convenient illustration, a two-winding transformer is taken as an example, the system model of which is shown in Figure 1.7. The protective relays are installed on both sides of the transformer and the positive direction for current is set as in the figure.

For transformer external faults, suppose a fault occurs at $F_1$ on the transmission line. According to the positive sequence equivalent network before and after the fault, the following expression can be obtained:

$$
\frac{\Delta V_{x1}}{\Delta I_{x1}} = -Z_{Gx1}, \quad \frac{\Delta V_{y1}}{\Delta I_{y1}} = -(Z_{Gy1} + Z_{Line1})
$$

where $\Delta V_{x1}$, $\Delta I_{x1}$, $\Delta V_{y1}$ and $\Delta I_{y1}$ represent the variation of positive sequence voltage and current on both sides of the transformer before and after the fault; $Z_{Gx1}$ and $Z_{trans1}$ are the positive sequence equivalent impedance of the system on the X-side and the transformer, respectively.

Similarly, according to the negative sequence equivalent network before and after the fault, the following can be obtained:

$$
\frac{\Delta V_{x2}}{\Delta I_{x2}} = -Z_{Gx2}, \quad \frac{\Delta V_{y2}}{\Delta I_{y2}} = + (Z_{Gy2} + Z_{trans2})
$$

where $\Delta V_{x2}$, $\Delta I_{x2}$, $\Delta V_{y2}$ and $\Delta I_{y2}$ represent the variation of negative sequence voltage and positive sequence current on both sides of the transformer before and after the fault; $Z_{Gx2}$ and $Z_{trans2}$ are the negative sequence equivalent impedance of the system on the X-side and the transformer respectively.

For transformer internal faults, suppose a fault occurs at $F_2$. Similarly, the positive and negative sequence impedances on both sides of the transformer can be calculated as shown in the following:

$$
\frac{\Delta V_{x1}}{\Delta I_{x1}} = -Z_{Gx1}, \quad \frac{\Delta V_{y1}}{\Delta I_{y1}} = -(Z_{Gy1} + Z_{Line1})
$$

$$
\frac{\Delta V_{x2}}{\Delta I_{x2}} = -Z_{Gx2}, \quad \frac{\Delta V_{y2}}{\Delta I_{y2}} = -(Z_{Gy2} + Z_{Line2})
$$

where $Z_{Gy1}$, $Z_{Line1}$, $Z_{Line2}$ and $Z_{Gy2}$ are the positive and negative sequence equivalent impedances of the system on the Y-side and the transmission line respectively.

It can be seen from Equations (1.7) and (1.8) that, when a transformer external fault occurs, the positive and negative sequence impedances felt by both sides of the transformer are different in direction – one positive and the other negative. And from Equations (1.9) and (1.10) it can be seen that, when a transformer internal fault occurs, the positive and negative sequence impedances felt by both sides of the transformer are the same in direction – both negative. Based on this fact, a method is put forward to distinguish between internal and external faults of the transformer (referred to as the ‘quadrant division method’ hereinafter): if the positive and negative sequence impedances on both sides of the transformer are different in direction – one located in first quadrant on the image plane and the other in the third quadrant – then the fault can be identified as an external fault; otherwise, if the positive and negative

![Figure 1.7 System model of a two-winding transformer](image-url)
sequence impedances on both sides of the transformer are the same in direction – both in the third quadrant on the image plane – then the fault can be identified as an internal fault. On the basis of the ‘quadrant division method’, the division of the image plane is revised by extending the regional boundary to the second and fourth quadrants. Simulation results show that this revision improves the reliability and sensitivity of identification to a certain degree. However, neither the ‘quadrant division method’ nor the revised method can counteract the negative influence of inrush current. Therefore, other criteria should be added to form an effective protection scheme. Furthermore, for transformer protection principles based on sequence impedance, the correct identification between the conditions of normal no-load switching and no-load switching at internal faults remains to be studied.

1.3.2.2 Loop Equation Principle

Microcomputer transformer main protection based on the loop equation principle is very different from traditional differential protection. The interference of inrush current is avoidable with this method, since it does not distinguish inrush current from the internal fault current according to the waveform characteristics of the inrush current. Moreover, this method is not affected by the connection mode of the transformer. Take a single-phase transformer as an example. The system model is shown in Figure 1.8, which can be described by the two differential equations in Equation (1.11). By eliminating the nonlinear item $d\psi_m/dt$ in Equation (1.11), which reflects the transformer’s core flux, the two equations in Equation (1.12) are obtained.

\[
\begin{align*}
\begin{aligned}
\frac{du_1}{dt} &= i_1 r_1 + L_1 \frac{di_1}{dt} + \frac{d\psi_m}{dt} \\
\frac{du_2}{dt} &= i_2 r_2 + L_2 \frac{di_2}{dt} + \frac{d\psi_m}{dt}
\end{aligned}
\end{align*}
\tag{1.11}
\]

\[
\begin{align*}
\begin{aligned}
\frac{du_{12}}{dt} &= L_1 \frac{di_1}{dt} - L_2 \frac{di_2}{dt} \\
\frac{du_{12}}{dt} &= u_1 - u_2 - i_1 r_1 + i_2 r_2
\end{aligned}
\end{align*}
\tag{1.12}
\]

In Equations (1.11) and (1.12), $u_1$ and $u_2$ are the voltages of the primary and secondary windings; $i_1$ and $i_2$ are the currents on the primary and secondary windings; $L_1$ and $L_2$ are the leakage inductances of the primary and secondary windings; $\psi_m$ is the mutual inductance flux between the primary and secondary windings; $r_1$ and $r_2$ are the resistances of the primary and secondary windings.

When the transformer operates in the normal state, $r_1 + r_2 = r_k$ and $L_1 + L_2 = x_k/w$, where $r_k$ and $x_k$ are the winding resistance and short-circuit reactance, respectively. By applying these two formulas to
Equation (1.12), two equivalent loop balance equations can be obtained:

\[
\begin{align*}
    u_1 - u_2 + i_2 r_k + \frac{x_k}{w} \frac{d i_2}{d t} &= (i_1 + i_2) r_1 + L_1 \frac{d (i_1 + i_2)}{d t} \\
    u_1 - u_2 - i_1 r_k - \frac{x_k}{w} \frac{d i_1}{d t} &= -(i_1 + i_2) r_2 - L_2 \frac{d (i_1 + i_2)}{d t}
\end{align*}
\] (1.13) (1.14)

Since Equation (1.12) is based on the normal operation state of the transformer, it is applicable for any circumstance except for a transformer internal fault. Therefore, the validity of Equation (1.12) can be used as a criterion to direct the action of the protective relay. However, this method needs improving in the following two aspects:

1. Currently no feasible method is available to obtain the leakage inductance of each winding in real-time.
2. Even if the leakage inductance parameters can be obtained, it is still dependent on accurate internal fault data to determine the protection scheme, protection criterion and the sensitivity check methods.

Addressing the above problems, the following measures for improvement are proposed.

Based on the transformer loop equation, the equivalent instantaneous leakage inductance of each winding is established; this can reflect the variation status of the transformer leakage magnetic field. The equivalent instantaneous leakage inductance bears similar changing characteristics to the actual leakage inductance. Thus, firstly each equivalent instantaneous leakage inductance is obtained in the cases of inrush current, excessive excitation or external fault, which is a constant value. Secondly, when a fault occurs to the transformer winding, the equivalent instantaneous leakage inductance of the fault phase will change significantly, rendering an obvious difference in value from the normal leakage inductance. Such difference or variation in the value of the equivalent instantaneous leakage inductance can be used to form new transformer main protection criteria.

**Establishment of Equivalent Instantaneous Leakage Inductance Parameter**

Equation (1.13) contains two unknown parameters \((r_1 \text{ and } L_1)\), so it cannot be solved directly. However, by establishing two independent equations using data measured at different moments, it can be solved. To this end, two adjacent moments, \(t_1\) and \(t_2\), are chosen to establish the equations:

\[
\begin{align*}
    u_{121}(t_1) &= r_1 i_d(t_1) + L_1 \frac{d i_d(t_1)}{d t} \\
    u_{122}(t_2) &= r_1 i_d(t_2) + L_1 \frac{d i_d(t_2)}{d t}
\end{align*}
\] (1.15) (1.16)

where \(u_{121} = u_1 - u_2 + i_2 r_k + \left(\frac{x_k}{w}\right) \left(\frac{d i_2}{d t}\right), i_d = i_1 + i_2\).

In implementation, current difference can be used instead of current differential in Equations (1.15) and (1.16). To this end, three adjacent sample values (three continuous points after the digital filtering) are chosen. Suppose that \(u_{k-1}, u_k\) and \(u_{k+1}\) represent the voltage samples at \(t_{k-1}, t_k\) and \(t_{k+1}\), and that \(i_{k-1}, i_k\) and \(i_{k+1}\) represent the current samples at \(t_{k-1}, t_k\) and \(t_{k+1}\). Set \(t_1\) to be in the midst of \(t_{k-1}\) and \(t_k\), and \(t_2\) in the midst of \(t_k\) and \(t_{k+1}\), with a sampling interval between \(t_1\) and \(t_2\). Then \(u_{121}(t_1), u_{122}(t_2), i_d(t_1), i_d(t_2), di_d(t_1)/dt\) and \(di_d(t_2)/dt\) in Equations (1.15) and (1.16) can be expressed by interpolation of the samples:

\[
\begin{align*}
    u_{121}(t_1) &= \frac{u_k + u_{k-1}}{2}, u_{122}(t_2) = \frac{u_k + u_{k+1}}{2} \\
    i_d(t_1) &= \frac{i_k + i_{k-1}}{2}, i_d(t_2) = \frac{i_k + i_{k+1}}{2} \\
    D_1 &= \frac{di_d(t_1)}{d t} = \frac{i_k - i_{k-1}}{T_s}, D_2 = \frac{di_d(t_2)}{d t} = \frac{i_{k+1} - i_k}{T_s}
\end{align*}
\] (1.17) (1.18) (1.19)
Combining Equations (1.15) and (1.16), the instantaneous leakage inductance $L_1$ at $t_1$ can be obtained, as shown in Equation (1.20). Thus, calculated instantaneous leakage inductance is based on the normal operating model of the transformer. In the case of an internal fault, since the loop equation is no longer valid, the calculated leakage inductance is not the actual measuring value but, rather, an equivalent one. Therefore, it is defined as the equivalent instantaneous leakage inductance.

$$L_1 = \frac{u_{121}(t_1)\dot{i}_d(t_2) - u_{121}(t_2)\dot{i}_d(t_1)}{i_d(t_2)D_1 - i_d(t_1)D_2} \quad (1.20)$$

Similarly, the equivalent instantaneous leakage inductance $L_2$ at $t_1$ can be obtained:

$$L_2 = \frac{u_{122}(t_1)\dot{i}_d(t_2) - u_{122}(t_2)\dot{i}_d(t_1)}{i_d(t_2)D_1 - i_d(t_1)D_2} \quad (1.21)$$

where $u_{122} = -(u_1 - u_2 - i_1 \tau - (x_k/w)(d i_1/dt))$.

**Design of the Protection Scheme**

**Main criterion:**

After the protection starts, calculate on-line the equivalent instantaneous leakage inductance of each phase and use a $1/4$ cycle length sliding data window to calculate the real-time average value of the leakage inductance. Compare the average equivalent instantaneous leakage inductances of different phases, then the protection criterion can be formed. It should be noted that the average equivalent instantaneous leakage inductance of the non-pick-up phase is represented by the normal leakage inductance of that phase.

Take the Δ-side of a three-phase Y/Δ-connected transformer as an example. The difference among the average equivalent instantaneous leakage inductances of the phases is described by $\sigma_1^2$ in Equation (1.22). When $\sigma_1^2 > \sigma_{zd}^2$, it can be identified as an internal fault and the protection should operate.

$$\sigma_1^2 = \frac{1}{3}((L_{lae}' - L_{lbe}')^2 + (L_{lbe}' - L_{lce}')^2 + (L_{lce}' - L_{lae}')^2) \quad (1.22)$$

where $L_{lae}'$, $L_{lbe}'$ and $L_{lce}'$ represent the average equivalent instantaneous leakage inductance of each phase on the Δ-side. If there is any phase not switched on (un-started), then its average equivalent instantaneous leakage inductance should be replaced by $L_{tie}' (i = 1, 2, 3)$, the normal leakage inductance of the phases on the Δ-side.

**Auxiliary criterion:**

When a serious internal fault occurs in the transformer, the differential current will be very large, so that the calculated leakage inductances will be small in value and minor in their differences. In this case, using only the main criterion may lead to operation failure of the protection. Therefore, the conventional differential current instantaneous break protection can be introduced as an auxiliary criterion for comprehensive identification.

**Scheme Verification**

Considering the influence of different switching moments, 20 measurements are conducted for each operation state. The calculation results of each group of 20 data are listed in Table 1.1.

As shown in the $\sigma_2^2$ column of Table 1.1, the minimum value of $\sigma_2^2$ under fault conditions (except inter-phase faults) is 80.65 times the maximum value of $\sigma_2^2$ under normal no-load switching conditions. If $\sigma_{zd}^2$ is set to be $10 \times (10^{-4} H)^2$, then according to the main criterion, it is possible to effectively distinguish between inrush current and internal fault current (except inter-phase faults). Furthermore, with the cooperation of the auxiliary criterion, correct and reliable operation of the protective relay under various internal fault conditions can be guaranteed.
Table 1.1  Calculation results of $\sigma_2^2$ under various situations

<table>
<thead>
<tr>
<th>Operation states</th>
<th>$\sigma_2^2(\times10^{-4} \text{H})^2$</th>
<th>Serial number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drop</td>
<td>Normal dropping</td>
<td>0.9538–1.2152</td>
</tr>
<tr>
<td>In star side fault</td>
<td>Inter-turn A9%</td>
<td>112.7443–125.3236</td>
</tr>
<tr>
<td></td>
<td>B18%</td>
<td>216.7854–223.7382</td>
</tr>
<tr>
<td></td>
<td>C18%</td>
<td>220.8367–231.1159</td>
</tr>
<tr>
<td>Grounding A</td>
<td></td>
<td>197.2485–222.1532</td>
</tr>
<tr>
<td>Grounding B</td>
<td></td>
<td>148.5279–160.2373</td>
</tr>
<tr>
<td>Inter-phase AB</td>
<td></td>
<td>1.9634–3.1248</td>
</tr>
<tr>
<td>Inter-phase BC</td>
<td></td>
<td>1.5586–3.0747</td>
</tr>
<tr>
<td>Star side fault under operation</td>
<td>Inter-turn A9%</td>
<td>98.0825–111.3468</td>
</tr>
<tr>
<td></td>
<td>B18%</td>
<td>205.4478–218.4637</td>
</tr>
<tr>
<td></td>
<td>C18%</td>
<td>161.2256–172.6055</td>
</tr>
<tr>
<td>Grounding A</td>
<td></td>
<td>212.6494–223.1037</td>
</tr>
<tr>
<td>Grounding B</td>
<td></td>
<td>155.3819–160.6530</td>
</tr>
<tr>
<td>Inter-phase AB</td>
<td></td>
<td>1.7832–2.9875</td>
</tr>
<tr>
<td>Inter-phase BC</td>
<td></td>
<td>1.6329–2.8321</td>
</tr>
</tbody>
</table>

1.3.2.3 Power Differential Principle

Transformer microcomputer main protection based on the power differential principle considers the voltage and current information synthetically based on the law of energy conservation. When the transformer operates in the normal state, little active power is consumed; but when the transformer insulation is damaged, the sparkling electrical arc will consume large amounts of active power. Therefore, by detecting the amount of active power consumed, it can be decided when an internal fault occurs. The power differential principle does not rely on the waveform characteristics of the inrush current and is a novel main protection scheme. However, there are still some problems about the scheme that remain to be solved:

- This scheme is not totally free from the negative influence of the inrush current. By avoiding the charging process in the first cycle when there is inrush current, the protection judgment will be delayed.
- When there is inrush current, the copper loss is difficult to calculate accurately and the iron loss will increase, which make the value setting complicated.
- For transformers with Y/Δ connection, the current on windings of the Δ-side cannot be obtained, thus the copper loss cannot be determined, which reduces the sensitivity of protection.

In view of the above questions, based on the normal operation state loop equation of the transformer, a two-terminal network containing only the leakage inductance and winding resistance is formed in this section. By analysing the input generalized instantaneous reactive power, the essential difference between the inrush current and internal fault is further revealed.

Design of the Two-Terminal Network

Taking the double-winding single-phase transformer as an example, the two-terminal network based on the voltage and current information can be designed.
According to Equations (1.13) and (1.14), two two-terminal networks can be formed. The one containing only \( r_1 \) and \( L_1 \) is shown in Figure 1.9, which is defined as the primary side two-terminal network. The other, containing only \( r_2 \) and \( L_2 \), is shown in Figure 1.10 and is defined as the secondary side two-terminal network.

The terminal voltage of the network in Figure 1.9 is:

\[
u_{121} = u_1 - u_2 + i_2 r_k + \frac{x_k}{w} \frac{di_2}{dt}
\]

(1.23)

The terminal voltage of the network in Figure 1.10 is:

\[
u_{122} = - \left( u_1 - u_2 - i_1 r_k - \frac{x_k}{w} \frac{di_1}{dt} \right)
\]

(1.24)

In both Figures 1.9 and 1.10, the arrow represents the direction of voltage drop and the current injected into the two-terminal network is: \( i_d = i_1 + i_2 \).

In the case of no-load switching, suppose that the secondary side of the transformer is not loaded, then a two-terminal network similar to that in Figure 1.9 can be formed according to Equation (1.12). In this case the terminal voltage is: \( u_{121} = u_1 - u_2 \) and the current injected into the two-terminal network is \( i_1 \).

Take the two-terminal network in Figure 1.9 for illustration. Although \( i_d(t) \) and \( u_{121}(t) \) of the input terminal are not correspondently related in the actual system, their product has the nature of instantaneous power. Thus, it can be defined as the generalized instantaneous power, that is, \( S_{gy1} = u_{121}(t)i_d(t) \), or in another form: \( S_{gy1}(t) = \bar{S}_{gy1} + \tilde{S}_{gy1}(t) \), where the DC part \( \bar{S}_{gy1} \) is the generalized instantaneous power absorbed by the primary side. Similarly, the generalized instantaneous power absorbed by the secondary side \( \tilde{S}_{gy2} \) can obtained. On this basis, define the difference between \( \bar{S}_{gy1} \) and the active power consumed by the normal winding resistance \( r_1 \) to be \( P_1 \), and the difference between \( \bar{S}_{gy2} \) and the active power consumed by the normal winding resistance \( r_2 \) to be \( P_2 \). Formulas to calculate \( P_1 \) and \( P_2 \) are:

\[
P_1 = \frac{1}{T} \int_0^T \left( u_{121}(t)i_d(t) - i_d^2(t)r_1 \right) dt
\]

\[
P_2 = \frac{1}{T} \int_0^T \left( u_{122}(t)i_d(t) - i_d^2(t)r_2 \right) dt
\]

(1.25)
It can be seen from Equation (1.25) that, in the cases of the normal operating state (including no-load switching and external faults), the generalized active power absorbed by the two-terminal network is all consumed by the winding resistance, thus $P_1$ and $P_2$ are both zero (not considering various kinds of errors). But in the case of internal faults, due to the power loss of the fault branch and the fact that $P_1$ and $P_2$ are calculated with the voltage and current after the fault and the winding resistance before the fault, $P_1$ and $P_2$ will no longer be zero. By setting an appropriate threshold value, it is possible to effectively distinguish between normal operation state and fault condition.

**Principle Verification**

The dynamic simulation results of the power differential principle and the novel principle applied in various cases are shown in Table 1.2. $P_m$ represents the maximum active power in three phases. Considering the influence of different closing moments, the calculation result under every operation state is the comprehensive analysis of 20 measurements.

**Table 1.2** Calculation results of the power differential method and the novel method when the transformer is energized

<table>
<thead>
<tr>
<th>Operation states</th>
<th>Pc/W</th>
<th>Pm/W</th>
<th>Serial number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal state</td>
<td>Normal switching on</td>
<td>854–1 393</td>
<td>0.76–2.2</td>
</tr>
<tr>
<td></td>
<td>Normal operation</td>
<td>309–348</td>
<td>0.53–0.96</td>
</tr>
<tr>
<td>Dropping fault with faults</td>
<td>Star side fault</td>
<td>Inter-turn</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A2.4%</td>
<td>1 161–1 484</td>
<td>27–36</td>
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<td>A6.1%</td>
<td>1 659–1 827</td>
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<tr>
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<td>A9%</td>
<td>2 471–2 539</td>
<td>62–69</td>
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<tr>
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<td>B18%</td>
<td>8 363–8 432</td>
<td>104–115</td>
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<td>C18%</td>
<td>8 016–8 109</td>
<td>112–124</td>
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<td>14 142–14 275</td>
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<td>16 057–16 148</td>
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<td>Inter-phase AB</td>
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<td>Angle side inter-turn fault</td>
<td>A1.8%</td>
<td>1 123–1 145</td>
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<td>A4.5%</td>
<td>1 582–1 737</td>
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<td>2 471–2 539</td>
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<td>A1.8%</td>
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