Thermal Aging of Power Distribution Transformers Operating under Nonlinear and Balanced Load Conditions

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Abstract. *The flow of harmonic current encountered in nowadays electrical installations causes numerous undesirable issues to the power grid. The most detrimental consequence is the premature aging or even failure of the in-service power distribution transformers from industrial facilities (originally designed to cope with the linear loads). Accordingly, the paper quantitatively examines the major thermal operating parameters of these transformers and predicts their lifetime expectancy under a certain harmonic load spectrum. The developed computation principle is based on the international standard recommendations and only demands the load current harmonic content (measured with a power quality analyzer) and the transformer rated data. The study is also carried out on a 250 kVA oil-type three-phase power distribution transformer from a pumping station.*

Keywords

Harmonics, thermal aging, transformers.

1. Introduction

The main culprits of the poor power quality in terms of distorted currents encountered in the modern electric installations are the nonlinear loads; electric equipment (industrial or domestic) with built-in electronic components that enable their control and energy efficient operation [1], [2], [3], [4] and [5]. On the other hand, due to the generated high order harmonic currents, they cause numerous instantaneous and long terms detrimental consequences on the installation components: circuit-breakers untimely tripping, overheating, mechanical stress, abnormal vibrations and acoustic noise of the electric machinery. The power distribution transformers from the in-service industrial plants were originally designed to serve linear loads and their lifespan was predicted to a few decades (with regular maintenance). The nowadays increased prevalence of the nonlinear loads additionally stresses the supply transformers by rising their intrinsic losses and consequently causing the machines premature aging or even failure [6], [7], [8], [9], [10], [11], [12] and [13]. The paper quantitatively examines the aging parameters of a power distribution transformer operating under balance and nonlinear load conditions (the typical industrial load state) [14], [15] and [16]. The transformer advanced thermal models [6] and [8] are often inefficient for in-situ investigation due to the numerous constructive and material required data. Thus, with the transformer rated data and the current harmonic spectrum, at the machine low-voltage side, the main electric and thermal operating quantities are continuously evaluated. Regarding also the international standards recommendations [17] and [18], the following transformer parameters are computed for different load factors: hot–spot temperature, the insulation relative aging acceleration factor, the percentage loss of life and lifetime expectancy. The harmonic load currents aging impact on the transformers is exemplified on a 250 kVA oil-type three-phase power distribution transformer that feeds an industrial facility (pumping station).

2. Transformer Aging Due to the Harmonic Currents

The aging process of any electrical equipment from an installation occurs, during its operation, mainly due to the deterioration of the equipment insulation materials.

This complex process is influenced by numerous factors such the mechanical stress or chemical aggression, moisture or oxygen content and, above all, the working temperature of the appliance [19], [20] and [21]. The latter is the most dominant parameter that ultimately determines the device lifespan. Since, in most appliances, the temperature is not uniformly distributed, the part that is operating at the highest temperature will commonly experience the greatest deterioration. Hence, in aging studies, it is usual to consider the aging effects produced by the highest (hot-spot) temperature [18].

2.1. Transformer Hot-Spot Temperature Evaluation

The expected lifetime of a distribution transformer is also very responsive to the machine hot-spot temperature. The harmonic currents of the supplied nonlinear loads cause supplementary losses within the transformer and may determine hot-spot temperatures that exceed the rated (reference) value. Therefore, a rapid degradation of the transformer insulation materials is expected followed by the reduction of transformer initial designed lifetime. For liquid-filled power distribution transformers, the windings hot-spot temperature θ_H is a function of ambient temperature θ_A, the oil temperature rise in respect to ambient temperature θ_{TO}, and the conductor hot-spot temperature rise relative to oil temperature θ_g [17]:

$$\theta_H = \theta_A + \theta_{TO} + \theta_g. \tag{1}$$

The last two terms involved in the above relation could be evaluated considering the machine rated data and losses distribution inside the transformer (ohmic losses P_{DC}, load losses P_{LL}, eddy current losses P_{EC}, other stray losses P_{OSL} and no load P_{NL} losses) [17]:

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

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 P_{DC-R}, P_{LL-R}, P_{EC-R} are the rated ohmic, load and eddy current losses respectively.

The operating transformer losses could be expressed in term of the load factor β (computed as the root mean square current I relative to transformer rated sinusoidal current I_{R2} at the low-voltage winding) and two power quality parameters that accounts the load current harmonic spectrum: harmonic loss factor (F_{HL} or K) and harmonic loss factor for other stray losses (F_{HL-STR}) [13], [15], [16] and [17]:

$$\begin{cases} P_{LL} = P_{DC} + P_{EC} + P_{OSL}, \\ P_{DC} = \beta^2 P_{DC-R}, \\ P_{EC} = \beta^2 P_{EC-R} F_{HL}, \\ P_{OSL} = \beta^2 P_{OSL-R} F_{HL-STR}, \end{cases}$$

with:

$$\begin{aligned} F_{HL} &= \frac{1}{I^2}\sum_{k=0}^{N} k^2 I_k^2, \\ F_{HL-STR} &= \frac{1}{I^2}\sum_{k=0}^{N} k^{0.8} I_k^2, \\ \beta &= \frac{S}{S_R} \cong \frac{I}{I_{R2}},\ I^2 = \sum_{k=0}^{N} I_k^2, \end{aligned} \tag{3}$$

where I_k is the effective value of the k current harmonic order, N is the highest accounted harmonic order (in our computations $N = 50$), S represents the apparent power and S_R is the transformer rated power under normal (sinusoidal) condition.

The rated winding eddy current losses P_{EC-R} and rated other stray losses P_{OSL-R} are conservatively estimated in accordance with the international standard recommendations [17]:

$$\begin{aligned} P_{EC-R} &= 0.33\,(P_{LL-R} - P_{DC-R}), \\ P_{OSL-R} &= 0.67\,(P_{LL-R} - P_{DC-R}). \end{aligned} \tag{4}$$

Supplementary, the transformer rated ohmic losses P_{DC-R} are computed on the basis of primary and secondary rated currents (I_{R1}, I_{R2}) and the windings DC ohmic resistances indicated by the manufacturer (R_1, R_2), respectively:

$$P_{DC-R} = 3(R_1 I_{R1}^2 + R_2 I_{R2}^2). \tag{5}$$

Since in the actual industrial power distribution systems the supply voltages waveforms are balanced and sinusoidal, the transformer no-load losses P_{NL} are invariable in respect to the current harmonic spectrum.

2.2. The Transformer Maximum Load Factor and Operating Capacity

In order to derive the admissible load factor $\beta_{\max}$ and its corresponding maximum permissible nonsinusoidal current I_{MPC} (effective value), one has to constrict the transformer operating hot-spot temperature θ_H (under any harmonic current conditions) to equal its initial reference value θ_{Href} (assumed for pure linear rated load).

$$\theta_A + \theta_{TO-R}\left(\frac{P_{LL\max} + P_{NL}}{P_{LL-R} + P_{NL}}\right)^{0.8} + \\ +\theta_{g-R}\left(\frac{P_{DC\max} + P_{EC\max}}{P_{DC-R} + P_{EC-R}}\right)^{0.8} = \theta_{Href},$$

with: (6)

$$\begin{cases} P_{LL\max} = P_{DC\max} + P_{EC\max} + P_{OSL\max}, \\ P_{DC\max} = \beta_{\max}^2 P_{DC-R}, \\ P_{EC\max} = \beta_{\max}^2 P_{EC-R} F_{HL}, \\ P_{OSL\max} = \beta_{\max}^2 P_{OSL-R} F_{HL-STR}. \end{cases}$$

The equation above is numerically solved (regarding the ambient temperature), and consequently, the transformer Reduction in Apparent Power Rating (RAPR) and its maximal operating capacity S_M are estimated:

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

To consider the most unfavorable (worst case) thermal operating conditions of the transformer, the maximum of rated windings eddy current losses is assumed. This can be appreciated, in per unites system relative to ohmic rated losses, according to [17]:

$$P_{EC-R}(p.u.)_{\max} = \frac{2.4 P_{EC-R}}{3 R_2 I_{R2}^2}. \quad (8)$$

2.3. Transformer Lifetime Estimation

The power distribution transformer lifespan is directly associated with the windings conductors' insulation life. Consequently, the actual standards [18] provide the rate at which the transformer insulation aging is accelerated compared with the aging rate at a reference hot-spot temperature θ_{Href} by a factor called aging acceleration factor F_{AA}. Its expression mainly depends on the transformer operating hot-spot temperature θ_H:

$$F_{AA} = \exp\left(\frac{B}{\theta_{Href} + 273} - \frac{B}{\theta_H + 273}\right), \quad (9)$$

where B is an insulation type material constant [18]. It is also important to reveal that if the relative aging acceleration factor has less than unity values, the transformers initial lifetime expectancy Normal Insulation Life (NIL) is preserved.

Considering the above-mentioned assumptions, the percent loss of life ($\%LOL$) of the transformer insulation can be evaluated [18], [19], [20] and [21]:

$$\%LOL = \frac{F_{AA}}{NIL} t \cdot 100. \quad (10)$$

where t is a certain period (indicated in years).

Practically, the machine lifetime is regarded as its insulation lifespan. Hence, the transformer Per Unit Life $Life(pu)$ (relative to its normal insulation lifetime), and the machine Remaining Life RL can be expressed in terms of the operating transformer hot-spot temperature θ_H and the aging acceleration factor F_{AA}, respectively [18]:

$$\begin{aligned} Life(pu) &= A \exp\left(\frac{B}{\theta_H + 273}\right), \\ RL &= \frac{NIL}{F_{AA}} = Life(pu) NIL, \end{aligned} \quad (11)$$

where A is a material constant, estimated also based on the Normal Insulation Lifetime (NIL). The constant B is the same as the one already indicated in [9].

For the power distribution transformers found in most of the in-service examined electric installations, the normal insulation life is considered 20 years. According to the manufactures indications, these transformers have an average winding temperature rise relative to ambient temperature of 55 °C and common (not thermally upgraded) conductor insulation type [18]. This corresponds to a reference (rated) hot spot temperature of $\theta_{Href} = 95$ °C and material constants values: $A = 2 \cdot 10^{-18}$ and $B = 15,000$ [18], [19], [20] and [21].

The operating parameters computation procedure presented here allows an in-situ, fast and less intrusive investigation method for the numerous, still working, power distribution transformers subjected to distorted currents from various industrial installations.

2.4. Transformer Thermal Aging Parameters Prediction-Case Study

The transformer thermal aging evaluation principle is illustrated on an oil-type 250 kVA power distribution unit that supplies nonlinear and balanced loads from an industrial pump facility - Fig. 1. The transformer rated characteristics, provided by the manufacturer, are illustrated in the Appendix. The main electric quantities of the machine are continuously measured and monitored at the transformer secondary part (low-voltage side) with a professional power quality analyzer [22]. The latter also transfers all the acquired data to a portable computer, which due to a developed software package (elaborated in accordance with the principle exposed

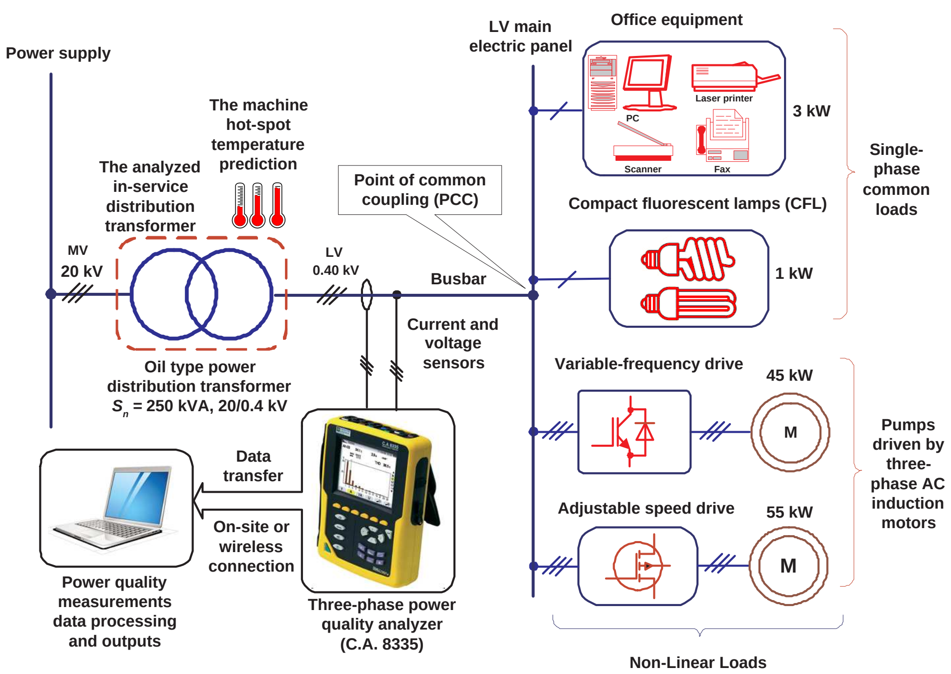


Fig. 1: The investigated three-phase power distribution transformer supplying single and three-phase nonlinear loads of an industrial pump facility.

in the previous section), predicts the operating transformer hot-spot temperature and its corresponding remaining life. Additionally, all the losses inside the machine, their division and the derating parameters are also determined.

For the investigated nonlinear load, the most relevant power quality parameters were constantly measured and acquired. Thus, the transformer currents waveforms and their harmonic spectrum are shown in Fig. 3 and Fig. 4, respectively. Figure 5 reveals the currents absolute values at the fundamental frequency, the phase displacement of the line voltages relative to the currents and the unbalance level. The phase currents root mean square and their harmonic parameters values are indicated in Fig. 5, while Fig. 6 and Fig. 7 show the load (active, reactive and apparent) powers and power factor. All the computed operating parameters (electrical and thermal) for the investigated transformer are presented in Tab. 1 for two different load factors. The first one corresponds to the measured transformer harmonic state: $\beta_1 = 0.377$ and the second one: $\beta_2 = 0.754$ assumes a double load with the same harmonic current spectrum. Supplementary, for comparison reasons, the parameters for the rated (pure sinusoidal state) $\beta = 1$ are also indicated in Tab. 1. Consequently, the first load factor generates within the machine the hot-spot temperature $\theta_{H1} = 66.238$ °C that is below its reference value ($\theta_{Href} = 95$ °C) and determines an ageing acceleration factor $F_{AA1} = 0.0315$. This subunit value indicates that the transformer preserves its normal insulation life ($NIL = 20$ years) - the percent loss of life value per year is neglected.

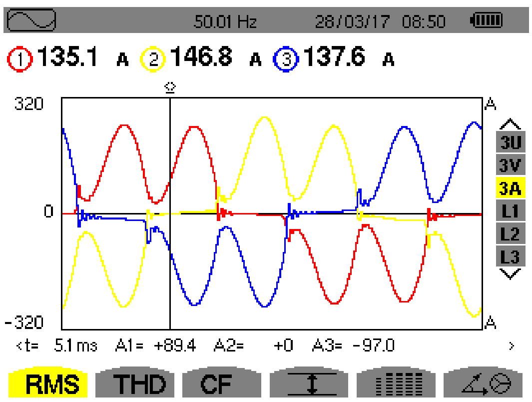


Fig. 2: The transformer currents waveforms and their root mean square values.

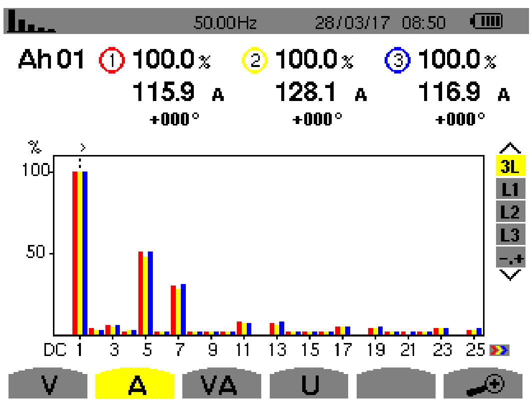


Fig. 3: The phase currents harmonic spectrum.

Tab. 1: Electrical and thermal operating parameters of the investigated transformer for different load factors.

A) Temperatures within the transformer and aging parameters			
Thermal aging parameters of the transformer	**Rated linear load**	**Various nonlinear loads ,(distorted currents), Load factor $\beta = I/I_{2R}$**	
	$\beta = 1$	$\beta_1 = 0.377$	$\beta_2 = 0.377$
The top oil temperature rise in respect to ambient temperature θ_{TO} (°C)	55	27.560	65.437
The conductor hot spot temperature rise relative to oil temperature θ_g (°C)	5	3.677	11.147
The transformer hottest spot winding temperature θ_H (°C)	95	66.238	111.585
Aging acceleration factor F_{AA}	1	0.0315	5.799
The percent Loss of Life ($\%LOL$) pro year	-	-	28.999
Remaining Life RL (years)	20	20	3.474
B) Losses distribution within the transformer			
Type of losses in the transformer (W)	$\beta = 1$	$\beta_1 = 0.377$	$\beta_2 = 0.754$
No load P_{NL}	650	650	650
DC Ohmic P_{DC}	2166.666	308.679	1234.717
Eddy current P_{EC}	357.5	608.209	2432.838
Other stray P_{OSL}	725.833	191.241	764.9677
Total P_T	3900	1758.130	5082.523
The nonlinear load harmonic loss factor F_{HL} or K		11.9416	
The nonlinear load harmonic loss factor for other stray losses F_{HL-STR}		1.849	
C) Transformer maximal acceptable operating parameters			
Maximum load factor		$\beta_{\max} = 0.646$	
Maximum permissible current		$I_{MCP} = 233.250$ (A)	
Maximal operating capacity		$S_M = 161.600$ (kVA)	
Reduction in apparent power rating		$RAPR = 35.359$ (%)	

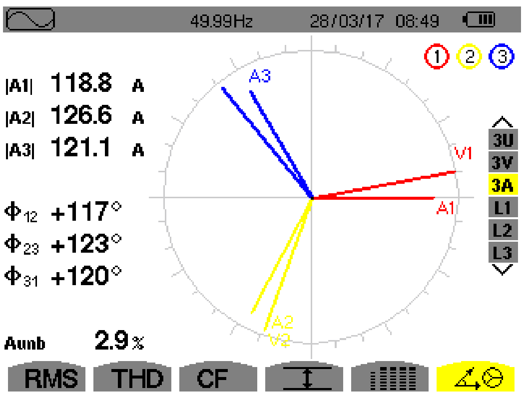


Fig. 4: The currents absolute values at the fundamental frequency, the phase displacement of the line voltages relative to the currents and the unbalance level.

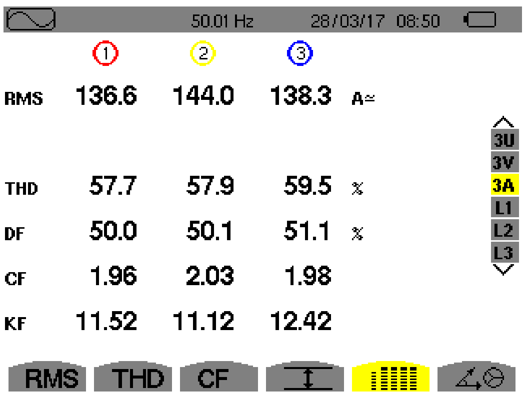


Fig. 5: The phase currents root mean square and their harmonic parameters values.

The transformer behaves completely differently when the load factor is doubled with the same currents harmonic content. Hence, for $\beta_2 = 0.754$, the main thermal operating parameters significantly exceeds their rated values: the hot–spot temperature becomes $\theta_{H2} = 111.585$ °C and the new aging accelerating factor reaches up to $F_{AA2} = 5.799$. Therefore, the transformer remaining life suddenly drops down to only $RL_2 = 3.474$ years (the percent loss of life year value is 28.99 %). All the above computations were performed considering the rated temperatures of the

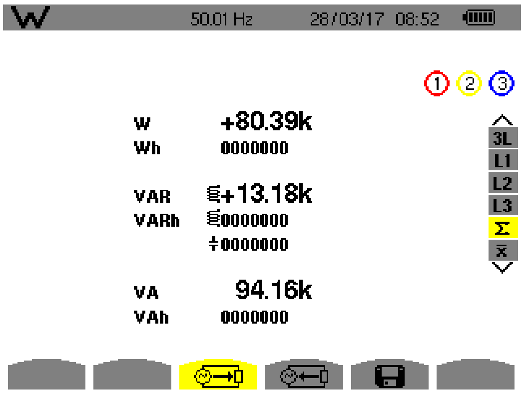


Fig. 6: The active, reactive and apparent powers.

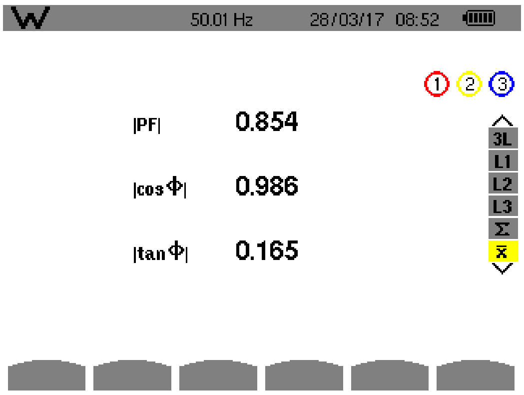


Fig. 7: The load power factor.

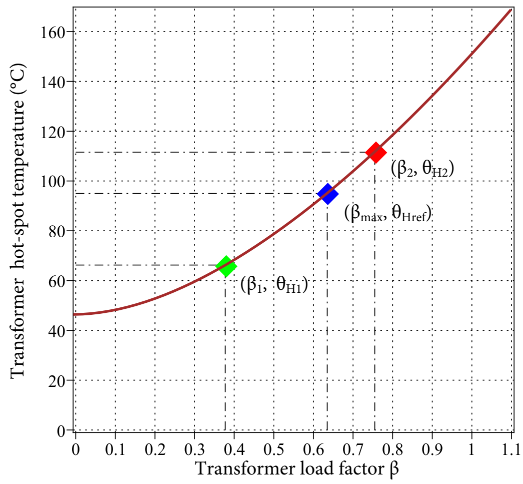
transformer shown in the Appendix and ambient temperature $\theta_A = 30$ °C.

The developed program also manages to adequately predict and visualize the transformer operating parameters variation with different alterations of the nonlinear load features. Thus, the effect of load factor changes on the hot-spot temperature, aging acceleration factor and the machine remaining life are represented in Fig. 8(a), Fig. 8(b) (in semilogarithmic representation) and Fig. 8(c) respectively. The maximal permissible load factor $\beta_{\max} = 0.646$ and its corresponding (rated) operating parameters: $\theta_{Href} = 95$ °C, $F_{AA} = 1$ and $RL = NIL$ are also depicted in Fig. 8.

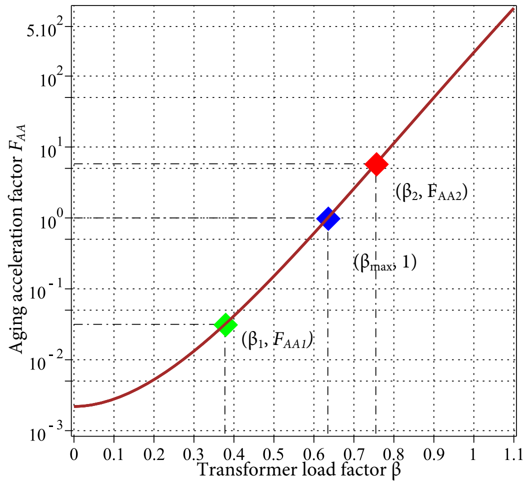
One can notice that for the measured load current harmonic spectrum, the transformer could maintain the initial insulation lifetime ($NIL = 20$ years) only up to almost half of the rated capacity ($\beta_{\max} = 0.646$).

3. Remarks and Conclusions

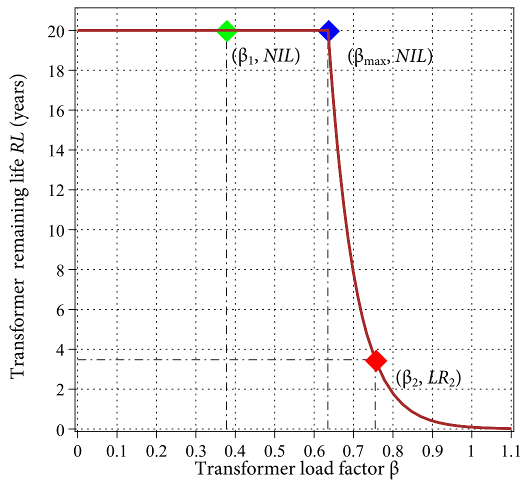
The electrical and thermal operating parameters of the actual in-service power distribution transformers that supply nonlinear loads were predicted and reviewed. Accordingly, the main transformer aging indi-



(a) The hot-spot temperature.



(b) Aging acceleration factor in semilogarithmic representation.



(c) The transformer remaining life.

Fig. 8: Transformer aging parameters dependency of the load factor: (a) the hot-spot temperature, (b) aging acceleration factor in semilogarithmic representation and (c) the transformer remaining life.

cators (hot-spot temperature, aging acceleration factor etc.) were continuously computed in accordance with the measured current harmonic load spectrum and the transformer rated data. The proposed computation principle is based on the international standards recommendations and constraints the machine operating hot-spot temperature to be under the rated (reference) value, indicated by the manufacturer. Thus, all the derating parameters (maximum permissible current, the reduction in apparent power rating etc.) are also evaluated along with their dependency with the load factor variation. This technique is to be easily implemented in any general-purpose computing software and could be further used as a low-cost and flexible on-site maintenance instrument of the transformer (especially as the power quality data could be nowadays wirelessly transferred to a mobile computation unit). To preserve the transformer rated lifespan, some additional on-site proactive maintenance measures are strongly advised. Hence, thermographic inspection and vibration investigation on the main transformer constructive part may be easily performed with the adequate equipment (portable infrared camera and vibration analyzer). The presented transformer aging computation procedure was systematically tested on many units with different rated powers from various industrial facilities. This could avoid the machine overloading by signaling the abnormal non-electric parameters. The presented hot-spot computation principle could be improved in terms of its accuracy and applicability in at least three major directions: better evaluation of the operating losses (by using high precision numerical method), the consideration of the load unbalances (especially useful in domestic installations with numerous single-phase loads) and finally by taking into account also the voltage distortions (occurring when high nonlinear loads are supplied by systems with low short-circuit power).

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Appendix A The Analysed Transformer Rated Data

- Rated power capacity $S_R = 250$ kVA,
- Primary rated voltage $U_{R1} = 20$ kV,
- Secondary rated voltage $U_{R1} = 0.4$ kV,
- No load power losses $P_{NL} = 0.65$ kW,
- Short circuit power losses $P_{LL-R} = 3.25$ kW,
- No-load current $i_0 = 2.1$ %,
- Short circuit voltage $u_{sc} = 6$ %,
- Per-phase DC resistance of primary winding at 75 °C: $R_1 = 10.4$ Ω,
- Per-phase DC resistance of secondary winding at 5 °C: $R_2 = 0.00416$ Ω,
- Ambient temperature $\theta_A = 30$ °C,
- Top-oil-rise over ambient temperature under rated conditions $\theta_{TO-R} = 50$ °C,
- Winding rise over ambient temperature under rated condition $\theta_{w-R} = 55$ °C,
- Rated (reference) winding hot-spot temperature $\theta_{Href} = 95$ °C,
- Cooling type: Oil Natural Air Natural (ONAN),
- Vector group: Dyn05.