Cao Rui[1], Luo Yongfen[1], Li Yanming[1], Shen Yu[2], Ruan Ling[2], Luo Wei[2]

1 School of Electrical Engineering, Xi'an Jiaotong University
2 Testing & Research Institute of Hubei Electric Power Company

Study on The Key Technologies of On-line Monitoring of Transformer Winding Deformation Based on Short-circuit Reactance Analysis

Abstract *The research about on-line monitoring of transformer winding deformation based on Short-Circuit Reactance is studied, then a method is put forward to calculate the leakage reactance of power transformer quickly. The equivalent resistance can be got from the ratio of voltage difference and current at the peak of current. Also, the equivalent inductance can be got from the ratio of voltage difference and current differential when current is zero. At the same time, it is helpful for improving the resolution of the algorithm to the maximum precision of AD acquisition card by magnifying the voltage difference of primary and secondary voltage before being gathered to AD card. The system designed by the two technologies above is tested on the laboratory platform and a criterion is proposed to help to judge the state of winding. The article provides an effective method to monitor on-line monitor the winding deformation of transformer*

Streszczenie. *W artykule przedstawiono metodę monitorowania w trybie on-line deformacji uzwojeń transformatora. Do analizy wykorzystano pomiar reaktancji w stanie krótkotrwałego zwarcia. Określana jest też zastępcza rezystancja i indukcyjność uzwojenia. Badania eksperymentalne potwierdziły skuteczność metody. (**Technologie monitorowania deformacji uzwojeń transformatora bazujące na analizie reaktancji zwarciowej**)*

Keywords: winding deformation; on-line monitoring; short-circuit reactance analysis; leakage reactance.
Słowa kluczowe: uzwojenie transformatora, deformacja uzwojenia. .

Introduction

Electric power transformer can affects the security of power system a lot that it is one of the most important devices in power system. Over several decades, transformer accidents were mainly caused by winding deformation by the statistical data[1-5]. And short circuit fault is one of the main reasons which cause winding deformation. So, it is meaningful to increase the production level of transformer and ensure the safety of power system by making further research on testing and diagnosing transformer.

Nowadays, off-line and low-voltage testing techniques are widely used in diagnosing transformer winding deformation. However, both of them have the same shortage with other preventive tests, such as heavy work and power cut during experiment, and also, the real-time of the test and the effectiveness of the diagnosis are weak[6,7]. In a word, off-line methods can not reflect the health of winding timely while transformer is operating.

Based on the reasons above, a kind of on-line test method and system is needed in order to avoid transformer fault caused by winding deformation. The on-line monitoring system doesn't affect the normal operation of the transformer, and it can also help to make the testing system automatic and intelligent. Furthermore, it can help to do predictable maintenance to the weak transformer. Therefore, on-line diagnostic test of transformer winding will be the development direction of transformer monitoring system future.

According to the theory of Short-Circuit Reactance, the article does some research on on-line transformer monitoring of winding deformation. From the research, a method is founded to work out the leakage reactance of transformer quickly. Also, an on-line monitoring system is designed and tested on lab's platform. A criterion is tentatively proposed from the test data in order to use in future field application.

The basic theory of on-line SCR method

According to the theory of Short-Circuit Reactance [8,9,11], structure parameters of transformer will change when winding deformation happened which will lead to the change of short-circuit reactance of the transformer. In the research, we choose the loop equation of transformer as parameter identification model.

A. Equivalent leakage impedance of single-phase transformer

Fig.1 is the model of single-phase transformer with Y/Y connection. Three-phase transformer with Y/Y connection which neutral point is grounded can be seemed as three separate single-phase transformers with Y/Y connection.

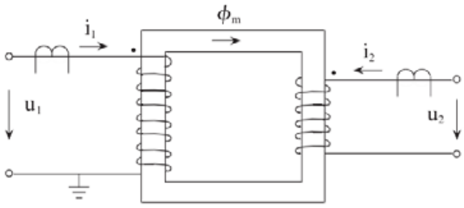


Fig.1 Single-phase model of Transformer

We can get the loop equation of transformer when the transformer is normal[10].

$$(u_1 - u_2') = r_k i_1 + L_k \frac{di_1}{dt} \quad (1)$$

In formula (1), r_k and L_k are the equivalent resistance and inductance which are transformed to the primary of transformer

B. Equivalent leakage impedance of transformer with Y/Δ connection

Fig. 2 is the model of three-phase transformer with Y/Δ connection, where u_{ab}, u_{bc} and u_{ca} represent the delta-side phase voltage of transformer, i_{La}, i_{Lb} and i_{Lc} represent the delta-side line current of transformer, i_a, i_b and i_c represent the delta-side phase current of transformer[11].

The way to calculate the equivalent impedance of transformer with Y/Δ connection is similar to the way of transformer with Y/Y connection. However, as the phase current of delta side can not be measured directly, we can treat the loop equation by the relationship between line current and phase current of delta side. After processing, the loop equation is:

$$
\left.\begin{aligned}
u_A - u_C - N(u_{ab} - u_{ca}) &= -r_K i_{La} - L_K \frac{di_{La}}{dt} \\
u_B - u_A - N(u_{bc} - u_{ab}) &= -r_K i_{Lb} - L_K \frac{di_{Lb}}{dt} \\
u_C - u_B - N(u_{ca} - u_{bc}) &= -r_K i_{Lc} - L_K \frac{di_{Lc}}{dt}
\end{aligned}\right\} \quad (2)
$$

In formula (2), $N=N_1/N_2$, $r_K=r_1+Nr_2$, $L_K=L_1+NL_2$. We can get the equivalent r_K and L_K by the way similar as the algorithm of transformer with Y/Y connection.

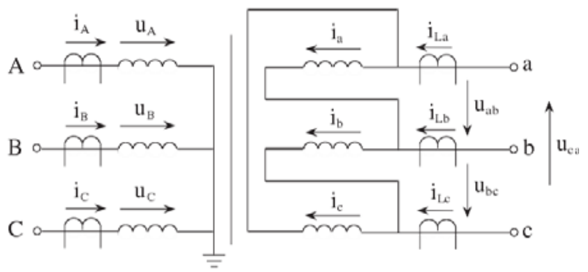
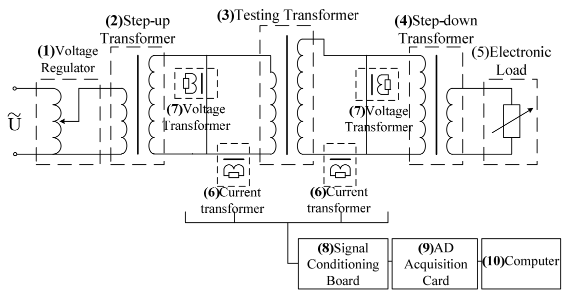


Fig. 2 Three-phase model of transformer with Y0/Δ connection

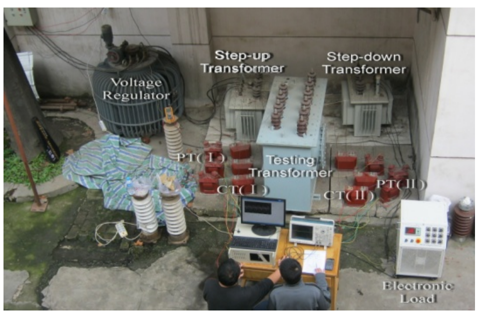
Constructions of on-line test platform of transformer winding deformation

Fig. 3(a) is the electrical connect graph of test platform (Fig. 3(a) is only the single phase of transformer). Fig. 3(b) is the real figure of test platform.

The design of the test platform is based on electronic load which has three types of load: resistance, capacitance and inductance, and the max power of electronic load is 33.3kVA/380V. The transformer for testing is oil-immersed which has the similar ways of enwinding as larger transformer. The connection of the transformer can be changed from Y to Δ by moving the lines which connect windings inside the transformer. And the cushion blocks of different thickness can be inserted to the windings which simulate the situation of winding longitudinal deformation. What's more, there are many taps of winding which are set aside to simulate the situation of winding short-circuit fault.



(a) Electrical connect graph of test platform(single phase)



(b) Research platform of transformer winding deformation

Fig.3 Setup of laboratory research platform of transformer winding deformation

Key technologies of on-line transformer winding deformation monitoring based on Short-Circuit Reactance analysis

A. Overall structure of test platform

The whole monitoring system is installed in a industrial PC which based on PCI bus. The whole system includes a signal conditioning board of voltage, another one of circuit, an AD acquisition card and so on. Fig. 4 is overall structure of monitoring system.

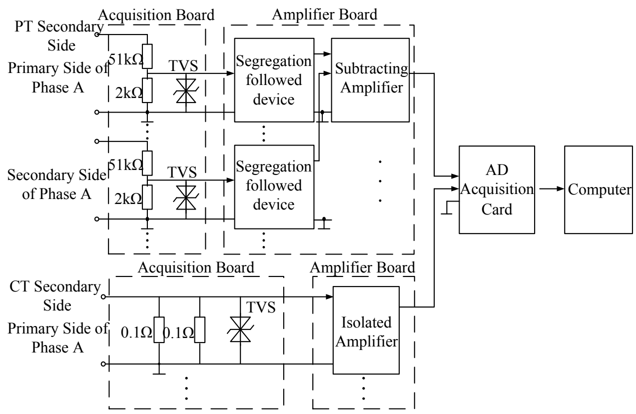


Fig.4 Structure of monitoring system

B. Advantages of the signal preprocessing hardware

Some short-circuit reactance on-line monitoring systems directly enter the voltage signal of both sides of transformer which transformed by PT into AD acquisition card for sampling, and then deduct them in the software (by formula (1) or (2)). This will cause great error and data drift, as shown in Fig. 5.

The secondary voltage of operating PT is generally 100V or 100/√3V. The primary output values and secondary voltage of transformer after transforming by PT are very approximate, and there is very little difference between them. The precision of AD acquisition card is limited and distinguishable bits will be very little after both sides of voltage deducting in the software, and that will cause great error. Resolution can be improved to the maximum precision of AD acquisition card through the ways that deducting primary and secondary voltage transformed by PT in the hardware firstly, and then magnifying them to the input extremum of AD acquisition card before the data acquired by AD card.

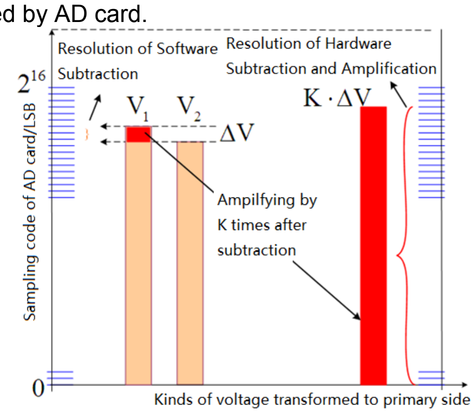


Fig.5 Advantage of subtracting the primary and secondary voltage by hardware

C. A kind of method fast calculating transformer winding leakage reactance

From formula (1) and formula (2), it can be known that there are two different connection types for transformers, and computational formulas of their leakage reactance are consistent in form: the left part of algorithm (before the equal) is value of voltage difference, while the right part (after the equal) is the addition between the product of equivalent resistance and current and the product of equivalent inductance and current derivative.

A kind of simple and practical method which calculates leakage reactance rapidly can be obtained by the two formulas above:

At the peak of current, the derivative of current is 0, and the ratio of voltage difference and current is used to calculate leakage resistance directly by ignoring the influence of leakage inductance on the right of equation. In the same way, at the current zero crossing point, the ratio of voltage difference and current derivative is used to calculate leakage inductance directly by ignoring the influence of first leakage resistance on the right of the equation.

Take the transformer of double winding with Y/Y connection for example, and Fig. 6 is the oscillograph which obtained in the actual measurement. In this figure, three curves with more higher harmonic are three-phase voltage difference of primary and secondary side which obtained from PT and deducted by hardware, while the smooth ones are current signals of each phase.

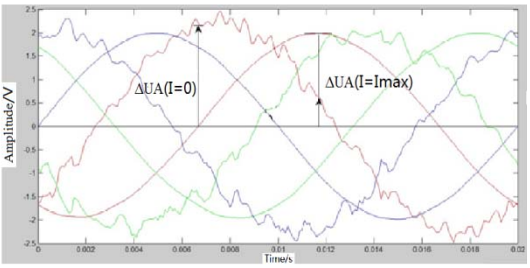


Fig.6 Oscillogram of voltage difference and current

Take the method that calculates the equivalent reactance of phase A for example: the voltage difference signal of phase A is ΔUA(I=0), at which point the current is 0. Only derivative of equivalent inductance and current derivative is left on the right of loop equation at this time, and equivalent inductance can be calculated. Similarly, only product of equivalent resistance and current is left on the right of loop equation when current curve of phase A is passing through peak value. At this time, voltage difference signal ΔUA(I=Imax) and current peak value can be obtained conveniently, thus equivalent resistance is calculated.

The method which uses current zero crossing point and the current derivative which is zero at current peak value can avoid huge arithmetic operations, and also it can minimize the influence of harmonic wave.

Laboratory studies of on-line monitoring system

A. Study on winding deformation of transformer with Y/Δ connection

Based on test platform in the lab and on-line monitoring system, the article did some researches on test transformer with Y/Δ connection. There are two kinds of load in the experiment: resistive load with R=4.84Ω, resistive and inductive load with R=4.84Ω and L=0.051H, both of which connect in parallel. There are also three conditions on winding during the experiment: normal, mild deformation with adjacent two pancake windings connecting capacitance in parallel which C=2.5nF, and serious deformation with capacitance in parallel which C=1.5μF. What's more, all the conditions were happened in Phase C, as shown in Fig. 7.

Tab. 1 is the equivalent resistance of each phase in the condition that the line voltage is 8.75kV and the load is resistive and inductive. Tab.2 is the equivalent inductance of each phase.

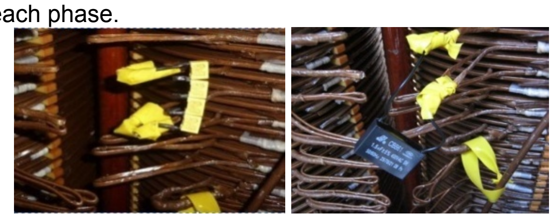


Fig.7 Simulation of winding defect (capacitance parallel to winding pies, Left : 2.5 nF, Right: 1.5 μF)

Table 1 Comparison of equivalent resistance (8.75kV)

Winding state and change		Phase A	Phase B	Phase C
Normal	Resistance/Ω	22.99699	23.16546	22.36737
	Relative Change (%)	0	0	0
2.5 nF	Resistance/Ω	21.99778	23.0301	21.56685
	Relative Change (%)	-4.34496	-0.58434	-3.57896
1.5 uF	Resistance/Ω	22.2168	22.99652	22.78986
	Relative Change(%)	-3.39258	-0.72927	1.88886

Table 2 Comparison of equivalent inductance(8.75kV)

Winding state and change		Phase A	Phase B	Phase C
Normal	Inductance/ H	0.457862	0.411685	0.459584
	Relative Change (%)	0	0	0
2.5 nF	Inductance/ H	0.45897	0.411062	0.458354
	Relative Change (%)	0.242134	-0.15126	-0.26762
1.5 uF	Inductance/ H	0.459948	0.409714	0.458184
	Relative Change (%)	0.455579	-0.4787	-0.30455

From the data shown in Tab. 1 and 2, we can know that the change of equivalent resistance is irregular. Comparing with equivalent resistance, the equivalent inductance of transformer changes more regular and the monitoring system can make the judgment of winding deformation with Y/Δ connection. From the experiment, we suggest that the criterion of winding deformation with Y/Δ connection could be shown below:

Firstly, monitor equivalent inductance of transformer repeatedly for more than 20 times, secondly, work out the short-term average value of equivalent inductance, and then compare the value with the long-term average value. When the short-term value of any phase changes more than 0.4% based on the long-term value, the testing transformer should be noticed. When the change becomes between 2% and 4%, there will be serious winding deformation according to the standard of IEC and GB.

B. Field Application of On-line Monitoring System

After research in lab, the monitoring system was tested in field in Shishan transformer substation, Hubei. The testing transformer with Y/Δ connection is shown in Fig. 8(a), as the monitoring system operating in field is shown in Fig. 8(b).

(a) Testing transformer in Shishan transformer substation


(b) On-line monitoring system operating in field

Fig.8 Transformer and on-line monitoring system operating in Shi Shan Substation

Due to test conditions, the field test was totally got for 20 groups. The average equivalent inductances L_K of three phases are 0.10039H, 0.10570H and 0.10328H, and these are called long-term average value. To calculate the average value of three phases with the first ten and last ten data, we can get the short-term average value of equivalent inductances L_K, and they are 0.10034H, 0.10562H, 0.10315H and 0.10044H, 0.10578H, 0.10341H. The relative changes of short-term value towards long-term value are 0.05%, 0.08%, 0.13%.

From the test result in field and the criterion put forward above, we can see that the transformer is in good condition.

Conclusions

According to the theory of Short-Circuit Reactance, the thesis does some research on on-line transformer monitoring of winding deformation based on parameter identification of equivalent inductances, and also, a research platform of winding deformation is built in the lab.

According to the loop equation of transformer, a method is founded to work out the equivalent reactance of transformer quickly. The equivalent resistance can be got from the ratio of voltage difference and current at the peak of current, while the equivalent inductance can be got from the ratio of voltage difference and current derivative when current is zero. The thesis also finds that it is helpful for improving the resolution of the algorithm to the maximum precision of AD acquisition card by magnifying the voltage difference of primary and secondary voltage before being gathered to AD card.

Finally, the thesis does some studies on transformer with Y/Δ connection in both laboratory and field based on on-line monitoring system. A criterion of transformer with Y/Δ connection is put forward according to the test. The system greatly reduces the complexity of calculating the equivalent inductance of winding, and helps to improve the accuracy of the results. The system provides an effective solution for on-line monitoring of winding deformation.

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Authors: *Master student Cao Rui High Voltage Division, School of Electrical Engineering, Xi'an Jiaotong University, China, 710049, E-mail:cradam@stu.xjtu.edu.cn; Doctor Luo Yongfen, High Voltage Division, School of Electrical Engineering, Xi'an Jiaotong University, China, 710049, E-mail:yfluo@mail.xjtu.edu.cn* **(contact author)***; Prof. Li Yanming, High Voltage Division, School of Electrical Engineering, Xi'an Jiaotong University, China, 710049, E-mail: ymli@mail.xjtu.edu.cn*