Study on the relationship between off-line PD and on-line PD of power transformers

Yu Shen
High Voltage Department
Hubei Electric Power Test & Research Institute
Wuhan, China
E-mail:totoshenyu@163.com

Ling Ruan
High Voltage Department
Hubei Electric Power Test & Research Institute
Wuhan, China
E-mail:ruanl2008@yeah.net

Abstract—**The contrastive analytical research is proceeded to off-line partial discharge and on-line partial discharge of power transformer in aspects of internal electric-field distribution, partial discharge signal extraction method, pattern-recognition method and anti-interference measure. 2D finite element model is adopted to emulator calculating for the internal electric-field of power transformer test condition and operating condition. Time harmonic electric-field solution method is adopted to simulate the frequency differences in test procedure and operational state. The relationship between off-line partial discharge and on-line partial discharge of power transformer is analytically inducted systematically and completely.**

Keywords-transformer; partial discharge; off-line detection; on-line detection; finite element

I. INTRODUCTION

Partial discharge detection and evaluation of power equipment are the important means of insulation condition monitoring. Presently, the detection methods of partial discharge mainly contain impulse current detection, supersonic detection, optical detection, gas chromatography detection, infrared detection, etc [1]. Impulse current detection and gas chromatography detection are applied extensively.

The partial discharge detection method specified by IEC60270 is impulse current detection [2] , which detects impulse current by connecting Rogowski Coil to the ground wire of transformer neutral, shell or bushing tap, or by using detection impedance connected to the transformer's bushing tap [3]. According to different detection situations, impulse current detection method is divided into two manners: off-line detection and on-line detection. This text systematically and comprehensively analyzing concludes the relationship between transformer partial discharge off-line detection and on-line detection from the aspects in electric field distribution, signal obtaining method and anti-interference method.

II. THE METHOD AND CHARACTERISTIC OF OFF-LINE DETECTION

Presently in China, the most widespread used partial discharge detection means for electric power transformer is regular off-line detection, the theory basis of which is: facilities can periodically return to the condition which is close to new facilities. Regardless of facilities' condition, the contents and cycle of repairing work on schedule are set by arrangement in advance for preventing or delaying fault occurrence to achieving the maximum facilities' operation reliability. Because of off-line detection proceeded in no power condition different from transformers' real operation condition, the partial discharge detection results don't have complete on-site equivalence, which is resulted in transformer off-line detection condition incompletely accordance with operation condition.

A. Off-line Detection Test Method

Off-line partial discharge test is carried out phase by phase. Take a three-phase double-winding power transformer for example, the connection group label of which is Yn0，d11. When A-phase is practiced partial discharge measurement test, voltage is applied to a-phase, c-phase grounding. The test circuit is showed as figure 1. Accordingly, when B-phase is on test, voltage is applied to b-phase, a-phase grounding. When C-phase is on test, voltage is applied to c-phase, b-phase grounding.

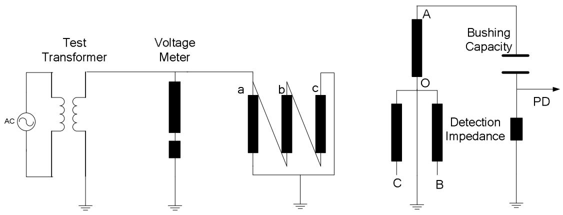


Figure1. Off-line PD test circuit

In off-line test, the highest test voltage of each phase can reach to 1.7 times of rated voltage. For preventing magnetic saturation, the test frequency is at least higher 1.7 times of rated frequency. Because three-phase coils are tested separately, the electric field distribution in off-line test transformer obviously varies from it in operation transformer.

B. The Signal Processing and Identification Method of Off-line Detection

Partial discharge detection on off-line condition has large advantage in the aspect of signal processing. Partial discharge signal is very weak and has plentiful frequency composition.

The affection of on-site distracting signal is large. Off-line PD test can greatly reduce outer noise interference, and reach to high detection sensitivity.

Off-line PD detection is more suitable for partial discharge mode identification. Because of greatly reducing the on-site detection interference source, the basic parameters of partial discharge signal, such as discharge waves, apparent discharge electric charges, discharge repetition, discharge energy, can achieve more accurate number, which can ascertain partial discharge type according to the obtained discharge model knowledge base in advance. It is important significance to exactly obtaining partial discharge type for realizing partial discharge location and judging insulation defects position.

Off-line condition detection has obvious advantages for PD location. Lots of interference sources are filtered out by artificial black-out maintenance, which make the PD signal spreading law inside transformer more accurate. In practical PD location, the faults location can be determined according to the relationship between start-end point voltage (or current) ratio and discharge point location during partial discharge inside transformer windings. Presently, partial discharge location can be preceded according to partial discharge energy ratio curves.

In general, the great advantage of partial discharge off-line detection is eliminating lots of on-site interfering sources in normal operation through black-out maintenance. However, the great disadvantage is that black-out maintenance can't exactly reflect transformer's normal operation conditions, and regular black-out maintenance neglect distinct operation conditions of different transformers.

III. THE MEANS AND CHARACTERISTICS OF PD ON-LINE DETECTION

Electric power facilities are engaged in normal preventive test in order on time, however, accidents still occur from time to time. One of the main reasons is that available test items and methods are often difficult to ensure no failures in one cycle. Because of the omen for most failures, developing a continuous or regular detection technology is requested, on-line detection produced in this situation. Electric power facilities' on-line detection technology can greatly improve the factuality and reliability of test, promptly discover insulation faults. Using on-line detection technology can select different detection cycles according to facilities insulation condition, which can greatly improve the test effective degree. On-line detection can accumulate lots of data, combine the tested facilities present test data (contain black-out and electrified detection) and past detection data, and use various numerical analysis methods to completely synthetically analyze and judge in time, which can discover and capture early faults, ensure save operation, and decrease inaccuracy induced by preventive test long interval [4].

A. *Transformers' PD On-line Detection Method*

When impulse current is produced in transformer partial discharge, impulse current will pass through transformer casing terminal, casing end grounding wire, shell grounding wire, core grounding wire, core clip grounding wire. Impulse current signal can be detected on these measurement points by high frequency current sensor (Rogowski Coil) electric coupling manner. In on-line detection, the installing location of high frequency current sensor on transformer is showed as figure 2. The form, pass band and installing location (measurement points) of sensor directly influence measurement sensitivity and signal noise ratio. Among those, the manner of installing sensor on high voltage casing end grounding wire is most common, the advantage of which is: high sensitivity, measuring split phase signal, so it is used generally.

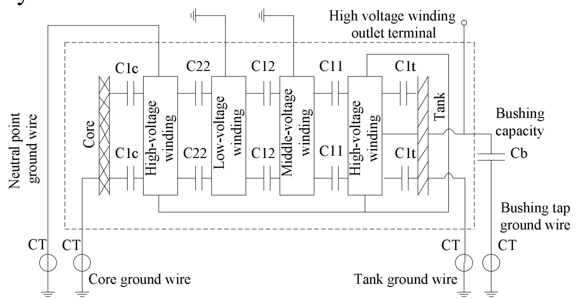


Figure2. Connecting diagram of on-line PD detection

From the on-line detection CT installing connection diagram, in on-line detection CT can timely obtain impulse current capacity reflecting operation condition, combine physics capacity gathered by other on-line detection devices physics capacity to analytically process, forecast transformer operation condition for providing alarm and faults diagnosis information essentially to avoid accidents happening resulted in faults further expand, guide transformer optimum maintenance time for providing condition-based maintenance real time data and timely prevent or discover unexpected faults. On-line detection test on operation condition, during which transformer may be with different loads and in various operation conditions, so detection data is more authentic, directly reflect facilities insulation real condition.

B. *The Signal Processing and Faults Identification Method of On-line Detection*

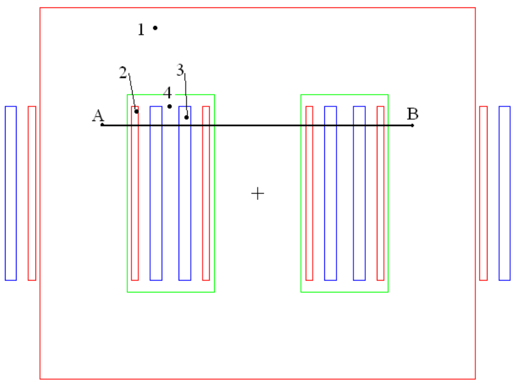
PD on-line detection also exist notable technical problems. Presently, one of the biggest problems is how to effectively restrain on-site noise interference.

Operating in substation and power-station circumstance, large-scale electric power transformer interfered with electromagnetic can de divided into three types of continuous periodic interference, impulse interference and white noise. In power system, continuous interference produced by higher-order harmonics, high-frequency protection, carrier communication and radio communication belongs to periodic interference. Impulse interference contains random impulse interference and periodic impulse interference. Random impulse interference produced by electric arc of high-voltage line corona, tap changer action, electric welder and electric motor brush; silicon controlled action (direct current power rectification and condenser excitation rectification) and impulse interference in ground net belong to periodic impulse interference. Winding thermal noise, ground net noise, various random noises coupling in distribution lines and transformer, relay protection signal lines belong to white noise. The characteristics of these electromagnetic interference signals and partial discharge signals are similar, sometimes even stronger than partial discharge signals, the accuracy of which is influenced. So it is necessary to adopt effective measures restraining interference for accurate partial discharge signals from background interference, which is the key to transformer partial discharge on-line detection technology [5].

Obviously, because of lots of noises interference affection, partial discharge pattern recognition and partial discharge location are more complicated than off-line PD detection. Additionally, because lots of on-line detection data are the basis of analyzing facilities operation condition, it is a problem need urgent solution to how to store lots of detection data.

IV. Comparison of Off-line and On-line Detection Manners

From the comparison of on-line detection and off-line detection test manners, we can see that three-phase coils are tested separately, the each phase's highest test voltage can reach to 1.7 times of rated voltage, and frequency is at least higher 1.7 times of rated frequency in off-line detection. In on-line detection, the voltage is applied to three-phase coils at the same time, voltage is the rated voltage, and frequency is the rated frequency. For comparing the difference of inner electric field distribution in this two conditions, and also comparing the difference of inner electric potential distribution in this two conditions, use finite element numerical calculation method to built model for typical 110kV power transformer, simulation calculation model is showed as follows:

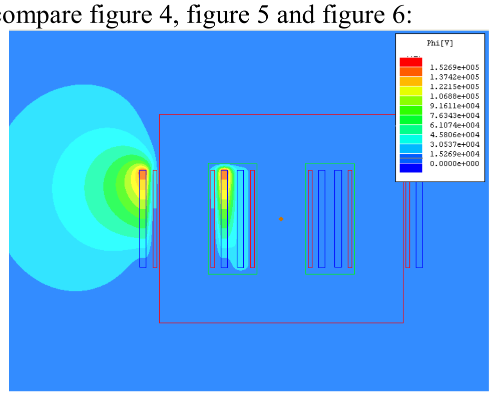


1 core 2 low-voltage winding 3 high-voltage winding 4 electric insulation oil

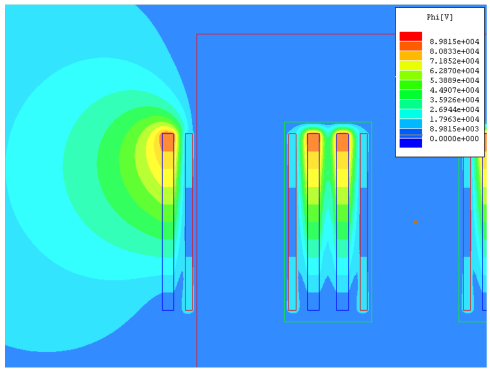
Figure3. Simulation calculation model of inner electric field distribution

110kV transformer adopts three-phase three-column core, core size is 3000×2560mm2 , core column diameter is 600mm, high-voltage winding voltage is 110kV, low- voltage winding voltage is 10.5kV. Using 2D plane symmetry method to built models for transformer's three-phase high, low-voltage windings. Low-voltage and high-voltage windings are equivalent to rectangular conductor in models. This text mainly investigates the electric field difference, for simplifying the analysis model, neglect the affection of insulating paper cylinder between windings and ceratocricoid, end ring below windings.

Use ANSOFT Maxwell2D electromagnetic simulation software to separately calculate 110kV transformer inner electric potential and field distribution in test condition and on-line normal operation condition. When simulate test conditions, the test voltage is applied only to low-voltage coil and high-voltage coil of A-phase (the left core column). When simulate normal operation condition, the normal operation voltage is applied stimulation to three-phase's each high, low-voltage winding. Low-voltage winding is triangle connection, high-voltage winding is star connection, and high-voltage winding end potential is 0V. Simulation calculation adopt alternative electric field solver, calculation results compare figure 4, figure 5 and figure 6:

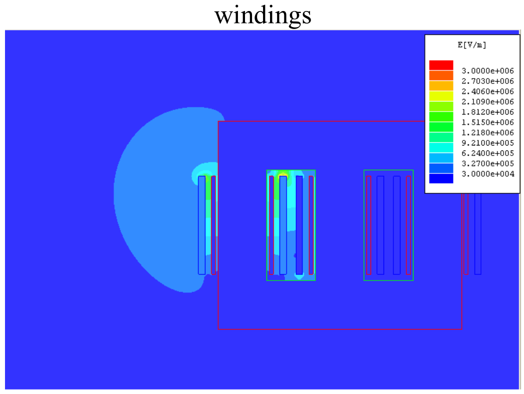


（a） test situation

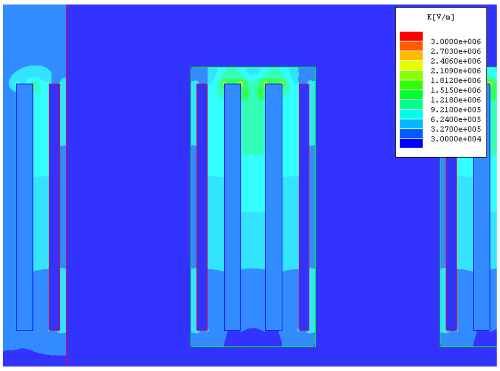


（b） operation situation

Figure4. Calculation results of potential distribution between windings



（a） test situation



(b) operation situation

Figure5. Calculation results of electric-field distribution between windings

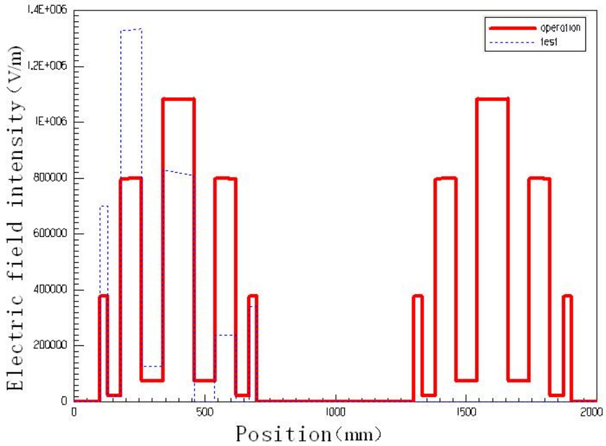


Figure6. Comparing of calculation results of electric-field distribution between test and operation situation (route A-B)

Figure 4 shows the electric potential calculation results in simulation test and simulation operating condition. From figure 4, we can see that in two conditions, the electric potential distribution tendency of coil outside core column and neighboring medium are approximately similar, but amplitudes are slightly different, which is due to the differences between the applied voltage amplitude and frequency. The coil electric potential distribution Inside core column is greatly different: in normal operation condition, any two-phase high-voltage coil electric potentials are all high, so the differences of electric potential distribution among coils between normal operation condition and test condition are large, the differences obviously influence electric field numeric values and distribution conditions among coils, which is showed as figure 5. From figure 5, we can see that in test condition, the maximum value of electric field intensity appears in the areas between test (a) phase high-voltage winding and low-voltage winding. However, in operation condition, the maximum value of electric field intensity appears in the areas among two-phase high-voltage windings. In two conditions, distribution tendencies of electric field intensity are greatly different. Figure 6 draws the comparing results of electric field intensity curves following the route AB in figure 3. In figure 6, we can obviously obtain that electric field intensity among high, low-voltage windings is maximum in test condition (dotted line), which is 60% higher than the same location electric field value in operation condition, and is also higher than electric field intensity value among two coils in operation condition. Therefore, partial discharge is much easier to occur inside transformer in test condition.

According to initial simulation analysis results, we can obtain that compared with normal operation, in off-line test, electric field intensity distribution inside insulation medium between transformer high, low-voltage windings and each phase winding greatly changes, and the maximum value of electric field intensity is also greatly high, which is much easier to appear partial discharge in weakness, the intensity and occurring area of partial discharge are different. Therefore, PD discharge information in off-line detection is different from discharge condition in normal operation, may be more serious than normal operation, which results in partial judgment.

From signal processing aspect, partial discharge signal is very weak, and frequency composition is abundant, which can be greatly influenced by on-site lots of interference signals. In off-line condition, partial discharge signal of PD detection can be obtained directly, and transformer step out from operating system, which greatly reduce outer noise interference and achieve high detection sensitivity. However, in on-line detection condition, detection signal can be achieved only indirectly from transformer casing terminal, casing end grounding wire, shell grounding wire, core grounding wire, core clip grounding wire, and PD discharge signal is influenced by on-site various interferences, which can be divided into continuous periodic interference, impulse interference and white noise. Useful signal is always submerged into noises, so complicated signal separation technology is needed, which results in low detection sensitivity.

Finally, because of the influence by lots of noise interferences in detection signal, the mode identification and partial discharge location of partial discharge signal obtained by on-line detection are more complicated than PD detection in off-line condition, which results in low identification accuracy, so on-line detection criterion often can’t be completely depended on.

V. CONCLUSION

In short, on-line detection and off-line detection are not opposing, but complement each other. The accident omen discovered by on-line detection often needs to be verified by off-line test, and off-line test condition is generally more severe. If accident hidden danger is discovered in on-line detection, it is necessary to completely check more thoroughly in off-line condition. However, it is not enough only to rely on off-line detection technology. Because of the greatly difference between test condition and normal operation condition, some recessive faults can’t appear, which results in difficult detection. After using on-line detection and fault diagnosis technology, preventive maintenance can be transited to predictable maintenance which is condition-based maintenance, from “periodical maintenance” to “maintenance in need”. Off-line and on-line detection should be combined in overhaul, which is showed in following points:

(1) Transformer needing on-line detection or not is should be divided in rank. The divided rank should be considered by following factors: the significance of transformer in electric network; black-out physical damage of power supply users and social consequences; transformer aging degree and probability of occurring ganger, which is dangerous level. The divided transformer rank also reflects in the tenth draft of transformer on-line detection directives addressed in 2001-10 IEEE: for aging transformer, especially with important position in system, it is suitable and valuable to continuously monitor the key parameter. On the contrary, the transformer with secondary position in system and good operation condition adopted by on-line detection will result in unnecessary physical damage. At this time, we can consider off-line detection.

(2) After deciding on-line detection for transformer, components and parameters of on-line detection should be analyzed. Because of the variety of faults, detection parameters and defects or faults can’t be correspondent with each other. So it is necessary to emphatically find effective detection parameters and detection methods for the most common faults, to synthesize data obtained by various effective detection methods, and to get the judgment through comparison.

(3) Off-line detection and on-line detection should be combined together closely, not be easily opposing. Two detection methods both have respective advantages and obvious defects, so on the basis of ensuring periodical off-line detection, on-line detection can be carried out for the high requests transformer, which can ensure the safe and reliable operation of transformer with seamless integration of two detection methods.

It is evident that off-line and on-line detection have obvious value for transformer stable and reliable operation. So it is necessary to combine the advantages of two detections to form a more reasonable condition-based maintenance mechanism.

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