Transformer protection, automation and monitoring systems

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Abstract. This paper presents the results of research on improving the protection, automation and monitoring systems of power transformers (PT) in 6-35 kV distribution networks. The authors have developed improved algorithms for differential and distance protection of a transformer based on measuring voltage and current synchrophasors, proposed additional criteria for blocking protection in the event of a magnetization inrush current (MIC), and considered the functions of the transformer monitoring and automation system based on synchrophasor technology.

1 Introduction

Statistics of primary equipment failures at substations show that power transformers with a high voltage of 6-35 kV have the greatest number of failures [1]. At the same time, existing transformer protection, automation and monitoring systems in distribution networks, in many cases, have limited functionality.

Analysis of power transformers and automation equipment for 6-35 kV networks shows that the most common nominal power of transformers is no more than 6.3 MVA. For transformers of lower power, overcurrent protection is mainly used, which does not provide the required tripping time in case of internal faults [2]. In addition, differential protection of transformers with a power of more than 6.3 MVA has low sensitivity in case of complex fault types (turn-to-turn short circuits, fire in steel) and must have a blocking during a magnetization inrush current [3]. In this regard, an important task is to improve the protection of a power transformer.

The paper examines the application of synchrophasor technology to improve transformer protection, automation and monitoring systems. First, this technology has advantages for the implementation of differential and distance protection principles [4-6]. In addition, the authors note that the transformer condition can be monitored by controlling its electromagnetic parameters based on voltage and current synchrophasor measurements [7]. This allows for timely detection and prevention of complex fault types.

Currently, the development of networks with distributed generation, including renewable energy sources (RES), causes the emergence of new tasks to improve the protection and automation of distribution networks [8]. Synchrophasor technology is a promising direction for solving these problems.

2 Power transformer analysis

The topology of distribution networks determines the presence of many taps supplying substations with power transformers of low rated power. Analysis of data from electrical networks of several Russian entities shows that the most common rated powers of transformers are 2.5 and 6.3 MVA, a significant portion of transformers have a power of 1 MVA or less (Fig. 1). In addition, a significant portion of transformers have a long service life, while substations have a low automation level, and transformer monitoring systems are absent in many cases.

In 6-35 kV networks, the share of electromechanical protection devices is more than 78 %, and the excess of their established service life is more than 59 % [9]. Electromagnetic current and voltage transformers are predominant, which is combined with a low integration level of protection systems and SCADA, and the incompatibility of the operating principles of existing protection with the requirements for protection in networks with distributed generation.

Overcurrent transformer protection, which is used in 6-35 kV networks, has limited capabilities and provides sensitivity only to faults in the high-voltage winding. Therefore, in order to provide transformer protection, special types of current protection with a significant time delay are added. The authors analyzed the expressions for calculating the tripping settings of overcurrent protection and the conditions for ensuring its sensitivity [2] to show that the protection characteristic significantly depends on the transformer impedance and the impedance of the equivalent power system in the minimum and maximum modes.

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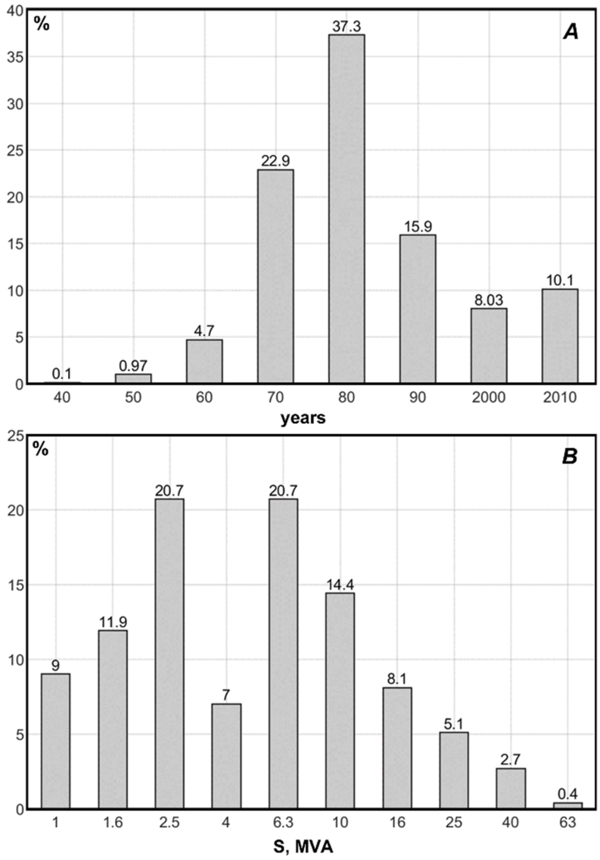


A – commissioning, B - rated power

Fig. 1. Statistics on power transformers 35-110 kV

The following expression represents this dependency:

$$\frac{|\underline{z}_{\text{c.max}} + \underline{z}_L + \underline{z}_T|}{|\underline{z}_{\text{c.min}} + \underline{z}_L|} \geq \frac{2}{\sqrt{3}} k_{\text{r}} k_{\text{s.min}}, \quad (1)$$

where $\underline{z}_{\text{c.min}}$, $\underline{z}_{\text{c.max}}$ – equivalent power system impedance in minimum and maximum mode, $\underline{z}_L$ – line impedance, $\underline{z}_T$ – transformer impedance, k_{r} – protection reserve coefficient, $k_{\text{s.min}}$ – minimum protection sensitivity coefficient.

There is an overcurrent protection type with a voltage setting start, but it also does not provide the required sensitivity characteristics. Distance transformer protection in networks up to 110 kV is rare, differential protection is used most often. However, differential protection is not sensitive to turn-to-turn short circuits and requires blocking at MIC.

In fact, at 35-110 kV substations, there are no transformer monitoring systems; in most cases, there are limited telemetry tools (Fig. 2, Table 1).

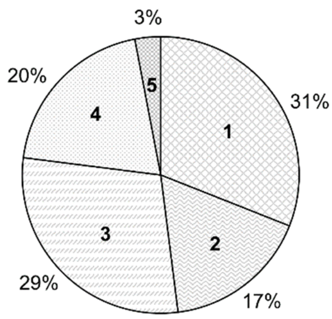


Fig. 2. Statistics on telemechanics of 35-110 kV substations

Table 1. Telemechanics levels.

Level (Fig.2)	Description
1	minimum telesignaling set ("General emergency", "Fault", "Ground fault", "Open")
2	minimum telesignaling set, telemetering for equipment ≥ 35 kV
3	full set of telesignaling and telemetering, remote control of high-voltage breakers 6-35 kV
4	full set of telesignaling and telemetering, remote control of high-voltage breakers of all voltage classes
5	full set of telesignaling and telemetering, remote control of all switching devices

The substation automation tools, which are connected with the power transformer control, also have a limited scope in distribution networks. The most frequently used is the automatic on-load tap changer (OLTC).

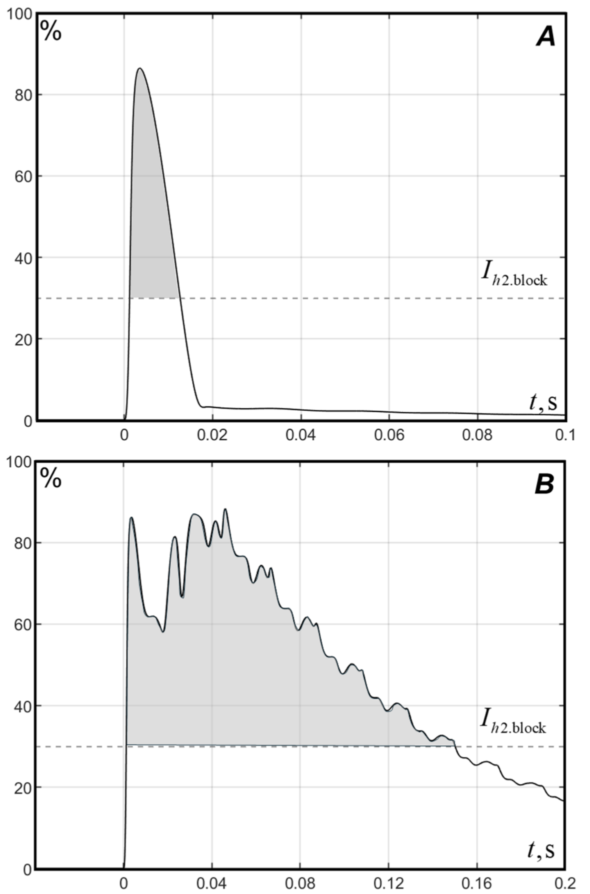
Thus, the power transformer analysis shows that distribution networks require a search for new principles and approaches to the development of protection, automation and monitoring systems, the use of new technologies and solutions, and the provision of measures aimed at increasing the observability and controllability of the network.

The development of modern communication technologies, mass production and reduction in the component's cost of intelligent electronic devices (IED) and microprocessor protection devices allows considering the use of synchrophasor technology for solving problems of distribution network automation. Based on these trends, the authors conducted research on the development of the synchrophasor technology theory and the expansion of its application in 6-35 kV networks [10]. The research results allow formulating the main directions for improving the power transformer protection, automation and monitoring systems.

3 Protection

Differential protection is one of the most reliable and widespread types of protection for power transformers. Modern microprocessor devices of differential protection provide adaptive differential current setting and can respond even to some complex fault types. However, the solution to the issue of differential protection blocking at MIC remains open, since the most widespread blocking principle by the relative value of the 2nd harmonic in the transformer current does not always ensure correct protection operation due to the presence of current transformer core saturation [11].

Electromagnetic current transformers (CT) with a steel core can saturate during a short circuit due to the presence of a significant aperiodic component of the current, even if their parameters were selected correctly. In this case, if the protection cannot act before the CT is saturated, it is significantly slowed down due to blocking by the 2nd harmonic (Fig. 3, B). Depending on the signal processing algorithms used, the protection can be blocked for the filter window length, since the 2nd harmonic level can also be large (Fig.3, A).



A - signal processing (short-circuit), B - CT saturation (MIC)
Fig. 3. 2nd harmonic relative value

Synchrophasor technology and electronic current transformers have significant advantages for improving digital transformer differential protection. Firstly, measuring transformer current synchrophasors based on electronic CTs without saturation provides a significant reduction in the protection unbalance current due to several factors: aperiodic component elimination, low CT error, and OLTC control. Electronic measuring current and voltage transformers are already used in 6-35 kV networks, and significant results have been obtained in this direction [12].

Secondly, measuring the transformer current synchrophasors $\dot{I}_1(t)$ and $\dot{I}_2(t)$ allows solving some issues related to blocking the differential protection at MIC and increasing its selectivity during external short circuits. The presence of angle measurements between $\dot{I}_1(t)$ and $\dot{I}_2(t)$ clearly determines the power direction in the transformer windings. Research shows that in case of transformer fault, an accurate angle estimate between the current synchrophasors can be obtained in a time shorter than the filter window length (for a rectangular window it is 20 ms).

Previously, the authors carried out research on the development of the synchrophasor technology theory to improve line distance protection principles [6]. Similarly, the analysis of power transformer differential equations shows that distance principles can also be effectively used to improve the transformer protection (Fig.4).

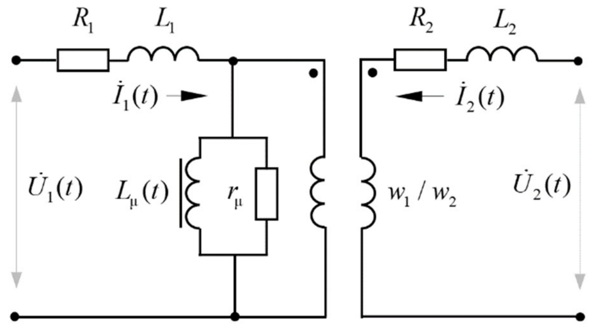


Fig. 4. Two-winding transformer equivalent circuit

Fig.4 shows an equivalent circuit of a two-winding power transformer, where its parameters are estimated by measuring the voltage and current synchrophasors. For transformer protection, the most important parameter characterizing its state is the impedance of the short-circuit branch $\underline{z}_{12}$. In addition, the authors consider the magnetizing inductance estimation $L_\mu(t)$ to provide an additional criterion for blocking the protection at MIC:

$$L_\mu(t) = \frac{\dot{U}_1(t) - \underline{z}_1 \dot{I}_1(t) - L_1 \dot{I}'_1(t)}{\dot{I}'_1(t) + j\omega_0 \dot{I}_1(t) - \dot{I}'_2(t) - j\omega_0 \dot{I}_2(t)}, \qquad (2)$$

where $\dot{I}_1(t)$, $\dot{I}_2(t)$ - transformer current synchrophasors related to the high-voltage side, $\dot{U}_1(t)$ – voltage synchrophasor, $\underline{z}_1 = R_1 + j\omega_0 L_1$, $\dot{I}'_1(t)$, $\dot{I}'_2(t)$ - derivatives of current synchrophasors.

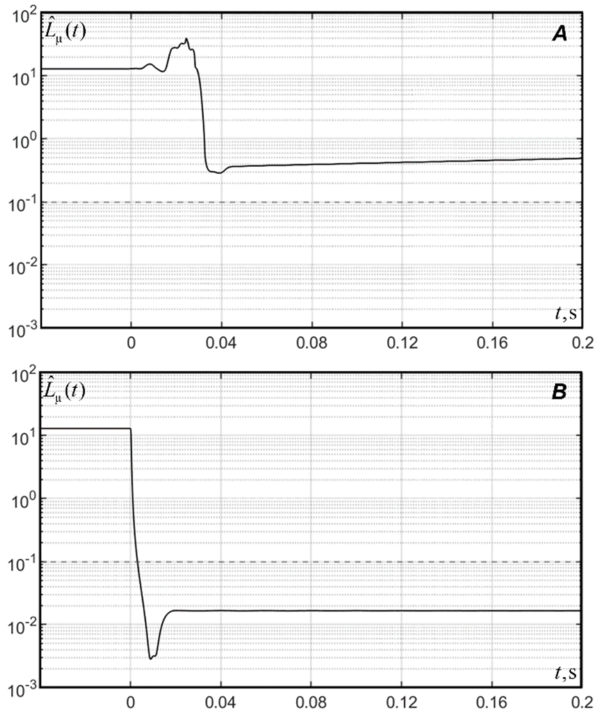
Based on expression (2), it can be shown that the minimum value $L_\mu(t)$ in case of transformer fault is less than the same value at MIC by more than 4-5 times for 35-110 kV power transformers. This allows using $L_\mu(t)$ as an additional criterion for blocking differential protection. In addition, the use of synchrophasor technology for analysing transformer differential equations, including for assessing inductance (2), is valid both in steady-state and in transient modes of the power system.

Fig. 5 shows the simulation of the MIC and short circuit in the high-voltage winding of a 35/6 kV transformer. The magnetizing inductance estimation according to expression (2) in different power system modes confirms the effectiveness of using this parameter as a protection blocking criterion.

Based on the research on improving the line distance protection [6], according to the equivalent circuit (Fig. 4), it can be shown that the expressions for estimating the line impedance during a short circuit for two-sided synchrophasor measurements are also valid for estimating the transformer impedance:

$$\hat{\underline{z}}_{12}(t) = \frac{\dot{U}_1(t) - \dot{U}_2(t) + \underline{z}_{12}\dot{I}_2(t) + L_{12}\dot{I}'_2(t)}{\dot{I}_1(t) + \dot{I}_2(t) + \underline{k}\left(\dot{I}'_1(t) + \dot{I}'_2(t)\right)}, \qquad (3)$$

where $\underline{k} = L_{12} / \underline{z}_{12}$.



A – MIC, B – short circuit

Fig. 5. Magnetizing inductance estimation

Thus, the advantages provided by two-sided synchrophasor measurements in line distance protection [6] are valid for transformer protection. In addition, a promising approach is one that uses the estimation of the difference in impedances $\hat{\underline{z}}_{12}(t)$ and $\hat{\underline{z}}_{21}(t)$ by analogy with the unbalance current in transformer differential protection. The distance principle ensures high sensitivity of such protection to transformer fault.

4 Monitoring and automation

The differential protection of a transformer must ensure sensitivity to internal short circuits and be selective to external short circuits. Additionally, this protection can also be sensitive to complex fault types, such as turn-to-turn short circuits. However, the peculiarity of turn-to-turn short circuits is that even modern digital differential protection cannot be sensitive to such fault with a small number of shorted turns. In this case, the detection and prevention of turn-to-turn short circuits can be ensured by a transformer monitoring system [7].

Traditionally, a transformer monitoring system provides control of some parameters that are measured using special sensors and devices. However, this equipment is rarely installed in distribution networks, as it is expensive. The authors propose using measurements of the transformer voltage and current synchrophasors to operate its monitoring system. This approach provides control of many electrical transformer parameters. In addition, in this case, the monitoring system does not require additional measuring equipment.

The short-circuit impedance (Fig. 4) is estimated based on the transformer voltage and current synchrophasors in the normal mode of the power system using the expression:

$$\hat{\underline{z}}_{12}(t) = \frac{2\left(\dot{U}_1(t) - \dot{U}_2(t)\right)}{\dot{I}_1(t) + \dot{I}_2(t) + \underline{k}\left(\dot{I}'_1(t) + \dot{I}'_2(t)\right)}. \quad (4)$$

Thus, the parameters (2) – (4) can be estimated both for the protection functions and for the transformer condition monitoring, which ensures the prevention of complex fault types, to which the transformer protection is not sensitive. In addition, electronic current and voltage transformers [12] ensure an accurate estimation of the transformer parameters both in the normal power system mode and during short circuits. This makes it possible to implement some monitoring functions in the transformer protection device.

The Engineering Center Energoservice LLC company has developed its own transformer monitoring system based on synchrophasor measurements. Currently, there is already a specialized device – a transformer condition monitoring module, which collects and processes transformer synchrophasor measurement data to evaluate the parameters and monitor its condition (Fig. 6). The device also generates a list of daily, weekly, monthly and annual reports on changes in the transformer condition. Any abnormal deviations in parameters are recorded on oscillograms.

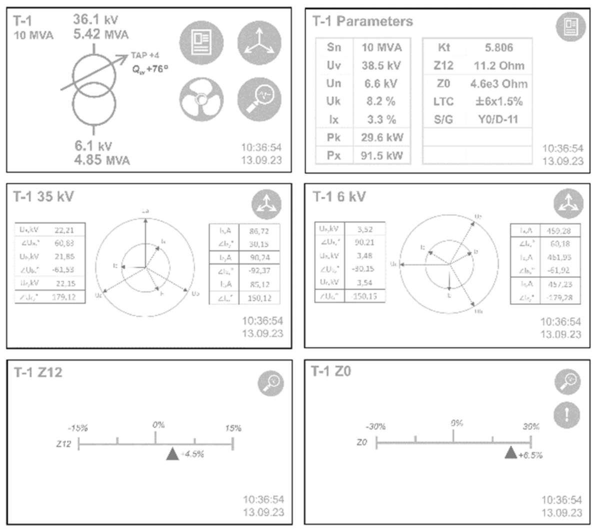


Fig. 6. Transformer monitoring module

Synchrophasor technology also has promising directions for transformer automation systems. One of the most significant functions of transformer automation is changing the transformation ratio using OLTC. Measuring voltage synchrophasors ensures control of switching duration, device drive resource, and allows recording cases of "self-running" and "jamming". Additionally, using synchrophasor technology, specialized OLTC algorithms can be implemented to ensure the required voltage level simultaneously for several consumers.

The principle of multi-sided synchrophasor measurements [6] provides additional conditions for automatic control of the 6(10)/0.4 kV transformer breaker, breaker failure backup device at large substations, automatic reclosing and automatic frequency transformer unloading. A special feature of synchrophasor technology is the possibility of creating wide area systems, when the current and voltage synchrophasors of different feeders are compared either at the same substation or at different ones.

At present, the introduction of various generation sources at medium and low voltage necessitates the search for new algorithms for the operation of distribution network automation systems. It is certain that for distributed generation network automation systems, the use of synchrophasor technology has the greatest advantages [8], since there are new tasks for improving the devices for mode control automation and emergency automation. Therefore, measuring voltage and current synchrophasors in transformer automation systems provides for the expansion of their capabilities and stimulates the development of protection, automation and monitoring systems for distribution networks as a whole.

5 Conclusion

Improvement of protection devices largely depends on the efficiency of using new technologies, intelligent devices, and modern technical means. One of such areas for improving transformer protection, monitoring, and automation systems is the use of synchrophasor technology.

The paper reviewed the main results of the authors' research on improving transformer protection, monitoring and automation systems based on measurements of voltage and current synchrophasors. The developed algorithms and operating principles of these systems were tested on mathematical and physical models, as well as during pilot operation at distribution network facilities.

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