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METHOD AND MEANS OF MONITORING THE THERMAL STATE OF ROTOR WINDINGS OF A POWER GENERATOR

Valerii HRANIAK, Candidate of Technical Sciences, Associate Professor
Mykhailo Kotsiubynskyi Vinnytsia State Pedagogical University
Oleg HAYDAMAK, Candidate of Technical Sciences, Associate Professor
Vinnytsia National Agrarian University

ГРАНЯК Валерій федорович, к.т.н., доцент
Вінницький державний педагогічний університет імені Михайла Коцюбинського
ГАЙДАМАК Олег Леонідович, к.т.н., доцент
Вінницький Національний Аграрний Університет

The article addresses the issue of detecting inter-turn insulation defects in the field windings of a power generator rotor at early stages of their development, which is critically important for ensuring the reliable and safe operation of power equipment. A new thermal diagnostic method is proposed, based on measuring the coolant temperature in the end region of the rotor's cooling system. When combined with correction coefficients for temperature rise in individual excitation windings, this approach enables highly accurate identification of local overheating zones. This, in turn, serves as an indicator of the presence of inter-turn insulation defects, regardless of their formation mechanism—whether due to partial discharges, mechanical damage, or thermal aging. A key advantage of the method lies in its capability to diagnose insulation defects early, before they reach a critical stage, allowing maintenance to be carried out before significant deterioration in operational characteristics occurs.

In addition, a structural diagram of a new control device has been developed to implement the proposed method. A major feature of this design is the non-contact nature of temperature measurement of the field windings, which eliminates the influence of additional components on rotor balancing and avoids introducing asymmetry into its mechanical structure. The use of a synchronization system ensures high precision in spatial positioning and selective temperature measurement at specific monitored points, providing maximum in formativeness and diagnostic value of the obtained data. The proposed approach can be effectively integrated into modern condition monitoring systems for power units, thereby enhancing the overall safety and reliability of the equipment. The research results open new prospects for further development of thermal diagnostic methods in the field of power engineering, particularly for complex objects with limited access to structural elements during operation.

Key words: *interturn short circuit, generator, heating, winding, insulation, temperature.*
Eq. 5. Fig. 2. Ref. 13.

1. Problem formulation

Monitoring the technical condition of power-generating units during operation is a promising approach to enhancing reliability and reducing operational costs. These costs are often associated with scheduled but not always technically justified maintenance work, as well as with production losses due to taking the unit out of service for repairs. Among the most common defects in the electrical part of a power unit is the inter-turn short circuit in the field windings [1]. A distinctive feature of this defect is the temperature rise in both the damaged and undamaged parts of the field winding. Since temperature is one of the key parameters that significantly influence the chemical and physical properties of materials [2, 3], including the dielectric properties of insulation, overheating of the undamaged sections results in accelerated wear. Upon reaching a critical temperature threshold, a runaway effect may occur, leading to rapidly escalating thermal degradation and substantial material losses.

Detection of such defects at the stage of the runaway process – when the current in the field winding sharply increases and thermal deviations become pronounced – is ineffective, as it indicates the presence of significant damage. On the other hand, early-stage detection is technically challenging, since it is difficult to distinguish current increases and thermal deviations caused by insulation defects from those induced by other non-informative factors, such as load fluctuations, the presence of higher harmonics, or ambient temperature changes. Therefore, the development of diagnostic methods and tools capable of detecting inter-turn insulation defects during operation at the early stages of their development is a relevant scientific and applied challenge that requires thorough investigation.

2. Analysis of recent research and publications

An urgent technical task of significant practical importance is the early diagnosis of inter-turn short circuits in the rotor windings of power-generating units. As demonstrated in studies [4, 5], a promising approach to the development of such diagnostic systems is the use of rotor winding temperature as an informative parameter, since its increase invariably accompanies the development of an inter-turn short circuit. Another advantage of this diagnostic method is the high accuracy of temperature measurement [1], as well as the high sensitivity of thermal losses to short circuits in part of the winding, since these losses are proportional to the square of the current.

The rotor windings of synchronous generators – being the most common type of power-generating electrical machines – have specific characteristics. These include the flow of direct current through the windings, with current levels regulated within relatively narrow limits (sufficient to ensure minimal generation of intrinsic reactive power and fully determined by the current load conditions); a relatively small number of turns in each winding (approximately 200); considerable length of the windings; and minor resistance variation, primarily due to the thermal dependence of the winding material's resistance [6].

3. The purpose of the article

Based on the above, the development of thermal diagnostic methods and compatible monitoring tools for assessing the technical condition of the inter-turn insulation in the excitation windings of power-generating units appears to be a promising direction. Such systems should enable the reliable detection of insulation defects at early stages of their development during regular operation within the technological process.

4. Results and discussion

The thermal state of the rotor’s field winding, in terms of the average temperature rise above the temperature of the air passing through the generator rotor, can be approximately described as follows [7, 8]:

$$\Delta T = \frac{p_{el}}{S_a \alpha}, \quad (1)$$

where α – conditional heat transfer coefficient from a conditional cooling surface; S_a – area of the conditional cooling surface of the winding; P_{el} – heat losses on the excitation winding conductors, which can be calculated using the Joule-Lenz law:

$$p_{el} = I_w^2 R_w, \quad (2)$$

where I_w – the winding current; R_w – active resistance of the winding.

A distinctive feature of inter-turn insulation defects is that their occurrence does not lead to changes in the effective cooling surface area or the effective heat transfer coefficient, as these are fully determined by the size and shape of the rotor and winding, as well as the parameters of the cooling system and the inlet temperature of the coolant [8]. Considering the fact that the transit time of the coolant along the winding is significantly longer than the rotation period of the generator rotor, the coolant flow, due to the rotational movement of the rotor, will interact uniformly with all field windings. Therefore, at the early stages of defect development, the temperature increase of the coolant caused by a single winding will not significantly affect the overall coolant temperature, which, under identical conditions, can be considered constant. At the same time, the relatively short length of the rotor ensures a small time constant for the temperature response of the coolant in the end part of the rotor, enabling the prompt detection of temperature changes, should they occur.

Analyzing the progression of known inter-turn insulation defects reveals that two extreme cases of additional heat source distribution can be identified: inter-turn short circuits with low and high transition resistance. In the case of a short circuit with low transition resistance (i.e., the fault resistance is much smaller than the resistance of a single turn), the heating of the winding will be general, without a distinctly localized hot spot. This is due to the increased current in the winding, caused by the reduction in overall coil resistance. Conversely, in the case of a high transition resistance (i.e., comparable to the resistance of a single turn), a significant increase in current is not observed, but the specific portion of the winding where the fault occurs will exhibit localized overheating.

It is important to note that, in real-world defective equipment, both types of heating mechanisms typically coexist, though their relative contributions may vary significantly [9]. Therefore, in the absence of prior information about the specific defect type, thermal diagnostic systems must be designed to detect both extremes and any intermediate cases.

In the event of an inter-turn short circuit with low transition resistance, the current in the affected winding will increase. Since the relative temperature rise in the early stages of the defect will not exceed a few degrees Celsius, the temperature-induced change in the winding's electrical resistance can be neglected. Thus, assuming a constant applied voltage, the new current value in the defective winding can be determined as follows:

$$I_{dw} = I_w \left(\frac{N}{N-k} \right), \tag{3}$$

where N – number of winding turns; k – number of turns shunted due to inter-turn short circuit.

Given the relatively small number of turns in the rotor winding (approximately 200), it becomes evident that a short circuit involving a single turn will lead to an increase in excitation current of approximately 0,5%. Taking into account equations (1) and (2), and assuming that the heat transfer conditions between the winding and the coolant remain unchanged, the resulting temperature rise of the winding above the coolant temperature will be around 1%. This value does not exceed the permissible range of temperature variation for the winding [10]. However, the temperature increase caused by such a defect will be localized. Considering the poor heat transfer between different windings and the relatively small absolute temperature difference, this effect will only concern a single winding, and such a localized rise will not be observed in cases where the temperature increase is caused by other factors.

In the case of an inter-turn short circuit with high transition resistance, the increase in excitation current can be considered negligible. Nevertheless, a hot spot will develop in the affected coil. Since the thermal conductivity of the winding's metal is several orders of magnitude higher than that of the inter-turn insulation [11], it is clear that heat transfer along the winding will be significantly more effective than in other directions. Taking this into account, along with the axial design of the rotor winding (winding slots are aligned parallel to the rotor shaft axis) [6], it can be concluded that heat from the overheated zone will effectively spread toward the end and frontal parts of the winding.

In physical terms, such a heat transfer system essentially behaves like a complex multilayer heat transfer model with an extended thickness of the initial section. The temperature field in this case will be characterized by a set of initial functions of the following type [8, 12]:

$$\begin{cases} T = A_1 \dfrac{x^{1-n}}{1-n} + B_1 - \dfrac{q_1 x^2}{2\lambda_1 (n+1)} \text{ if } x_1 \le x \le x_1, \\ T = A_2 \dfrac{x^{1-n}}{1-n} + B_2 - \dfrac{q_2 x^2}{2\lambda_2 (n+1)} \text{ if } x_2 \le x \le x_3, \\ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \\ T = A_j \dfrac{x^{1-n}}{1-n} + B_j - \dfrac{q_j x^2}{2\lambda_j (n+1)} \text{ if } x_j \le x \le x_{j+1}, \\ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \\ T = A_k \dfrac{x^{1-n}}{1-n} + B_k - \dfrac{q_k x^2}{2\lambda_k (n+1)} \text{ if } x_k \le x \le x_{k+1}, \end{cases} \tag{4}$$

where x – spatial coordinate associated with the origin at the center of the overheated zone; A_1, B_1, A_1, B_1, … A_k, B_k – integration constants; q_1, q_2, … q_k – established specific power of internal heat sources of each section of a complex system; λ_1, λ_2, … λ_k – average thermal conductivity of sections of a complex system.

When solving equation (4) for the considered complex system, the following expression for the heat flux density can be obtained:

$$Q = \frac{T_1 - T_2}{\sum_{i=1}^{k} \frac{x_i}{\lambda_i}}, \tag{5}$$

where T_1 – temperature of the center of the overheated zone; T_2 – temperature of a certain section of the winding.

As seen from (5), the excess temperature rise at a given point of the winding is linearly related to the overheating at the center of the abnormally heated zone. Moreover, considering that the thermal conductivity of the winding metal is orders of magnitude higher than that of the inter-turn insulation, the determining factor in the sensitivity of heat transfer reduction will be the thickness of the insulation coating rather than the axial distance from the defective zone. Based on this, it can be concluded that in the event of such an inter-turn insulation defect, temperature monitoring at multiple spatially distributed points on the winding surface is ineffective, since the measured excess temperature rise will not significantly differ.

Taking into account the fact that an actual defect is typically characterized by features of both types discussed above, it can be concluded that the most effective location for monitoring the temperature of the excitation windings is their end-winding area. This area is the farthest from the inlet of the cooling system and is the most convenient (considering the generator's design) for measuring the temperature of the excitation pole windings.

An additional complication in detecting inter-turn insulation defects is the presence of temperature variation between identical point positions on different windings. For non-defective equipment, this variation lies within the range of 4.5-8.2% [8], making it ineffective to directly compare the temperature of a specific winding to the average value. However, as shown in [1, 13], the relative temperature excess at a specific point on a particular winding remains constant regardless of the operating mode. This makes it possible to account for such variation by introducing appropriate correction coefficients for each coil.

Taking this into account, the method for monitoring the condition of the inter-turn insulation of synchronous generator windings can be represented in the form of an algorithm shown in the block diagram (Fig. 1).

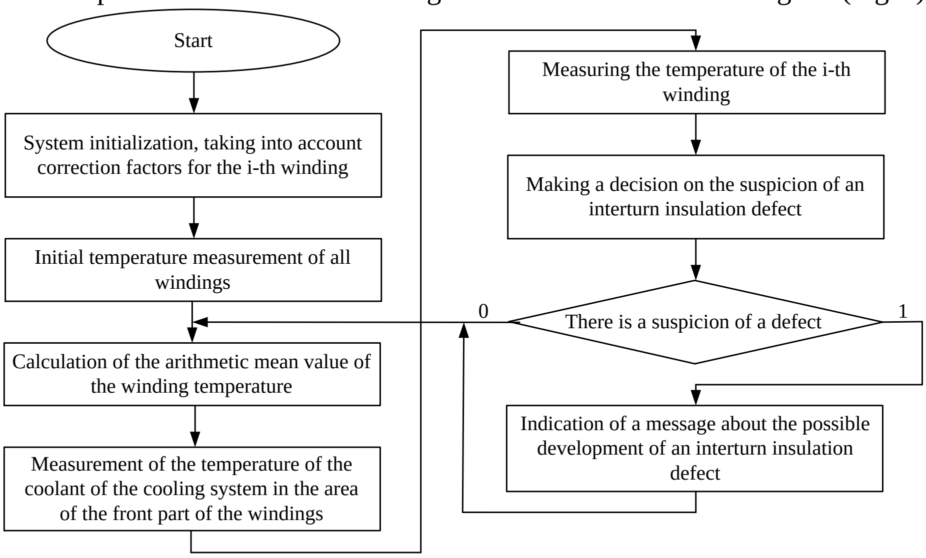

Fig. 1. Block diagram of the implementation of the method for monitoring the development of defects in the interturn insulation of the windings of a power generator

The structural feature of implementing this method is the limited possibility of placing additional technical devices on the surface of the excitation windings, which necessitates the use of non-contact temperature measurement methods. In this case, an important task, considering the rotational movement of the rotor and the need to monitor the inter-turn insulation condition in both steady and transient operating modes of the unit, is the spatial synchronization of the sensor with the selected controlled positions of the points on each of the windings. Any deviation from these positions can introduce significant measurement errors. Therefore, to ensure synchronization of the rotor's angular position with the moment of starting the measurement conversion, it is advisable to introduce an additional channel for measuring the rotor's angular position into the monitoring system. The temperature measurement of the cooling medium in the front part of the unit can be carried out using contact measurement devices, and, given the inertia of the temperature change process, it does not require additional synchronization.

Thus, for the implementation of the proposed monitoring method, a device is suggested, the structural diagram of which is shown in Fig. 2.

The device presented in Fig. 2 works as follows: The non-contact temperature sensor 1 converts the temperature of the designated position of the excitation winding into a proportional voltage value. The signal from the output of the non-contact temperature sensor 1 is fed through the first informational input of the multiplexer 4 to the input of the analog-to-digital converter.

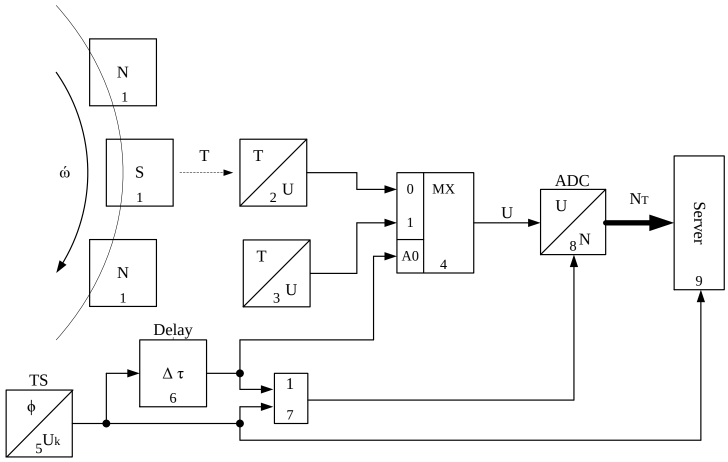

Fig. 2. Structural diagram of a means of monitoring the condition of interturn insulation of an electric generator

The special feature of the multiplexer 4 is that its first informational input is connected to its output when a logical zero signal is applied to the address input. The second informational input of the multiplexer 4 is supplied with the voltage value from the output of the contact temperature sensor 3, whose output signal is proportional to the temperature of the cooling medium in the front part of the unit. When the rotor of the unit turns to the next position, the output of the angular position sensor 5 generates a signal, which is sent to the input of the delay line 6, the second input of the OR logic element 7, and the synchronization input of the server 9. The output of the OR logic element 7 sends the signal to the control input of the analog-to-digital converter 8, which, on its rising edge, initiates the measurement conversion process of the signal proportional to the temperature of the excitation winding. After the analog-to-digital conversion is completed by the converter 8, the delay line 6 generates a high-level logical signal that lasts for the time sufficient for the conversion process to be completed. The high-level logical signal from the output of the delay line 6 switches the multiplexer 4 and initiates the measurement conversion process of the analog-to-digital converter 8, which then measures the signal from the output of the contact temperature sensor 3. The results of the temperature measurements of the excitation winding and the cooling medium are transmitted via a communication line to the server 9, where they are processed and, if necessary, displayed.

5. Conclusion

A new thermal method for diagnosing defects in the inter-turn insulation of the rotor windings of a power generator has been proposed. This method, by measuring the temperature of the coolant in the front part of the rotor and introducing correction factors for the temperature excess of each individual excitation winding, enables the early-stage diagnosis of inter-turn insulation defects, regardless of their formation type.

A structural diagram of a new device for monitoring the state of the inter-turn insulation of the pole windings of the power generator has been developed. This device, implementing the proposed monitoring method, is characterized by non-contact temperature measurement of the pole windings, which does not introduce asymmetry in the mechanical part of the rotor, while providing increased measurement accuracy through the use of a synchronization system. This system allows for temperature measurement at selected controlled positions of the windings.

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МЕТОД ТА ЗАСІБ КОНТРОЛЮ ТЕРМІЧНОГО СТАНУ ОБМОТОК РОТОРА ЕЛЕКТРОГЕНЕРАТОРА

У статті розглянуто проблему виявлення дефектів міжвиткової ізоляції полюсних обмоток збудження ротора силового електрогенератора на ранніх етапах їх розвитку, що є критично важливим для забезпечення надійної та безаварійної роботи енергетичного обладнання. Запропоновано новий термічний метод діагностування, який базується на вимірюванні температури теплоносія системи охолодження у лобовій частині ротора, що у поєднанні з уведенням поправочних коефіцієнтів на перевищення температури окремих обмоток дозволяє з високою достовірністю ідентифікувати локальні зони перегріву. Це, своєю чергою, є індикатором наявності дефектів міжвиткової ізоляції, незалежно від механізму їх утворення – часткові розряди, механічні пошкодження або термічне старіння. Важливою перевагою методу є його здатність до ранньої діагностики ізоляційних дефектів ще до моменту їх критичного розвитку, що дозволяє проводити технічне обслуговування агрегата на етапі, коли ще не відбулося суттєвого погіршення експлуатаційних характеристик.

Крім того, розроблено структурну схему нового засобу контролю, який реалізує запропонований метод. Основною особливістю цієї схеми є безконтактний характер вимірювання температури полюсних обмоток, що усуває вплив додаткових елементів на балансування ротора й не викликає асиметрій у його механічній частині. Завдяки використанню системи синхронізації досягається висока точність просторового позиціювання та вибіркового вимірювання температури у конкретних контрольованих точках, що забезпечує максимальну інформативність отриманих даних та їхню діагностичну цінність. Представлений підхід може бути ефективно інтегрований у сучасні системи моніторингу стану енергетичних агрегатів, підвищуючи загальний рівень безпеки та надійності обладнання. Результати дослідження відкривають нові перспективи для подальшого розвитку методів термодіагностики в галузі енергетичного машинобудування, зокрема – для складних об'єктів з обмеженим доступом до елементів конструкції в умовах експлуатації.

Ключові слова: *міжвиткове коротке замикання, генератор, нагрів, обмотка, ізоляція, температура.*

Ф. 6. Рис. 2. Літ. 13.

INFORMATION ABOUT THE AUTHORS

Valerii HRANIAK – Candidate of Technical Sciences, Associate Professor, Associate Professor of the Department of Mathematics and Informatics, Mykhailo Kotsiubynskyi Vinnytsia State Pedagogical University (32, Ostrozkogo St., Vinnytsia, 21008, Ukraine, e-mail: titanxp2000@ukr.net, https://orcid.org/0000-0001-6604-6157).

Oleh HAYDAMAK – Candidate of Technical Sciences, Associate Professor, Associate Professor of the Department of Power engineering, electrical engineering and electromechanics of Vinnitsa National Agrarian University (3 Soniachna St., Vinnitsa, Ukraine, 21008, e-mail: haidamak@vsau.vin.ua, https://orcid.org/0000-0001-5116-6017).

ГРАНЯК Валерій Федорович – кандидат технічних наук, доцент, доцент кафедри математики та інформатики Вінницького державного педагогічного університету імені Михайла Коцюбинського (вул. Острозького, 32, м. Вінниця, 21001, Україна, e-mail: titanxp2000@ukr.net, https://orcid.org/0000-0001-6604-6157)

ГАЙДАМАК Олег Леонідович – кандидат технічних наук, доцент, доцент кафедри Електротехніки, електроенергетики та електромеханіки Вінницького національного аграрного університету (вул. Сонячна, 3, м. Вінниця, Україна, 21008, e-mail: haidamak@vsau.vin.ua, https://orcid.org/0000-0001-5116-6017).