Test of the method for calculation of derating of workshop transformers on engineering plants

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Abstract. Today’s innovations in engineering production are aimed at the improvement of equipment efficiency in order to reduce losses and to save environment. It is conventional that the adjustable-speed drive improves electrical and mechanical transients of workshop units, but power electronics’ devices are current harmonics sources. Presence of high harmonic currents in the workshop's network is a substantial reason for transformer derating. The article discloses the method approbation, the method for calculating additional losses in an idle transformer for non-sine feeding voltage. The approbation was carried out via comparing the calculated data with the experimental data. The article describes the studies method, its strong and weak sides, and it also presents the actual calculation of coefficients for a math model, when calculating losses in a transformer, based on existing experimental data. The conclusion comprises the observation regarding possibility to use the method described to solve practical tasks.

1. Introduction
The operation under nominal load, but with higher harmonic components results in heating certain parts of an electric device, therefore, the entire transformer heated, too. The operation at temperatures above normal accelerates insulation-aging processes for all types of insulation – both organic and nonorganic, resulting further in a decreased lifespan of a transformer [1-3]. A transformer often has to work under bad conditions, with higher harmonics and voltage falls [4, 5]. In connection with this, the operation in a non-sine mode needs the transformer power to be restricted. To do so, we have to evaluate additional losses, emerging in connection with the non-sine currents and voltages, with appropriate accuracy.

Additional losses due to higher harmonics in copper mainly result from the proximity effect and the skin-effect [1-3, 6, 7]. Those losses depend on currents in windings of a transformer and rise when the transformer works for a nonlinear load.

Additional losses in iron comprise losses from re-magnetizing, which are in a proportion with frequency and eddy-current losses, which are in a proportion with the square of the frequency. Such losses appear, when the magnetizing transformer current comprises higher harmonics. It is possible when the steel core of the machine is saturated, or when the feeding voltage is not a sine wave. The latter is particularly bad for power transformers working 24 hours a day, because this increases idle operation losses, which might be substantial [8-10].

A popular method to resolve the problem of additional losses evaluation for a transformer operating in a non-sine mode might be computer simulation of the transformer operation, using the end element method. This method proved to be good [1, 6, 7], but implementing it practically needs
much initial data, dedicated software and powerful computers. Therefore, a more preferable approach might be studying simplified analytical models. It is assumed that those models allow predicting idle losses of the power transformer precisely to obtain the derating factor. The model that considers values of voltage harmonics to obtain idle losses of the power transformer is described in the paper. The principal aim of the research is a verification of the model by comparing the calculated losses value with experiments results.

2. Materials and methods
Fuchs and Masoum, in their book ‘Power Quality in Power Systems and Electrical Machines’, introduce a math model for assessing additional losses in a transformer [3] working idle, the model describes the dependency of additional losses of a transformer operating idle only on feeding voltage harmonics, with known model coefficients. The ratio of additional losses under non-sine voltage to nominal losses in the transformer, operating idle, is to be presented as a function of feeding voltage amplitudes:

\[
\frac{W_{\text{total,62}}}{W_{\text{total,1}}} = K_1 \sum_{h=2}^{\infty} \frac{1}{h^2} \left( \frac{V_{ph}}{V_{p1}} \right)^h,
\]

where \(W_{\text{total,62}}\) is the additional power losses due to higher harmonics of the feeding voltage, \(W_{\text{total,1}}\) is the power loss of a transformer working idle in sine mode, \(V_{ph}\) is the voltage’s \(h^{th}\) harmonic amplitude, \(V_{p1}\) is the amplitude of the 1\(^{st}\) harmonic of voltage in the second case, \(k, l, K_1\) are coefficients of the analytical model.

During the process of making formula (1), the authors made some assumptions, which inevitably affect the accuracy of the model. However, the approach is still acceptable, because using this method significantly simplifies the analysis procedure in connection with the need for lowering the transformer power, as in order to determine additional losses of an idle transformer, one needs to know only coefficients of the model and a voltage harmonics spectrum. Only determining the math model coefficients is complicated. Recommended values for coefficients \(k\) and \(l\) for a single-phase transformer are given in table 1.

**Table 1. Recommended coefficients values**

| Coefficient | Value       |
|-------------|-------------|
| \(k\)       | 0.9 ± 0.3   |
| \(l\)       | 1.75 ± 0.25 |

3. Results and discussion
To approbate the method, studies data about losses in transformers working idle, obtained by Mohammad Yazdamy-Asrami et al. [7] were used. The experiment that was described in the article was a computer simulation of a single-phase power transformer based on end element method, to assess additional losses due to higher harmonic components of voltage. The applicability of the model was confirmed by matching between the computer simulation results and those obtained via a natural experiment.

The nominal power of the single-phase power transformer is 25 kVA, and the idle losses of the electrical machine is 76 W.

The transformer was studied under three different non-sine voltages, and the harmonic component amplitudes in connection with this are presented in table 2.
The task was formulated to obtain results, which would correspond to those results that were described in article [7], with the help of described math model (1), and to assess the possibility to use the recommended coefficients (table 1) to solve practical tasks. To do so, one has to determine model coefficients, with which the calculation results match the reality. To exclude coefficient $K_l$ from the calculation, functions of ratios between additional losses for different feeding voltages by harmonics amplitudes were studied:

$$
\frac{W_h^{\text{case1}}}{W_h^{\text{case2}}} = \sum_{k} \frac{1}{h^k} \left( \frac{V_h^{\text{case1}}}{V_1} \right)^k \cdot \left( \sum_{k} \frac{1}{h^k} \left( \frac{V_h^{\text{case2}}}{V_1} \right)^k \right)^{-1},
$$

where $W_h^{\text{case1}}$ are additional power losses in the first case, $W_h^{\text{case2}}$ are additional power losses in the second case, $V_h^{\text{case1}}$ is the amplitude of the $h^{th}$ voltage harmonic in the first case, $V_h^{\text{case2}}$ is the amplitude of the $h^{th}$ voltage harmonic in the second case.

The right part of equation (2) may be represented as the function of coefficients $k$ and $l$ in 3D space with coordinates $k, l, z$, where axis $z$ reflects the values of the function:

$$
f_{\text{case1,2}}(k,l) = \sum_{k} \frac{1}{h^k} \left( \frac{V_h^{\text{case1}}}{V_1} \right)^k \cdot \left( \sum_{k} \frac{1}{h^k} \left( \frac{V_h^{\text{case2}}}{V_1} \right)^k \right)^{-1}.
$$

Three experiments were carried out, each resulting in formulation of an equation in accordance with expression (3):

$$
\begin{align*}
&f_{\text{case1,2}}(k,l) = \sum_{k} \frac{1}{h^k} \left( \frac{V_h^{\text{case1}}}{V_1} \right)^k \cdot \left( \sum_{k} \frac{1}{h^k} \left( \frac{V_h^{\text{case2}}}{V_1} \right)^k \right)^{-1}, \\
&f_{\text{case1,3}}(k,l) = \sum_{k} \frac{1}{h^k} \left( \frac{V_h^{\text{case1}}}{V_1} \right)^k \cdot \left( \sum_{k} \frac{1}{h^k} \left( \frac{V_h^{\text{case3}}}{V_1} \right)^k \right)^{-1}, \\
&f_{\text{case2,3}}(k,l) = \sum_{k} \frac{1}{h^k} \left( \frac{V_h^{\text{case2}}}{V_1} \right)^k \cdot \left( \sum_{k} \frac{1}{h^k} \left( \frac{V_h^{\text{case3}}}{V_1} \right)^k \right)^{-1}.
\end{align*}
$$

The dependences of the values of functions $f_{\text{case1,2}}(k,l)$, $f_{\text{case1,3}}(k,l)$, and $f_{\text{case2,3}}(k,l)$ on coefficients $k$ and $l$, and the plane of true values of ratios are represented by figure 1 (a, b, c).

The solution for each particular equation in the described space is a curve created by crossing between the plane of all possible values of the given function and the plane of its true value. It is clear that the solution for the system of equations (4) shall be surface normal $z = 0$, having common points with all curves that are solutions for the system of equations. The projection of curves, equation system solutions, onto $z = 0$ is represented with figure 1 (d).

We can derive from figure 1 (d) that the system has no solution, for the curves do not cross in one point. However, with acceptable accuracy, we may assume, that the coefficients of the analytical model correspond to some point in surroundings of point $M(0.2, 1.24)$. As it may be seen in this case, the values of coefficients $k$ and $l$ are outside the area, which was specified by the authors of the book (Table 1). Therefore, obtaining satisfactory results using the standard coefficient is not possible.

| Harmonic # | 1 | 2 | 5 | 7 | 9 | THD, % | P, Watt |
|------------|---|---|---|---|---|-------|--------|
| 1 case     | 1 | 0.2 | 0.1 | 0.05 | 0.01 | 23 | 82 |
| 2 case     | 1 | 0 | 0.3 | 0.2 | 0 | 36 | 85 |
| 3 case     | 1 | 0.3 | 0.2 | 0.1 | 0.05 | 38 | 88 |

### Table 2. Spectrums of supplying voltages

The values of coefficients $k$ and $l$ are outside the area, which was specified by the authors of the book (Table 1). Therefore, obtaining satisfactory results using the standard coefficient is not possible.
Coefficient $K_i$ in this example was calculated as the arithmetical mean value of the coefficients obtained for each of the system’s equation. Comparison of the calculation results of the analytical model with the results represented in article [5] is presented in table 4.

Figure 1. 3D plots of: a – function $f^{\text{case}1,2}(k,l)$; b – function $f^{\text{case}1,3}(k,l)$; c – function $f^{\text{case}2,3}(k,l)$ and d – projections of curves of individual equation solutions onto plane $z = 0$

Table 4. Comparison of calculated and measured results

| No. of experiment | Measured value of the transformer idle run additional losses, Watt | Calculated value of the transformer idle run additional losses, Watt | Relative error, % |
|-------------------|-------------------------------------------------------------------|-------------------------------------------------------------------|------------------|
| 1                 | 6                                                                 | 6.026                                                             | 0.43             |
| 2                 | 9                                                                 | 9.067                                                             | 0.74             |
| 3                 | 12                                                                | 11.86                                                             | 1.15             |

4. Conclusion
Using analysis, as presented in the article and based on results from table 4, the quantitative correlation was proved to exist between the sum of ratios of voltage amplitude harmonics and additional losses in a transformer.

For a particular transformer, the analytical model coefficients may be selected in a manner when acceptable convergence would be reachable between calculated and experimental data, at least, within small surroundings of changes of the THD voltage, with the harmonics spectrum structure preserved.
It is further worth noticing that additional experimental studies are necessary to make a final conclusion regarding the applicability of the proposed model, which reflects the correlation between losses of a transformer operating idle and the amplitudes of the feeding voltage harmonic components, thus giving a chance to the expanded methodology for adequate determination of coefficients for the studied model to be developed.

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