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Calculation of the impact of mechanical stress caused by differential protection operation on the service life of a power transformer

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ABSTRACT: This study investigates the impact of mechanical stress caused by differential protection operation on the service life of power transformers. During short-circuit conditions, the current in transformer windings can exceed its nominal value by several times, generating intense radial and axial forces that accelerate deformation, insulation cracking, and mechanical fatigue. A mathematical model was developed to determine equivalent short-circuit currents and resulting mechanical stresses using axial and radial stress coefficients derived from the transformer's geometry. Based on fatigue theory, a cumulative damage function D(t) was formulated to quantify mechanical degradation over time.The model enables evaluation of how differential protection–induced stress affects transformer lifetime and provides a foundation for predictive diagnostics, lifetime estimation, and improved operational reliability of power transformers.

KEYWORDS: Power transformer, differential protection, mechanical stress, short-circuit current, axial force, radial force, fatigue strength, cumulative damage, lifetime estimation, thermal and mechanical loading, electromagnetic forces, winding deformation, mathematical modeling, reliability assessment, remaining useful life (RUL).

I.INTRODUCTION

Since power transformers are among the most critical components in electric power generation, transmission, and distribution systems, their reliable and long-term operation ensures the stable performance of the entire power network. Among the main factors that determine the technical lifetime of transformers are thermal loading, electrical insulation aging, and mechanical stresses that occur during short-circuit conditions.

During a short circuit, the current flowing through the transformer windings can exceed its nominal value many times, resulting in significant radial and axial mechanical forces. Consequently, winding deformation, insulation cracking, and mechanical fatigue processes accelerate within the internal structure of the transformer. Therefore, short-circuit events — even when protection devices operate promptly — can significantly reduce the overall service life of the transformer.

Differential protection is one of the most important protection schemes that reliably safeguards power transformers against internal short circuits. It operates within an extremely short time (10–40 ms), effectively preventing major faults. However, the operation of this protection itself produces high levels of mechanical stress in the transformer structure. Hence, evaluating the influence of short-term but intensive loads caused by differential protection on transformer lifetime is of both scientific and practical importance.

II. RESULTS AND DISCUSSIONS

When the differential protection of a transformer is activated, it is first necessary to determine the value of the short-circuit current I_{qt} observed in the transformer, as well as the resultant equivalent current across the phases. The instantaneous value of the short-circuit current can be determined using Equation (3.1) below:

$$I_{qt}=\frac{I_n}{\frac{U_{k\%}}{100}} \tag{3.1}$$

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Here, I_{qt}— the instantaneous value of the short-circuit current (A); I_n — the rated (nominal) current of the transformer (A);($U_{k\%}$) — the short-circuit voltage of the transformer (%).

When a short-circuit fault occurs in a transformer, it should be noted that this phenomenon can appear in all three phases simultaneously. Consequently, the total current responsible for the overall mechanical loading is equal to the algebraic sum of the short-circuit currents in the three phases. Therefore, the algebraic equivalent value of the short-circuit currents in the three phases of the transformer is determined using Equation (3.2).

$$I^2_{ekv}= I^2_{qt.a} + I^2_{qt.b} + I^2_{qt.c} \tag{3.2}$$

Here, I_{ekv} — the equivalent effective value of the short-circuit currents acting on the transformer during the short-circuit condition (A); I_{qt} — the instantaneous values of the short-circuit currents in the three phases (A).

During the short-circuit process, the instantaneous values of the equivalent phase currents are identical, since the internal impedances of the windings are equal, which means that the same current flows through each phase. Taking this into account, the value of I_{ekv} can be expressed by Equations (3.3) and (3.4).

$$I^2_{ekv}= 3\ I^2_{qt} \tag{3.3}$$

$$I_{ekv}= \sqrt{3}I_{qt} \tag{3.4}$$

Through Equation (3.4), a relationship between the resultant values of the equivalent currents and the instantaneous short-circuit current is established. Using this expression, the maximum mechanical stress generated in the transformer during the short-circuit event can be determined.

During a short circuit, radial and axial (horizontal and vertical) compression forces arise in the magnetic core and windings of the transformer within a few milliseconds. Once the instantaneous values of these forces are identified, the resultant force acting on the transformer can be determined, which represents the total mechanical load experienced by the structure.

To evaluate the mechanical stress within the transformer's internal components, calibration values of the axial and radial forces must be determined. The calibration values of the vertical and horizontal mechanical stresses acting on the transformer windings are calculated using Equations (3.5) and (3.6).

$$\sigma_a=k_a\ I^2_{ekv} \tag{3.5}$$

$$\sigma_r=k_r\ I^2_{ekv} \tag{3.6}$$

Here, σ_a — the mechanical stress acting in the axial direction; σ_r= — the mechanical stress acting in the radial direction; k_a and k_r — the axial and radial mechanical stress coefficients, respectively, which arise in the transformer windings as a result of inductive current effects.

Since the axial and radial mechanical stress coefficients vary depending on the internal design and geometry of the transformer, their values are determined by the number of winding turns (N), the winding radius (r), and the winding height (h), as expressed by Equations (3.7) and (3.8).

$$k_r= \frac{\mu_0 N^2}{2\pi r} \tag{3.7}$$

$$k_a= \frac{\mu_0 N^2}{2h^2} \tag{3.8}$$

Here, k_r and k_a are the radial and axial mechanical stress coefficients that arise in the transformer windings as a result of inductive current effects; N — the number of winding turns; μ_0 — the magnetic constant permeability, $4\pi\times10^{-7}$ H/m, h — the height of the transformer winding m; r — the radius of the transformer winding (m).

Based on the obtained expressions, the resultant mechanical stress limit can be determined using the Pythagorean theorem, which combines the axial and radial stress components into a single resultant value.

$$\sigma_n =I_{ekv} * \mu_0 * \frac{1}{2}\sqrt{(\frac{N^2}{\pi r})^2 + (\frac{N^2}{h^2})^2} \tag{3.7}$$

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III. CONCLUSION

Based on the derived Equation (3.7), the resultant value of mechanical stress makes it possible to determine, according to the fatigue theory, the extent of mechanical loading experienced by the transformer during the short-circuit event.

Each material used in a transformer has a specific strength limit, which gradually decreases over time under the influence of varying pressures and stresses. The mechanical strength limit and the fatigue strength limit of a material differ in magnitude, and the ratio between these two parameters represents the cumulative damage fraction for that particular material.

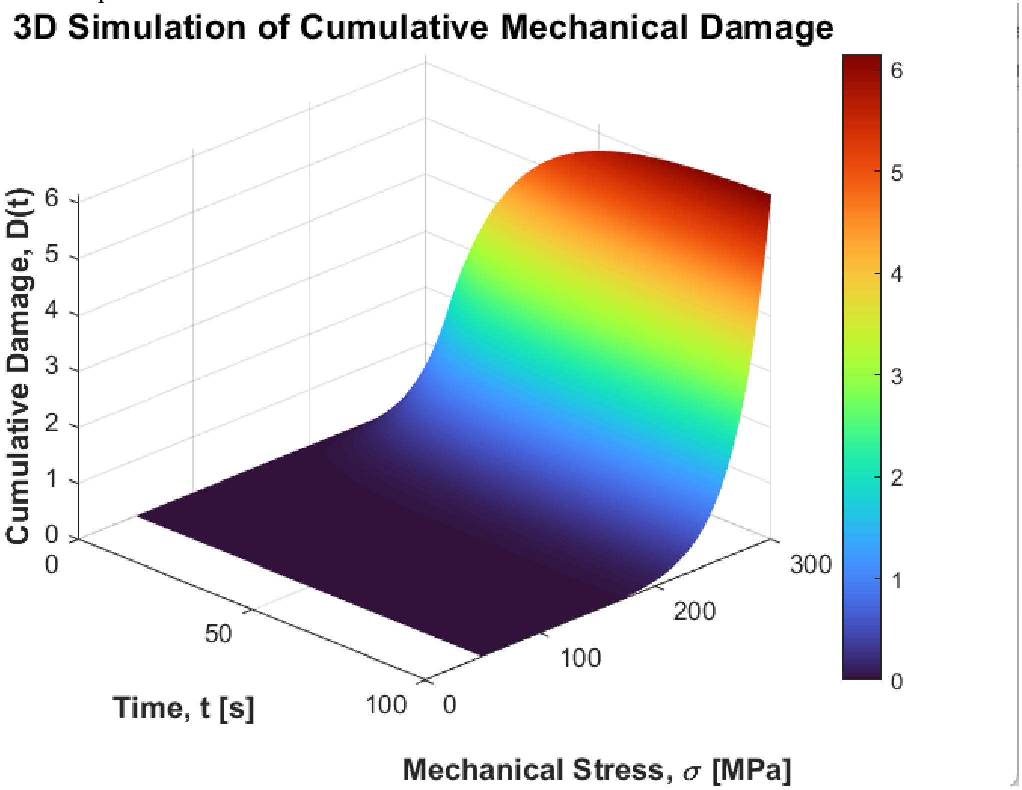

Figure 1. Simulation of cumulative damage as a function of mechanical stress

Before evaluating this damage fraction, it is necessary to determine the strength limit of the aluminum used in the transformer windings, as it defines the material's resistance to stress under repeated short-circuit conditions.

$$\sigma_{ch}=k\sigma_m \qquad (3.8)$$

Here, k is a coefficient determined by the specific material type. Since aluminum is commonly used as the winding material in transformers, its value can be assumed to be 0.35. represents the ultimate tensile strength of the material and is considered equivalent to the stress required to cause fracture in aluminum, measured in N/m^2.

The cumulative damage fraction that develops over time is determined by the time-dependent integral of the ratio between the instantaneous mechanical stress and the material's strength limit, as expressed by the following relation:

$$D(t)=\int_0^t \left(\frac{\sigma_n}{\sigma_{ch}}\right)^{1/b} d(t) \qquad \dots\dots\dots\dots\dots\dots\dots (3.9)$$

Here, σ_n — mechanical stress generated as a result of differential protection operation (N/m²); σ_{ch} — strength limit of the material used in the transformer windings (N/m²); b — fatigue strength exponent of the material.

Using the obtained value of (D(t)), which represents the cumulative damage fraction, the remaining service life of the transformer under mechanical stress can be determined. Since the results are expressed as fractional values, multiplying them by the rated (guaranteed) service life allows determining the exact remaining operating time in days, months, or years.

REFERENCES

1.Togaymurodov S.Z, Ataullayev N.O, Rasulova B.I " MOYLI TRANSFORMATORLARNI QOLGAN XIZMAT QILISH MUDDATINI BIRLAMCHI PARAMETRLARIDAN KELIB CHIQQAN HOLDA TASHXISLASH" Konchilik Xabarnomasi jurnali, Navoiy 2025 DOI:10.54073/GV.2025.3.102.021, 98-103 pages

2.S.Z Togaymurodov "TRANSFORMATORLARNING ISHLASH JARAYONLARIDA TEMPERATURANING O'ZGARISHI VA UNING TA'SIR NATIJASIDA MAGNIT O'ZAKNING FERROMAGNIT XUSUSIYATINI YO'QOTISH SABABLARI" Journal of Advances in ENERGY Engineering Technology Vol.6(18) Navoi, 2025, 37-41 betlar

3.Ataullayev A.O, Togaymurodov S.Z "Transformatorlarda magnit o'tkazgichlarining tashqi elektr maydonini kuchaytirishi sabablari" Fargona davlat texnika universiteti ilmiy texnik jurnali–2025/29/4 Farg'ona, 103-107 pages

4.de Azevedo, A. C., Delaiba, A. C., de Oliveira, J. C., Carvalho, B. C., & de S. Bronzeado, H. (2007). Transformer mechanical stress caused by external short-circuit: a time-domain approach. Proceedings of the 2007 IEEE International Power System Technology (POWERCON). ipstconf.org+1

5. Zahra, S. T. (2025). Power transformer health index and life span assessment. Electric Power Systems Research. ScienceDirect

6. Majzoobi, A., Mahoor, M., & Khodaei, A. (2017). Machine Learning Applications in Estimating Transformer Loss of Life. arXiv preprint. arXiv

7. Soleimani, M., & Kezunovic, M. (2020). Economic Evaluation of Transformer Loss of Life Mitigation by Energy Storage and PV Generation. arXiv preprint. arXiv

8. Moradzadeh, A., Pourhossein, K., Mohammadi-Ivatloo, B., Khalili, T., & Bidram, A. (2020). Radial Deformation Emplacement in Power Transformers Using Long Short-Term Memory Networks. arXiv preprint. arXiv

9. Köhler, M., et al. (2017). Load Assumption for Fatigue Design of Structures and Components. Springer. PDF библиотека

10. Dowling, N. E. (2012). Mechanical Behavior of Materials: Engineering Methods for Deformation, Fracture, and Fatigue (4th ed.). Pearson. dl.ojocv.gov.et

11. Budynas, R. G., & Sadegh, A. M. (2020). Roark's Formulas for Stress and Strain (9th ed.). McGraw-Hill. Википедия