Harmonic Distortion Effects on Low-Voltage Distribution Transformers under Rising EV and Nonlinear Load Penetration

Fayezeh Mahmoudnezhad, Araceli Hernández
Escuela Técnica Superior de Ingenieros Industriales
Universidad Politécnica de Madrid
Madrid, Spain
f.mahmoudnezhad@upm.es, araceli.hernandez@upm.es

Pablo Rodríguez-Pajarón
REE
Madrid, Spain
pablo.rpajaron@upm.es

***Abstract*—The growing proliferation of power electronic-based non-linear loads is leading to non-sinusoidal waveforms of currents and voltages in the modern power systems. These non-linear loads inject harmonic components that have a significant impact on low-voltage (LV) distribution transformers. The primary effect of harmonic currents is the amplification of frequency-dependent losses, leading to higher operating temperatures and accelerated thermal degradation of the transformer's insulation system. This article explores the application of IEEE Std C57.110 in realistic scenarios involving the integration of electric vehicles (EVs) and residential nonlinear loads, based on field measurements of harmonic current injections from both sources. The analysis assesses the resulting harmonic distortion and its impact on LV distribution transformers. The results demonstrate that harmonic distortion can potentially increase transformer losses and thermal stress, particularly under high penetration of EVs and other nonlinear loads. Furthermore, the study underscores the importance of appropriate transformer sizing and strategic over-dimensioning as effective measures to mitigate these adverse effects. These findings suggest that existing harmonic standards and transformer design practices may require revision to account for the evolving composition of modern distribution networks.**

***Index Terms*—Electric vehicles, power quality assessment, Current harmonics, harmonic loss factor, IEEE C57.110™, transformer**

I. Introduction

In modern low-voltage (LV) distribution networks, the growing proliferation of power-electronic-based residential loads and electric vehicles (EVs) represents a major step toward developing sustainable and decarbonized power systems [1]. However, widespread integration of these nonlinear loads inherently introduces harmonic distortion in both current and voltage waveforms, primarily due to the switching operation and control strategies of their power-electronic interfaces [2], [3]. Since network components are designed to operate under nearly sinusoidal steady-state conditions, harmonics can substantially deteriorate power quality and system reliability. Uncontrolled harmonic levels lead to additional power losses, excessive heating of the conductors and transformers, overloading of the neutral conductors, unintended relay operations, and potential resonance with network impedances [4], [5].

These harmonic currents further accelerate the degradation of critical infrastructure components—particularly distribution transformers and cables—resulting in reduced operational lifespan, increased thermal stress, intensified losses, and higher maintenance requirements [6], [7]. As the share of these nonlinear loads continues to increase, field measurement–based harmonic assessment has become essential to accurately characterize harmonic emission profiles and their cumulative effects on transformer performance, thermal behavior, and lifetime expectancy.

To address these challenges, our study performs a field measurement–based assessment of harmonic distortion effects on LV distribution transformers under increasing penetration of residential nonlinear loads and EVs. Steady-state and dynamic thermal aging analyses are combined to quantify transformer stress under temporally clustered and highly variable operating conditions, and to demonstrate transformer sizing as an effective mitigation strategy for ensuring reliable LV network operation in the context of the ongoing energy transition.

II. IEEE Std C57.110 Framework for Transformer Thermal Assessment

IEEE Std C57.110 is a recommended practice focused on determining the loading capability of liquid-immersed and dry-type power and distribution transformers when they supply non-sinusoidal load currents [8]. This recommended practice applies exclusively to two winding transformers [9] and does not cover rectifier transformers [10]. This study focuses on oil-immersed transformers, as they are more commonly employed in residential distribution networks than dry-type transformers [11]. The following sections present key standard-based principles and governing equations for analyzing harmonic effects in transformers. The standard has been applied to several case studies to demonstrate how harmonics introduced by nonlinear loads can affect transformer performance, thermal behavior, and lifetime expectancy.

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A. Transformer Loss Components

Transformer losses are classified into no-load (excitation) loss, denoted as P_{NL}, and load (impedance) loss, denoted as P_{LL}. The load loss is subdivided into I^2R (copper) loss, P, and the stray loss, P_{TSL}. Stray losses originate from stray electromagnetic flux in the windings, core, core clamps, magnetic shields, and the tank structure. Accordingly, the total stray loss is divided into the winding stray loss, P_{EC}, and the stray loss in other metallic components, P_{OSL}. The total load loss can then be expressed as follows:

$$P_{LL} = P + P_{EC} + P_{OSL} \tag{1}$$

B. Transformer Harmonic-induced Losses

A fundamental impact of harmonic distortion is the increase in the RMS load current experienced by the transformer, arising from the cumulative contribution of individual harmonic components and highlighting the need to explicitly incorporate these effects into transformer loading and thermal performance assessment. The governing expression is as follows:

$$I = \sqrt{\sum_{h=1}^{h=h_{\max}} (I_h)^2} \tag{2}$$

where I is the total RMS load current, $h_{\max}$ is the highest significant harmonic order, I_h is the RMS load current associated with the h-th harmonic order.

The load losses in a transformer subjected to nonsinusoidal load currents can be characterized using harmonic loss factors, which quantify the frequency-dependent increase in winding eddy-current losses, F_{HL}, and in other stray losses, F_{HL-STR}. These factors capture the enhanced electromagnetic and thermal stresses caused by harmonic components, and the resulting total load loss under harmonic loading is expressed as:

$$P_{LL} = (P_R + F_{HL} \times P_{EC-R} + F_{HL-STR} \times P_{OSL-R}).I_{pu}^2 \tag{3}$$

where the superscript R indicates rated-load conditions, and I_{pu} is defined as the ratio of the harmonic load current to the rated load current.

The harmonic loss factor for winding eddy-current losses is given by:

$$F_{HL} = \frac{\sum_{h=1}^{h=h_{\max}} I_h^2 h^2}{\sum_{h=1}^{h=h_{\max}} I_h^2} \tag{4}$$

and the harmonic loss factor associated with other stray losses is defined as:

$$F_{HL-STR} = \frac{\sum_{h=1}^{h=h_{\max}} I_h^2 h^{0.8}}{\sum_{h=1}^{h=h_{\max}} I_h^2} \tag{5}$$

C. Transformer Thermal Aging Modeling

After determining harmonic-dependent load losses—including all stray loss components relevant in liquid-immersed transformers—the corresponding thermal response can be assessed through the top-oil temperature (TOT) rise over ambient, θ_{TO}, and the hottest-spot temperature (HST) rise over the top-oil layer, θ_g, as expressed by the following equations:

$$\theta_{TO} = \theta_{TO-R} \times \left(\frac{P_{LL} + P_{NL}}{P_{LL-R} + P_{NL}} \right)^{0.8} \tag{6}$$

$$\theta_g = \theta_{g-R} \times \left(\frac{P_{LL}}{P_{LL-R}} \right)^{0.8} \tag{7}$$

where θ_{TO-R} is the TOT rise over ambient under rated conditions (°C), and θ_{g-R} is the HST rise over the top-oil under rated conditions (°C). Having determined the corresponding top-oil and hottest-spot temperature rises, the HST in the transformer winding, θ_{HS}, is obtained as:

$$\theta_{HS} = \theta_{TO} + \theta_g + \theta_{Ambient} \tag{8}$$

where $\theta_{Ambient}$ is the ambient temperature (°C). Once the harmonic contribution to the HST has been determined, the resulting loss-of-life (LOL) can be estimated. The aging acceleration factor, F_{AA}, is defined in Equation (9) using a reference HST of 110 °C. For HST values higher than 110 °C, $F_{AA} > 1$ indicates accelerated insulation aging, whereas $F_{AA} < 1$ reflects a reduced ageing rate. The empirical constant of 15 000 represents the effective activation energy of the insulation degradation process, expressed in Kelvin.

$$F_{AA} = \exp\left(\frac{15000}{383} - \frac{15000}{\theta_{HS} + 273} \right) \tag{9}$$

Based on F_{AA}, which quantifies the temperature-dependent rate of insulation degradation, the real-life expectancy of the distribution transformer, $\text{Life}_{\text{real}}$, can be assessed as follows:

$$\text{Life}_{\text{real}} = \frac{\text{Life}_{\text{norm}}}{F_{AA}} \tag{10}$$

where $\text{Life}_{\text{norm}}$ denotes the normal insulation life, expressed in years, at reference HST of 110°C.

III. System Description and Measurement-Based Harmonic Assessment Framework

A. Network and Transformer Description

The studied network is a three-phase LV residential distribution system serving 150 single-phase customers through a 20/0.4 kV, 155 kVA liquid-immersed distribution transformer. The principal parameters of the transformer examined in this study are summarized in Table I and follow the illustrative examples provided in the reference standard [8]. Each consumer is allocated to one phase of the network, and a perfectly balanced allocation of 50 single-phase residential consumers to each transformer phase is assumed in the analysis. Each load point includes residential nonlinear household appliances

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TABLE I
TECHNICAL PARAMETERS OF THE STUDIED DISTRIBUTION TRANSFORMER

Parameter	Value	Parameter	Value
HV winding resistance	18.207 Ω	LV winding resistance	0.02491 Ω
Rated power	155 kVA	No-load loss	9.5 kW
Primary voltage	20 kV	Load loss	35 kW
Secondary voltage	400 V	Ambient Temperature	35 °C
Power factor	0.95	Rated top-oil temperature rise	55 °C
Normal insulation life	30 years	Rated hottest-spot temperature rise	80 °C

equipped with EV charging infrastructure, reflecting modern LV residential networks with a high penetration of power-electronic-based loads.

B. Characterization of Harmonic Injection Profiles Using Field Measurements

To generate representative weekly EV harmonic current profile, field-measured harmonic current waveforms obtained from 40 charging cycles of 14 EVs, representing nine different manufacturers and models, are employed, as reported in detail in [12], [13]. The charging start time for each EV has been generated using statistical distributions derived from real measurements reported in [14], while the corresponding charging durations are sampled from the empirical distributions observed during the same field measurement campaign. A temporal resolution of 1-min is assumed throughout the analysis.

In addition to EV charging, residential harmonic current injections are incorporated at the load points. For this purpose, one-week harmonic injection profiles from 25 individual residential customers are included, based on real measurement data obtained from the MEMORIA public database [15].

To accurately characterize the cumulative harmonic distortion imposed on the LV distribution transformer, the harmonic current contributions from residential loads and EV charging are combined using vector addition (phasor summation), considering harmonic phase-angle diversity, harmonic superposition and cancellation effects in the aggregated transformer current. The most prominent harmonic current components observed in the conducted measurements, up to the 13th harmonic order, are analyzed in this study.

C. Case Study Definitions and Transformer Loading Scenarios

The long-term challenge in LV residential networks is that existing installed distribution transformers were originally sized and designed for operating conditions fundamentally different from those expected under future demand profiles. As a result, assessing their performance under emerging loading patterns (increased harmonic distortion and thermal stress) has become essential.

In this study, a distribution transformer with relatively limited capacity has been intentionally selected to evaluate its behavior under extreme harmonic and loading conditions. This choice enables the transformer to operate near its rated limits, enabling a more realistic and critical assessment. Given the rated secondary voltage, the corresponding rated secondary current is approximately 224 A, which is only slightly higher than the maximum expected current in a scenario where all residential consumers are equipped with EV charging infrastructure. To analyze the effect of transformer rating and loading conditions on harmonic-induced thermal aging and life expectancy, four cases are examined:

- Case 1: 50 residential loads without EVs.
- Case 2: 50 residential loads, all equipped with EV charging infrastructure.
- Case 3: 50 residential loads, all equipped with EV charging infrastructure, supplied by a transformer oversized by 25%.
- Case 4: 50 residential loads, all equipped with EV charging infrastructure, supplied by a transformer oversized by 55%.

IV. EFFECT OF TRANSFORMER RATING ON HARMONIC-INDUCED AGING AND LIFE EXPECTANCY

A. Steady-State Thermal and Aging Assessment

To perform a steady-state assessment of transformer harmonic-induced thermal and aging performance, weekly average magnitude of each harmonic component is used as a representative value. The transformer loading level, expressed as the percentage of rated load, is required because the total losses must be adjusted to account for both the reduced RMS current (operating below rated conditions) and the additional contribution arising from harmonic distortion. The determined harmonic spectra correspond to loading levels of 40%, 87%, 72%, and 58% for Cases 1 through Case 4, respectively.

The results of steady-state assessment are summarized in Table II. Across the four cases analyzed, Case 1 exhibits the higher harmonic loss factors than Cases 2–4. When EV charging is introduced (Cases 2–4), their associated harmonic components—present only during relatively short charging intervals—contribute limitedly to the weekly mean harmonic spectrum, whereas EV penetration leads to a pronounced increase in the weekly-average fundamental current. As a result, despite higher absolute harmonic loading in Cases 2–4, the harmonic loss factors—which are normalized by the fundamental current—decrease. Fig. 1 illustrates the time evolution of the fundamental, third, and fifth harmonic current components over the representative one-week period for the defined loading cases, highlighting that the pronounced change from Case 1 to Cases 2–4 is the increase in the fundamental current relative to higher-order harmonics. So, under the considered loading cases, the contribution of increased fun-

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damental current is more significant than enhanced harmonic content in determining transformer thermal stress.

As summarized in Table II, the transformer's thermal and aging stress peaks in Case 2, reflecting the combined effect of increased RMS loading and frequency-dependent stray-losses associated with harmonic currents. In contrast, Case 3 and Case 4, which employ oversized transformers under identical harmonic content relative to Case 2, show reduced θ_{TO}, θ_g , θ_{HS} and F_{AA} compared to Case 2. This confirms that transformer oversizing is a robust and effective mitigation strategy for reducing harmonic-induced thermal rise under the increasing power-electronic-based loads. Moreover, F_{AA} remains below 1 in all cases, suggesting no accelerated LOL under the weekly-average harmonic spectrum.

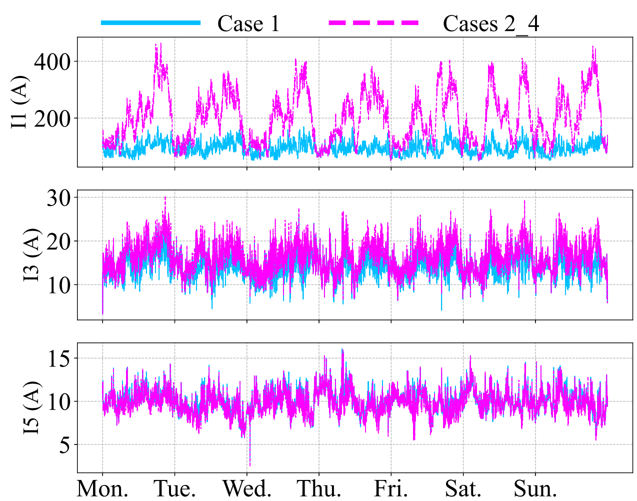

Fig. 1. Time evolution of the fundamental, third, and fifth harmonic current components for defined loading cases.

B. Dynamic Thermal and Aging Assessment

EV charging sessions with considerable temporal variability introduce time clustering and phase-angle-dependent aggregation and cancellation of harmonics, which can result in short-duration thermal extremes that are not represented by weekly-mean spectra; therefore, a dynamic assessment of transformer thermal and aging behavior is necessary.

Fig. 2 represents the statistical distribution of harmonic loss factors over the analyzed week for the four loading scenarios. Case 1 exhibits a broader distribution and increased harmonic loss factor values than Cases 2–4, indicating a comparatively stronger contribution of higher-order harmonic currents relative to the fundamental component in the aggregated transformer current. Significantly, Fig. 2 demonstrates that transformer oversizing (Cases 3 and 4) does not alter the harmonic loss factors distributions (Case 2), confirming that these factors are governed by the harmonic spectrum of the connected loads rather than by the transformer rated capacity.

Fig. 3 represents boxplots of the transformer HST for the defined Cases over a representative one-week period with 1-minute resolution. As shown in this figure, Case 1 shows a closely clustered HST distribution with limited dispersion, indicating thermally stable performance. In contrast, the introduction of extensive EV charging without transformer oversizing (Case 2) result in a pronounced upward shift in both the median and upper tail of the HST distribution, reaching up to approximately 240°C and exceeding its 110°C design threshold. This behavior confirms that harmonic-enhanced losses significantly intensify thermal stress during clustered charging periods, even when average indices remain within acceptable threshold. Progressive transformer oversizing (Case 3 and Case 4) shifts the HST distribution downward and mitigates high-impact extreme hot-spot events, which are the primary contributors to accelerated insulation aging and LOL in EV-dense LV networks.

Fig. 4 presents the weekly distribution of the F_{AA} for the evaluated loading cases. Case 1 exhibits low insulation aging despite comparatively higher harmonic loss factors. Case 2, reflecting the combined impact of increased RMS current and frequency-dependent stray losses, shows extreme upper outliers in the F_{AA} boxplot, indicating that transformer insulation aging is affected by rare but severe thermal extremes. Transformer oversizing (Case 3 and Case 4) effectively mitigates outliers, thereby limiting peak insulation stress and stabilizing the temporal aging profile despite unchanged harmonic injection compared to Case 2.

Overall, the results indicate that temporally clustered EV charging sessions raise RMS loading and harmonic-induced stray losses and lead to short-duration thermal extremes that are not reflected in weekly-average indices. So, strategic transformer sizing—combined with ongoing harmonic monitoring and targeted mitigation—can substantially reduce extreme HST outliers and preserve expected transformer lifetime under increasingly nonlinear, power-electronics-based residential loads.

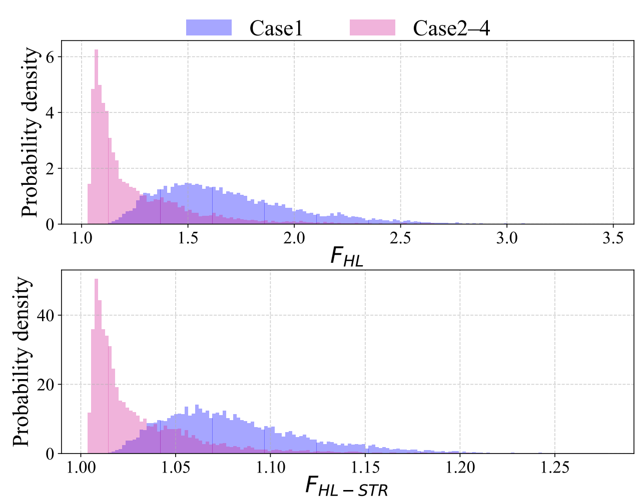

Fig. 2. Histogram of harmonic loss factors for defined loading cases.

TABLE II
SUMMARY OF STEADY-STATE TRANSFORMER HARMONIC-INDUCED THERMAL AND AGING PERFORMANCE

Parameter	Case 1	Case 2	Case 3	Case 4
F_{HL}	1.5758	1.1361	1.1361	1.1361
F_{HL-STR}	1.0695	1.0169	1.0169	1.0169
θ_{TO} (°C)	25.26	48.37	38.96	31.39
θ_{g} (°C)	8.28	21.99	16.12	11.29
θ_{HS} (°C)	68.55	105.36	90.08	77.68
F_{AA}	0.0086	0.6185	0.1167	0.0271
$\text{Life}_{\text{real}}$ (year)	30	30	30	30

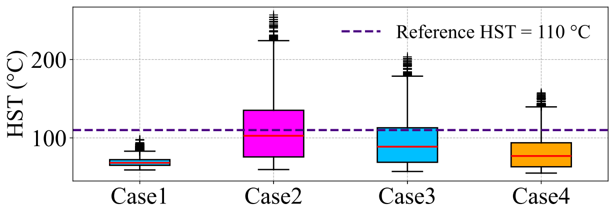

Fig. 3. Boxplot of HST for defined loading cases.

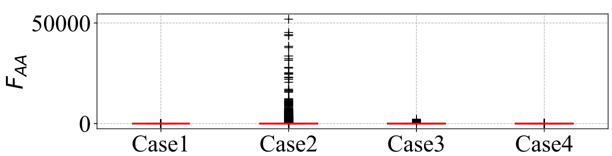

Fig. 4. Boxplot of aging acceleration factor for defined loading cases.

V. CONCLUSION

This work provides a field measurement–based assessment of harmonic distortion impacts on LV distribution transformers under increasing penetration of residential nonlinear loads and EVs. Realistic harmonic injection profiles aligned with the IEEE C57.110 thermal-aging framework, demonstrates that high EV penetration significantly impacts transformer thermal and aging through the combined effect of increased RMS loading and frequency-dependent stray losses pronounced during temporally clustered charging sessions. While weekly-average harmonic indices may remain within acceptable limits, dynamic analysis reveals short-duration thermal extremes that exceed transformer design thresholds and contribute to insulation aging. The analysis further confirms that transformer oversizing does not alter the harmonic spectrum injected by connected loads, but it substantially mitigates extreme thermal events and aging outliers.

The findings emphasize the need for utilities to revise traditional transformer sizing practices to explicitly account for nonlinear load dynamics, harmonic phase-angle diversity, and the temporal clustering of EV charging. The study also highlights the importance of continuous harmonic monitoring and dynamic thermal assessment to ensure reliable transformer performance and preserve asset lifetime as EV adoption accelerates.

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