Impact of mechanical stresses caused by differential protection operation on power transformer lifetime

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Abstract. Power transformers play a critical role in the stability of the power system; their reliability over a long period of time is important. Even ultra-fast differential protection (10 40 ms clearing time) results in very large short-circuit currents, subjecting the windings to large radial and axial electromagnetic forces, and resulting in significant mechanical stresses. The stresses cause winding deformation, make the insulation weaker over time, and mechanical fatigue increased. The study involved an in-depth examination of a transformer of 20 MVA that used oil as the coolant. The magnitude of short-circuit current, the equivalent mechanical stresses (radial, axial and resultant) and cumulative damage were determined analytically. The linear damage accumulation rule of Miner was used to determine the loss of the remaining useful life due to mechanical action of a difference protection activity only.

INTRODUCTION

Power transformers are among the most critical equipment in electric power generation, transmission and distribution systems. Therefore, their reliable and long-term operation directly guarantees the stable functioning of the entire power system. Among the main factors determining the technical resource of transformers, the following play a key role in assessing the remaining serviceability of oil-immersed transformers: variations in thermal loading, aging of paper insulation in the windings, cumulative damage caused by mechanical stresses arising from short-circuit currents [1-4].

In transformers with oil filled in them, the current within the windings during a short-circuit fault can be tens of times that of the nominal value. This causes the windings to be exposed to very high mechanical forces both radial and axial (horizontal and vertical) forces. As a result, winding deformation, insulation breakdown, and mechanical fatigue actions are enhanced in the internal structural components of the transformer. That is why, despite the operation of fast-acting protection systems, short-circuit incidences still result in the observed decrease of the total service life of the transformer [5-9].

However, one of the most significant and dependable types of power transformer protection against short circuits inside the transformer is the existence of differential protection. It acts also in very short period (10 – 40 ms), thus eliminating serious emergencies. Nevertheless, the process of the protection actuation generates high-level mechanical stresses in the transformer structure. Thus, the scientific and practical significance of investigating the effectiveness of these momentary, but heavily loaded overloads which are manifested when a current differential occurs on the work of the transformer and its service life is enormous [10-12].

EXPERIMENTAL RESEARCH

To determine the cumulative damage occurring in the internal structure of an oil-immersed transformer due to the operation of differential protection, the primary passport parameters of the transformer are required. The present

research was carried out on a 20 MVA power transformer [13]. Its specific technical parameters are fully listed in Table 1, and all calculations were performed based on the data provided in Table 1.

Table 1. Technical parameters of the 20 MVA power transformer

Designation	Parameter value	Note
S_n	20 MVA	nominal power
U_1	110 kV	high voltage
U_2	6 kV	low voltage
$U_k\%$	10 %	short circuit voltage
μ_0	$4\pi \times 10^{-7}$ H/m	magnetic constant
N	220 ta	number of turns
r	0.25 m	radius of turns
h	0.5 m	hight of turns

Based on Table 1, the short-circuit current magnitude ($I_{s.c}$) occurring during differential protection operation, as well as the resultant equivalent short-circuit current across the phases, were first determined [14].

$$I_{s.c} = \frac{I_n}{\frac{U_{k\%}}{100}} \tag{1}$$

$I_{sh.c}$ – instantaneous short-circuit current, A; I_n – transformer rated current, A; $U_{k\%}$ – short-circuit voltage of the transformer, %.

Seeing that the total mechanical loading can be calculated by the algebraic (vector) sum of the currents in each of the three phases, a short-circuit event in a transformer can be caused by a short-circuit in a single or two or all three phases [28-30]. Thus, equation was used to work out the equivalent short-circuit current that produces the total mechanical stress in all three phases (2):

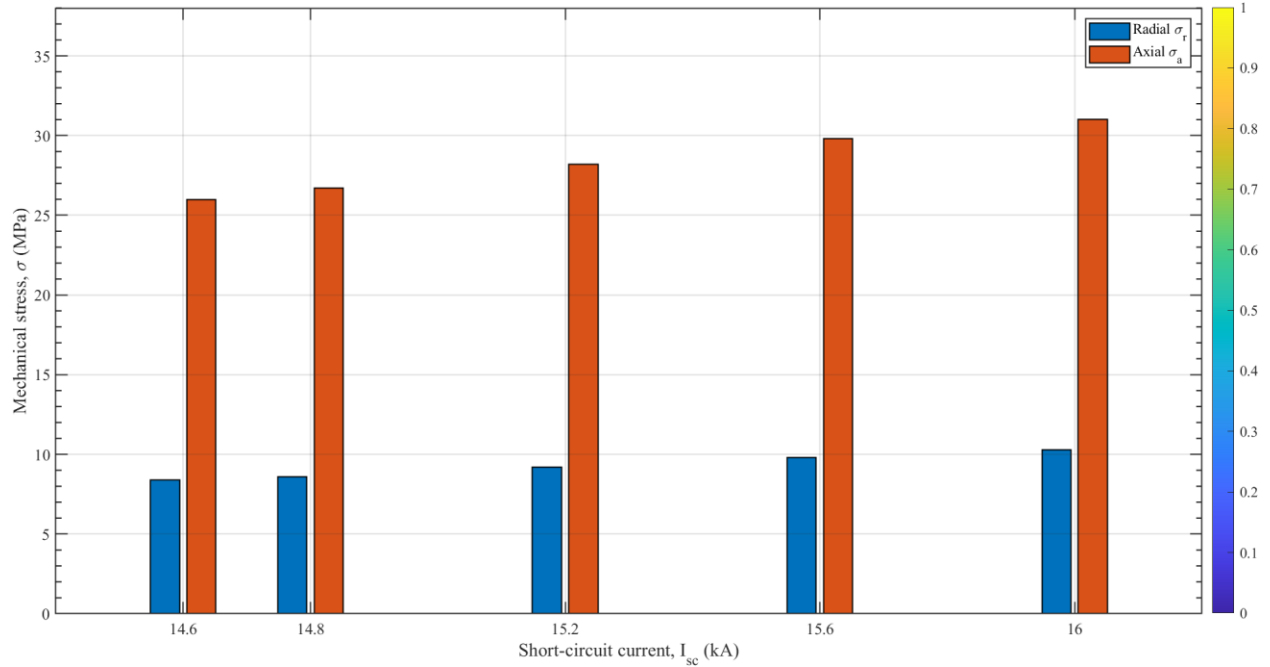$$I^2_{ekv} = I^2_{sc.a} + I^2_{sc.b} + I^2_{sc.c} \tag{2}$$

Figure 1. Correlation between short-circuit current and radial/axial mechanical stresses

Radial and axial (horizontal and vertical) electromagnetic forces are highest in a few milliseconds during short-circuit occurrence in transformer cores and windings which creates major mechanical strains in windings. The calibrated values of radial and axial forces have to be first determined to calculate the mechanical stresses in the inside structure of the transformer. The vertical (axial) and horizontal (radial) mechanical stresses of the windings of the transformer were obtained by equation (5) and (6) and calibrated to obtain the calculated values:

$$\sigma_a = k_a\, I^2_{ekv} \tag{3}$$

$$\sigma_r = k_r I^2_{ekv} \tag{4}$$

where: σ_a – mechanical stress acting in the axial direction, N/m²; σ_r – mechanical stress acting in the radial direction, N/m²; k_a, k_r – axial and radial mechanical stress coefficients arising from the inductive current in the transformer windings, respectively.

Since the axial and radial mechanical stress coefficients depend on the internal structural design of the transformer, their values were calculated as functions of the number of winding turns, winding radius, and winding height using Equations (5) and (6):

$$k_r = \frac{\mu_0 N^2}{2\pi r} \tag{5}$$

$$k_a = \frac{\mu_0 N^2}{2h^2} \tag{6}$$

where: k_r and k_a – radial and axial mechanical stress coefficients resulting from the inductive current in the transformer windings; N – number of winding turns; μ_0 – permeability of free space, $4\pi \times 10^{-7}$ H/m; h – height of the winding, m; r – mean radius of the winding, m.

Based on the derived expressions, the resultant mechanical stress was determined using the Pythagorean theorem. Figure 3.1 presents the characteristic dependence of radial and axial stresses on short-circuit current in the form of a bar chart constructed from the final calculated results for the 20 MVA transformer [15].

$$\sigma_n = I_{ekv} * \mu_0 * \frac{1}{2} \sqrt{\left(\frac{N^2}{\pi r}\right)^2 + \left(\frac{N^2}{h^2}\right)^2} \tag{7}$$

where: σ_n – resultant mechanical stress, N/m²; I_{ekv} – equivalent short-circuit current, A; μ_0 – permeability of free space, $4\pi \times 10^{-7}$ H/m; N, h, r – number of winding turns, winding height, and mean winding radius, respectively, m.

Graphical determination of the functional relationship between the resultant mechanical stress and the corresponding short-circuit current was made by use of equation (7). Using the resulting mechanical stress value of this equation, the extent of mechanical fatigue realized by the transformer was measured relative to the fatigue theory per incidence of short circuit. The transformer has a definite strength capacity of every material it is composed of, which is consumed gradually with constant mechanical stress and strains [25-54]. The expression of the ratio between the current mechanical stress to which the material is subjected and the fatigue strength limit of a material itself represents as a fraction of cumulative damage that has been accredited in the identical material. A deflection of this damage fraction must be calculated after establishing ultimate tensile strength (yield strength) of aluminum that is used in transformer windings first [16].

$$\sigma_{ch} = k\sigma_m \tag{8}$$

where: tensile strength (yield strength) of material, MPa; k coefficient depending on the material, in case of aluminum conductors commonly used in transformer windings, k = 0.35 is assumed; 0break tensile strength of material, assumed to be the pressure needed to rupture an aluminum., N/m² (or MPa).

RESEARCH RESULTS

The cumulative damage fraction is determined using the time-dependent integral of the mechanical stress ratio:

$$D(t) = \int_0^t \left(\frac{I_{ekv} * \mu_0 * \frac{1}{2} \sqrt{\left(\frac{N^2}{\pi r}\right)^2 + \left(\frac{N^2}{h^2}\right)^2}}{\sigma_{ch}} \right)^{1/b} d(t) \tag{9}$$

where: σ_n – resultant mechanical stress caused by the operation of differential protection, N/m²; σ_{ult} – ultimate tensile strength (yield strength) of the material used in the transformer windings, N/m²; b – fatigue strength exponent of the material [38-40].

Table 3. Cumulative damage fraction after observed short-circuit events

Type of short circuit	$I_{sh.c}$ (kA)	I_{ekv} (kA)	σ_a (M N/m²)	σ_r (M N/m²)	σ_n (M N/m²)	D(t) fraction	Cumulative damage(%)
1 phase	16	16.00	31.14	9.91	32.68	0.024963	2.50 %
1 phase	14.8	14.80	26.64	8.48	27.96	0.038339	1.34 %
1 phase	15.2	15.20	28.10	8.95	29.49	0.157482	1.66 %
1 phase	15.6	15.60	29.60	9.42	31.07	0.177878	2.04 %
1 phase	14.6	14.60	25.93	8.25	27.21	0.884591	1.20 %

Using the procedure outlined above, the equivalent short-circuit current, the resulting mechanical stress, and the cumulative damage fraction due to radial and axial stresses were evaluated for five registered short-circuit events

cleared by differential protection. The influence of this cumulative damage on the transformer's remaining technical lifetime is presented in table 3.

Using the computed value of the cumulative damage fraction $D_{d.p}(t)$, one can estimate the remaining operating life of the transformer under continuing mechanical stress. As the damage is normalized to the total lifetime, multiplying this fraction by the nominal design lifetime directly yields the reduction in residual life in calendar units (days, months, or years).
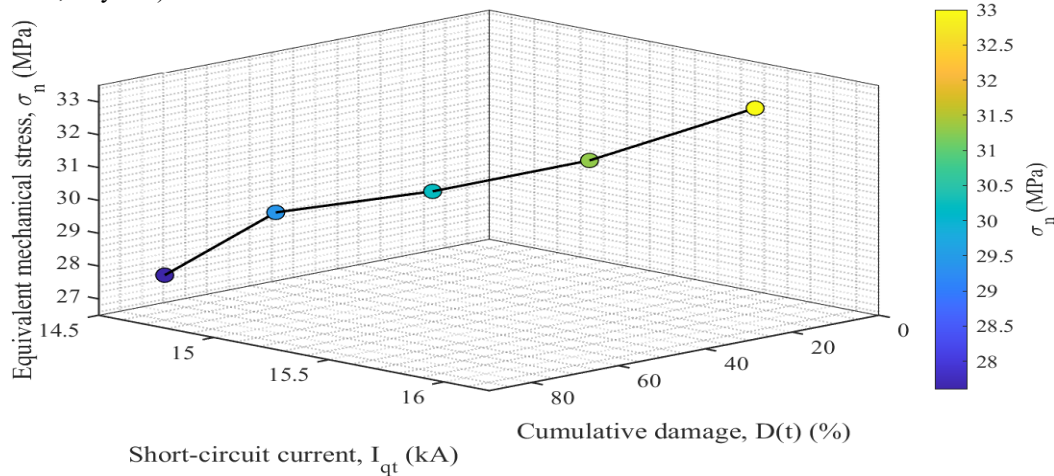

Figure 3. Relationship between cumulative damage and equivalent mechanical stress

To evaluate the residual lifetime of an oil-immersed transformer following the operation of differential protection, the remaining life can be expressed in terms of the cumulative damage fraction, as given by equation (10).

$$L_{l.l} = L_0 (1-D(t)) \tag{10}$$

where: $L_{l.l}$ – remaining service life of the transformer after the short-circuit event, years; L_0 – guaranteed (design) service life of the transformer, years; $D(t)$ – cumulative damage fraction.

On the basis of equation (10), the study shows that mechanical stresses, alongside insulation aging, must be taken into account in any realistic assessment of transformer residual life. The decline in service life is treated as an inverse function of accumulated damage and is modeled using Miner's linear damage accumulation rule coupled with mechanical fatigue theory. This method provides a quantitative measure of the lifetime lost after each operation of the differential protection [17-22].

Table 4. Change in transformer service life following observed short-circuit events

σ_n (M N/m²)	$D_{d.p}(t)$ fraction	Cumulative damage(%)	I_{ekv} (kA)	D (year)	L_l (year)
32.68	0.024963	2.50 %	16.00	0.6250	24.375
27.96	0.038339	1.34 %	14.80	0.3266	24.048
29.49	0.157482	1.66 %	15.20	0.399	23.648
31.07	0.177878	2.04 %	15.60	0.472	23.165
27.21	0.884591	1.20 %	14.60	0.277	22.887

The results presented in table 4 clearly show that the cumulative mechanical damage caused by short-circuit events is inversely proportional to the remaining service life of oil-immersed transformers. As the equivalent short-circuit current and the resultant mechanical stress increase, the reduction in the transformer's service life becomes more pronounced.

Figure 3.4 is a change in the remaining service life of a 20 MVA power transformer as a result of short circuit events observed over the past year. Despite the fact that the structural elements of the studied transformer (Scrolls, magnetic core, insulation system) are in an almost new state, the input cable lines connected to it are much more outdated. For this reason, a large number of single-phase ground short-circuit events have occurred within a year in connection with this transformer. According to calculations carried out according to IEC 60076-5 and IEEE heat aging models, the five recorded one-phase short circuit events reduced the remaining service life of the transformer to 2,113 years (771 days).
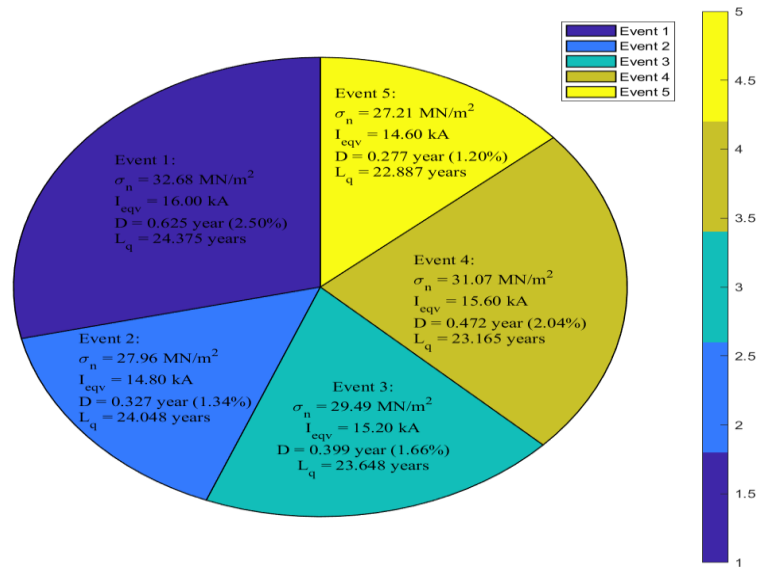
Figure 4. Dependence of the cumulative loss-of-life percentage of a 20 MVA power transformer on its service life

This means that the oil transformer is required to be replaced earlier than originally planned by 2,113 years (771 days). The indicated 2,113-year life loss corresponds only to cumulative insulation aging caused by thermal effects of external short circuit currents when differential protection is activated. The actual reduction in service life can be even greater if additional factors such as mechanical degradation of the scrolls, overloading hot spot temperature, moisture penetration are taken into account [23,24].

CONCLUSIONS

A understandable analysis on a 20 MVA power oil transformer indicated that even though the extremely fast (10-40 ms) start time of differential protection, repetitive short circuit events lead to very harmful and irreplaceable mechanical damage in the winding structure. When the electromagnetic force calculation method was applied in conjunction with Miner's linear damage cumulative rule and material fatigue theory, it was found that five one-phase Earth short-circuit events that occurred over a year reduced the remaining useful life of the transformer to 2,113 years (771 days) due to cumulative mechanical fatigue in wraps alone, then the electromagnetic force calculation method was applied in conjunction with Miner's linear damage cumulative rule and material fatigue theory, it was found that five one-phase Earth short-circuit events that occurred over a year reduced the remaining useful life of the transformer to 2,113 years (771 days) due to cumulative mechanical fatigue in wraps alone. The results clearly show that mechanical damage from external short circuit currents is a very important, but often overlooked, factor in assessing the end of life of Transformers. The insulation system is in an almost new state, and even when no visible thermal degradation is observed, concentrated mechanical stresses significantly accelerate the overall aging process, gradually weakening the winding fastening structures, distancing elements and conductors.

Therefore, when accurately assessing the remaining service life of power transformers in service, it is necessary to forcibly take into account the cumulative mechanical effects of all historical and ongoing short circuit events caused by the start-up of differential or other fast protections, other than traditional hot spot temperature and isolation degradation models (IEEE C57.91, IEC 60076-7). If mechanical damage is ignored, the lifetime of transformer can be predicted optimistically which may increase the unexpected failures in the future The method we developed, based on the analytical determination of Radial and axial forces, equivalent mechanical stress and fatigue-based damage totals, provides a practical and scientifically based tool for energy organizations for quantitative assessment of the mechanical life resource and optimization of transformer replacement or overhaul strategies. Heat-mechanical aging models are introduced to inform the significance of reliability of electrical systems Asset management and expensive unwanted interruptions are prevented.

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