Comparative analysis of online monitoring methods for transformer insulation performance of 330—750 kV substation

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Abstract: The online-monitoring methods for insulation performance of current transformers of 330—750 kV substation are analyzed and compared. The effectiveness and availability of each method are discussed. Main features, advantages and disadvantages of each method and its corresponding standard are also described.

Key words: continuous control; insulation performance; online monitoring; substation

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The 330—750 kV transformer is one of the most accident prone parts of grids. In most cases, the accident current transformers (CT) are accompanied by the complete destruction of the machine and sometimes nearby equipment. Failure data analysis suggests that the most typical defects for CT 330—750 kV are local defects, the development of which may lead to thermal breakdown, partial discharge and electrical breakdown of basic insulation[1-3]. Such defects in the early stage of development can be detected by measuring the dielectric loss tangent at the operating voltage and thermal imaging measurement. The causes of defects include short-circuit current, high-frequency surge, moisture, conductive deposits on the inner surface of the bus bar for porcelain bushings, etc. The partial discharge change the dielectric loss tangent of basic insulation. The defects in insulation can develop and become progressively worse within two weeks, therefore periodic monitoring is not always possible to find them and it calls for the use of devices for continuous monitoring of the insulation characteristics of current and high-voltage inputs. Nowadays there are several manufacturers for such devices based on these control methods, however, various methods have inadequate and not equally effective[4-9]. Currently, most energy companies have implemented a variety of isolation transformers and high-voltage inputs based on continuous control systems. However, different manufacturers use different control methods, which, as above noted, are not equal and equally effective.

In this paper, to assess the possibility and effectiveness for continuous monitoring of insulations, the existing several control methods are analyzed and compared.

1 Balance method

One of the most common methods of control is an unbalanced-compensation method or balance method. It is based on the assumption that all three isolation characteristics of the controlled objects and three-phase group can not change simultaneously and equally. In the event of any defect in the insulation of one or two objects of the three-phase group, there will always be a current imbalance. The current imbalance quantified characterizes the degree of defect in the insulation, and the angle of the unbalance cur-

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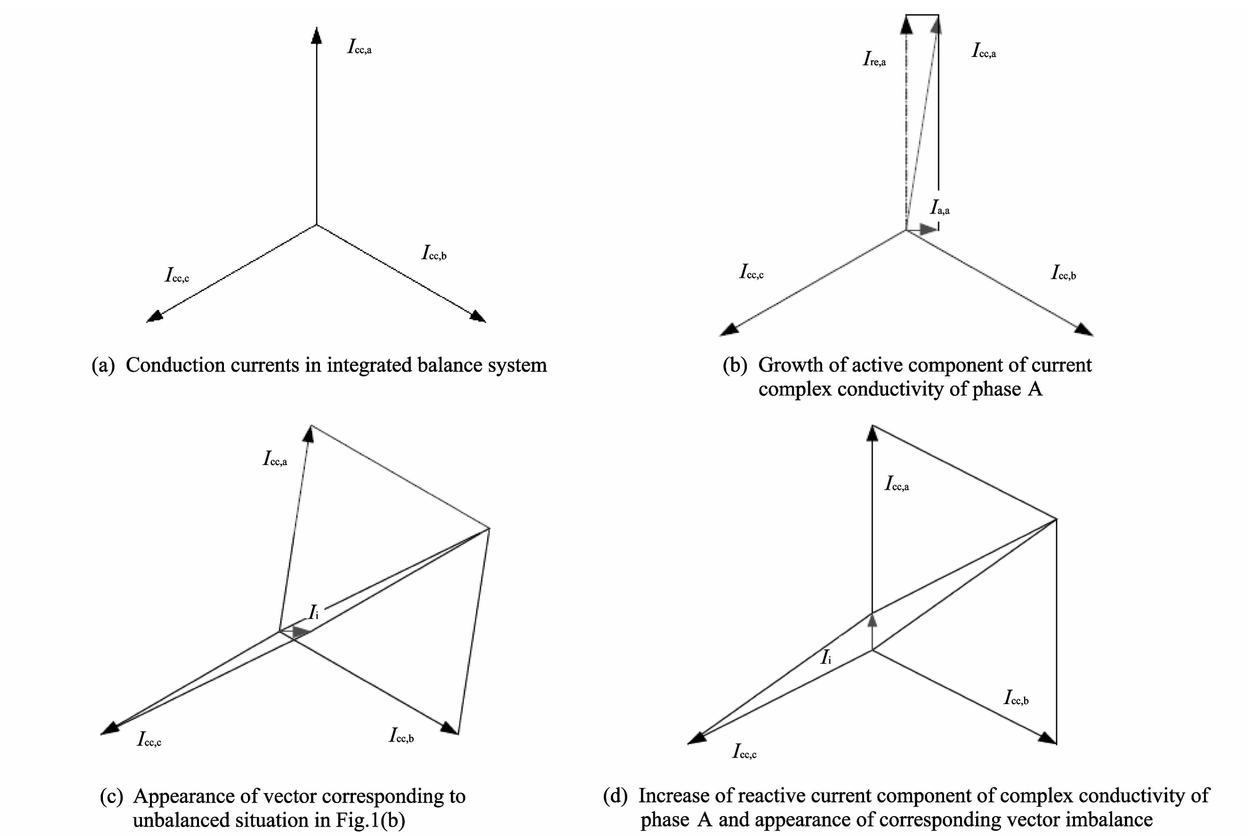
rent indicates the phase in which the change occur. Fig. 1 shows vector diagrams illustrating the principle of the method. Practical implementation of this method is quite diverse.



(a) Conduction currents in integrated balance system

(b) Growth of active component of current complex conductivity of phase A

(c) Appearance of vector corresponding to unbalanced situation in Fig.1(b)

(d) Increase of reactive current component of complex conductivity of phase A and appearance of corresponding vector imbalance

Fig. 1 Vector diagram explaining principle of balance control method

In Fig. 1, $I_{cc,a}$, $I_{cc,b}$, $I_{cc,c}$ refer to current complex conductivities of insulation objects corresponding to phases; I_i refers to current imbalance; $I_{re,a}$ and $I_{a,a}$ are reactive and active current components of the complex conductivity of the insulation of the object phase A, respectively.

The energy companies have extensive experience in actual operation and isolation input control by other devices based on this principle. However, in most cases, it is contrary to expectation. The main reasons for this are accuracy and unreliability of the information provided by these systems in operation conditions that affect the grid mutual angles between the vectors of phase voltage grid. All these angles change that occur after the balancing scheme automatically lead to errors in the calculation and unreasonable diagnostic conclusions.

The main factors affecting the vectors of phase voltages are as follows:

1) Changes of line and load impedances in phases. Because line current flows through the load, the load voltage drop across the phases will be different, which will lead to angular misalignments of the vectors of phase voltages;

2) Switching devices for transformer voltage control (TVC);

3) Deformation of the windings of the transformer in case of exposure to short-circuit currents;

4) Changing the connection type of the transformer to the grid;

5) Adjustable reactive power compensator in the grid nodes because the change of reactive power flowing through the lines may result in phase voltage drop across these transmission lines;

6) Change between the phase angles of the main vectors due to change of moving direction by controlled energy transformer. e. g. the transformers serving hydro electric station switch the working mode of hydroelectric systems from power generator mode to motor mode;

7) Climate condition. It affects the transmission of power system due to seasonal changes of power.

The second negative factor for the balance method is that the devices based on it are not able to notice the defect isolation even dangerous stage of development, since pre-crash the installation of such devices is 3% normally, and 5%—7% in an emergency of rated current of the complex conductivity of the insulation. Lower setting values in these devices lead to unnecessary equipment failure and may mislead operational personnel at substations. Considering a group of three-phase transformers of 330 kV with a capacity of 700 pF and the initial $\mathrm{tg}\delta_1$ of 0.2%, the following paramcters can be calculated as

$$i_c = UwC_1 =$$

$$330\ 000/3^{0.5} \times 314 \times 700 \times 10^{-12} = 41.89 \text{ mA},$$

$$i_a = i_c \mathrm{tg}\delta_1 = 41.89 \times 0.002 = 0.083\ 8 \text{ mA},$$

$$i = (i_a^2 + i_c^2)^{0.5} = 41.9 \text{ mA},$$

where i_c is reactive component of the current complex conductivity of insulation, i_a is an active component of the current complex conductivity of insulation; and i is current complex conductivity of insulation.

Calculating the change in the parameters with unbalance of 5%, they can be got by

$$i = i + 0.05\ i = 44 \text{ mA},$$

$$i_a = (i - i_c^2)^{0.5} = 13.445 \text{ mA},$$

$$\mathrm{tg}\delta_1 = 13.445/41.89 = 32\%.$$

In case of the maximum rated value $\mathrm{tg}\delta_1$ of 0.8% for CT 330 kV, it is evident that the equipment failure occurs long before the operation of the insulation monitoring device. However, the devices based on this method are suitable for issuing alarms when the main insulation overlaps, since the total capacity of the object will increase and accordingly the current complex conductivity of the insulation will increase, too. For example, if you take the oil-filled CT of 330 kV, with 13 plates of a capacitor, the capacity of a single plate is

$$C_{1-1} = 700 \times 13 = 9\ 100 \text{ pF}.$$

The total capacity after overlap of the capacitor is

$$C_{1-12} = C_{1-1}/12 = 9\ 100/12 = 758 \text{ pF}.$$

The current complex conductivity is

$$i_{c-12} = UwC_{1-12} =$$

$$330\ 000/3^{0.5} \times 314 \times 758 \times 10^{-12} = 45.34 \text{ mA}.$$

The current will be changed to

$$\Delta i = 45.34 - 41.89 = 3.45 \text{ mA}.$$

However, there are no very sensitive instruments to determine change of the current.

Similarly, for the second most common method, measurement of the complex conductivity, the control is carred out in two ways: measuring the conductivity of the complex Y or measuring dielectric loss tangent $\mathrm{tg}\delta_1$ and current transforment input coupling capacitor C_1. We can not agree with the fact that the proposed methods are equivalent, because the control of the complex conductivity is suitable for tracking change in capacitance, but is not suitable for monitoring the change of $\mathrm{tg}\delta_1$ since the change of 0.6% will increase the current complex conductivity only 1.4 μA for current transformer of 330 kV with a capacity of 700 pF. Control of such a change of the current complex conductivity requires high-precision equipment and therefore it can not be in actual use due to the effects of the elements of the measuring scheme, such as wetted surface, corrosion resistors, surge arresters, temperature instability of the measuring system, noise, various currents, etc.

2 Bridge method

Another method is automatic measurement taking $\mathrm{tg}\delta_1$ and C_1 as alternating current bridge. This method requires a reference object, for example, an object of the same name with a known phase $\mathrm{tg}\delta_1$ C_1 input coupling capacitor of current transformer or a voltage transformer. Accurate results when measuring the dielectric loss tangent $\mathrm{tg}\delta_1$ at the operating voltage can be obtained only by using a bridge circuit grounding wire screens at one point, the device being connected to the measuring electrode. Wire screens do not have common points in the bridge circuit, otherwise the bridge will measure the potential difference of ground points of standard and controlled objects. In order to prevent temperature recalculations, it is better to take the same type of object with a close temperature magnitude.

This method needs enough time to balance the bridge, but the accuracy is high up to 0.01%. To continuously monitor the bushing isolation, the device usually uses the method of direct measurement. The operating principle is based on the calculation of capacity and insulation tgδ C_1 by means of direct measurement of conduction current and input voltage applied to it and the measured expansion of periodic signals into orthogonal components[3].

There are two signals to be measured, applied voltage and conduction current input, which are distorted by higher harmonic and jitter as

$$u(t)=U\cos(\omega t+\psi_u)+\sum_{k=2}^{\infty}U_k\cos(k\omega t+\psi_u)+\xi_u(t),$$

$$i(t)=I\cos(\omega t+\psi_u+\phi)+\sum_{k=2}^{\infty}I_k\cos(k\omega t+\psi_{ik})+\xi_i(t),$$

where ψ_u is phase shift of the signal voltage relative to a reference sine wave, φ is the phase difference between the first harmonic current and voltage signals; and $\xi(t)$ is random signal components. The cosine and sinus components of voltage and current are calculated by

$$U_c=\frac{1}{\pi}\int_{-\pi}^{\pi}\cos(\omega t)u(t)\mathrm{d}\omega t,$$

$$U_s=\frac{1}{\pi}\int_{-\pi}^{\pi}\sin(\omega t)u(t)\mathrm{d}\omega t,$$

$$I_c=\frac{1}{\pi}\int_{-\pi}^{\pi}\cos(\omega t)i(t)\mathrm{d}\omega t,$$

$$I_s=\frac{1}{\pi}\int_{-\pi}^{\pi}\cos(\omega t)i(t)\mathrm{d}\omega t.$$

The current value of input leakage current is determined by the ratio

$$I_B=\sqrt{\frac{I_c^2+I_s^2}{2}},$$

and tangent angle loss $\delta=\frac{\pi}{2}-\phi$ is can be calculated by the ratio

$$\mathrm{tg}\delta=\frac{I_c}{I_s}.$$

The capacity of the basic insulation input can be got by

$$C_1=\frac{I_s}{\omega U_c}.$$

The leakage resistance of the main insulation is

$$R=\frac{U_c}{I_c}.$$

In accordance with known quantization theorem, the integral in the first term of a Fourier series can be replaced by summation of discrete values N as

$$F=\frac{1}{\pi}\int_{-\pi}^{\pi}f(t)\cos\left(\omega t-\frac{\pi}{2}m\right)\mathrm{d}\omega t=$$

$$\frac{1}{N}\sum_{k=0}^{N-1}f\left(\frac{Tk}{N}\right)\cos\left(2\pi\frac{k}{N}-\frac{\pi}{2}m\right),$$

where $m=0$ for the cosine components and $m=1$ for sinusoidal components.

If the spectrum of the signal $f(t)$ does not contain a frequency above, the critical frequency can be got by

$$f_c=\frac{N-1}{T}.$$

The following conditions ensure the input signals at nodes normalization being filtered. For example, when $N=1\,024$, the distortion frequency f_c is weakened by 2π times, whose amplitude is usually small and therefore a first-order filter is needed with a time constant of $T/1\,024$ or about 20 ms at a frequency of 50 Hz. The difference of the phase shift between the current and voltage channels associated with the initial spread of the time constants of the filters will be of the order of 1 ms, and it can be compensated by software after the initial calibration. During calibration, phase errors are compensated by current transformer built into voltage transformer[3].

The disadvantage of this method is that enough time is required for balancing the bridge. The advantage of this method is high accuracy of 0.01%.

3 Vector comparison method

The most progressive method compared with bridge method is vector comparison method, which use the reference and controlled objects. To determine $tg\delta_1$, insulation is used for asynchronous "write" reference current and the controlled object, and then the difference between the initial phases of the first harmonic is calculated. The vector diagram calculating the absolute value of $tg\delta_1$ is shown in Fig. 2.

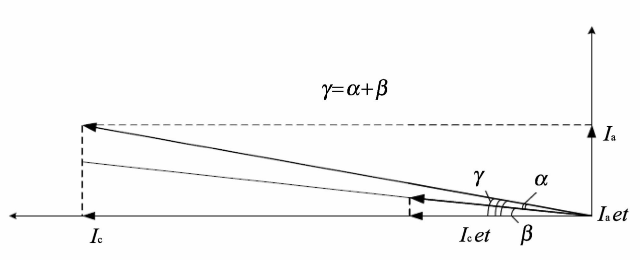


Fig. 2 Vector diagram calculating dielectric loss

In Fig. 2, α is the measured angle between two vectors of complex conduction currents, β is the angle of dielectric loss of the reference object and γ is the true angle of dielectric loss of the controlled object.

The main problem for this method is the need for reliable reference object. Such an object could be another CT and high-voltage of the corresponding phase or the voltage measuring winding voltage transformer. The accuracy of the results increases with the number of objects increasing. Such devices use synchronous multi-channel analog-to-digital converter (ADC) to measure the relative $tg\delta_1$ with absolute accuracy up to 0.01%—0.02% and enable a timely response to changes in the isolation facilities. The main disadvantage of vector comparison method is that it can be used on the substations with a small number of control objects.

4 Partial discharge registration method

It is possible for voltage transformer to realize a combined device with control circuits interturn ($3U_0$). Partial discharge of CT and high-voltage inputs are the root cause of changes of $tg\delta_1$ and C_1. Therefore, it would be logical to control the intensity level and the total power of partial discharges. To be identified in operating conditions, partial discharges usually have higher intensity, and it is not difficult for measuring devices to reach up to this sensitivity. However, the ability to detect insulation defects is not usually determined by equipment sensitivity, but by external interference. The problem of measuring the operating conditions of partial discharges is primarily associated with the elimination or reduction of their noise level. Interference in the measurement of partial discharges can be caused by any process in the network associated with abrupt changes of current and high voltage sources. In measurement of partial discharges under operating conditions, interference sources, as a rule, can not be eliminated. The frequency range occupied by the most intense sources of high-frequency noise ranging from 40—70 kHz to 300—500 kHz. The interference sources below 15 kHz may affect higher harmonics of power frequency; the interference sources higher than 2 MHz may reduce the signal level of partial discharges. The upper frequency range is often potential local interference from radio transmitters, which also limits the application of high frequency band. The main sources of noise unavoidably in operational conditions are corona discharges on the wires, fixtures and equipment, namely so-called basic level of interference. In switchgear, sometimes there is an extra high-level interference, which is usually caused by partial discharges, externally against the controlled object.

These interference sources include the level of the rails, ranks among the elements conductors, pointy bits on the edges of the valve or at the ends of the disabled blades of disconnectors, etc. Therefore, the main problem in the measurement under operating conditions is the selection of partial discharge by both acoustic and electrical measurement methods. In some devices, for continuous monitoring of the insulation CT and high-voltage inputs, there are algorithms for automatic selection and calculation of partial discharges. However, these algorithms are not valid and unable to filter all kinds of interference such as additional interference from external discharges. There is also no regulatory framework or experience to find rejection equipment for the partial discharges.

Partial discharge registration method could be a more sensitive tool in the diagnosis of insulation bushings, but today there are no reliable method for the separation of partial discharges in the inputs and in insulation (auto) transformers or reactors, in which these inputs are assembled. Danger criteria differs by more than an order of magnitude: the partial discharges are allowed to be charged up to 3 nC at the maximum operating voltage, while the inputs to 0.05—0.1 nC. High level of interference prevents accurate diagnosis. However, if you use all the tried and tested methods for the selection of interference realized in sophisticated electronic equipment and special software, it is possible to reliably detect the partial discharges with an intensity of about 1 nC or more. Using simpler and cheaper devices, for example standard storage oscilloscope or peak detector circuits without interference cancellation, it is possible to record the partial discharge level about 10—100 nC, i. e. only in pre-emergency state of controlled input. With the general deterioration of the input insulation and big average current of the partial discharge, i. e, high iteration rate, this process displays itself in increasing tgδ[7].

Table 1 shows the advantages and disadvantages of various methods, and the best one is bridge method.

Table 1 Advantages and disadvantages of various methods

Methods	Advantages	Disadvantages
Balance method	Simple; common; diverse	Accuracy, unreliability, deformation of windings; voltage drop across the phases; unable to notice isolation defect
Bridge method	High accuracy (0.01%)	Need for sufficiently long time
Vector comparison method	The most progressive method compared with bridge method	Need for reliable reference object
Partial discharge registration method	Logical to control intensity level and total power of partial discharges	Insulation defects are usually not determined by equipment sensitivity; Unavoidable noise

5 Conclusion

A system for continuous monitoring of high-voltage inputs of insulation CT is designed to ensure the reduction of accidents in power. The needed data are accumulated to improve system diagnostics, automated measurement and analysis, and in addition, to reducte load of staff and the impact of human factors. The automatic recording and storage of measurement data can identify the trend and rate of change of the parameters and timely signals on deviations. They should allow planned repair of equipment and, if necessary, to make an emergency shutdown of objects in pre-emergency condition. However, to ensure these high standards, the method is needed to measure the main characteristics of insulation tgδ1 and C1 pricisely.

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330－750 kV 变电所变压器绝缘性能的在线监测方法比较分析

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摘 要： 分析了 330－750 kV 电压下工作的电流互感器绝缘性能的在线监测方法及每种方法的有效性和可用性。总结了每种方法的主要特性和优缺点及其对应的标准。

关键词： 连续控制；绝缘性能；在线监测；变电所

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