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A Method for Diagnosing Lower Transformer Faults Based on Current Signal Trajectories and Its Implementation

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Abstract. In practical power systems, transformers are continuously involved in voltage conversion and electrical-energy transmission, so once abnormal operating conditions appear inside the equipment, the influence may gradually spread to the stability of the entire grid. Because early-stage transformer faults are usually weak and not easy to observe directly from conventional electrical quantities, this paper investigates a fault-monitoring method based on current-signal trajectories and discusses its application to transformer operating-state analysis. In the proposed approach, the primary-side and secondary-side current signals are taken as the basic data source, and the corresponding Lissajous trajectories are then constructed under different operating conditions. Instead of analyzing only waveform amplitude or phase separately, the method converts the current relationship into geometric trajectory characteristics, making the variation process easier to observe visually. To examine whether the method remains effective under different fault levels, a transformer equivalent-circuit model was built in Multisim, and several abnormal operating conditions were reproduced by changing equivalent impedance parameters and related electrical quantities. During the simulation analysis, several ellipse-related quantities were extracted from the generated trajectories, mainly including ellipse area together with the ratio between the major axis and minor axis. These geometric quantities were then compared under healthy and faulty operating conditions. The obtained results show that even under relatively weak parameter disturbances, such as ±3% variations, the trajectory shape had already changed slightly compared with the normal state, and the corresponding feature deviation approached about 5% in some simulation cases. After the disturbance level continued to increase, especially when the parameter variation reached around ±30%, the deformation of the ellipse became much more obvious, while part of the geometric feature variation exceeded 32%. From the overall simulation results, it can be seen that the trajectory characteristics still maintain visible differences under different transformer operating conditions, including relatively weak abnormal states appearing at an early stage. Compared with directly using conventional electrical signal quantities for analysis, the proposed method represents operating-state variation through geometric trajectories, so some small parameter changes can be reflected more intuitively. The study therefore suggests that current-signal trajectory analysis may provide another possible way for transformer online monitoring and operating-condition evaluation in practical engineering applications.

Keywords: transformer, fault, current signal, trajectory, feature

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1. Introduction

Power transformers are widely used in modern power systems for voltage conversion and electric-energy transmission, and their operating condition has a direct influence on whether the grid can remain stable and reliable during long-term operation [1-3]. In actual service environments, transformers are continuously affected by electrical stress, temperature rise, vibration, external humidity, and other operating factors. After long periods of operation, these influences may gradually accumulate and finally lead to several common fault conditions, including insulation oil aging, insulation short circuits, winding turn-to-turn faults, and insulation breakdown [4]. In many cases, the abnormal characteristics at the early stage are not obvious enough to be identified immediately, which means that some incipient defects can remain hidden for a relatively long time. Once the fault continues to develop, however, the internal condition of the transformer may deteriorate rapidly, and severe cases can eventually result in equipment shutdown, unexpected power outages, or even large-scale blackout accidents, causing considerable economic losses and operational risks to the power system [5]. Because of this, transformer fault diagnosis has remained an important research topic in power engineering, especially for methods intended for online monitoring and early abnormality detection.

Over the past few years, researchers have carried out extensive work on transformer fault diagnosis using different theoretical approaches. One commonly used direction is electrical-parameter analysis. For example, the impedance-based method in [6] identifies abnormal operating conditions by comparing impedance variation under different states. Frequency response analysis (FRA) has also been discussed quite frequently in transformer fault studies. This method mainly evaluates changes in frequency-domain characteristics and is often used for identifying winding deformation or core displacement problems [7]. Some researchers did not rely on a single electrical quantity only, but instead combined voltage, current, power factor, and several other parameters together so that the diagnosis result could remain more stable under complicated operating conditions [8]. Apart from electrical methods, there have also been attempts based on non-electrical information. For example, ultrasonic monitoring and vibration-signal analysis have both been introduced into transformer condition assessment, especially in partial-discharge monitoring and mechanical-state observation [9-11].

Even though these approaches have provided useful references, several limitations can still be observed when they are used under practical operating conditions rather than ideal laboratory environments. One relatively common problem is that weak faults do not always produce sufficiently obvious signal variation. When the parameter disturbance remains small, some diagnostic methods become less sensitive, and the possibility of false judgment still exists to a certain extent [6-8]. Another issue is related to environmental interference during actual transformer operation. In engineering applications, electrical signals are rarely completely stable because load fluctuation, electromagnetic interference, ambient noise, sensor error, and even measurement drift may all influence the collected data. Under these conditions, waveform disturbance caused by noise may become comparable to the variation introduced by weak faults themselves, making the diagnostic result less stable than expected [12]. Therefore, although some methods perform well in simulation studies, their effectiveness may decrease after being applied to actual operating systems. From this perspective, transformer fault-monitoring methods that can still preserve both sensitivity and disturbance tolerance under practical conditions remain worth studying further.

Based on the above considerations, this work investigates a transformer fault-monitoring approach using current-signal trajectories. The overall idea is not complicated. Current signals from

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the primary side and secondary side are collected directly, after which Lissajous trajectories are generated according to the relationship between the two signals. Instead of observing only amplitude or phase separately, the operating condition is represented through geometric variation of the trajectory pattern. Since the method mainly depends on existing electrical signals inside the transformer system, additional sensing structures are not heavily required, which makes the approach easier to apply in online monitoring scenarios.

In the simulation study, a transformer equivalent-circuit model was established first in the Multisim environment. Several transformer abnormal conditions, including winding deformation, insulation deterioration, and inter-turn short circuits, were reproduced by modifying impedance-related parameters in the circuit model. After the circuit parameters had been adjusted, the current signals at both sides of the transformer were collected under different operating conditions, and the corresponding Lissajous trajectories were generated. Several geometric quantities related to the ellipse were then analyzed further, including ellipse area, axis ratio, and rotation angle, so that the relationship between trajectory variation and fault severity could be examined more clearly.

From the obtained simulation results, the trajectory characteristics did not remain fixed after the transformer parameters changed. Even when the disturbance level was relatively weak, such as around ±3%, small but observable variations had already appeared in the ellipse-related parameters compared with the healthy operating state. After the disturbance increased further, the trajectory deformation became more obvious, especially under larger parameter variations. In addition, the trajectories under different operating conditions still maintained visible differences from each other, which means that the operating-state variation can be distinguished more directly from the geometric patterns. These results indicate that the proposed approach still maintains a certain degree of sensitivity for both weak faults and relatively serious transformer abnormalities, while also showing potential for online operating-condition monitoring and early fault identification.

2. Current signal trajectory method

Before carrying out the simulation study, an equivalent transformer model needed to be prepared so that the electrical behavior under both normal and abnormal operating conditions could be analyzed more conveniently. In this work, the transformer was represented by a π-type two-port equivalent circuit, as illustrated in Fig. 1. This kind of model is still frequently used in power-system analysis because the structure is relatively compact, yet the main electromagnetic characteristics of the transformer can still be retained to a reasonable extent. Instead of describing the internal winding structure directly, the model uses admittance parameters to express the electrical relationship between the two ports [13]. In practical fault analysis, this representation is easier to handle mathematically, since changes in insulation condition, winding coupling, or magnetic characteristics are usually reflected through parameter variation in the equivalent network.

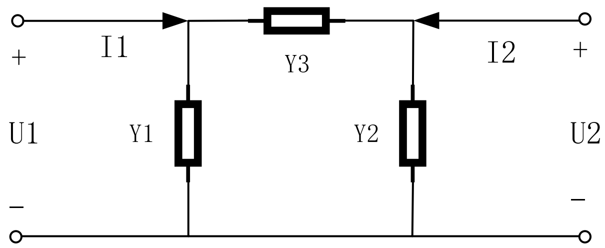

Figure 1. Equivalent circuit diagram of a transformer

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For the equivalent network shown in Fig. 1, the parameters Y1 and Y3 are connected with the shunt branches located at the primary side and secondary side of the transformer. In practical operation, these two quantities are influenced mainly by excitation-related characteristics, such as core loss, magnetizing reactance, and several distributed effects associated with capacitance and conduction to ground. Different from them, Y2 is linked with the coupling branch between the two windings, so its variation is more closely related to leakage impedance and electromagnetic coupling behavior. During normal transformer operation, the values of these admittance parameters usually remain relatively stable, and the transformer can therefore keep normal voltage-conversion and energy-transfer capability.

After internal abnormalities appear, however, the equivalent parameters gradually deviate from their original state. In actual transformers, faults including insulation deterioration, winding displacement, insulation breakdown, and turn-to-turn short circuits all influence the internal electromagnetic distribution to some degree. For instance, once a turn-to-turn short circuit occurs, the effective winding turns become smaller than before, which further changes leakage-flux distribution and also affects excitation inductance. Under this condition, the parameter Y2 often changes more obviously. By contrast, when insulation performance weakens gradually, the conductive path between winding and ground may increase, and the corresponding variation becomes more visible in Y1 or Y3. Because these equivalent quantities are closely related to transformer operating condition, observing their variation can provide indirect information about internal fault development and operating-state change.

Under the ideal sinusoidal steady-state assumption, the currents on both sides of the transformer can be regarded as sinusoidal quantities with the same angular frequency ω. Therefore, the instantaneous expressions of the primary-side current and secondary-side current can be written as follows

$$i1(t) = I1msin(wt + \psi 1) \tag{1}$$

$$i2(t) = I2msin(wt + \psi 2) \tag{2}$$

where I1m and I2m represent the current amplitudes of the primary and secondary sides, respectively; ω is the power-frequency angular frequency, while ψ1 and ψ2 denote the initial phase angles of the two currents. The amplitude ratio together with the phase difference between these current signals are jointly affected by the admittance parameters Y1, Y2, and Y3, and these quantities later become the key inputs for constructing the Lissajous ellipse trajectories.

The Lissajous trajectory method is based on the phase and amplitude relationship between two sinusoidal signals of identical frequency. When the two signals are plotted along perpendicular coordinate axes, a closed trajectory can be obtained. Under stable conditions, the trajectory usually appears as an ellipse, while its geometric shape changes according to the amplitude ratio and phase difference between the two signals. If the two signals are expressed as x(t)=Asin(ωt) and y(t)=Bsin(ωt+ψ), the corresponding trajectory satisfies

$$\frac{x^2}{A^2} + \frac{y^2}{B^2} - \frac{2xy}{AB} cos\phi = \sin^2\phi \tag{3}$$

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where A and B are the signal amplitudes and ψ denotes the phase difference. From this relationship, it can be found that several geometric quantities of the ellipse, including the area, eccentricity, and the ratio of major axis to minor axis, are directly determined by the amplitude ratio and phase shift of the signals.

Based on the above principle, the proposed approach does not judge transformer condition only from a single electrical quantity. Instead, the operating state is described through the geometric evolution of current trajectories. In practical processing, the primary-side and secondary-side current signals are sampled simultaneously, and the corresponding Lissajous curves are then generated point by point. Once the transformer condition changes, the trajectory shape also changes with it, so the operating-state variation can be reflected in a more direct manner through the ellipse geometry rather than through waveform observation alone. Compared with checking only current amplitude or phase separately, the trajectory pattern usually makes the variation trend easier to distinguish during analysis.

When the transformer is operating normally, the equivalent parameters Y1, Y2, and Y3 stay relatively stable, and the trajectory keeps a regular elliptical shape. After internal abnormalities appear, however, these parameters no longer remain unchanged. Faults such as insulation deterioration, winding displacement, insulation breakdown, or inter-turn short circuits all disturb the original electromagnetic distribution inside the transformer to different extents, which further changes the amplitude relationship and phase difference between i1(t) and i2(t). Because the trajectory is constructed directly from these two current quantities, even a relatively small parameter disturbance can still produce visible geometric variation in the ellipse.

For instance, when the leakage impedance related to Y2 becomes larger, the phase lag between the primary-side and secondary-side currents generally increases as well, and the trajectory gradually shows a more elongated shape. On the other hand, if insulation aging causes the equivalent insulation resistance to decrease, the current amplitude relationship between the two sides may fluctuate more noticeably, so the ellipse area and axis distribution will also change accordingly. Under some fault conditions, the ellipse rotation angle becomes more obvious at the same time, indicating that the coupling relationship between the two sides has already deviated from the healthy operating state.

In the present study, two geometric quantities were selected for condition evaluation, namely the ellipse area and the ratio between the major axis and minor axis. Compared with several other geometric descriptors, these two parameters remain comparatively stable during calculation, while their variation can still be observed clearly even when the electrical disturbance is relatively weak. By comparing the trajectory features obtained under different operating conditions, abnormal transformer states can be identified online, and the fault severity can also be estimated to some extent.

Another point worth noting is that the trajectory-based representation reduces the dependence on direct waveform observation. In conventional analysis, waveform fluctuation caused by noise or operating disturbance can easily interfere with the judgment result. After converting the electrical variation into geometric characteristics, however, the overall trajectory trend remains easier to separate visually, even when small disturbances exist in the signal itself. Because of this characteristic, the proposed current-signal trajectory method still maintains relatively good sensitivity and interference tolerance under different operating conditions, which makes it more suitable for transformer online monitoring and early-stage fault analysis.

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3. Results and discussion

3.1. Model development

Besides the commonly used π-type equivalent circuit, transformers can also be described through a T-type equivalent model. In order to check whether the proposed current-signal trajectory method could still maintain sufficient sensitivity under different operating conditions, a simulation model close to the behavior of an actual transformer was established in Multisim. Figure 2 shows the T-type equivalent circuit adopted in this work for a 220 V distribution transformer. Compared with some simplified models, the T-type structure retains winding resistance, leakage inductance on both sides, and the excitation branch at the same time, so the relationship between circuit parameter variation and internal fault behavior can be reflected more directly; the detailed parameters are listed in Table 1.

During the simulation process, the primary side was supplied with a rated sinusoidal voltage, while a resistive–inductive load was connected to the secondary side so that the operating condition would be closer to the actual working state of the transformer. On this basis, several fault conditions were introduced by adjusting the equivalent impedance ZK, where ZK=R1+R2+jL1+jL2. Together with several related electrical parameters. Small disturbances of ±3% and ±10% were used to represent early-stage abnormal conditions, such as slight insulation degradation or weak inter-turn insulation defects. Larger parameter changes, namely ±30% and ±50%, were introduced to imitate more serious faults, including insulation breakdown and inter-turn short circuits. Since different fault mechanisms may eventually influence the equivalent impedance in a similar way, the present work mainly focuses on fault detection and operating-state variation, rather than detailed fault classification.

In the simulation environment, a 220 V, 50 Hz sinusoidal source was applied at the transformer primary side, and the secondary side was connected with a standard resistive–inductive load. Under this condition, the transformer can be regarded as operating normally. After that, the equivalent impedance ZK and several associated parameters were gradually adjusted to reproduce different fault states. In practical transformers, faults such as winding deformation, insulation aging, or inter-turn short circuits usually affect leakage impedance and the excitation branch more obviously. For example, when an inter-turn short circuit occurs, the effective number of turns decreases, which further changes the leakage inductance and increases the circulating current; as a result, the equivalent series impedance becomes smaller. By comparison, insulation deterioration may increase local heating and contact resistance, causing the effective resistance component to rise.

Following the above analysis, the simulated operating conditions in this work were not treated as a single fault type. Instead, they were separated into two groups according to the disturbance level of the equivalent parameters. The first group represents relatively weak abnormal conditions. In these cases, the parameter variation was limited to ±3% and ±10% with respect to the healthy state. Such disturbances are closer to the early stage of transformer deterioration, for example slight insulation-oil aging, local insulation weakening between turns, or small mechanical displacement inside the winding structure. Under this kind of operating condition, the transformer can usually still maintain normal power transmission, while the current waveform distortion remains relatively limited. Because the electrical variation is small, conventional relay protection or direct waveform inspection often does not respond very clearly at this stage.

The second group corresponds to comparatively serious fault conditions. Here, the parameter disturbance was further enlarged to ±30% and ±50% so that more severe operating abnormalities could be reproduced in the simulation model. These cases mainly imitate conditions such as obvious

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insulation breakdown, multiple turn-to-turn short circuits, or stronger winding deformation after long-term operation. Although the transformer may continue running temporarily under such circumstances, the internal electromagnetic state has already deviated considerably from the normal condition, and the risk of further failure increases noticeably. At the same time, the current relationship between the primary side and secondary side also changes more significantly than under weak-fault conditions, making the corresponding trajectory deformation easier to observe.

To avoid the analysis being affected only by one-sided parameter variation, both increasing and decreasing trends of the equivalent impedance were considered during simulation. The parameter disturbance was therefore expanded over four different levels, namely ±3%, ±10%, ±30%, and ±50%. By adjusting the impedance in both directions rather than considering only an increasing trend, the resulting trajectory variation becomes more complete, and the influence of different operating states on ellipse characteristics can be compared more directly. At the same time, resistive-dominant and reactive-dominant parameter variations were also included in the simulations. For every operating condition, the steady-state current waveforms on both the primary and secondary sides were collected with a sufficiently high sampling frequency so that the phase information could still be preserved accurately. These datasets later provided the basis for constructing the Lissajous trajectories and extracting the related geometric features.

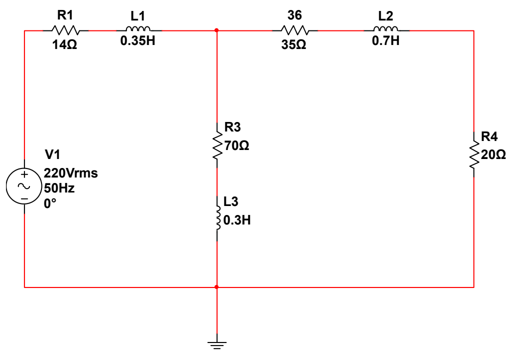

Figure 2. Circuit simulation diagram

Table 1. Circuit parameters

Parameter	Value
Primary voltage value	220 V
R_1、R_2	20 Ω
L_1、L_2	05 H
R_3	50 Ω
L_3	1 H
$R4$	20 Ω

3.2. Analysis of graphical results

Based on the method described in the previous section, Lissajous trajectories of the transformer current signals were obtained under several operating conditions, including the healthy state, slight fault conditions with impedance variations of ±3%, and more serious fault states. The corresponding results are presented in Fig. 3.

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According to the equivalent-circuit relationship of the transformer, once internal abnormalities appear, some electrical quantities inside the model will shift away from their original values. Parameters related to leakage impedance, shunt branches, and winding coupling are all affected to different degrees. After these quantities change, the amplitude correspondence and phase relationship between the primary-side current and secondary-side current also become different from those under normal operation. Because the Lissajous trajectory is generated directly from the two current signals, the ellipse shape cannot remain unchanged either. In other words, different fault conditions disturb the equivalent parameters in different ways, and this eventually appears as different trajectory distributions in the graphical results.

It can be observed from Fig. 3 that the trajectory under the healthy operating condition is close to a standard ellipse, and the overall curve remains comparatively smooth and symmetrical. After fault conditions are introduced into the simulation model, the ellipse gradually deviates from its original form. In some operating states, the trajectory becomes narrower and longer, while under other conditions the ellipse appears compressed or rotated. At the same time, the inclination angle also changes continuously with the increase in fault severity. Compared with the healthy-state trajectory, the deformation trend under abnormal conditions can still be distinguished relatively clearly. Another feature worth noting is that the trajectories corresponding to different operating states do not overlap obviously along the main axis directions, so the visual difference between fault levels remains observable during analysis.

For smaller parameter disturbances, especially under the ±3% variation condition, the ellipse deformation is still limited, although slight changes in stretching degree and rotation angle have already appeared. As the disturbance continues to increase, the geometric variation becomes easier to identify from the trajectory pattern. Under more serious fault conditions, the axis length and ellipse rotation differ much more obviously from those of the healthy transformer, indicating that the electrical relationship between the primary and secondary sides has already experienced a relatively significant change.

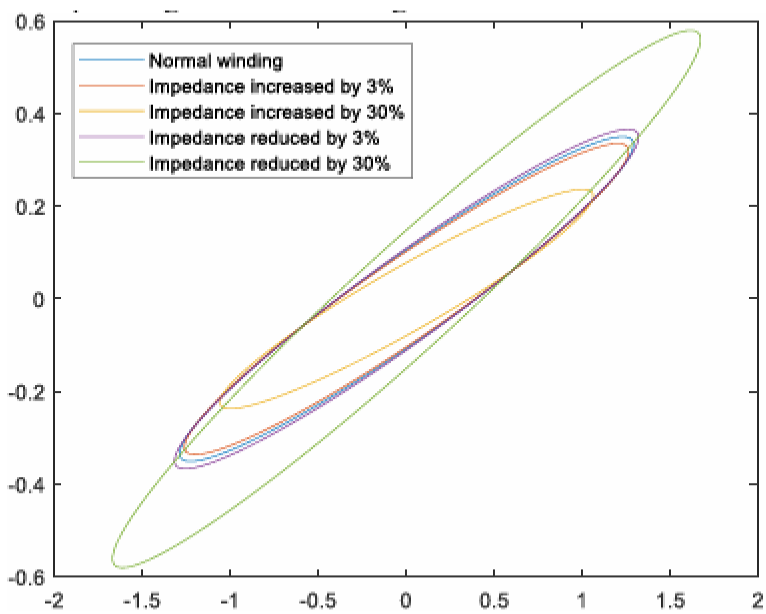

Figure 3. Lissajous figures for healthy and faulty windings

Taken together, the graphical results show that the Lissajous trajectory can reflect transformer operating conditions in a comparatively intuitive way. Different fault severities correspond to

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different ellipse characteristics, and the variation trend can still be recognized visually from the trajectory distribution. This suggests that the proposed current-signal trajectory approach has practical potential for transformer operating-state monitoring and fault assessment.

3.3. Analysis of feature parameters

To further analyze the trajectory variation quantitatively, several geometric parameters were extracted from the Lissajous ellipses, including the major axis, minor axis, and inclination angle. The calculated results are summarized in Table 2.

Table 2. Comparison of elliptical feature values of Lissajous figures under different deformation conditions

	Major Axis	Minor Axis	Inclination Angle	Fault Severity	Magnitude of change
Normal Transformer	3.769	0.2915	14.6152°	No Fault	0%
Increased by 3%	3.6828	0.2828	14.2987°	Minor Fault	2.1%
Increased by 30%	3.067	0.2183	11.9459°	Severe Fault	38.1%
Decreased by 3%	3.86	0.3005	14.9451°	Minor Fault	2.6%
Decreased by 30%	4.9875	0.3999	18.6741°	Severe Fault	32.0%

According to the data listed in Table 2, the geometric characteristics of the Lissajous ellipse show a relatively clear relationship with transformer fault severity.

When the disturbance level remained relatively small, the ellipse obtained from the current trajectory did not change very drastically compared with the healthy operating condition. The major axis, minor axis, and inclination angle only shifted within a comparatively narrow range, indicating that weak faults mainly cause limited disturbance to the transformer electrical state. Even under this condition, however, slight geometric variation could still be observed after the ellipse parameters were extracted. In other words, although the waveform difference was not particularly obvious in the early stage, the trajectory characteristics had already started to deviate from the normal state to some extent.

As the parameter disturbance became larger, the trajectory gradually moved away from the original healthy-state shape, and the deformation trend became much clearer in the graphical results. Especially under the larger disturbance conditions, the ellipse stretching and rotation could be identified more directly, while the variations in major axis, minor axis, and inclination angle all increased noticeably. In several cases, the corresponding feature variation exceeded 30%, suggesting that the trajectory characteristics remained sensitive to parameter changes related to the winding and insulation system inside the transformer.

Another phenomenon observed during simulation is that the feature variation did not appear completely random. Instead, the ellipse parameters followed a relatively consistent trend as the equivalent impedance changed. When the equivalent impedance increased, the ellipse usually became smaller overall, and the inclination angle also tended to decrease gradually. On the contrary, after the equivalent impedance was reduced, the trajectory expanded outward more obviously, while the inclination angle increased together with the axis variation. This tendency appeared repeatedly under different disturbance levels, which means the geometric characteristics still preserve a certain relationship with transformer operating condition.

Compared with evaluating only current amplitude or phase independently, the Lissajous trajectory provides a more visible way to describe operating-state variation. The extracted ellipse parameters can not only reflect whether the transformer has deviated from the healthy condition, but can also provide some reference for judging fault severity. From the present simulation results, the geometric quantities still maintained comparatively clear separation under different operating conditions, showing that the trajectory-based approach may still have practical applicability in transformer online monitoring and condition assessment.

4. Conclusions

This paper studied transformer fault monitoring by combining current-signal Lissajous trajectories with equivalent-circuit simulations developed in Multisim. Through the analysis of ellipse-related geometric quantities, including the ellipse area and the ratio between the major and minor axes, the operating condition of the transformer could be reflected under different fault levels. The main conclusions obtained from this work are summarized below.

A fault diagnosis method based on Lissajous trajectories was developed for transformer condition analysis. In this approach, the primary-side and secondary-side current signals were taken as the input quantities, and the corresponding Lissajous ellipses were constructed from the two current waveforms. Fault conditions, including insulation degradation and inter-turn short circuits, were reproduced in the equivalent-circuit model by changing impedance-related parameters. Simulation results showed that even under relatively small parameter disturbances, such as ±3%, the geometric features of the ellipse still changed in a detectable way. Variations could already be observed in the ellipse area and axis ratio, suggesting that the proposed method remains sensitive to early-stage abnormalities.

Different operating conditions produced different trajectory characteristics. Compared with the healthy state, the Lissajous figures under fault conditions showed visible deformation, while the degree of deformation became more obvious as the fault severity increased. The extracted feature parameters also changed with the operating condition, and a general correlation could be observed between parameter variation and fault severity. These results indicate that the trajectory characteristics can be used not only to distinguish abnormal states from normal operation, but also to provide a rough indication of fault level.

The present study mainly relied on mathematical feature extraction and simulation analysis. Although the obtained results verified the feasibility of the method, several aspects still need further improvement. One aspect is that intelligent recognition algorithms or pattern-classification methods may later be introduced to improve feature identification accuracy. Another aspect is related to practical operating conditions. In an actual power system, measurement noise and environmental disturbances cannot be avoided completely, so experimental verification with hardware platforms will still be necessary in future work.

Overall, the current-signal trajectory method converts variations in transformer electrical parameters into geometric changes that can be observed directly from the Lissajous ellipse. Compared with conventional parameter analysis alone, the trajectory features are easier to distinguish visually and show a certain level of resistance to interference. Therefore, the proposed method can provide useful support for transformer online monitoring and condition assessment in practical applications.

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