Contribution of inrush current to mechanical failure of power transformers windings

Rafael M.R. Barros, Edson G. da Costa, Jalberth F. Araujo, Filipe L.M. de Andrade, Tarso V. Ferreira

1 Department of Electrical Engineering, Federal University of Campina Grande, Aprigio Veloso St., 882, Campina Grande, Brazil
E-mail: rafael.barros@ee.ufcg.edu.br

Abstract: This work presents a study regarding the contribution of inrush current to the occurrence of mechanical fatigue in windings of a power transformer and, consequently, the impact of that phenomenon on the equipment's lifetime. In order to perform the study, electromagnetic transient simulations were used to determine the inrush current in a three-phase transformer model. Then, three-dimensional simulations, based on the finite element method, were performed to determine the electromechanical stresses in the equipment windings, under the effect of the inrush current. Next, the methods of critical plans and Palmgren–Miner were applied to perform the fatigue study. From the results, the impact of inrush current on the integrity of the transformer's windings was determined, as well as, to estimate the reduction of lifespan of the equipment due to inrush occurrence. The number of inrushes needed for the total reduction of lifespan of the equipment due to mechanical fatigue was also determined. The results can be used in the transformers design stage, with the purpose of assisting the evaluation of mechanical withstand of equipment, which can minimise the possibility of failure and increase its lifespan.

1 Introduction

Among the factors that can cause the failure of a power transformer, those associated with electromechanical stresses in the windings can be highlighted. In literature, mechanical problems are the main cause of faults in large power transformers [1–3]. This type of failure may occur due to nonconformity in design or materials, in which case the transformer structure does not support electromechanical stresses due to overcurrent to which the equipment can be subjected.

Mechanical failures are characterised by the presence of deformations or displacements of windings, which in addition to structural damages, can lead to the failure of equipment insulation [4]. Deformations and displacements occur due to the action of electromechanical forces in windings. Those forces are associated with the high amplitudes and asymmetries of overcurrent that may arise in a transformer in some operational situations, like short circuits and energisations [5].

In order to reduce the probability of mechanical failure, the design of a transformer must include mechanical studies that ensure the equipment will withstand stresses to which it will be subjected. The design criterion employed by most manufacturers consists of avoiding stresses above the yield point of winding material. In this case, three-phase short-circuit current is considered the situation where the transformer would be subjected to the greatest amplitudes of mechanical stresses [6].

This consideration is due, in part, to international standards that are applicable to power transformers, since most of them treat short-circuit as the most critical operating condition for the equipment, as the case of IEC Standard 60076-5:2006, which deals with transformers mechanical withstand. Since the equipment must be accepted in tests described by these standards, manufacturers direct the project to meet their requirements.

However, during energisation of a transformer, the inrush current can reach values very close to the values of short-circuit current with a duration significantly longer [7]. The effects of the inrush current, in turn, are aggravated by the fact that inrush is considered a normal operating condition and, therefore, protection systems are programmed to not act when it occurs. This causes the inrush current to have a longer duration and a higher occurrence frequency than the short circuit current. In addition, even if forces acting on windings are lower than the material yield point, after a long period of operation, the component may fail due to the cumulative effect, or in other words, by fatigue.

In general, none of the two aspects highlighted in the previous paragraph are considered in transformers design methods currently. Moreover, there are a growing number of researches that point to the importance of these aspects, some of which can be cited [8–11]. Therefore, in order to determine the importance of such aspects in power transformers design, in-depth research on the cumulative effect of electromechanical stresses caused by inrush currents is necessary. This research can help to minimise the occurrence of mechanical failures and, consequently, to increase the lifespan of transformers, since results can help in the design stage of this equipment with respect to dimensioning of mechanical supports for its active parts.

In this context, the objective of this paper is to investigate the contribution of inrush current to mechanical fatigue of power transformer windings. To achieve this goal, the following steps were performed: determine the worst inrush current for a specific power transformer model; determine the electromechanical forces acting on the transformer windings during inrush; verify the possibility of mechanical fatigue in the windings due to inrush current and quantify the reduction of lifespan of the transformer due to the occurrence of successive inrushes.

2 Mechanical failure criteria

The choice of a certain criterion to analyse the mechanical failure of a component depends on the type of failure to be analysed. Mechanical failures can occur due to static mechanical stress, in which damage occurs at the same instant of the stress application, or due to fatigue, in which damage occurs after a long period of mechanical stress load repetition.

For static mechanical stress analysis, the most widely used criterion in ductile materials is the criterion of the maximum energy of distortion, also known as von Mises criterion, which will not be discussed in this paper [12].

In contrast, fatigue failure is a complex phenomenon, it occurs due to the application of fluctuating stresses that are lower than the stress required to cause failure during a single application of stress. When a material is subjected to repeated loading and unloading a
process of cumulative damage will occur, this process is briefly explained in the following three steps [13].

Step 1: microscopic cracks will begin to form at stress concentrators such a notch or other surface discontinuity. Even in the absence of a surface defect, crack initiation will eventually occur due to the formation of persistent slip bands, so called because traces of the bands persist even when the surface damage is polished away.

Step 2: Crack growth occurs when the first crack changes direction and propagates in a direction normal to the applied stress. Crack growth proceeds by a continual process of crack sharpening followed by blunting. Crack propagation during crack growth often produces a pattern of fatigue striations, with each striation representing one cycle of fatigue.

Step 3: Ultimate failure occurs when the fatigue crack becomes long enough that the remaining cross section can no longer support the applied load.

There are several methods that can be applied to fatigue analysis depending on the dynamic of mechanical stress load that a structure will be submitted. In the case of stresses caused by inrush current, a suitable criterion for evaluating fatigue failure is the critical plane method [14].

This method is useful for an initial analysis of the possibility of fatigue occurrence in a material subjected to a certain cycle of mechanical stresses. However, it is not sufficient to make a prediction about when the material will fail or how much its lifespan has been reduced after a certain stress load. To reach these goals, the Palmgren–Miner method can be used to evaluate cumulative damage on material [15]. Both methods and their applications for the case of power transformers are discussed in the following subsections.

2.1 Critical plans method

The critical plans method is based on the principle that fatigue is caused by a microstructural fissure that will take place and propagate in a specific plane of a structure's volume. This plane is known as the critical plane and has the conditions of stress or deformation, most favourable for appearance and propagation of the crack.

The method examines the state of mechanical stress in different orientations of space. The stress state, at a particular point of a volume element, can be described as a tensor with three normal components and three torque components. Therefore, the method considers the effects of multiaxiality and variation of stress amplitude [16].

The amplitude of stresses components varies each time the volume element is oriented in a different direction. This means that if a cut through a volume element is performed, the stress state in the plane that was created by the cut will vary depending on the orientation of this plane [14], which is illustrated in Fig. 1.

In the figure, it is noticed initially that the only components of traction and compression act on the plane with a certain amplitude, but, as the orientation of the plane modifies, torque components with different amplitudes also take place, which illustrates the principle of variation of stress state with the variation of plane orientation.

Thus, several plans can be considered for the same volume element and there are several criteria that can be used to determine which of the plans will be the critical plan. The Findley criterion, which is one of the most used, considers as the critical plane one in which the combination between the normal component and torque component is maximised. Mathematically, the Findley criterion is defined by (1) [14]

$$f = \frac{r^2 + k \cdot \sigma_n}{\tau}$$

wherein, $k$ and $f$ are typical parameters of the material, with $f$ given in Pascal and $k$ dimensionless; $r$ is the maximum torque in a plane, given in N m, and $\sigma_n$ is the maximum normal stress in the same plane, given in Pascal.

The material constant $k$ is related to the material's sensitivity to normal stresses. For ductile materials, $k$ typically varies between 0.2 and 0.3 [17]. The material constant $f$ is related to the torsional fatigue strength coefficient, which can also be related to the tensile fatigue strength [18].

The criterion can also be understood as follows: the plane that maximises the left side of (1) is the critical plan.

The result of the Findley criterion is given in terms of the fatigue utilisation factor ($f_{ud}$). This factor can be considered as a reciprocal of a safety factor, in which, for values above a certain limit fatigue failure will occur. Mathematically, $f_{ud}$ is defined by the ratio between the left side of (1) and the parameter $f$ of the material, as

$$f_{ud} = \frac{(r^2 + k \cdot \sigma_n)}{f}$$

A value of $f_{ud} < 1$ indicates that the component's stress cycle is below its fatigue limit and therefore, fatigue will not occur on the structure. In contrast, values of $f_{ud} > 1$ indicate that the structure will fail by fatigue.

Considering the information above, the critical plane method can be characterised as a design criterion. From its use and knowing the stress load to which a component will be submitted, it is possible to determine if will occur fatigue during its use or not. In contrast, the method does not allow to predict when fatigue will occur, in other words, it is not possible to know how many cycles of the mechanical stress load are necessary to occur failure, or yet, what is the impact of a mechanical stress load on the lifespan of a component.

In order to predict the moment of fatigue failure in a power transformer, a method that considers the cumulative effect of damages in the windings caused to each inrush event should be applied. The Palmgren–Miner method is widely used in literature with a similar purpose in the case of metal fatigue [15]. However, to apply this method, a deepening in the concepts of mechanical fatigue of metals is necessary, which will be realised in the following subsection together with the method presentation.

2.2 Palmgren–miner method for cumulative damage

The main way to characterise fatigue of a material is by using the Wöhler curves, or S–N curves. These curves relate applied stress amplitude to the number of cycles for fatigue failure of a material, as shown in Fig. 2.

The S–N curve of a material is obtained through fatigue tests standardised by a set of ASTM standards. However, in cases where an experimental program is not justified, the S–N curve can be estimated [19].

For the high-cycle fatigue region ($>10^5$ cycles) the S–N curve can be represented by a straight line on the logarithmic scale given by (3). Thus, to obtain the parameters of the curve, it is enough to know two points of it.

$$\sigma = aN^b$$

wherein, $\sigma$ represents the applied stress given in Pascal, $N$ is the number of cycles to failure, $a$ and $b$ are dimensionless parameters of the S–N curve which values depend on the material and tests conditions.
According to [19], for ductile materials the following procedure can be used to determine the S–N curve:

- the first point at $10^3$ cycles: alternating tension $\sigma_N = 0.75 \times \sigma_f$;
- the second point at $10^6$ cycles: fatigue limit tension $\sigma_p = 0.35 \times \sigma_f$.

Therefore, in the high-cycle fatigue region, the S–N curve of a material can be estimated based on its tensile strength ($\sigma_f$).

The S–N curve, obtained with the procedure above, estimates the behaviour of the test specimen standardised and tested under controlled environmental conditions. In practice, the behaviour of a material can be influenced by an extensive series of parameters, of which the following can be highlighted: surface finish, component size, working temperature, and stress concentration. For design purpose, scale factors may be added to the S–N curve in order to compensate for the influence of such parameters [12].

These factors are called reduction factors of the S–N curve and are applied to the fatigue limit tension as

$$\sigma_p = (k_k k_i k_t) \times \frac{1}{\eta} \times \sigma_{F0}$$

wherein, $k_k$ is the coefficient of surface finish, $k_i$ is the component size coefficient, $k_t$ is the coefficient of reliability, $k_t$ is the temperature coefficient, $\eta$ is the dynamic safety factor and $\sigma_{F0}$ is the fatigue limit for the original S–N curve given in Pascal, all other coefficients are dimensionless. Typical values of reduction coefficients for each type of material can be found in literature and, in the case of electrolytic copper used in transformer windings, are presented in Table 1.

From the presented concepts, it is possible to notice that the area below the S–N curve is related to the lifespan of a component in a given stress condition. Therefore, the area of the S–N curve of a new component is larger than that of a component in use, on other words, as the lifespan of a component decreases, its S–N curve changes [15]. This effect is known as reduction of the S–N curve and is illustrated in Fig. 3.

It is noted in Fig. 3 that each time the component undergoes a stress load, the S–N curve is reduced to a new shape with a lower area than the previous one. In this way, after a high number of applied stresses, the curve will be reduced to a shape that represents the end of the component's lifespan. This occurs because, under each stress situation, the component undergoes microstructural damage that is imperceptible, but causes a reduction in its supportability to new stresses loads.

It can also be noted from Fig. 3 that the reduction of S–N curve considers the changes in mechanical characteristics of the material after a certain number of successive events. Hence, the Palmgren–Miner method simulates an S–N curve that the material would have after suffering some damage, which means that the material characteristics are changing over time.

Based on this reduction principle, [20] proposed a method for estimating the percentage reduction in the lifespan of a component subjected to successive stresses loads. The method is based on a cumulative damage parameter defined as

$$D = \sum \frac{n_i}{N_i}$$

wherein, $D$ is a dimensionless parameter that represents the cumulative damage to a component after a quantity $q$ of stresses loads, $n_i$ is the number of applied cycles for a given stress $\sigma_i$ in Pascal, during the load and $N_i$ is the number of cycles required for that same stress $\sigma_i$ to damage the material.

The value of $N_i$ may be determined from (6), which is based on the coefficients of the material S–N curve

$$N_i = \left(\frac{\sigma_i}{\sigma_0}\right)^{a_i}$$

wherein

$$n_i = \left(1 - \frac{n_i}{N_i}\right)N_i$$

wherein $N_i$ is the number of cycles required to reach the fatigue limit of the material, which can be assumed to be $10^6$ for ductile materials [19]. The parameter $N_i$ can also be interpreted as a reduced material fatigue limit.

Based on the above information, after a number $q$ of stress loads, a reduced S–N curve can be determined for the material as

$$\begin{align*}
\sigma_{red} &= \frac{\log \sigma - \log \sigma_0}{\log n_i - \log N_i} \\
N_{red} &= 10^{\log n_i - \log N_i}
\end{align*}$$

Table 1 Typical values of the reduction coefficients for electrolytic copper

| Coefficient | Value |
|-------------|-------|
| $k_k$       | 0.800 |
| $k_i$       | 0.750 |
| $k_t$       | 0.689 |
| $k_f$       | 0.948 |
| $\eta$      | 3.000 |

Fig. 2 S–N curve for a non-ferrous metal

Fig. 3 Reduction effect in the S–N curve due to stress occurrence

After each stress load, it is possible to determine the number of remaining cycles $n_i$ according to

$$n_i = \left(1 - \frac{n_i}{N_i}\right)N_i$$

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In addition, it can be concluded that the percentage reduction $R_{\%}$ in the lifespan of the material, due to a certain number of stress loads, is given by

$$R_{\%} = 1 - \frac{n_f}{N_f}.$$  \hfill (9)

Therefore, the Palmgren–Miner method presents a suitable tool for analysis of cumulative damage in transformer windings due to the occurrence of inrush currents and can be used to determine the number of loads required to cause fatigue in a component or to reduce its lifespan by a certain percentage.

### 3 Material and methods

This section describes the methodology used to obtain the results of this research. In general terms, the procedures for obtaining results can be divided into stages, which are outlined in Fig. 4.

Colours in the flowchart frames indicate the tool used in each step. Thus, for the determination of inrush currents in the windings, a tool for electric modelling of power transformers and simulation of electromagnetic transients should be used. Next, to build the physical model of the transformer, a Computer Aided Design (CAD) software can be used.

Then, to determine the electromechanical stresses caused by inrush current, simulations in a multiphysics modelling software must be performed. From the determination of electromechanical stresses, the Findley criterion and the Palmgren–Miner method must be applied to verify the possibility of fatigue failure in the windings, as well as the reduction of lifespan due to successive inrashes.

In the next subsection, each stage is detailed in order to guarantee the full comprehension and reproducibility of the procedures used in this research.

#### 3.1 Transformer modelling

The AutoCAD® software is used to build the three-dimensional (3D) power transformer model. The model corresponds to a three-phase 100 MVA transformer, whose datasheet information, constructive characteristics, and resulting model are presented in Table 2 and Fig. 5, respectively.

#### Table 2 Transformer datasheet information

| Parameter                  | Value          |
|----------------------------|----------------|
| nominal power              | 100 MVA        |
| nominal voltage of outer   | 230 kV         |
| voltage of inner winding   | 69 kV          |
| percent impedance         | 13.18%         |
| turns number of outer      | 909            |
| winding                     |                |
| turns number of inner      | 422            |
| winding separator          |                |
| nominal flux density       | 1.53T0         |

In addition, it can be concluded that the percentage reduction $R_{\%}$ in the lifespan of the material, due to a certain number of stress loads, is given by

$$R_{\%} = 1 - \frac{n_f}{N_f}.$$  \hfill (9)

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### 3.2 Inrush current determination

In order to determine inrush current in the windings of the designed power transformer, an electromagnetic transient simulation at the moment when the equipment is energised must be performed. Among the most used software in engineering, three can be highlighted: EMTP/ATP, PSCAD®, and Matlab®/Simulink™. In the research presented in [21], authors carried out a comparative study between the three software, in which the simulation of a 150 MVA transformer was performed. The authors concluded that there are no significant differences between the results presented by the three tools.
In this way, the use of any of the three tools is suitable for solving the problem. In this paper, Matlab®/Simulink™ is selected due to its features for digital signal processing, better user interface, and more variety of three-phase transformers models.

Fig. 6 Representation of the transient simulation performed using Simulink™

Simulink™ is a tool that allows one to model, simulate, and analyse dynamic systems [22]. Simulation is a two-step process, the user first creates a block diagram using the model editor, which graphically represents time-dependent mathematical relationships between inputs, states, and system outputs. In the case under study, the diagram in Fig. 6 is used to perform the inrush simulation. Then, a series of parameters is set to simulate the system represented from an initial instant to a specified final instant.

In the simulation, the transformer is considered to be connected to an equivalent electrical system, which has a short circuit power equals to the short-circuit power of the transformer and a ratio $V/R = 14$, which is a typical ratio for 230 kV systems [23]. In addition, the energisation is performed with no load, at the instant of time corresponding to the passage through zero of the voltage signal in the central phase of the transformer. The existence of residual flux in the core is also considered, being 85% positive in the central phase, 85% negative in the first phase and null in the third phase. In this way, the simulated case represents the worst condition of the transformer energisation.

The model representing the transformer in Fig. 6 is available in the Simulink™ library and is equivalent to a saturable three-phase core-type $Y/A$ transformer. The component allows the saturation characteristic of the transformer to be modelled considering the residual flux in the core. It is mainly based on the transformer equivalent circuit data and the core saturation characteristic, which are presented in Figs. 7 and 8, respectively. In addition, it is also necessary to provide information about power, frequency, voltage, zero sequence dispersion reactance and residual flux in the core.

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Table 3 Physical properties of the materials used in the simulation

| Property                  | Copper | Oil  | Silicon steel |
|---------------------------|--------|------|---------------|
| Electric conductivity (S/m)| $6.0 \times 10^{12}$ | $3.3 \times 10^{12}$ | $1.12 \times 10^{7}$ |
| Relative permittivity     | $1.0 \times 10^{5}$   | 2.2  | $1.0 \times 10^{5}$   |
| Relative magnetic permeability | 1.0       | 1.0  | —              |
| Density (kg/m$^3$)        | 8700    | 890  | 7660          |
| Young modulus (GPa)       | 110     | —    | 210           |
| Nominal flux density      | 0.35    | —    | 0.29          |

Table 4 Mechanical copper properties

| Parameter                        | Value   |
|----------------------------------|---------|
| $\sigma_t$ — Tensile strength limit | 220 MPa |
| $\sigma_y$ — Yield point         | 70 MPa  |
| k — Findley criterion parameter  | 0.3     |
| f — Findley criterion parameter  | 6.25 MPa|

3.3 Mechanical stress determination

To determine electromechanical stresses in the transformer windings, the multiphysics modelling and simulation software Comsol Multiphysics® are used. It allows to simulate any physical phenomenon that can be modelled by partial differential equations. The software uses the finite element method to find approximate solutions to differential equations and, therefore, requires a high computational effort [24].

A major advantage associated with Comsol Multiphysics® is that it can simulate, in an integrated way, two physical phenomena of different natures. In the case under study, the simulation is performed both in the field of electromagnetic physics and mechanical physics.

The electromagnetic physics has main variables, which includes the electric current and the magnetic flux density. They, in turn, determine the value of variables in mechanical physics, which are force and stress. Therefore, the simulation has as input variable the inrush current and as output variable the electromechanical stress in the windings.

In addition to the input variables, in order to obtain the results, it is necessary for the characterisation of materials that compose the model and determination of boundary conditions that shape the problem, besides procedures to generate the geometry mesh.

Regarding the characterisation of the materials, in Table 3 physical properties used in the simulation are presented [12, 25].

3.4 Fatigue analysis

To verify the possibility of fatigue failure in the windings, the Findley criterion is used. The criterion can also be implemented using Comsol Multiphysics®. For the criterion application, the mechanical properties described in Table 4 are considered [24, 25].

Next, the Palmgren–Miner method is implemented in Matlab® environment. It is applied to perform prediction of the fatigue failure moment in the windings, as well as to quantify the impact of a certain number of inrushes on the lifespan of the equipment.

Therefore, the presentation of procedures indicated in this section is enough for the understanding of how the results of the research were obtained, as well as, to guarantee its reproducibility.

In the next section results are presented and discussed.
4 Results and discussions

The inrush current was initially determined in three phases of the transformer under study. The current was determined according to the procedures presented in Section 3.2 and the result is presented in Fig. 9.

In the Fig. 9 it is verified that the first peak of the inrush current reached a value of 12.4 p.u. in the central phase of the transformer. This is a typical value for inrush current in large power transformers [26]. Current in central phase has a greater amplitude than in the others due to the simulation conditions, in which the transformer was energised at the moment when the voltage in this phase passed through zero when this happens, the flow is maximum in the phase.

Thereby, it is expected that stresses in the central phase also have higher amplitudes in relation to the other phases. In addition, because in the simulated situation the transformer has no load, the currents in the secondary windings are nulls. Therefore, the secondary windings will not suffer any stress and so no analysis is made for them.

Knowing the amplitude and waveform of the inrush current and using the procedures presented in Section 3.3, the stresses that arise in the transformer windings can be determined. The results obtained are presented in Fig. 10 in the form of axial and radial components of the Lorentz force. Additionally, Fig. 11 presents the distribution of von Mises stress on the windings.

In Fig. 10, it is possible to verify that the axial component of the Lorentz force is compressive while the radial component is tractive. This indicates that the winding tends to take the form of a barrel, as is indicated in Fig. 11. It is worth noting that the barrel shape presented by the coil in Fig. 11, serves only to illustrate the tendency of deformation of the component. As the deformation occurs on a much smaller scale, it has been enlarged 2000 times to become perceptible in the figure.

It is important to note, still in Fig. 10, that the force components are indicated on a force scale per unit volume. Thus, in order to obtain the force itself, a volumetric integration in the windings must be performed. This procedure can be performed in the simulation software itself.

After integration, it was verified that the total force acting on the external winding of the central phase during the inrush is 19.61 MN. According to the transformer’s manufacturer, the winding can withstand a force of up to 83.82 MN. Therefore, as expected, the inrush current would not be able to cause a destructive failure of the windings.

The result obtained indicates that the inrush would not be enough to provide an instantaneous failure in the transformer. However, its cumulative effect on the windings also needs to be evaluated as it can cause a failure due to fatigue. Knowing this, and as discussed in Section 2.1, the Findley criterion was used to evaluate the possibility of fatigue.

While using the criterion, it was considered that the windings have the characteristics presented in Table 4 and the load cycles are the von Mises stress in the winding. The result obtained after the application of Findley criterion is presented in Fig. 12.

In Fig. 12, it is possible to verify that the mechanical stress caused by inrush current is enough to lead the material to fatigue, since the fatigue utilisation factor is >1 at several points of the winding as indicated by the colour scale. It is also possible to verify that the central region is the most likely to occur fatigue in the winding. This was expected, since in Fig. 11 it is indicated that the central region is the one that concentrates the highest stress values.
The analysis of Fig. 13 allows one to verify that the greater the reduction of windings lifetime is, the smaller is the area under the S–N curve. Thus, when the reduction is 100%, i.e. the winding failure moment, the curve is represented only by a line on the abscissa’s axis.

In addition, a graph was drawn relating the number of inrushes required to reach a certain level of reduction in the winding lifetime, which is presented in Fig. 14.

Analysing Fig. 14, it is observed that initially, the reduction of lifespan takes place in a slower way, being necessary for a greater number of inrushes to degrade the windings. However, from 20%, the degradation becomes more accelerated, so that the same inrush will produce a greater reduction in the lifespan of the winding than in the previous level. This is evidenced by the shape of the curve in Fig. 14, in which up to 20% of reduction has a fairly steep shape, and after this level, the curve becomes flatter. This behaviour can be explained as the material undergoes electromechanical forces, it will be degrading and losing its capacity to withstand new stresses.

Still in Fig. 14, it is possible to note that the number of energisations required to cause the final fracture of the windings, i.e. 100% of reduction in its lifespan, is 30,137. To determine the lifetime of the equipment in terms of days, months, or years it is necessary to know how many inrushes occur periodically in the equipment. However, this is quite subjective information, since the amount varies according to the conditions of the electrical system in which the transformer is operating.

There are few references in literature that would allow one to determine a reasonable number of daily inrushes in a typical electrical system. However, in [27] the authors state that in poor regions of India, where the condition of electrical system is critical, up to 15 reclosing operation can occur per day in a distribution transformer. Assuming this condition in the case under study, it would take 5.5 years in operation for the transformer fail by fatigue due only to the inrush currents.

However, to assume this condition is not reasonable for a large power transformer. Thus, assuming a number of inrushes 80% lower than that quoted in [27], it would require 27.5 years in operation for the transformer failure. This time is less than the average lifespan expectancy of the equipment, which is 35 years. However, it is important to emphasise that, as stated previously, the values cited are quite subjective and were presented only to demonstrate the applicability of this research results.

It is also important to highlight that, in this analysis, only the inrush contribution to winding fatigue is considered. However, fatigue is not only sponsored by the inrush current but other events such as short circuit, vibration and thermal expansion contribute together for the degradation of the components.

5 Conclusions

The electromechanical stresses that act on the windings of a transformer during its energisation were qualitatively and quantitatively evaluated. From computational simulations, the values of the inrush current and the electromechanical stresses acting in the windings during an energisation were determined.

With the obtained values, the possibility of mechanical failure of the windings was verified. The Findley criterion was applied to verify the possibility of fatigue failure and the Palmgren–Miner criterion was applied to quantify the reduction of the lifetime of the transformer due to the occurrence of successive inrushes.

The fact the inrush current, for the case under study, is not enough to cause an instantaneous failure of the windings and this could be concluded from results analysis. However, the current is enough to cause failure due to its cumulative effect on the windings. Furthermore, at a certain point, the shortening of the lifetime of the transformer accelerates due to the cumulative effect of successive stress loads.

The number of inrushes required to drive the transformer to failure, or to reduce its lifetime by a certain percentage could be determined by the presented methodology.

It is important to emphasise that the presented results consider the effects of inrush currents singly, with no influence of other events. However, it is obvious that in the real world other events...
may occur and cause worse damage to the transformer like short-circuits, oil contamination, partial discharge, overheat, etc.

Finally, it is suggested that the methodology presented in this work can be used in power transformers design stage, with the purpose of assisting in the dimensioning of its active parts and supporting structures. By using the presented methodology, it would be possible to establish desired level of withstand of the components to inrush current, reducing the probability of failure and, consequently, increasing its lifetime.

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