Wide area monitoring, protection, automation, and control systems for medium voltage networks

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Abstract. Distribution medium voltage networks have a branched structure, many power centers, long cable and overhead lines. This complicates the process of their automation, since significant capital costs for new equipment are required. New solutions based on modern technologies can help speed up this process and make it more efficient. The authors propose the use of synchronized phasor measurement technology for automating medium voltage networks. This paper considers approaches that describe the possibilities of implementing the WAMPAC principles in such networks, provides several examples where these principles apply.

1 Introduction

A gradual increase in the proportion of distributed generation and non-linear network elements reduces the reliability and stability of the operation of energy systems and increases the risk of abnormal and emergency situations, consumer shutdown [1]. Simultaneously, at first glance, some insignificant events often lead to major accidents, which can occur in the medium voltage distribution network.

In order to ensure the necessary reliability and stability of the network, a significant improvement in the infrastructure of protection, automation, monitoring, and control systems is required. The automation of medium voltage distribution networks includes two levels: the first (local), associated with the automation of transformer substations 6–10 kV. The second level (regional) involves automating distribution network power centers - step-down substations and distribution points.

According to the unified technical policy of PJSC Rosseti [2], one of the main tasks of the company in the electric grid complex is to increase the observability of the electric grid, the efficiency of managing grid assets, the introduction of modern systems for monitoring the technical condition, diagnostics and monitoring technological equipment. In this regard, it can be argued that the search for effective and comprehensive solutions for automating distribution networks is of considerable interest. Such solutions involve the use of multifunctional devices and modern technologies, which include the technology of synchronized phasor measurements (SPM) [3].

The advantage of using SPM technology to improve the reliability of energy systems is the ability to implement wide area monitoring, protection, automation, and control systems (WAMPACS). This paper discusses the propagation of WAMPACS ideas in relation to medium voltage distribution networks, including automation of their power centers.

2 Proposed approach

Currently, in the world energy industry, much attention is paid to WAMPACS in conjunction with the use of synchronized phasor measurements [4]. The scientific literature has already formed general approaches and conceptual solutions for the use of SPM technology to implement protection, automation, monitoring, and control devices [5]. However, questions remain regarding the application of WAMPACS principles to medium voltage networks.

Until recently, it was believed that the application of WAMPACS, including SPM technology, is a prerogative for high-voltage networks, since the cost of solutions based on these technologies was very high a few years ago. However, the development of these technologies recently has made it possible to significantly reduce their cost, and at the same time expand the scope of their application. Additionally, the development of communication technologies, such as cellular communication technology, makes it possible to consider the application of WAMPACS and SPM technology not only for theoretical projects, but also for practical implementation [6].

Currently, the most common SPM devices (PMUs) are developed in accordance with the IEEE C37.118 standard [7]. However, the development of other types of devices supporting SPM is also of practical interest. For example, in the concept of PJSC Rosseti [8], the main task of creating automated systems involves the introduction of inexpensive, modern, high-tech and multifunctional devices.

One of the most promising areas of application of WAMPACS and SPM technology for distribution networks is the implementation of the FLISR (fault

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location, isolation, and service restoration) system. According to statistics, about 80% of all consumer outages are associated with a disruption in the operation of the medium voltage network [9]. Therefore, given the low level of network automation, the implementation of the FLISR system is an urgent task that requires the use of efficient and inexpensive solutions.

To create a FLISR system, the use of SPM technology provides an opportunity to implement new principles of fault localization during short circuits and ground faults, and more advanced energy monitoring. Significant advantages are offered by the SPM technology for automation of power supply centers:

- distributed protection systems for busbars and a power transformer, built on the differential principle with absolute selectivity;
- automatic control of networks with distributed generation [10];
- monitoring of electrical equipment (power and measurement transformers, high-voltage breakers) [11];
- systems for data collection and transmission (reducing the time of analysis of emergency situations).

Since the automation of distribution networks is associated with large capital costs, this task requires the search for effective solutions and planning the stages of their implementation.

3 FLISR System

The FLISR system of 6–10 kV networks is an effective structure for determining and restoring emergency sections of the network. FLISR is designed to automate the supervisory control of 6–10 kV distribution networks in normal and post-emergency modes, as well as in modes with a single-phase ground fault.

Automation of distribution networks, as a rule, is carried out in several stages. Fig.1 shows the block diagram of such automation. For example, in Fig. 1, the following objects are shown: sections of the step-down substation SS-1, distribution points DP-1 and DP-2, transformer substations TS-11 - TS-5N. SS-1 supplies the overhead line with branches.

Regardless of the type of network, automation should start with power centers (stage 1). At the first stage, part of the transformer substations that supply important consumers can be automated.

In the second and third stages of network automation, equipment is installed at the remaining distribution points and transformer substations. When planning automation stages, it is important to make a reasonable choice of fault localization sections and controlled transformer substations. This is necessary so that all automation solutions do not contradict each other at different stages.

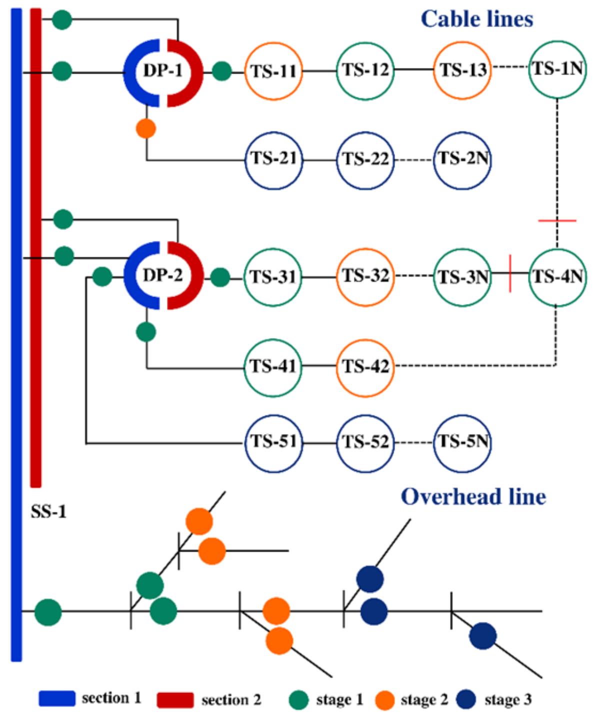


Fig. 1. Stages of network automation.

The tasks of automation include the following positions:

- installation of current measuring sensors and short-circuit current indicators at substations, distribution points and transformer substations (data collection level);
- installation of devices that provide the functions of a fault localization system, energy monitoring, remote control of circuit breakers/disconnectors, telemechanics systems (level of data transmission and processing);
- implementation of the level of dispatch control (servers with specialized software, collection, visualization and long-term storage of information, formation of remote control commands).

Automation of overhead lines has its own specifics, since overhead lines are characterized by a minimum level of automation with a significant length of lines. Fig. 1 shows one of the options for automation of overhead lines - the installation of new equipment at the branching points of the line (on supports) in the order of hierarchy from the power center of the overhead line. The equipment to be installed includes reclosers, line status indicators, and data acquisition devices.

Currently, various companies around the world are developing FLISR systems, so they have their own characteristics. Fig. 2 shows an example of the implementation of the FLISR system using the equipment of Engineering Centre Energoservice.

A feature of the presented system (Fig. 2) is the use of special fault localization devices (ENLZ), which have the support of synchronized phasor measurements. This allows for the implementation of the WAMPACS principles regarding network monitoring and control [12].

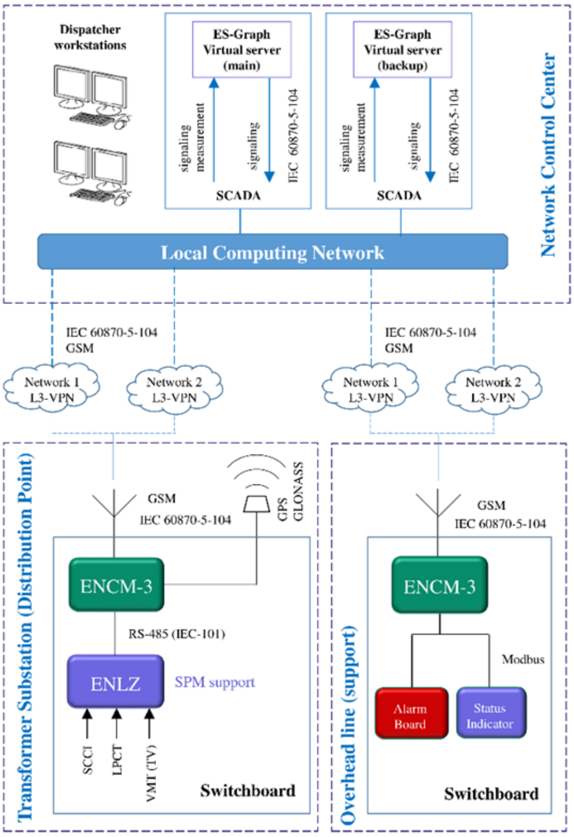


Fig. 2. Example of FLISR system.

ENLZ devices operate in fault localization systems in distribution networks. ENLZ provide synchronized phasor measurements of zero-sequence currents and voltages, processing data from short-circuit current sensors (SCCIs).

One ENLZ can simultaneously control measurements from two cable lines. The device has six optical inputs for connecting SCCIs and two analog inputs for measurements $3I_0$ and $3U_0$. Zero-sequence current transformers (LPCTs) and a voltage measuring transformer with an "open delta" winding are connected to the analog outputs using a VMT step-down transformer. The states of optical inputs and digitized analog signals are available via RS-485 in the form of telesignaling and telemetry (amplitude, phase angle).

Correct operation of the ENLZ requires accurate time synchronization, which is performed by the ENCM-3 data acquisition device with a built-in GLONASS/GPS receiver.

The specialized software tool ES-Graph ensures the operation of the FLISR system. The ground fault localization algorithm is based on the analysis of the amplitudes and angles of the zero-sequence current and voltage phasors measured in different parts of the network.

In the cable distribution network, new equipment is installed at transformer substations. ENLZ can also be installed at step-down substations and distribution points, where they measure the zero-sequence voltage.

Data is sent to the Network Control Center (NCC) via redundant dedicated cellular communication channels, which ensures relatively low equipment costs and efficient data transmission to SCADA. NCC carries out processing, transmission and storage of data on the state of the network, and generates signals for the control of switching devices.

Special overhead line status indicators (ISL) are located on supports at a certain distance from the wires. This device provides monitoring of the overhead line condition, determination and indication of the ground faults and short circuits in the network. The ISL is connected to the ENCM-3 data collection and transmission device, which is located in the switchboard on the support. All data is also transmitted to SCADA.

Thus, the considered FLISR system uses synchronized phasor measurements to perform a number of network monitoring and control tasks. In the future, the development of such systems will also make it possible to implement the functions of relay protection and automation in medium voltage networks.

4 Monitoring and protection of power transformers

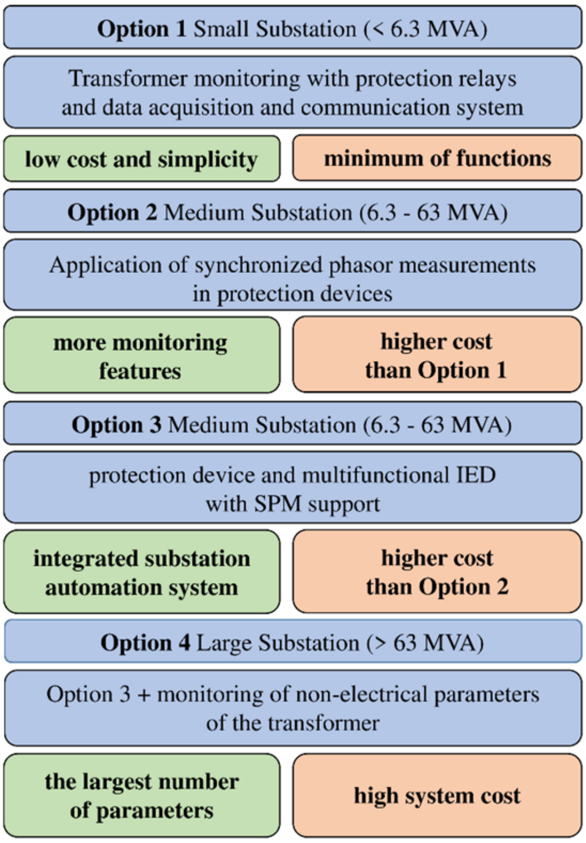
The implementation of protection and monitoring systems for power transformers at step-down substations in medium voltage networks has certain features. First, the power rating of most transformers does not exceed 6.3 MVA, therefore, as a rule, the requirements for protection and monitoring of such transformers are lower than in high voltage networks. Second, a significant proportion of power transformers have reached their specified service life, so their residual value often becomes less than the necessary costs for substation automation. However, the long service life of transformers increases the probability of their failure. Therefore, planning the execution of automation tasks requires the search for rational, efficient, and integrated solutions.

Fig. 3 shows the options according to which the automation of step-down substations in medium voltage networks can be carried out, taking into account the application of the WAMPAC principles.

For small substations with the lowest level of automation, the most rational solution is to implement a simple monitoring system based on relay protection devices and a data collection and transmission system without the use of SPM. Such a system will provide control of the basic set of transformer parameters (overload capacity, short-circuit currents, overvoltages).

If, according to technical and economic indicators, the installation of SPM devices is justified, the transition to option 2 allows the implementation of a fully functional transformer monitoring system with control of a much larger number of parameters, including the equivalent parameters of the transformer circuit [11].

The most rational option is the use of multifunctional intelligent electronic devices with the SPM support, because they allow implementing several substation automation subsystems (telemechanics, energy metering, and control of electricity quality indicators).


Option 1 Small Substation (< 6.3 MVA)

Transformer monitoring with protection relays and data acquisition and communication system

low cost and simplicity | **minimum of functions**

Option 2 Medium Substation (6.3 - 63 MVA)

Application of synchronized phasor measurements in protection devices

more monitoring features | **higher cost than Option 1**

Option 3 Medium Substation (6.3 - 63 MVA)

protection device and multifunctional IED with SPM support

integrated substation automation system | **higher cost than Option 2**

Option 4 Large Substation (> 63 MVA)

Option 3 + monitoring of non-electrical parameters of the transformer

the largest number of parameters | **high system cost**

Fig. 3. Options for protection and monitoring systems for power transformers.

For larger substations, it becomes possible to implement monitoring systems with control of electrical and non-electrical parameters [13]. This approach requires significantly more costs, but at the same time, we get more effective control and performance of a greater number of tasks for monitoring and diagnosing the transformer.

5 SPM application for transformer monitoring

Most often, electromagnetic processes lead to the occurrence of defects and accidents in transformers in a large way. Therefore, it is fundamentally important that monitoring systems use a predictive way of identifying the likelihood of dangerous damage, and not identifying the consequences of damage that has already occurred.

A promising solution to this problem is the use of protection devices with transformer monitoring functions based on synchronized phasor measurements. In addition, SPM allows improving the protection functions of the transformer [11].

The paper [14] considers the issues of identification of the T-shaped equivalent circuit parameters of a power transformer based on the measurement of current and voltage synchrophasors. According to the dynamics of changes in these parameters, the monitoring system determines the defects and malfunctions of the transformer. Nevertheless, in addition to the stationary modes of transformer operation, when analyzing its state, it is important to control the parameters of the transformer equivalent circuit during transients. However, paper [14] concerns only the stationary modes of operation of the transformer, that is, this is the performance of monitoring functions. Relay protection of a transformer requires the ability to control its parameters in transient modes, so the analysis of such modes is of practical importance for developing protection devices.

Based on the current and voltage synchrophasors of the transformer, a system of differential equations can be implemented that describes its operation in non-stationary modes, similarly to a system of equations based on instantaneous values of current and voltage. There can be many such systems of equations, depending on the chosen transformer equivalent circuit and calculation conditions. As an example, we consider an L-shaped equivalent circuit of a power transformer with non-linear parameters of the magnetization branch (Fig. 4).

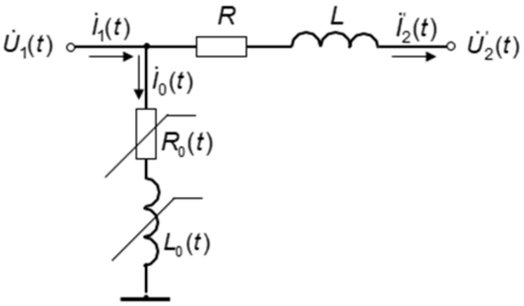


Fig. 4. L-shaped equivalent circuit.

The L-shaped equivalent circuit of a power transformer has two branches: a branch with winding impedances and a magnetization branch. A significant change in the parameters of the magnetization branch occurs during the inrush of the magnetizing current (MIC) in the transformer when it is turned on to idle or to the load, and also after the supply voltage is restored after the external short circuit is turned off.

The differential equation of the magnetization branch for the analog prototype system, which describes the mode of the magnetization inrush current, has the following form:

$$u_1(t) = i_0(t)R_0(t) + L_0(t)\frac{di_0(t)}{dt}. \qquad (1)$$

Expression (1) is a non-stationary first-order differential equation because it contains two variable coefficients. Analysis of such an equation in the instantaneous values of current and voltage is not always efficient and simple. Therefore, the use of data on current and voltage synchrophasors on the high and low sides of the transformer makes it possible to change the approach to estimating its parameters in the transient mode.

The transition from instantaneous values of current and voltage to process synchrophasors is carried out as follows:

$$u_1(t)\to \dot{U}_1(t)e^{j\omega_0 t}, i_0(t)\to \dot{I}_0(t)e^{j\omega_0 t}. \qquad (2)$$

After this replacement, we transform expression (1) to the following form:

$$\dot{U}_1(t)=\underline{z}_0(t)\dot{I}_0(t)+L_0(t)\frac{d\dot{I}_0(t)}{dt}, \qquad (3)$$

where $\underline{z}_0(t)=R_0(t)+j\omega_0 L_0(t)$, $\omega_0=2\pi 50$ рад/с.

Current synchrophasor in the magnetization branch:

$$\dot{I}_0(t)=\dot{I}_1(t)-\dot{I}_2^*(t), \qquad (4)$$

where $\dot{I}_2^*(t)$ - current synchrophasor of the low side referred to the high side.

We introduce the following notation:

$$\underline{z}_1(t)=\frac{\dot{U}_1(t)}{\dot{I}_0(t)}=R_1(t)+jX_1(t). \qquad (5)$$

Paper [15] considers the analysis of synchrophasors of various transients in the power system. We use one of the transformations [15] to estimate the inductance of the magnetization branch:

$$L_0(t)=X_1(t)\left[\omega_0+\mathrm{Im}\left(\frac{\dot{I}_0'(t)}{\dot{I}_0(t)}\right)\right]^{-1}, \qquad (6)$$

$$R_0(t)=R_1(t)-L_0(t)\mathrm{Re}\left(\frac{\dot{I}_0'(t)}{\dot{I}_0(t)}\right), \qquad (7)$$

where $\dot{I}_0'(t)=\frac{d\dot{I}_0(t)}{dt}$.

The following replacement in expressions (6) and (7) allows determining the parameters of the transformer windings R and L:

$$\dot{U}_1(t)\to \dot{U}_1(t)-\dot{U}_2^*(t), \dot{I}_0(t)\to \dot{I}_2^*(t). \qquad (8)$$

Thus, the obtained expressions (6) and (7) make it possible to determine the parameters of the transformer equivalent circuit under transient conditions. For example, in the magnetizing current inrush mode, we can determine the change in the inductance of the magnetizing branch. This change is one of the signs of identification of such a mode.

The analysis of process synchrophasors also allows the development of other new algorithms for transformer protection and monitoring [15]. For this purpose, an effective solution is the simulation of electrical circuits, for example, in MATLAB/Simulink. In particular, Simulink has a Nonlinear Transformer model that can be used for calculations based on numerical methods.

Fig. 5 shows the equivalent circuit of a no-load transformer based on the Simulink model. The peculiarity of this model is that the resistance and inductance of the magnetization branch are connected in parallel. This allows analysis of the magnetization inductance separately from other parameters.

Fig. 6 shows the Simulink transformer model developed by the authors as part of this study. Simulation of the idle mode of transformer provides data on the non-linear change in magnetizing inductance (Fig. 7). Such changes are characteristic only for this mode; therefore, the calculation of the magnetization inductance is of interest for improving the operation of the differential protection of the transformer.

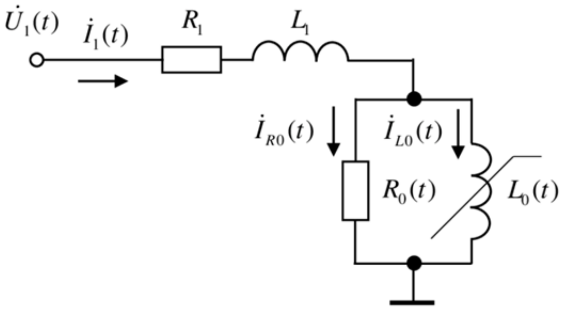


Fig. 5. Equivalent circuit of transformer model.

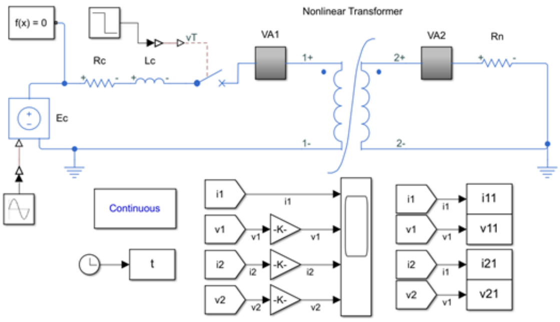


Fig. 6. Simulink model.

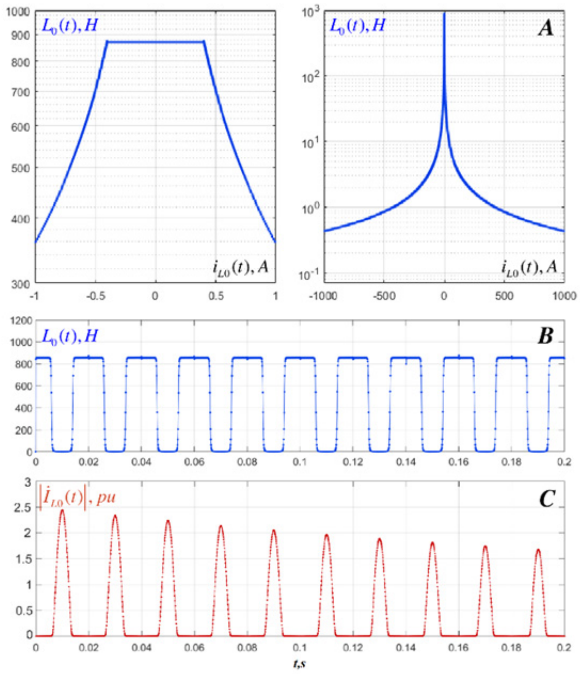


Fig. 7. Inductance (a, b) and magnetizing current (c).

The values of the magnetization inductance (Fig. 7, b) are obtained by solving a system of equations based on process synchrophasors. Significant inductance changes occur every period of fundamental frequency. Thus, the synchrophasors of the voltage and current of the transformer make it possible to determine the mode of the magnetization inrush current.

Currently, the authors are developing new algorithms for protecting and monitoring a power transformer. Testing of the proposed algorithms is already being carried out as part of a special power transformer monitoring system at substations 7 and 8 in Arkhangelsk, Russia [14].

6 Discussion

Expressions (6) and (7) contain the derivative of the current synchrophasor, the correct calculation of which in digital systems depends on the signal sampling frequency. In the general case, there are systems with a low sampling rate, which can lead to a decrease in the accuracy of calculating the current derivative and the efficiency of the proposed algorithms.

In some cases, the transmission rate of synchrophasors from PMU with a frequency of 50 Hz or less may be unacceptable. On the one hand, this problem can be solved by increasing the synchrophasor transmission rate, but this is not always acceptable. The second option is to calculate the derivative of the current synchrophasor in the PMU itself. The authors suggest that the second option may be more promising for medium voltage networks.

7 Conclusion

The development of modern technologies makes it possible to consider their application in new energy areas and directions. The technology of synchronized phasor measurements in combination with the implementation of WAMPAC principles is a promising direction for automation of medium voltage distribution networks.

The paper considers the general principles of organizing the process of automation of distribution networks based on the SPM technology, taking into account the specifics of their work.

Fault localization systems based on SPM are able to perform the functions of telemechanics, energy metering, monitoring system for the condition of electrical equipment. The control of the transformer electromagnetic parameters based on the measurement of current and voltage synchrophasors makes it possible to implement the functions of the transformer monitoring system, which ensures the detection of faults and abnormal modes of its operation.

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