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ВНЕДРЕНИЕ ИНТЕЛЛЕКТУАЛЬНЫХ СИСТЕМ МОНИТОРИНГА ТРАНСФОРМАТОРОВ НА ЭНЕРГЕТИЧЕСКИХ ОБЪЕКТАХ IMPLEMENTATION OF INTELLIGENT MONITORING SYSTEMS FOR TRANSFORMERS IN ENERGY FACILITIES

Аннотация. На энергетических объектах силовые трансформаторы используются не только для преобразования электрической энергии, но и являются стратегическими активами с точки зрения надежности, бесперебойности и экономической эффективности сети. По этой причине мониторинг состояния трансформаторов не только посредством периодических лабораторных испытаний, но и в режиме реального времени с использованием датчиков, интеллектуальных электронных устройств (ИЭУ), централизованной аналитики и инструментов кибербезопасности стал одним из основных направлений современной электроэнергетики. Стандарты МЭК 60076-2 (превышение температуры), МЭК 60076-7 (нагрузка и тепловое старение), МЭК 60599 и IEEE C57.104 (интерпретация содержания растворенных газов), МЭК 61850 (связь и интеграция), а также семейство стандартов МЭК 62351 (безопасная связь) составляют основные регуляторные основы в этой области.

Abstract. In energy facilities, power transformers are not only used for electrical energy conversion but are also strategic assets in terms of network reliability, continuity, and economic efficiency. For this reason, monitoring transformer condition not only through periodic laboratory tests but also in real time using sensors, intelligent electronic devices, centralized analytics, and cybersecurity tools has become one of the main directions of modern power engineering. IEC 60076-2 for temperature rise, IEC 60076-7 for loading and thermal aging, IEC 60599 and IEEE C57.104 for dissolved gas interpretation, IEC 61850 for communication and integration, and the IEC 62351 family for secure communication constitute the main regulatory pillars in this field.

Ключевые слова: Силовой трансформатор, интеллектуальная система мониторинга, мониторинг в реальном времени, анализ растворенных газов.

Keywords: Power transformer, intelligent monitoring system, real-time monitoring, dissolved gas analysis.

Introduction. Digitalization in the energy sector is considered one of the key tools for reducing costs, increasing efficiency, enhancing resilience, and improving the оператив nature of operational decision-making. The International Energy Agency emphasizes that digital technologies help reduce costs and improve efficiency and resilience in energy systems. Industry practices presented by CIGRE show that transformer monitoring is structured as a unified value chain consisting of sensors, communication infrastructure, data acquisition, algorithms, user interfaces, and operational alerts. This approach helps reduce the scale of failures, decrease the volume of systematic maintenance, and increase asset availability.

An intelligent monitoring system does not replace classical relay protection; rather, it complements it by enabling the assessment of the transformer's remaining life, early detection of initial fault symptoms, risk-based maintenance planning, and optimization of operating conditions. Therefore, the concept of intelligent monitoring is not limited to "installing sensors," but represents the integration of sensor–data–analytics–decision support–cybersecurity into a unified engineering platform.

1. Regulatory and Methodological Framework

For evaluating the thermal regime of transformers, IEC 60076-2 defines temperature rise tests and limits for winding hot-spot temperature rise in liquid-immersed transformers [1-3]. IEC 60076-7 explains the impact of different ambient temperatures and loading conditions on transformer lifetime and provides recommendations for evaluating loading above rated capacity when necessary. The interpretation of dissolved and free gases in oil-filled equipment is carried out according to IEC 60599, while evaluation based on gas generation and fault types is performed according to IEEE C57.104 [4]. At the communication layer, IEC 61850 standardizes data exchange between intelligent electronic devices in substation automation systems. At the security layer, IEC 62351-3 defines confidentiality, integrity, and message-level authentication principles for SCADA and telecontrol protocols operating over TCP/IP, while IEC 62351-6 specifies the security of IEC 61850-based communications.

2. Structure of Intelligent Monitoring Systems for Transformers

In the modern approach, an intelligent monitoring system for transformers is structured with at least five functional layers:

-Measurement layer – sensors for temperature, loading, gas, moisture, bushings and OLTC;

-Field layer – data acquisition module, intelligent electronic device (IED), or RTU;

-Local processing layer – initial filtering, event detection, and local alarm generation;

-Central analytics layer – database, trend analysis, predictive models and operator interface;

-Cybersecurity and integration layer – identification, access control, logging, and SCADA/EMS integration.

In CIGRE practice, this architecture enables the implementation of separate monitoring modules for the active part, cooling system, bushings, voltage transformers, and OLTC. The IEC 61850 process bus approach allows signals from instrument transformers to be sampled and transmitted in digital form to one or more protection and measurement devices (figure 1).

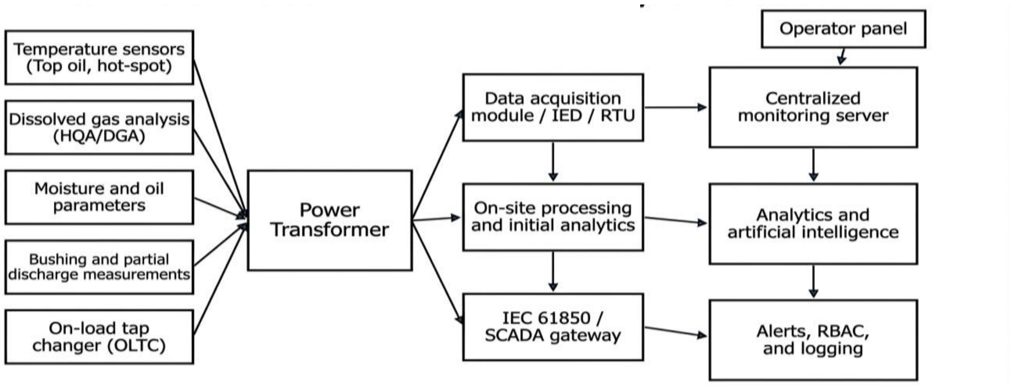

Figure 1. Schematic structure of an intelligent monitoring system for transformers

In the application example presented by CIGRE, data sources are not limited only to sensors specifically installed on the transformer; variables such as voltage, current, and temperature obtained from SCADA are also integrated into diagnostic modules. For monitoring the cooling system condition, measured temperatures are predicted based on load and ambient temperature and, in some cases, compared with neural network-based models. For bushings, current amplitude and phase differences are monitored, while for OLTC, vibro-acoustic and motor current signal analysis is applied [5-8].

3. Monitoring Indicators and Analytics

In an intelligent monitoring system, the following variables should primarily be monitored: top-oil temperature, winding hot-spot temperature or its calculated equivalent, load current, ambient temperature, moisture in oil, dissolved gases, bushing current/phase indicators, OLTC motor current, and vibro-acoustic signals. Partial discharge monitoring can also be used as an additional diagnostic layer; industry sources present it as an important trending indicator that complements gas analysis, temperature, vibration, and load data. Dissolved gas analytics is of particular importance. In an industrial example described by CIGRE, an alarm is generated when the composite gas indicator exceeds 50 ppm and the rate of increase surpasses thresholds of 10 ppm/day, 20 ppm/week, or 30 ppm/month [9]. These values are not universal standards for all transformer fleets; however, they serve as important practical reference points for building trend-based decision support modules.

H_2 – hydrogen, CO – carbon monoxide, CH_4 – methane, C_2H_6 – ethane, C_2H_2 – acetylene, C_2H_4 – ethylene, CO_2 – carbon dioxide

The increase of these gases is associated with the following fault indications:

Table 1.

Dissolved gas components and corresponding probable fault type

Gas Component	Possible Process
H_2	Partial discharge, low-energy dielectric defects |
CH_4	Low-temperature heating
C_2H_4	High-temperature heating
C_2H_2	Electric arc, high-energy discharge
CO, CO_2	Thermal degradation of cellulose insulation

For practical applications, an integrated condition indicator can be constructed as follows:

$$VI = 0{,}30T + 0{,}25Q + 0{,}15R + 0{,}15G + 0{,}15Y \quad (1)$$

Where: T – temperature and loading, Q – dissolved gases, R – moisture/aging, G – bushings, Y – OLTC.

As an example, the following classification can be applied:

VI< 0.30 – normal condition, 0.30≤VI < 0.60 – warning zone, VI ≥ 0.60 – critical zone.

This model is not a normative standard; it should be calibrated based on fault history, manufacturer recommendations and operational statistics for each specific asset. In calculating the temperature sub-index, the load factor

$$K_y = \frac{I}{I_n} \quad (2)$$

can be used as one of the key variables, where I is the current load current and I_n is the rated current. IEC 60076-7 specifically links loading with transformer lifetime and thermal aging; in critical units, fiber-optic measurement solutions are preferred for direct observation of the hot-spot temperature. The fact that the standard itself provides recommendations on the number of fiber-optic sensors for temperature rise testing further emphasizes the importance of this approach [10-13].

4. Communication and Cybersecurity

For the reliable operation of an intelligent monitoring system, interoperability and cyber resilience are equally important. IEC 61850 ensures standardized data exchange between intelligent electronic devices (IEDs) and also considers communication requirements beyond substation boundaries. IEC 62351-3 defines confidentiality, integrity, and authentication mechanisms for TCP/IP-based SCADA and telecontrol protocols, while IEC 62351-6 describes specific security mechanisms for IEC 61850 derivatives.The effectiveness of an intelligent monitoring system is determined not only by the quality of sensors but also by the prompt and secure delivery of data to the processing center.

A transformer monitoring system is typically integrated with the substation's SCADA system. This integration enables the following functions:

Visualization of measurement data on the operator panel; Logging of events and fault signals; Generation of trend graphs; Real-time alerts for limit violations; Formation of reports for maintenance personnel.

The IEC 61850 protocol is particularly suitable for this purpose, as it provides a semantic data model and enables equipment from different manufacturers to operate on a common platform.

From a cybersecurity perspective, the following measures are essential:

Role-based access control; User authentication; Data packet integrity verification;

Certificate-based protection; Segmentation of the network into technological and corporate domains; Event logging and storage; Provision of backup communication routes.

Without these measures, the monitoring system itself may become a new source of risk.

5. Practical Design Model

Sensorizing the entire transformer fleet at the same level of depth is not always economically efficient. In an industrial case presented by CIGRE, online gas monitoring was prioritized for transformers of 47 MVA and above, as well as shunt reactors of 120 kV and above; this demonstrates that a phased and criticality-based implementation is rational [15].

Accordingly: Phase I: For strategic transformers in the 110–330 kV class, implementation includes a full HQA module, at least 3 temperature channels, bushing monitoring, OLTC (on-load tap changer) motor current and vibro-acoustic channel, IEC 61850/SCADA gateway, and a centralized analytics server.

Phase II: For medium-critical assets, a simplified transmitter measuring H_2 + moisture + oil temperature together can be applied, along with software-based trend analysis of load and temperature, event-based alerts, and a non-cloud local archive solution. Online transmitters measuring H_2, moisture, and temperature simultaneously are presented in industrial documentation as a separate solution class.

As a practical initial operating mode, the following is recommended:

1–5 minutes for temperature and load; 15–60 minutes for HQA;

Event-based monitoring for OLTC; 24/7 alert mechanisms for operator notifications.

Conclusion

The implementation of intelligent transformer monitoring systems in energy facilities is not merely a sensorization project, but the creation of a standards-based cyber-physical platform. This platform must integrate data on thermal regime, gas analysis, moisture, bushings, and OLTC into a unified analytical environment, ensuring interoperability through IEC 61850, security through IEC 62351, and diagnostic validity through IEC 60076 and IEC 60599/IEEE C57.104.

References:

1. IEC 60076-2. Power Transformers – Part 2: Temperature rise for liquid-immersed transformers.

2. IEC 60076-7. Power Transformers – Part 7: Loading guide for mineral-oil-immersed power transformers.

3. Ilham Rahimli, Rashida Karimova, Najiba Piriyeva. Development of a Two-Parameter Inductive Sensor for use in Digital Program Control Systems for Machine Tools. PRZEGLAD Elektrotechniczny ISSN 0033-2097, R.100 NR 08/2024. WARSZAWA. pp.194-197

4. IEC 60599. Mineral oil-filled electrical equipment in service – Guidance on the interpretation of dissolved and free gases analysis.
5. Мамедова Г.В., Пириева Н.М., Ширинова М.Ч. Диагностика силовых трансформаторов // Интернаука: электрон. научн. журн. 2023. № 6 (276).
6. IEEE C57.104. Guide for the Interpretation of Gases Generated in Mineral Oil-Immersed Transformers.
7. Rzayeva S.V., Piriyeva N.M., Ganiyeva N.A. Modern methods of diagnostics of electric power equipment. The 19th International Conference on “Technical and Physical Problems of Engineering” 31 October 2023 International Organization of IOTPE. Rumıniya s.105-110
8. Wang, M., Vandermaar, A., Srivastava, K. Review of condition assessment of power transformers in service.
9. Rzayeva S.V., Ganiyeva N.A., Piriyeva N.M. Modern approaches to electrical
equipment diagnostics. İnternational Journal on “Technical and Physical Problems of Engineering” (IJTPE) – Issue 58, Volume 16, Number 1, March 2024
10. Пириева Н.М., Гусейнов З.Х. Анализ неисправностей в силовых трансформаторах. Международный научный журнал «Вестник науки» № 7 Том 4 (64) 2023 г. С 297-304
11. Tenbohlen, S., Jagers, J. Diagnostic measurements for power transformers.
12. Jahromi, A. N., Piercy, R., Cress, S. An approach to power transformer asset management using health index.
13. Абдуллаев Я.Р., Керимзаде Г.С., Мамедова Г.В, Пириева Н.М. Обобщенные показатели электромагнитных устройств с левитационными элементами. Известия ВУЗов" Приборостроение". Т.60, Санкт-Петербург. 2017, № 5. с.17 – 23
14. Пириева Н.М., Гусейнов З.Ф. Характеристики синхронных двигателей. Международный научный журнал «Вестник науки» № 3 (60) Том 4. С.241-246
15. Piriyeva N.M., Karimova R.K., Abdullayeva G.K. High-temperature heat-insulating materials: a compromise between thermal conductivity and reliability. Reliability: Theory and Applications, RTA, №2 (84) Vol. 20, 408-413 June 2025.
16. I.M.Marufov, Piriyeva N.M., E.S.Safiyev. Investigation of the application of the new induction system in vertical axis wind generators Reliability: Theory & Applications. 2025, December 4 (89), Vol. 20: 209-215
17. Пириева Н.М., Тагизаде Л.Н. «Ограничители перенапряжения и защита трансформаторов от перенапряжений». Международный научный журнал «ВЕСТНИК НАУКИ. № 1 (70) Том 3. 2024. С 772-778.