Nonsinusoidal Load Current Effect on the Electrical and Thermal Operating Parameters of Oil Filled Power Distribution Transformers

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Abstract— **Most of the in-service power distribution transformers from the industrial electric facilities were designed to operate under pure sinusoidal state conditions. Nevertheless, the majority of the loads from modern electric installations are intrinsically nonlinear and consequently, they generate nonsinusoidal currents. These high-order harmonics (present into the current waveform spectrum) have a negative impact on the transformers thermal and electrical operating parameters and, ultimately, limit the machine loading capability. The paper quantitatively investigates the transformer behavior under distorted current conditions by developing a procedure for evaluating different relevant operating quantities (maximum permissible current, the hottest spot temperature, aging acceleration factor and the machine remaining lifetime). The computation relays on the international standard recommendation and mainly uses the load current harmonic spectrum and the transformer rated data. To reveal the proposed procedure performance, a distribution transformer of 400 kVA from an industrial plasterboard facility is investigated.**

Index Terms — **Derating, Distribution transformers, Harmonics, Hot spot Temperature, Power Quality.**

I. Introduction

One of the most common power quality issue encountered in the modern electric power grids is the distortion of the current or voltage waveforms. That is mainly caused by the proliferation of the nonlinear loads, which are to be found in any industrial or domestic low-voltage installations [1-3]. One could rightly state, that due to the extensive electronic device usage, the linear loads are nowadays increasingly rare. Additionally, the high penetration of photovoltaic plants, various energy storage systems or the electric vehicles charging devices, significantly contribute to the current harmonics dispersion into the electric network [4-6]. These non-sinusoidal load currents adversely impact all the electric equipments involved into power delivery process. Thus, the current harmonics increase the equipment intrinsic losses, rise their normal operating temperatures and, finally, reduce their life time expectation. Consequently, the international standard regulations [7] recommend specific values for various power quality factors (*e.g.* total harmonic distortion) in order to maintain all function parameters (electrical and thermal) of the appliances or installation under their rated values.

The power distribution transformers from many industrial facilities were design to serve linear loads. Therefore, they are severely affected by the non-sinusoidal load currents. Consequently, the reduction of their loading capability (derating) is commonly adopted [8-10]. It is useful to mention that other remedial measures to harmonic problems could also be considered: installing harmonic filters, nonlinear load aggregation or even replacing of the actual transformer with a *K*-rated unit (specially designed to work under non-sinusoidal condition) [11, 12]. These measures are to be applied only if the electric installation allows network topology changes or a major maintenance action is scheduled. Unfortunately, these situations are rare, and hence, the transformer is to be derated. The most advanced derating techniques and thermal models of the transformer use numerical computation methods, which demand detailed constructive data and active materials properties [13, 14]. The latter are mostly unavailable for in-service distribution transformers. Thus, for the energy audit studies and proactive maintenance actions, this paper suggests an efficient determination practice of the transformer electrical and thermal parameters, suitable for field measurements.

The suggested method considers the international standard recommendations [15, 16] and requires the load current harmonic spectrum (easy to measure and acquire) and the transformer rated data. Thus, the transformer main critical thermal and electrical operating parameters are continuously monitored. The developed procedure is also able to predict the transformer's maximum loading capability and its life expectancy under the non-sinusoidal steady-state regime. The here proposed investigation procedure was exemplified on a 400 kVA power distribution transformer that supplies an industrial plasterboard facility.

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II. THE TRANSFORMER NON-SINUSOIDAL STEADY –STATE OPERATION CONDITION

A. Losses Distribution within the Transformer

The total losses within a distribution transformer under distorted current condition P_T are commonly categorized in two classes [2, 15]: no load losses P_{NL} (excitation losses) and load losses P_{LL} (impedance losses). The latter comprises ohmic winding losses or DC losses P_{DC} and the total stray losses P_{TSL}, which could be further subdivided into the winding eddy current losses P_{EC} and other than winding eddy current losses P_{OSL} (that come out in core, core clamps, magnetic shield, tank or other transformer constructive parts). This power losses division is presented in Fig. 1. Consequently, one could write:

$$P_T = P_{NL} + P_{LL}, \; P_{LL} = P_{DC} + P_{TSL}, \; P_{TSL} = P_{EC} + P_{OSL}. \quad (1)$$

The DC losses in the windings conductors P_{DC} are properly considered to be directly proportional with the square of the load effective current value. It has been also proven [15] that the eddy current losses P_{EC} are proportional with the square of the effective value of the load current and considered proportional with the square of the frequency. Additionally, the other stray losses P_{OSL} increase with the square of the winding current effective value too and with an exponential factor for the frequency, conservatively adopted as 0.8 [15]. Therefore, to account the harmonic effect of the transformer operation, two power quality factors have been defined: the harmonic loss factor F_{HL} and the harmonic loss factor for other stray losses $F_{HL\text{-}STR}$, respectively [15]:

$$F_{HL} = \frac{1}{I^2}\sum_{k=1}^{N} k^2 I_k^2, \quad F_{HL-STR} = \frac{1}{I^2}\sum_{k=1}^{N} k^{0.8} I_k^2, \quad (2)$$

where $I = \sqrt{\sum_{k=1}^{N} I_k^2}$ is the root mean square of the transformer current of N harmonic components with effective values I_k. In our further computation, we consider $N=50$.

Considering the above-mentioned factors, one can express the load losses for any non-sinusoidal current in terms of transformer rated DC losses $P_{DC\text{-}R}$, rated eddy current losses $P_{EC\text{-}R}$ and rated other stray losses $P_{OSL\text{-}R}$:

$$\begin{aligned} &P_{LL} = P_{DC} + P_{EC} + P_{OSL}, \quad \text{with} \quad P_{DC} = \frac{P_{DC-R}}{I_{R2}^2}\sum_{k=0}^{N} I_k^2, \\ &P_{EC} = \frac{P_{EC-R}}{I_{R2}^2}\sum_{k=0}^{N} k^2 I_k^2, \quad P_{OSL} = \frac{P_{OSL-R}}{I_{R2}^2}\sum_{k=0}^{N} k^{0.8} I_k^2 \quad \text{and} \\ &P_{LL} = \left(\frac{I}{I_{R2}}\right)^2 \left(P_{DC-R} + P_{EC-R}F_{HL} + P_{OSL-R}F_{HL-STR}\right) = \\ &\quad = \beta^2\left(P_{DC-R} + P_{EC-R}F_{HL} + P_{OSL-R}F_{HL-STR}\right), \end{aligned} \quad (3)$$

where β is the load factor defined as the root mean square current of the load I relative to transformer rated sinusoidal current at the secondary winding I_{R2}: $\beta = I/I_{R2}$.

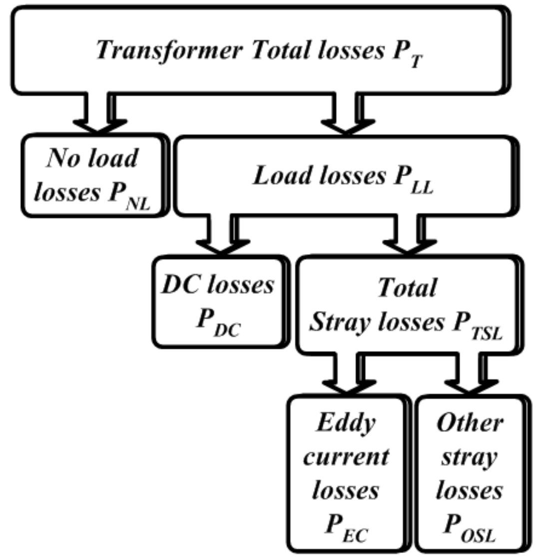

Figure 1. Power losses categorisation within a power distribution transformer under non-sinusoidal operating condition.

To compute the transformer rated DC losses, the primary (R_1) and secondary (R_2) windings per-phase DC resistances are required along with the machine rated currents (I_{R1} and I_{R2}). These data are to be taken from the transformer's manufacturer tests report, which indicate also the no load losses P_{NL} and rated load losses $P_{LL\text{-}R}$. Thus, one may write:

$$\begin{aligned} P_{DC-R} &= 3(R_1 I_{R1}^2 + R_2 I_{R2}^2), \\ P_{TSL-R} &= P_{LL-R} - P_{DC-R}. \end{aligned} \quad (4)$$

Additionally, according to the international standard recommendations [15], for oil filled distribution transformers, the rated winding eddy current losses $P_{EC\text{-}R}$ and rated other stray losses $P_{OSL\text{-}R}$ could be conservatively estimated:

$$P_{EC-R} = 0.33 P_{TSL-R}, \quad P_{OSL-R} = 0.67 P_{TSL-R}. \quad (5)$$

The transformer loading capability or the transformer maximum permissible current (I_{MPC}) is to be determined by constraining the transformer load losses P_{LL} (when supplying non-sinusoidal load currents) to equal its initial rated load losses $P_{LL\text{-}R}$ (indicated under pure sinusoidal state):

$$I_{MPC} = I_{R2}\sqrt{\frac{P_{LL-R}}{P_{DC-R} + P_{EC-R}F_{HL} + P_{OSL-R}F_{HL-STR}}}. \quad (6)$$

The transformer corresponding maximum load factor β_{max}, the reduction in apparent power rating ($RAPR$) and its corresponding maximal operating capacity S_M can be derived:

$$\begin{aligned} &\beta_{max} = I_{MPC}/I_{R2}, \\ &RAPR = \frac{S_R - S_M}{S_R}\cdot 100\% = [1-\beta_{max}]\cdot 100\%. \\ &S_M = \beta_{max} S_R, \end{aligned} \quad (7)$$

where S_R is the transformer rated power indicated by the machine manufacturer under normal (sinusoidal) condition.

B. Transformer Hot Spot Temperature Estimation

The constructive parts of the transformer are constantly subjected to thermal stress of different intensity during the normal machine operation. Supplementary, the non-sinusoidal load currents, due to the harmonic content, significantly contribute to the transformer temperature rise and could generate its premature failure or malfunction [15-18]. The most important (dominant) parameter that causes the destruction of the transformer insulation materials and finally establishes the machine lifetime expectancy is the hot spot temperature θ_H of the windings. The latter could be expressed in terms of the oil temperature rise with respect to ambient temperature θ_{TO}, conductor hot spot temperature rise relative to oil temperature θ_g, and the ambient temperature θ_A [15]:

$$\theta_H = \theta_{TO} + \theta_g + \theta_A. \tag{8}$$

The terms involved in the hot spot temperature relation could be evaluated considering the current harmonic spectrum (F_{HL}), the load factor (β) and the transformer rated data [15]:

$$\begin{aligned}
\theta_{TO} &= \theta_{TO-R}\left(\frac{P_{LL}+P_{NL}}{P_{LL-R}+P_{NL}}\right)^{0.8},\\
\theta_g &= \theta_{g-R}\left(\frac{\beta^2 P_{DC-R}+\beta^2 F_{HL}P_{EC-R}}{P_{DC-R}+P_{EC-R}}\right)^{0.8} \text{ or}\\
\theta_g &= \left(\theta_w-\theta_{TO-R}\right)\left(\frac{\beta^2 P_{DC-R}+\beta^2 F_{HL}P_{EC-R}}{P_{DC-R}+P_{EC-R}}\right)^{0.8},
\end{aligned} \tag{9}$$

where θ_{TO-R} is the rated oil temperature rise with respect to the ambient temperature, θ_{g-R} is the rated conductor temperature rise, relative to oil temperature, and θ_w is the rated winding (conductor) rise over the ambient temperature.

C. Thermal Aging and Transformer Lifetime Expectacy

To appreciate the transformer conductor insulation deterioration level due to the hot spot temperature, an aging acceleration factor F_{AA} was adopted [16]. This mainly indicates the rate at which the transformer insulation aging is accelerated compared with the aging rate at a reference hot spot temperature (θ_{Href}). Its expression mainly depends on the insulation type and the transformer by a material constant B and the operating hot spot temperature θ_H [16]:

$$F_{AA} = \exp\left(\frac{B}{\theta_{Href}+273} - \frac{B}{\theta_H+273}\right). \tag{10}$$

The aging acceleration factor F_{AA} will have values less than unity for hot spot temperatures under the reference value ($\theta_H < \theta_{Href}$). This restriction will keep the transformer operating parameters under their rated values maintaining its initial life time estimation (also under distorted current conditions).

The transformer life span is mainly a function of the machine hot spot temperature and it is directly associated with the conductor insulation degradation [17, 18]. Thus, the insulation life time expectancy is formulated as an adaptation of Arrhenius reaction rated theory (indicated relative to the normal insulation life) [16]:

$$Life(pu) = A\exp\left(\frac{B}{\theta_H+273}\right), \tag{11}$$

where A and B are constants evaluated according to insulation material and the reference hot spot temperature defined for the material normal insulation life. That is usually considered 20.55 years for transformers with an average winding temperature rise relative to ambient temperature of 65 ºC and common insulation type (not thermally upgraded). This corresponds to a reference hot spot temperature of 110 ºC and material constants values of $A = 9.8\cdot 10^{-18}$ and B =15000 [16].

Supplementary, the transformer percent loss of life %LOL for a certain time t (indicated in years) and the machine remaining life RL prediction could be also evaluated [16-18]:

$$\begin{aligned}
\%LOL &= \frac{F_{AA}\cdot t\cdot 100}{NIL},\\
RL &= \frac{NIL}{F_{AA}} = Life(pu)NIL,
\end{aligned} \tag{12}$$

where NIL represents the transformer normal insulation life.

The here presented transformer investigation method was implemented in a computation procedure, whose flowchart is illustrated in Fig. 2. That enables an in-situ, fast and continuous operating parameters computation for in-service distribution transformers that supply nonlinear loads. The load current harmonic spectrum and the transformer rated data are the only required input data.

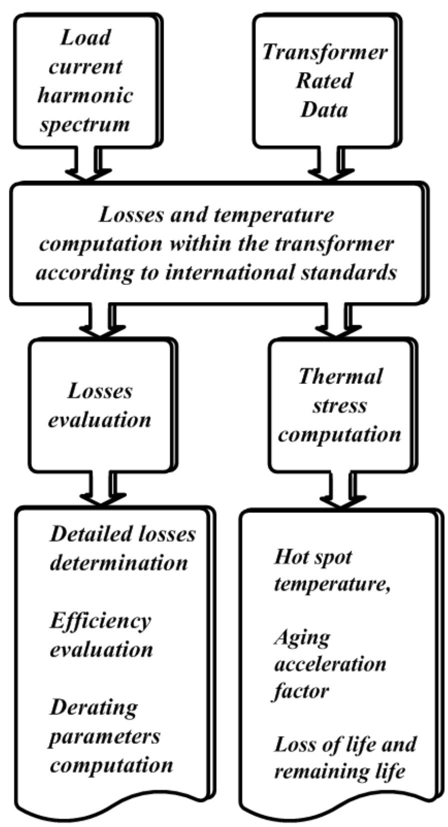

Figure 2. The flowchart for proposed procedure of computing the transformer electrical and thermal operating parameters.

III. Derating and Thermal Stress Parameter Computation – Case-Study

The derating procedure and the thermal stress computation for a distribution transformer subjected to distorted currents are further exemplified on an oil-filled 400 kVA unit. The machine feeds both linear and nonlinear loads of an electrical industrial plasterboard facility. The loads are operating continuously and do not change their main electric features during operation. They are illustrated in Fig. 3, where the investigated transformer is also exposed. The main transformer rated parameters are indicated in the Appendix. An electric energy audit study on this in-service power distribution transformer is performed, mainly focusing on the potential power quality issues encountered at the machine low-voltage windings (installations' point of common coupling). Accordingly, the main features of the electric quantities are properly acquired by a high performance (IEC-class A) power quality analyzer [19] connected at the main electric panel installation. Additionally, the investigation intends to establish whether the entire load could be safely increased with 30% considering that the harmonic spectrum of the current through the transformer secondary windings is preserved. Consequently, a software package was developed, mainly implementing the derating and thermal computation procedures presented in the previous section, and exploiting the transformer manufacturer's test report and the power quality parameters (current harmonic spectrum) at the transformer low-voltage side. Thus, the electrical and thermal operating parameters of the machine are continuously computed and monitored. The measured currents waveforms, their harmonic spectrum and unbalance level are presented in Figs. 4-6, while Fig. 7 depicts the measured absorbed active, reactive and apparent power with the associated power factors.

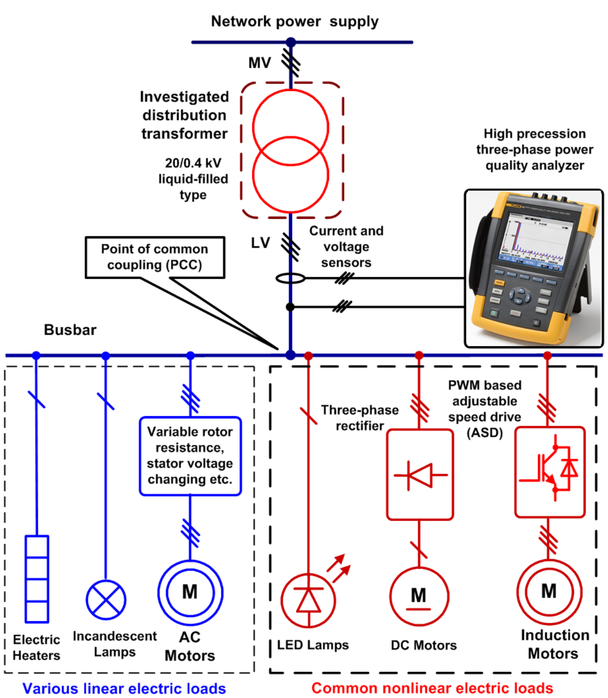

Figure 3. The analysed three-phase power distribution transformer serving a mixture of linear and nonlinear loads.

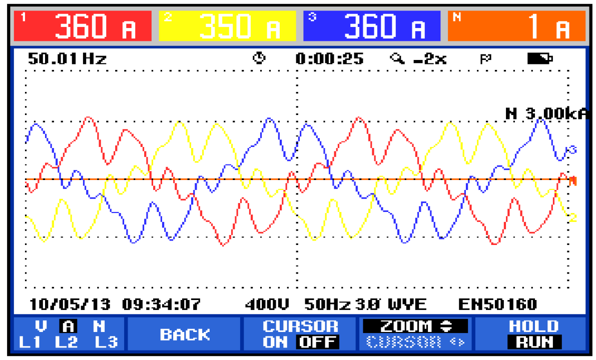

Figure 4. The phase currents waveforms through the transformer's secondary windings (at low-voltage side).

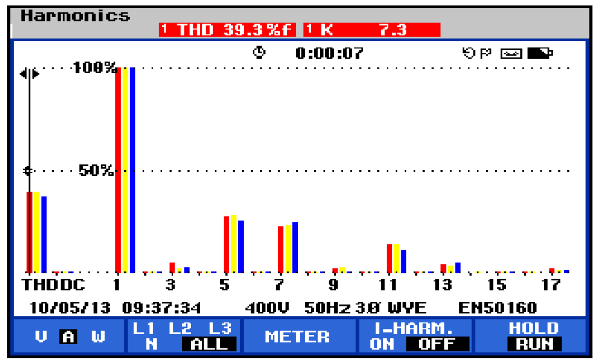

Figure 5. The harmonic spectrum of phase currents at transformer's secondary part.

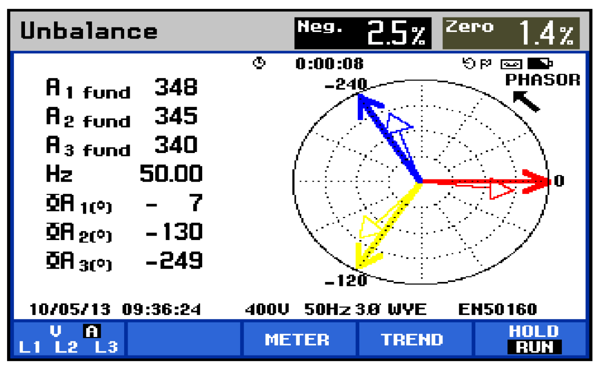

Figure 6. The unbalance level of the low-voltage phase currents.

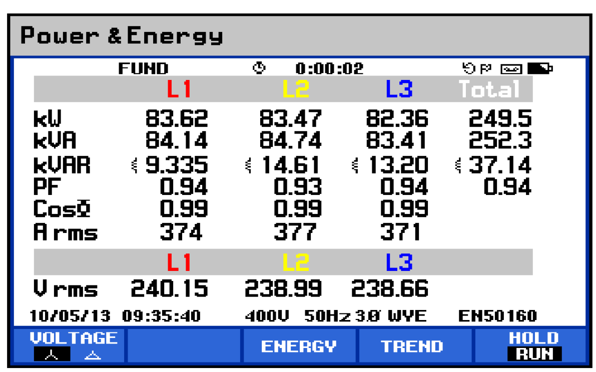

Figure 7. Active, reactive and apparent power.

The most relevant transformer operating parameters (electrical and thermal) are continuously computed in accordance to the load factor and current harmonic spectrum changes. Thereby, in Table I the values of the power losses distribution within the transformer and the machine significant temperatures values are indicated for two different load factors. Thus, the first load factor $\beta_1 = 0.623$ corresponds to the transformer actual state (characterized by the parameters presented in Figs. 4 – 7) and the second one $\beta_2 = 0.810$ is achieved when the load is increased with 30 % relative to the first state, maintaining its harmonic spectrum.

In the actual harmonic steady-state ($\beta_1 = 0.623$), the load generates a hot spot temperature value $\theta_{H1} = 96.139$ ºC, that still lies under the acceptable reference value of $\theta_{Href} = 110$ ºC (the other transformer rated temperatures are indicated in the Appendix). Correspondingly, the insulation relative aging acceleration factor has a subunit value ($F_{AA1} = 0.229$) and the percent loss of life per year is insignificant. Accordingly, the transformer preserves its initial estimated life time expectancy that equals the machine normal insulation life: 22.5 years. For the second load factor $\beta_2 = 0.81$, the thermal operating parameters of the transformer exceed their rated values: $\theta_{H2} = 120.94$ ºC, $F_{AA2} = 2.969$ (super unit value) and the percent loss of life pro year reaches 14.45 %. Therefore, the transformer remaining life dramatically declines to only $RL_2 = 6.92$ years. These phenomena are properly illustrated in Fig. 8, Fig. 9 (semi-log plot) and Fig. 10, where the maximal acceptable load factor of $\beta_{max} = 0.743$ with $\theta_{Href} = 110$ ºC, $F_{AA} = 1$ and $RL = NIL$ is also presented.

TABLE I. THE COMPUTED TRANSFORMER OPERATING PARAMETERS

A) Losses and temperatures within the transformer			
Type of losses in the transformer (W)	***Rated linear load (sinusoidal currents)***	***Different nonlinear loads (non-sinusoidal currents)*** Load factor $\beta = I/I_{2R}$	
	$\beta = 1$	$\beta_1 = 0.623$	$\beta_2 = 0.810$
No load P_{NL}	980	980	980
DC Ohmic P_{DC}	3933.333	1530.352	2586.295
Eddy current P_{EC}	649	1865.262	3152.293
Other stray P_{OSL}	1317.666	754.198	1274.595
Total P_T	6880	5129.813	7993.185
The top-oil-rise over the ambient temperature θ_{TO} (ºC)		50.170	71.866
The hottest spot conductor rise over top-oil temperature θ_g (ºC)		5.968	9.082
The transformer hottest spot winding temperature θ_H (ºC)		96.139	120.948
Aging acceleration factor F_{AA}		0.229	2.969
The percent loss of life (%*LOL*) pro year		1.118	14.450
Remaining life *RL* (years)		20.55	6.922
B) Transformer maximal acceptable operating parameters			
Maximum load factor		$\beta_{max} = 0.743$	
Maximum permissible current		$I_{MPC} = 429.404$ A	
Maximal operating capacity		$S_M = 297.500$ kVA	
Reduction in apparent power rating		$RAPR = 25.624$ %	

Practically, the transformer maximal operating capacity is restrained, due to the harmonics effects, at $S_M = 297.5$ kVA, which corresponds to a reduction of the apparent power rating (*RAPR*) of more than 25 %. The maximum permissible current reaches $I_{MPC} = 429.404$ A ($\beta_{max} = 0.743$).

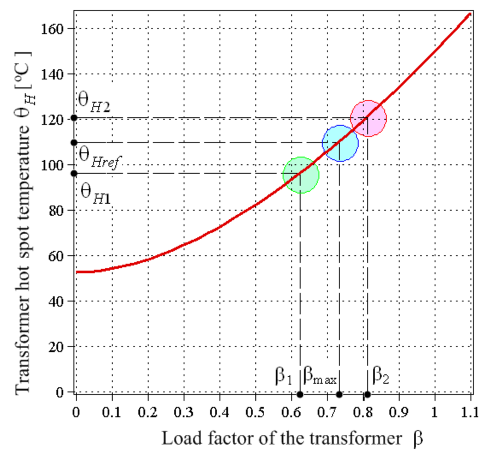

Figure 8. The transformer hot spot temperature dependency of the load factor.

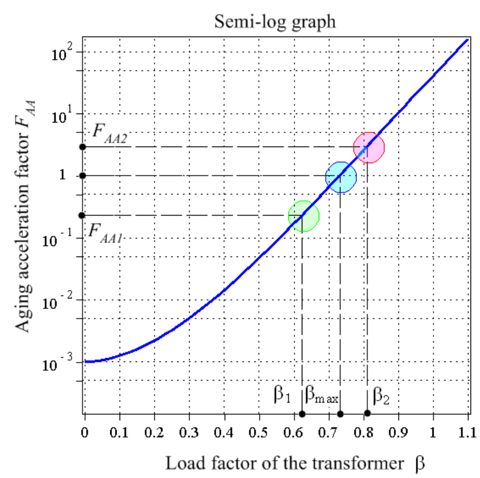

Figure 9. The relative aging acceleration factor of the transformer versus load factor (semilogarithmic plot).

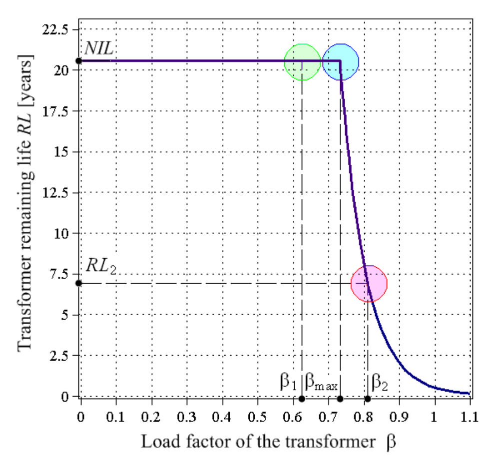

Figure 10. The real life estimation of the transformer versus load factor .

IV. Conclusions

The steady-state functionality of an in-service power distribution transformer that feeds a mixture of linear and nonlinear loads was quantitatively examined and analyzed. The study comprises the computation of both the electrical and thermal operating parameters of the transformers using on-site measured power quality data, non-invasively acquired at the machine low-voltage side. The method principle mainly follows the international standard recommendations and only demands the harmonic current spectrum at the transformer secondary part along with machine manufacturer test report data. The whole computation procedure for evaluating the losses and temperature distribution within the transformer was implemented in a very flexible general-purpose software package. The developed code allows farther extensions and changes to increase its computation potential and interconnectivity with various power quality analyzers. Thus, the main transformer thermal and electrical parameters are continuously monitored, and their abnormal values are to be signaled to the protection equipments. Consequently, the transformer normal life span (indicated under pure sinusoidal condition) is preserved. The here adopted derating and thermal computation technique is to be improved in terms of its accuracy by a more precise determination of the winding eddy current losses and other stray losses and by considering also other commonly encountered power quality issues (e.g. load unbalances or voltage waveform distortion).

Appendix

TABLE II. RATED DATA FOR INVESTIGATED TRANSFORMER

Rated power capacity	S_R = 400 kVA
Cooling type	Oil Natural Air Natural (ONAN)
Vector group	Dy0-11
Primary rated voltage	U_{1R} = 20 kV
Secondary rated voltage	U_{2R} = 0.4 kV
No load power losses	P_{NL} = 0.98 kW
Rated load losses at 75 ˚C (Short circuit power losses)	P_{LL-R} = 5.9 kW
Magnetization current	i_0 = 1.9 %
Short circuit voltage (Impedance voltage at rated current)	u_{sc} = 6 %
Per-phase DC resistance of primary winding at 75 ˚C	R_1 = 7.375 Ω
Per-phase DC resistance of secondary winding at 75 ˚C	R_2 = 2.950 mΩ
Ambient temperature	θ_A = 40 ˚C
Top-oil-rise over ambient temperature under rated conditions	θ_{TO-R} = 60 ˚C
Winding rise over ambient temperature under rated condition	θ_{w-R} = 65 ˚C

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