ON-SITE DERATING OF IN-SERVICE POWER DISTRIBUTION TRANSFORMERS SUPPLYING NOLINEAR LOADS

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The paper analyzes the intentional reduction of the maximum load capacity (derating) for the in-service dry-type three-phase power distribution transformers that operate under nonsinusoidal steady state condition. A real-time, less intrusive and efficient derating procedure was developed and implemented in accordance with the international standards recommendations. Due to a flexible developed software package, the proposed computation method only requires the nameplate data of the investigated transformer and the harmonic spectrum of the load current measured at transformer secondary (low-voltage) windings. Thus, the additional harmonic losses within the transformer and their corresponding maximal permissible nonsinusoidal current are continuously computed according to the characteristics of load changes. In order to validate the results, the procedure was tested on a distribution transformer that supplies heavy nonlinear loads of an industrial facility.

1. INTRODUCTION

The three-phase power distribution transformers are one of the most critical, numerous and expensive electric equipment involved in the power delivery process. Consequently, their operation with the electric parameters under the rated values is mandatory for power supply continuity of the electrical installation. Nowadays, as a consequence of the energy-efficiency requirements, in modern industrial electric drive systems, the extensive usage of solid-state electronics was adopted [1, 2]. These intrinsically nonlinear loads generate undesirable power quality issues in the network, particularly the distortion of the current waveforms. The harmonic currents additionally stresses different component of the transformer, which was originally design to operate under pure sinusoidal steady-state condition, and may determinate the transformer abnormal functionality and ultimately its premature failure [3, 4]. In order to limit the harmonic currents adverse effects on the transformer, its maximum load capacity is intentional

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reduced. The procedure is also known as *derating* of the transformer [5–7]. Hence, the transformer maximal permissible current (MPC) and the corresponding reduction in apparent power rating (RAPR) are to be evaluated for a certain nonsinusoidal current according to the device rated data and the harmonics current waveform spectrum [5, 6]. Thus, quite numerous *derating factors* have been derived that regard the transformer construction data and various current and voltage power quality parameters measured at the transformer secondary part [8–10]. Unfortunately, for most of the field measurements the geometrical data of the transformer windings conductor is often unavailable and furthermore the load characteristics rapidly change. Therefore, the paper suggests a simple and efficient on-site derating computation method for in-service dry-type three-phase power distribution transformers. The proposed nonintrusive procedure relies on the international standards recommendations [11] and only requires the transformer nonsinusoidal current waveform features and the transformer nameplate data. Due to a developed code, an updated *derating report* is generated according to the loads changes. The main computed data comprises in the report refers to the losses within the transformer and their corresponding maximal apparent power operating capacity (*S*<sub>M</sub>). Thus, the so called transformer *derating curve* is extracted. The suggested derating procedure was tested on a 2000 kVA distribution transformer that serves heavy nonlinear industrial loads of a pulp and paper processing facility.

2. THE DERATING PARAMETERS DETERMINATION

The total losses *P*<sub>T</sub> within a transformer that supply nonlinear loads are distinguished into no-load (iron) losses *P*<sub>NL</sub> and load (copper) losses *P*<sub>LL</sub>. The latter can be also split into ohmic winding losses *P*<sub>DC</sub> (due to DC resistance of windings), and the total stray losses *P*<sub>TSL</sub>. Usually, the total stray losses comprise the windings eddy current losses *P*<sub>EC</sub> and other than windings stray losses *P*<sub>OSL</sub> (in structural part of the transformer). Thus, one can write [5, 11]:

\[
P_T = P_{NL} + P_{LL}, \quad P_{LL} = P_{DC} + P_{TSL}, \quad P_{TSL} = P_{EC} + P_{OSL}.
\]  

(1)

It is important to mention that for dry type transformers, windings eddy current losses *P*<sub>EC</sub> are the most significant stray losses and therefore other stray losses *P*<sub>OSL</sub> can be neglected [11]. Additionally, in our further study we also consider the undistorted voltage waveforms and balanced harmonic current loads. These requirements are commonly satisfied in industrial electric plants, where a great short circuit power is provided and the three-phase equipments are dominant. Thus, the transformer no-load losses *P*<sub>NL</sub> (directly dependent to the voltage waveform) remain constant under nonsinusoidal currents.
Since windings eddy current losses $P_{EC}$ are proportional to square of frequency [3–5], the load losses of a transformer with a secondary rated current $I_{R2}$ under a nonsinusoidal operating condition can be expressed in terms of harmonic currents waveform spectrum at the transformer low-voltage part [5, 11]:

$$P_{LL} = P_{DC-R} \left( \sum_{h=1}^{h_{\text{max}}} \left( \frac{I_h}{I_{R2}} \right)^2 + P_{EC-R} \sum_{h=1}^{h_{\text{max}}} \left( \frac{I_h}{I_{R2}} \right)^2 \right),$$

(2)

where $P_{DC-R}$, $P_{EC-R}$, are the DC ohmic losses and windings eddy current losses under rated condition, $h$ is the harmonic order, $h_{\text{max}}$ the highest significant harmonic number and $I_h$ are the root mean square current at harmonic $h$.

The rated ohmic losses $P_{DC-R}$ can be estimated by multiplying the measured DC ohmic transformers windings phase resistances $(R_1$ and $R_2$) with the square of the transformer rated currents $(I_{R1}$ and $I_{R2})$ for the primary and secondary transformer part, respectively. In addition, the rated total stray losses $P_{TSL-R}$ are to be evaluated by subtracting the rated ohmic losses from the rated load losses $P_{LL-R}$, measured during the short-circuit test:

$$P_{TSL-R} = P_{LL-R} - P_{DC-R} \cong P_{EC-R}, \text{ with } P_{DC-R} = 3\left( R_1 I_{R1}^2 + R_2 I_{R2}^2 \right).$$

(3)

In order to quantitatively regard the harmonic attendance in the current waveform spectrum, different time and frequency domain parameters have been developed [1]. The most commonly used, also indicated by the majority of modern power quality analyzer, are: total harmonic distortion THD, distortion factor DF, crest factor CF and harmonic loss factor KF – denoted also with $F_{HL}$. They are defined using the current fundamental $I_1$, effective $I$, or amplitude $\hat{I}$ value [1, 5]:

$$\text{THD} = \sqrt{\sum_{h=2}^{h_{\text{max}}} \frac{I_h^2}{I_1}}, \quad \text{DF} = \sqrt{\sum_{h=2}^{h_{\text{max}}} \frac{I_h^2}{I}}, \quad \text{CF} = \frac{\hat{I}}{I},$$

$$\text{KF} = F_{HL} = \frac{\sum_{h=1}^{h_{\text{max}}} h^2 I_h^2}{\sum_{h=1}^{h_{\text{max}}} I_h^2}, \quad \text{with } I = \sqrt{\sum_{h=1}^{h_{\text{max}}} I_h^2}.$$  

(4)

The most useful parameter in evaluating transformer additional losses generated by the nonlinear loads is the harmonic loss factor $F_{HL}$. The transformer loads losses expression (2) can be rewritten in terms of harmonic loss factors $F_{HL}$. 

Derating of in-service power transformers supplying nonlinear loads
and transformer load factor $\beta$, defined as the root mean square current $I$ relative to transformers rated sinusoidal current $I_{r2}$ at the secondary winding:

$$P_{LL} = P_{DC} + P_{EC} = \beta^2 (P_{DC-R} + P_{EC-R} F_{HL}), \quad \text{with} \quad \beta = I/I_{r2}. \quad (5)$$

In order to simplify the load losses computation a per unit system is adopted, in which base losses are the rated DC windings losses $P_{DC-R}$. Hence, a general load losses equation when transformer supplying a harmonic load can be derived:

$$P_{LL} (\text{p.u.}) = \beta^2 \left[ 1 + P_{EC-R} (\text{p.u.}) F_{HL} \right]. \quad (6)$$

Constricting the transformer load losses under certain harmonic conditions $P_{LL}$ to equal its rated load losses $P_{LL,R}$ (with no harmonics), the maximum load factor $\beta_{\text{max}}$ or per unit maximal permissible nonsinusoidal current (in respect to rated secondary winding value) $I_{\text{max}} (\text{p.u.})$ is estimated:

$$I_{\text{max}} (\text{p.u.}) = \beta_{\text{max}} = \sqrt{\frac{P_{LL,R}}{P_{DC-R} + P_{EC-R} F_{HL}}} = \sqrt{\frac{1 + P_{EC-R} (\text{p.u.}) F_{HL}}{1 + P_{EC-R} (\text{p.u.}) F_{HL}}}. \quad (7)$$

Transformer derating level is also indicated in terms of the device maximal operating load capacity $S_M$, relative to its rated value $S_R$. Accordingly, the reduction in apparent power rating RAPR factor is commonly adopted:

$$\text{RAPR} = \frac{S_R - S_M}{S_R} \times 100\% = \left[ 1 - I_{\text{max}} (\text{p.u.}) \right] \times 100\%. \quad (8)$$

The exactness of the transformer derating parameters depends strongly on the per unit rated eddy current windings losses evaluation accuracy. Consequently, analytical and numerical methods were developed for its precise computation [12–16]. Unfortunately, they require numerous additional transformer construction data, which normally, are unavailable for the field measurements. In order to overcome this issue, in our derating computation procedure the worst case is considered. Thus, according to [9, 11], for large power dry-type three-phase distribution transformers (with rated currents greater than 1 kA), the rated winding eddy current losses can be expressed as $P_{EC-R} = 0.67 P_{TSL-R}$, and its corresponding maximum per unit value $M$ is conservatively adopted:

$$M = \max[P_{EC-R} (\text{p.u.})] = \frac{2.8 P_{EC-R}}{3 R_2 I_{2R}^2}. \quad (13)$$

The above assumption mainly relies on the eddy current losses division between the transformer high and low-voltage windings and also considers their nonuniform distribution within each winding [9, 11].
3. PROCEDURE IMPLEMENTATION – A CASE STUDY

The proposed on-site derating procedure was tested on an in-service three-phase power distribution transformer that serves heavy nonlinear loads from an industrial facility (a pulp and paper processing line). Mainly, two large motors driven by power static converters are to be supplied by the investigated transformer. Figure 1 shows the schematic layout of the power installation along with the adopted procedure of measurement, acquisition and processing of the electric parameters. Hence, a power quality analyzer [17] monitors the main electric energy parameters from the transformer secondary winding and transfers them to a portable computer. The latter, due to a robust and flexible developed code, continuously (in real-time) evaluates the transformer losses distribution and the corresponding derating parameters (MPD, RAPR) in accordance with load changes. The necessary transformer rated data are taken from its nameplate or access a local large database (periodically updated) with transformers rated parameters.

Fig. 1 – The investigate three-phase power distribution transformer supplying nonlinear loads.
The investigated in-service transformer rated data are presented in Appendix 1. Captured images of three-phase currents waveforms and their corresponding harmonics spectrum histogram (percentage contribution of each component relative to the fundamental) are illustrated in Fig. 2 and Fig. 3, respectively. The main harmonic parameters of phase currents (defined in the previous chapter) are presented in Fig. 4, while Fig. 5 shows the currents absolute values at fundamental frequency and the phase displacement of the line voltages relative to the currents. For this regime, the computed losses within the transformer and the corresponding derating parameters are presented in Table 1, where also the windings harmonics eddy current losses contribution are highlighted. It is useful to recall that the operating parameters of the transformer are permanently evaluated according the load alternations.

Fig. 2 – The secondary (low-voltage) windings transformer currents waveforms and their root mean square values.

Fig. 3 – The phase currents harmonic spectrum at the transformer secondary part and the effective values of their fundamental components.

Fig. 4 – The phase currents root mean square and their harmonic parameters values at the transformer secondary part.

Fig. 5 – The currents absolute values at the fundamental frequency and the phase displacement of the line voltages relative to the currents.
Table 1

<table>
<thead>
<tr>
<th>Type of loss</th>
<th>Rated losses (kW)</th>
<th>Load losses (kW)</th>
<th>Harmonic loss factor</th>
<th>Corrected Losses (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No load ( P_{NL} )</td>
<td>3.500</td>
<td>3.500</td>
<td></td>
<td>3.500</td>
</tr>
<tr>
<td>DC ohmic ( P_{DC} )</td>
<td>13.023</td>
<td>3.094</td>
<td>3.094</td>
<td>13.023</td>
</tr>
<tr>
<td>Winding eddy currents ( P_{EC} )</td>
<td>1.258</td>
<td>0.299</td>
<td>4.37</td>
<td>1.306</td>
</tr>
<tr>
<td>Total losses ( P_T )</td>
<td>17.781</td>
<td>6.892</td>
<td>7.899</td>
<td></td>
</tr>
<tr>
<td>Load factor ( \beta )</td>
<td>1</td>
<td>0.48</td>
<td></td>
<td>0.48</td>
</tr>
</tbody>
</table>

Transformer per unit and absolute maximum permissible load current (MPC)

\[
I_{\text{max (p.u.)}} = 0.628
\]

\[
I_M = 1815 \text{ A}
\]

Transformer reduction in apparent power rating (RAPR) and maximal operating capacity (\( S_M \))

\[
\text{RAPR} = 37.11 \%
\]

\[
S_M = 1257 \text{ kVA}
\]

One can remark that harmonic currents reduce transformers maximum permissible nonsinusoidal current (MPC) to 1815 A, representing only 62.8 % of the transformer rated current (2 890 A). Accordingly, transformers power apparent capacity limits to \( S_M = 1 257 \text{ kVA} \). The transformer derating curve, which represents the transformer per unit MPC as a function of harmonic loss factor, is also illustrated in Fig. 6.

Fig. 6 – Transformer derating curve – per unit MPC dependency of harmonic loss factor.
Complementary to the transformer derating, a periodical thermal inspection of the device is strongly recommended, since its operating efficiency is usually decreasing after the reduction of the load capacity. Nowadays, that could be nonintrusive and quite precisely carried out by a portable infrared camera.

Due to the increased use of large variety of both industrial and domestic nonlinear loads, derating the distribution transformer is only a temporary solution. Consequently, other remedial measures to the harmonics currents detrimental consequences are to be taken into account. Thus, the installation active power line conditioners (filter) at the transformers secondary winding could mitigate the main power quality issues, including harmonic currents [2, 5]. Their main drawbacks consists in a high price per unit power and rather large dimensions, which make them often unsuitable for mounting at the transformer secondary part. Additionally, they are very sensitive installation equipments due to the numerous comprised electronic devices. One of the most efficient harmonics correction actions for power transformers is the replacement of the actual device with a corresponding $K$-rated unit. The latter are specially designed devices, which, due to their particular characteristics (upsized windings conductors and enforced isolation), cope well with the additional thermal stress generated by harmonic currents [18, 19]. These transformers manage to serve a various degree of nonlinear loads according to their $K$-rated number – a derived harmonic current parameter, similar to loss factor, but defined relative to the transformer rated current [11, 18]. Despite of the high costs of such transformers, they are the most appropriate solution in power supply of industrial facilities, where nonlinear loads are involved.

4. CONCLUSIONS

An on-site derating procedure for in-service dry-type power distribution transformers that supply nonlinear loads was proposed, tested and discussed. The procedure basis on the international standard recommendations and only requires the transformers rated data and the harmonic content of the load current. Thus, an integrated measurement and data processing system was developed, which continuously scrutinize the load characteristics and compute the transformer operating parameters. Accordingly, a real-time derating report is created that comprises the losses distribution within the transformer, the maximal permissible nonsinusoidal current (MPC) and transformer reduction in apparent power rating (RAPR). Supplementary, the device derating curve is extracted and visualized.

The suggested procedure is very suitable for field measurement, where less data are available and transformer subsequent nonlinear load rapidly changes (in accordance to the technological process). In order to enhance the value of procedure, simple derating transformer phase mounted devices may be developed. They would monitor transformer harmonic currents and signal the exceeding of its
load capacity. It is also useful to mention that although the whole procedure was illustrated for dry-type transformers, it can be easily adapted for oil-filled devices.

The rough evaluation of the per unit rated winding eddy current losses limits the derating method accuracy and tends to provide conservative results. That can be overcome by adopting a more advanced and precise model of the rated eddy current evaluation — e.g. using finite element computation methods. Supplementary, taking also into account the load unbalances and the voltage distortion, the derating computation procedure would be more comprehensive and could be applied for transformers that work in any modern electric distribution network.

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APPENDIX 1

The transformer main technical data are shown in Table 2.

Table 2

<table>
<thead>
<tr>
<th>The investigated single phase power transformer data</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_n = 2000 \text{ kVA}$</td>
</tr>
<tr>
<td>Dy05</td>
</tr>
<tr>
<td>$U_{in} = 6 \text{ kV}$</td>
</tr>
<tr>
<td>$U_{in} = 0.4 \text{ kV}$</td>
</tr>
<tr>
<td>$P_{NL} = 3.5 \text{ kW}$</td>
</tr>
<tr>
<td>$P_{LL} = 14.9 \text{ kW}$</td>
</tr>
<tr>
<td>$i_0 = 1.1 %$</td>
</tr>
<tr>
<td>$u_w = 6 %$</td>
</tr>
<tr>
<td>$R_1 = 0.7112 \Omega$</td>
</tr>
<tr>
<td>$R_2 = 0.5091 \text{ m\Omega}$</td>
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</tbody>
</table>
REFERENCES