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Influence of EV Charging Stations on the Performances of Three-Phase Distribution Transformers in Residential Grids

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ABSTRACT

Electric vehicle charging stations significantly impact the performance of three-phase (11/0.4 kV) distribution transformers, as unbalanced and variable loads lead to higher temperatures and increased power loss. They also contribute to reduced transformer life and increased risk of failure. This paper demonstrates the impact by analyzing the challenges arising from the nonlinear and variable nature of electric vehicle charging loads, such as harmonic distortions, electrical stresses, and voltage imbalance. The electrical network was simulated using the Electrical Transient Analyzer Program (ETAP) software, and the potential risks to (11/0.4 kV) distribution transformers due to nonlinear and variable charging loads were identified. The results revealed that the distribution transformer's capacitance near to the loads (T3) suffered a 12.40 % voltage drop at full load. On the other hand, the total distortion on the secondary side of the transformer (T3) reached 55.71% for a six-pulse, single-harmonic IEEE source and 40.53% for a twelve-pulse, single-harmonic IEEE source. This analysis indicates a potential risk to transformer performance, which calls for consideration of adding harmonic filters to improve power quality. It also aims to enhance the reliability and efficiency of converters by providing accurate analyses and simulations of the impact of electric vehicle charging stations on converter performance.

Keywords:

Electric Vehicle, Charging Station, Distribution transformer, Distribution Networks, Transformer Loss profiles.

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1. INTRODUCTION

In cities, electric cars greatly lower carbon emissions and enhance the quality of the environment. The use of electric vehicles in urban transportation is rapidly growing. One of the major causes of greenhouse gas (GHG) emissions, a major factor in climate change, has been the use of conventional automobiles. These automobiles are powered by fossil fuels, which release a lot of nitrogen oxides, carbon dioxide, and other pollutants into the environment. Electric.

vehicles (EVs), on the other hand, run on electricity, which can be produced using renewable resources like solar and wind energy and produces very little [1–3] Eco-friendlier and efficient engine technologies, including electric vehicles (EVs), must gradually replace conventional engine technologies to fulfill future mobility demands, lower pollutants linked to the climate and human health, and phase out reliance on oil. In addition, a number of nations (such as Germany, Denmark, and Sweden) have decided to switch to renewable energy sources rather than fossil fuels. for their power generation, making electric cars (EVs) even more environmentally benign than internal combustion motors [4]. The distribution network is most likely to suffer the greatest effects from electric vehicle (EV) charging on power systems [5], [6].

The utility grid is typically used to charge electric vehicles (EVs), particularly battery-electric vehicles (BEVs) and plug-in hybrid EVs (PHEVs). Assessing the possible overloading impact of extensive EV charging on the operation and design of power distribution networks is crucial, given the increasing use of EVs in both residential and commercial settings, as well as the quick installation of EV charging [7]-[9] are serious consequences to EV integration in the distribution network, including network imbalance and decreased network reliability. The majority of EV-related research and effort concentrates on how to integrate EVs into the transportation system from the perspective of the user and how to lessen the issues that come with it [10], [11]. However, from the utility's point of view, it is equally necessary to lessen the effects of the inevitable integration of EV (e.g., transformer losses, line overloading, etc.) [12]-[15] EVs' detrimental effects on the power distribution system are one of the main barriers to their successful integration into the current transportation infrastructure [16]-[20]. Electric vehicle (EV) charging stations pose several challenges for residential three-phase distribution transformers. Because charging loads are non-linear, these stations generate significant harmonic distortion, which can cause overheating and increased transformer losses. Efficiency and dependability may be jeopardized by voltage imbalances and overload situations brought on by the high and erratic charging demand. The grid's overall power quality is also affected by the cumulative effect of harmonics, making it difficult for transformers and associated equipment to operate and ultimately increasing maintenance and replacement costs. This research makes a new scientific and applied contribution by quantifying the impact of electric vehicle charging stations on three-phase (11/0.4 kV) distribution transformers under realistic operating conditions. Unlike previous studies that have generally focused on electric vehicle integration, this work develops an integrated simulation framework in ETAP to analyze power flow and power quality at the transformer level.

The novelty of the research lies in:

1. Integrating the nonlinear load characteristics of electric vehicle charging with renewable energy sources to depict the complex interactions in modern residential networks.

2. Providing an accurate quantitative assessment of Total Harmonic Distortion (THD) and voltage unbalance on transformers, enabling a deeper understanding of their performance degradation mechanisms.

3. Demonstrating multiple scenarios of electric vehicle penetration levels (low, medium, and high) to demonstrate the gradual impact on transformer efficiency and network reliability.

4. Proposing practical mitigation solutions, such as optimizing charging strategies and reducing harmonic distortions, to support the sustainability of residential networks and improve power quality.

The results of this research contribute to future load planning, improving grid stability, and supporting the transition to sustainable energy by linking electric vehicle charging behavior with distribution transformer performance.

This work's main objective is to examine how electric vehicle (EV) charging stations affect the reliability and efficiency of 11/0.4 kV three-phase distribution transformers in residential grids. Key problems such as harmonic distortions, voltage imbalances, thermal strains, and increased loads brought on by the non-linear features of EV chargers are the main focus of the study. In light of the growing need for EV charging infrastructure, this research aims to improve the operational efficiency, longevity, and reliability of distribution transformers by proposing practical mitigation techniques.

2. THE PROPOSED METHODOLOGY FOR ANALYZING THE IMPACT OF ELECTRIC VEHICLE CHARGING ON THE RESIDENTIAL DISTRIBUTION NETWORK USING ETAP

The flowchart shown in Fig. 1 outlines the steps for studying the impact of electric vehicle charging stations on the residential distribution network using the ETAP program. The study begins by modeling a three-phase (11/0.4 kV) residential distribution network in a simulation environment, providing an accurate representation of network components, including transformers, lines, and loads. Electric vehicle charging stations are then incorporated as dynamic loads that vary over time, which is essential for representing the realistic and near-realistic behavior of these loads. Several scenarios are then developed, including the base case (without electric vehicles) and multiple scenarios involving a group of electric vehicles in the network. Finally, simulations are conducted for each case, including power flow analysis and harmonic analysis, to evaluate the performance of the transformer and network under the loads generated by vehicle charging.

The main steps include:

1. Modeling the Residential Distribution Network in ETAP

An integrated distribution network model is constructed in ETAP, including essential components such as transformers, lines, and conventional loads.

2. Integrating Electric Vehicle Chargers as Dynamic Loads

EV chargers are added to the model as dynamic loads, reflecting their time-varying nature and nonlinear behavior, which may affect system stability.

3. Developing Study Scenarios (Base Case and EV Penetration Scenarios) as follows:

• Scenario 1: Baseline case with no EV charging loads, normal load distribution, and a load value change from 10% to the full load of the transformer T3. Load flow analysis, voltage stability, and harmonics are studied for all cases.

• Scenario 2: High EV deployment: EVs are connected to the home grid, and the load and EV are shifted at compatible ratios from 10% to 100%

of the full load of the transformer T3 (80-100%), with charging overlap during peak hours.

• Scenario 3: Moderate EV deployment: EVs are connected to the home grid, and the load and EV are shifted at compatible ratios from 10% to 50% of the full load of the transformer T3 (approximately 50% of households owning EVs).

Each scenario evaluates the spatial and temporal distribution of EV chargers across the network.

4. Conduct a power flow simulation for each scenario.

A power flow simulation is used to analyze how currents, voltages, and power are distributed in the system under each penetration scenario.

5. Evaluate power quality indicators for each scenario, including important power quality indicators such as THD (Total Harmonic Distortion).

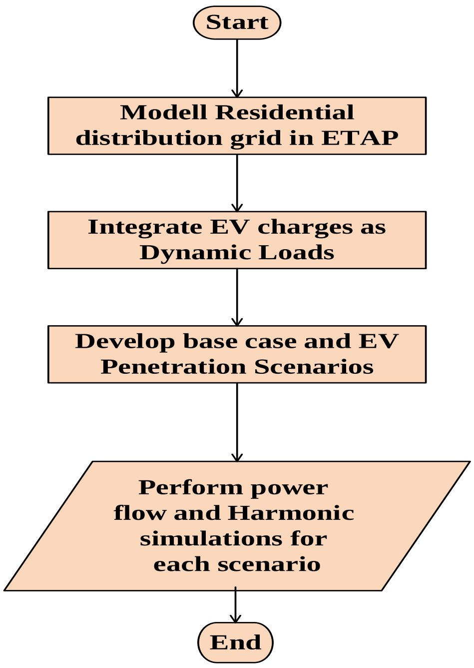

Fig. 1 Flowchart of the work method.

In this research, several studies were conducted to evaluate system voltage and power, as well as the quality of power. These studies include:

2.1. Power System Analysis Using ETAP

Analysis of Power Systems: The transformer operates on a home grid simulated in ETAP software. EV charging stations are incorporated into the grid model, and power flow analysis is performed to evaluate voltage stability and loading circumstances. ETAP's harmonic load flow measures the impact of harmonics on transformers and other equipment by assessing how they propagate throughout the system. This enables a full understanding of the effects on the entire grid. The transformer operates on a simulated home distribution network using the Electrical Transient Analyzer Program (ETAP), a software tool for modeling and simulating electrical networks. ETAP is used by power system engineers to create an "electrical digital twin" and analyze power system dynamics, transients, and protection. The residential network was modeled using the ETAP program, as shown in Fig. 2. The network consisted of a generator, loads, two transmission transformers, and a distribution transformer connected to the electric vehicles. The network parameters were as listed in Table 1.

Table 1: Parameters of residential distribution network response.

Item	Kv	MVA	FLA (Full Load Current)
Generator	16 Kv	421.053	15193
T1(Primary)	16Kv	50	3608
T1(Secondary)	132Kv	50	437.4
T2(Primary)	132Kv	20	87.48
T2(Secondary)	11Kv	20	349.9
T3(Primary)	11Kv	0.5	8.748
T3(Secondary)	0.4Kv	0.5	721.7
Load 1	16Kv	5.432	196
Load 2	0.4	0.05-0.5	72.17-721.7
EV(AC Rating)	0.4	1.96	2829
EV(DC Rating)	0.795	1.5	1887

Fig. 2 illustrates a typical low-voltage residential distribution network. The system consists of a main substation that feeds multiple radial feeders via three-phase distribution transformers with capacities ranging from 50 to 500 kVA. Residential load models are designed based on typical household consumption patterns using ETAP's Load Flow module, and diversity factors are applied to reflect realistic demand conditions.

Electric vehicle charging stations are modeled as dynamic, time-varying loads. Different levels of electric vehicle charging infrastructure, Level 1 (slow), Level 2 (medium), and DC fast chargers are integrated into the system. The charging models are based on data from IEEE Std 2030.1.1 and actual user behavior to accurately simulate peak and off-peak demand. The loads for electric vehicles were variable-voltage (0.4 kV), variable-power (1960 kVA), and maximum load current (2829 A). The DC ratings for these loads were 795 V, 1500 kW, and a maximum load current of 1887 A.

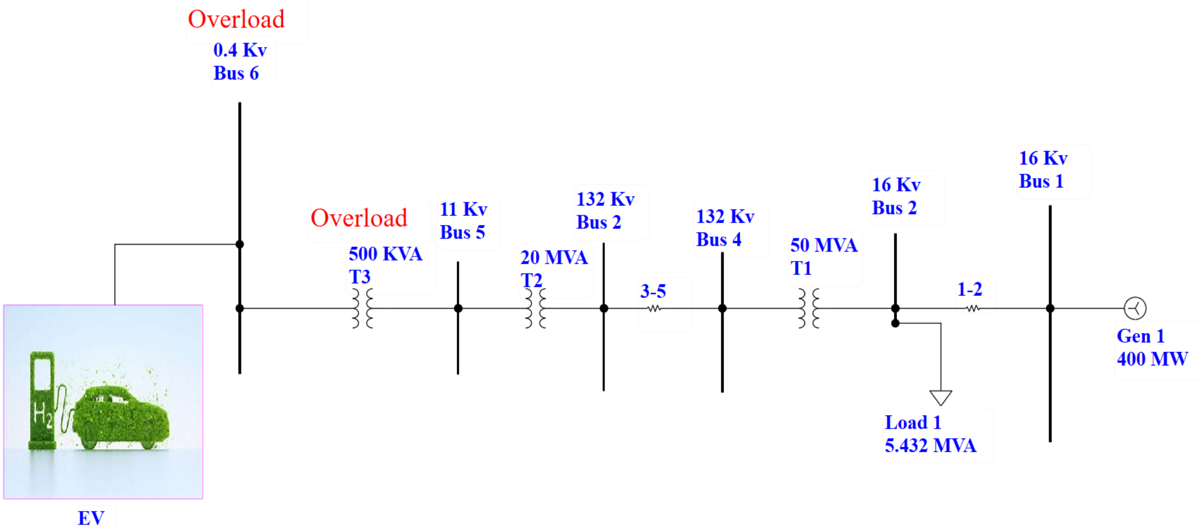

Fig. 2 Residential Network Proposed.

Transformer T3 is a crucial component in this electrical system, as it steps down the voltage from the medium distribution level (11 kV) to the low-voltage (0.4 kV) used to power electric vehicle charging stations. Its importance lies in its role as the link between the main distribution network and the non-linear loads, such as electric vehicle chargers, which generate currents containing harmonic components that affect power quality. Transformer T3 also provides electrical isolation between the two sides, reducing the transmission of harmonic distortions and disturbances to the main grid. However, its exposure to high loads resulting from fast charging makes it more susceptible to overload conditions, which necessitates monitoring its operation and analyzing its thermal state to ensure continuous performance and efficient power distribution.

To demonstrate the effect of electric vehicle charging on the distribution transformer performance, variable load ratios (electric vehicles) were taken relative to transformer T3. Then, a study was conducted to analyze the load flow, power, and voltage stability. Furthermore, variable harmonic sources with variable electric vehicle ratios, which are actually used in electric vehicle charging operations, were taken, and a harmonic analysis was conducted for all loads and all sources.

2.2. Load Flow Analysis

The ETAP load flow analysis module calculates the mains voltage, substation power factors, currents, and power flows across all elements of the electrical network. ETAP offers many advantages, including support for diverse energy sources, multiple connections for various types of electrical power grids, and a range of engines and generators. It can also perform most types of mathematical analyses for loop and radiative systems. ETAP offers three methods for calculating load flow: Adaptive Newton-Raphson, Newton-Raphson, and Fast-Decoupled. These methods have different convergence properties, and sometimes one method is more suitable for achieving optimal performance. In this study, the Adaptive Newton-Raphson method was used. The Adaptive Newton-Raphson method provides a set of mini-steps for iterations that encounter potential divergence. These mini-steps can help solve load flow in some systems where the traditional Newton-Raphson method may fail.

The Newton Raphson method is based on a Taylor series approximation. To simplify the solution and increase its step size, linear interpolation/extraction is performed at additional time-step increments to improve the solution.

$$f(\mathrm{x_k} + \alpha_k * \Delta x_k) < f(x_k) \qquad (1)$$

where

$\mathrm{x_k}$ The current guess (approximate solution) at iteration k.

Δx_k The Newton step (or update direction)

α_k The step size (or damping factor)

$f(x_k)$ The value of the function at the current guess $\mathrm{x_k}$

$f(\mathrm{x_k} + \alpha_k * \Delta x_k)$ The function value after taking a step of size α_k.

To find a possible solution for the next solution step, the incremental steps are controlled by changing the value of αk. The adaptive load flow method has been proven through test results to improve convergence in transmission and distribution systems with large series capacitance (negative reactance). On the other hand, it improves convergence in systems with very small impedance values, but this is not guaranteed. A noticeable decrease in computation speed is observed due to the incremental schemes used in the solution. The DC load value was increased by 10% relative to transformer T3, and a load flow analysis was conducted, yielding active and reactive power flow values, as well as losses, for all transformers T1, T2, and T3.

2.3. Harmonic Analysis

Due to the widespread application of electronic and digital control devices, such as variable-speed drives, static power converters, rectifiers, uninterruptible power supplies (UPS), static voltage compensators (SVCs), and others, these devices have affected the quality of power system current and voltage in many areas. In these regions, components other than the fundamental frequency can be found in distorted current and voltage waveforms. These are usually integer multiples of the fundamental frequency and are called harmonics. On the other hand, some nonlinear loads, including electric arc furnaces, saturated transformers, toroidal current transformers, and fluorescent lamps, cause significant deterioration in the quality of the power system. The presence of harmonics in a power system can lead to a variety of problems, including equipment overheating, power factor deterioration, deterioration of electrical equipment performance, improper operation of protection relays, interference with communication devices, and, in some cases, resonance in the electrical circuit, causing electrical equipment insulation failure and other serious damage [21]-[24].

Using computer simulations, the harmonic phenomenon in the residential network was modeled and analyzed using two types of harmonic sources. The Harmonic Analysis module in ETAP provides the best tool for accurately modeling various components and devices in power systems, including their frequency-dependent behavior, nonlinearity, and other characteristics in the presence of harmonic sources [25]. Harmonic analysis in power systems involves modeling the frequency characteristics of various power system components, calculating harmonic indices for specific conductors and branches, identifying problems associated with existing harmonics, and providing a framework for simulating and testing mitigation methods [26], [27].

2.4. Harmonic Indices

The effect of harmonics is typically measured through several indicators, including:

Total Harmonic Distortion (THD), also known as the Harmonic Distortion Factor (HDF), is the most common indicator used to measure the level of harmonic distortion relative to voltage and current. It is a measure of the root-mean-square ratio of all harmonics to the fundamental component. In an ideal system, THD is equal to zero. THD is determined by:

$$THD = \frac{\sum_2^\infty F_i^2}{F_1} \qquad (2)$$

where Fi is the value of the ith harmonic.
F1 is the value of the fundamental component [28]-[30].

To study harmonics, two types of harmonic sources were used to compare their effect on power quality, as they are considered the most common.

i. **IEEE6 Pulse 1 Harmonic sources:**

The six-pulse rectifier circuit is used in most AC motors due to its simplicity and design. However, at full load, the input THD can exceed 100% without a harmonic filter, with the 5th, 7th, and 11th harmonics being the dominant harmonic parts. Fig. 3 shows a six-diode bridge rectifier with a DC-link reactor. Motors over 30 hp have a built-in DC-link reactor as standard, and the input THD is about 40% at full load. By connecting additional AC reactors to the DC-link choke, the input THD can also be reduced to about 25% for general purposes. There are obstacles to reducing the THD below 30% due to the expansion of the AC reactor and the lower line voltage [31].

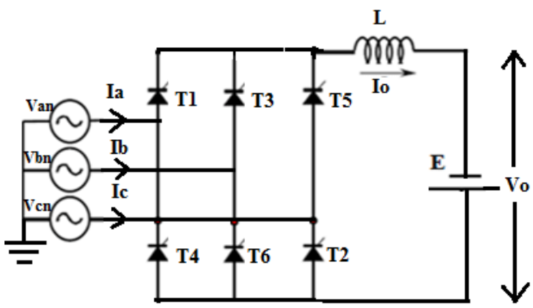

Fig. 3 A 6-pulse converter circuit diagram.

ii. **IEEE 12 Pulse 1 Harmonic sources:**

In large-power applications, such as high-voltage DC transmission and DC motors, a 12-pulse output is typically required to reduce output ripple and increase its frequency [31]. In this case, two sets of nonlinear loads are fed by the windings of a two-phase offset transformer using a 12-pulse transformer, and the 5th and 7th harmonics can be canceled on the primary side of the transformer [32]. The outputs of two dual-bridge rectifiers can be connected in series via a DC-link choke, as shown in the figure, or connected independently to two isolated motors. The polyphaser transformer can be an isolated transformer or an autotransformer with a 30° offset, providing two three-phase voltage sources that cross the 5th and 7th harmonics. Fig. 4 shows a 12-pulse rectifier with a delta-wye isolation transformer and the subsequent input current waveform, where the 11th and 13th harmonics are the effective harmonic components. A THD of about 10% can be achieved for the input current. In many cases, values may vary depending on the distortion and imbalance of the source voltage. Three-phase voltage sources with a 30-degree phase angle can be generated using several approaches [32].

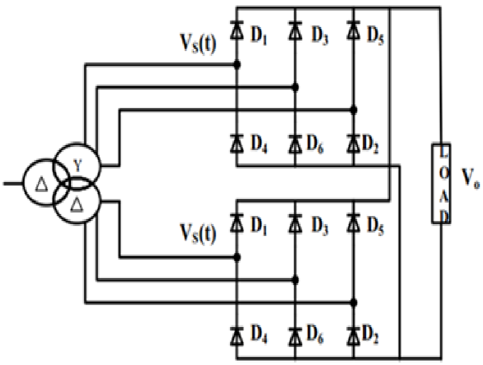

Fig. 4 12-pulse circuit diagram.

2.5. EV PENETRATION LEVELS

The electric vehicle (EV) penetration levels in this study were chosen to reflect realistic and gradual deployment scenarios in residential networks, ensuring a comprehensive assessment of their impact on distribution transformer performance:

Low (10%): Represents the early stage of EV integration. This is a near-term scenario reflecting current or projected adoption rates, in which the proportion of EVs in the total vehicle fleet remains low. This level helps establish a baseline for estimating early changes in harmonic distortions and transmitted power.

Medium (≈50%): Simulates a medium-term scenario in which EV penetration expands in residential neighborhoods (approximately half of households own an EV). This scenario was chosen to represent moderate challenges to the grid from harmonic loads and thermal stress, and is important for estimating the point at which the grid begins to experience significant operational stress.

High (80–100%): Reflects an extreme or long-term scenario in which EV penetration peaks and charging times overlap during peak hours. This scenario demonstrates the T3 transformer's maximum capacity and helps identify critical risks, such as overheating, increased total harmonic distortion (THD), and potential reliability degradation.

Adopting these levels enables a gradual progression from the baseline (no EVs) to high-stress scenarios, providing decision-makers with a clear view of the short-, medium-, and long-term impacts of integrating EVs into residential grids.

3. RESULTS AND DISCUSSIONS

3.1. Load Flow Results

Power flow analysis was performed at different load levels (10%-100% of the transformer capacity) and for different Scenarios (single load, EV charger, and combined charger and load) to study voltage drop and load distribution in the network. Scenario 1&2: In this scenario, the performance of the T3 transformer is studied under a resistive load (linear load) for the first scenario and EV for the second Scenario, excluding the impact of electric vehicle loads. The load level is gradually changed from 10% to 100% of the transformer's full capacity to analyze:

- Voltage drops across the transformer.
- Transformer efficiency at various load levels.
- Power loss resulting from overload.
- System Stability under Variable Load Conditions.

As shown in Table 2, load flow analysis results were recorded at all load levels, from 10% to full load. Fig. 5 and Fig. 6 show the home network with the load flow analysis results at full load of Scenarios 1 and 2. The results indicate that transformer T3 is overloaded under these conditions.

Table 2: Load flow results for scenarios 1 and 2

Loading	PF T3 (Load)	T3 η (%) (Load)	Vd% T3 (Load)	PF T3 (EV)	T3 η (%) (EV)	Vd% T3 (EV)
10%	0.9483	100	1.54	0.81	98.85	0.99
20%	0.9465	99	1.06	0.7982	97.89	0.27
30%	0.9447	98.1	0.57	0.7914	96.62	1.58
40%	0.943	98	0.09	0.7854	95.07	2.93
50%	0.9412	97.3	0.38	0.7797	93.82	4.34
60%	0.9394	97.09	0.86	0.7739	92.42	5.81
70%	0.9376	96.6	1.33	0.7679	90.86	7.35
80%	0.9358	96.3	1.81	0.7616	89.21	8.97
90%	0.9339	95.83	2.27	0.7516	87.5	10.68
100%	0.9321	95.43	2.74	0.7449	85.78	12.40

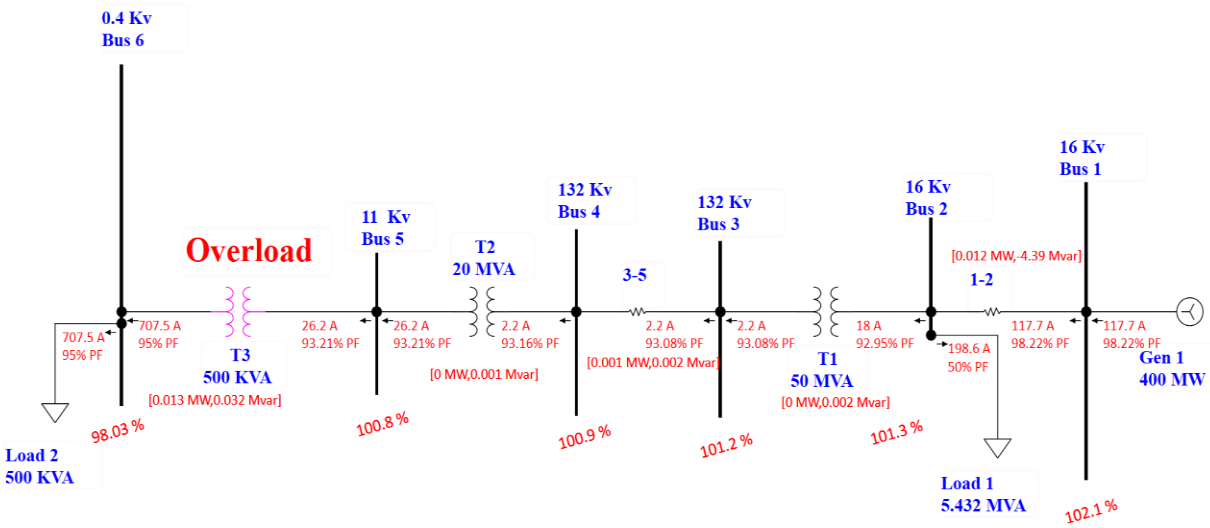

Fig. 5 Load flow analysis of the residential network for a load of 100% loading.

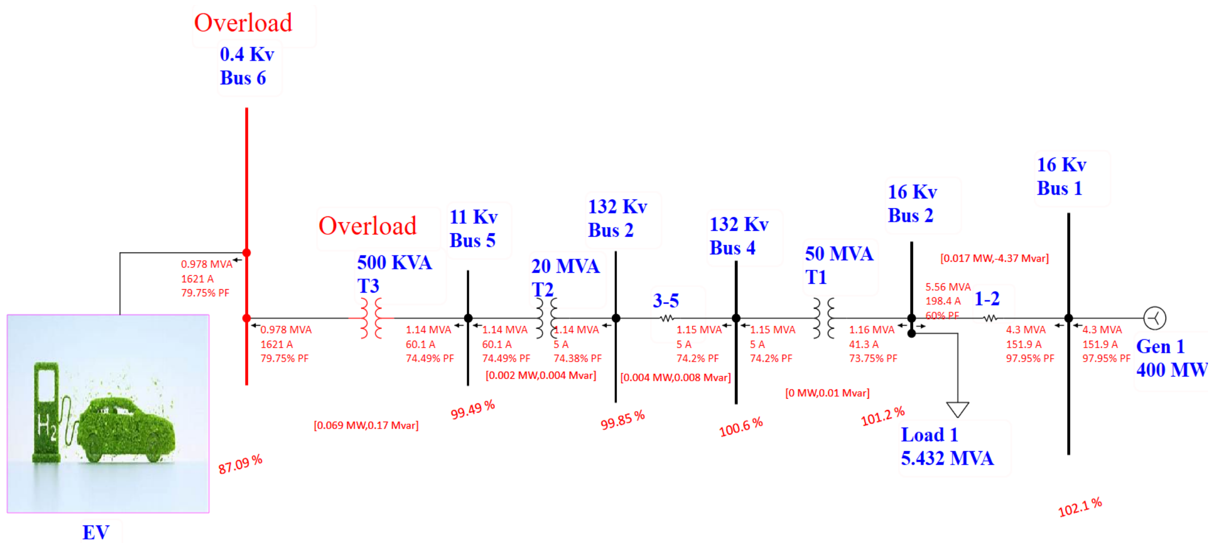

Fig. 6 Load flow analysis of the residential network for EV of 100% loading.

A load flow analysis was conducted by varying the home and electric vehicle loads together at ratios ranging from 10% to 50% of the transformer T3's full load, as shown in Table 3, which presents the load flow results for all load levels in this scenario. Fig. 7 shows the home grid with load flow results at 50% of the full capacity.

It is noticeable that the transformer T3 is in an overload state, indicating that it has exceeded its rated operating capacity.

Table 3: Load flow analysis results for scenario 3.

Loading	T3 Plosses (KW)	T3 Plosses (Kvar)	Vd% T3	PF T3	T3 η (%)
10%	0.8	1.9	0.61	0.8268	98.34
20%	3	7.5	0.83	0.8194	97.1
30%	6.8	16.9	2.3	0.8118	95.6
40%	12.2	30.2	3.8	0.804	94.2
50%	19.3	47.6	5.32	0.796	92.92

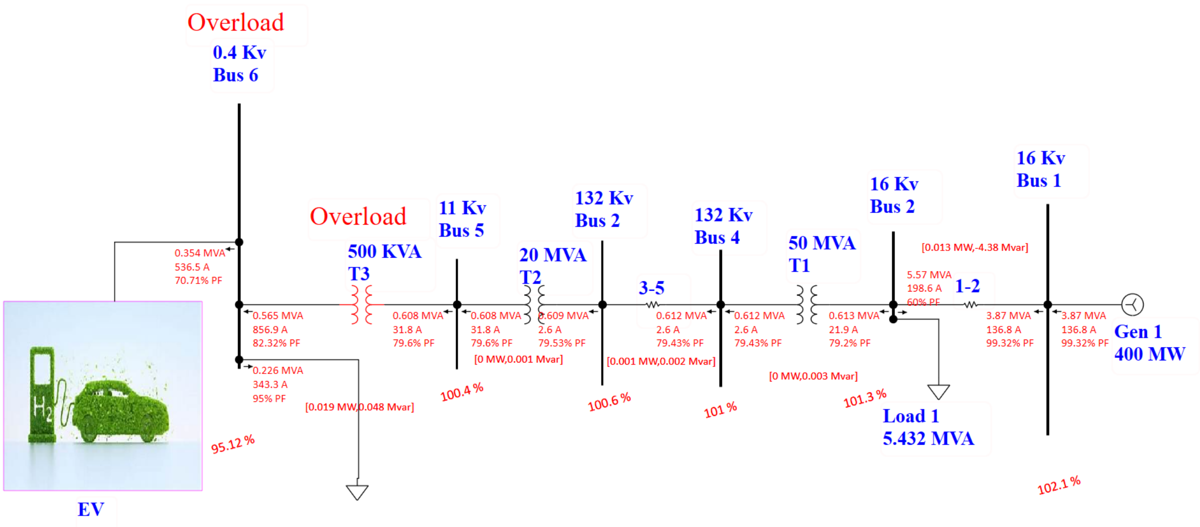

Fig. 7 Load flow analysis of the residential network for load & EV of 50% loading.

A comprehensive analysis of the harmonic flow in the electrical network was conducted for the base case. The load level (Load, EV) was gradually increased from 10% to 100% of transformer T3's full capacity. It was observed that in the case of a resistive load and without a source of harmonics, there was no harmonic distortion as the load increased. Fig. 8 shows the current waveform for transformer T3, which is a sine wave without any harmonic distortion.

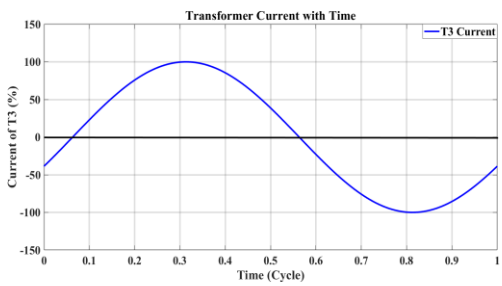

Fig. 8 Waveform of transformer current with cycles of the residential network for a load of 100% loading without a harmonic source.

3.2. Harmonic Renaults

Analysis of the harmonic flow in the electrical network was conducted for the base case, with an IEEE 6 Pulse 1 harmonic source and the load level gradually increasing from 10% to 100% of the full capacity of transformer T3. Table 4 shows the detailed results of the harmonic analysis for all load levels and Types (Load, EV), from 10% to full load. It was observed that in the case of a load and with an IEEE 6 Pulse 1 harmonic source, the voltage THD value increased with increasing load, and the current THD decreased with increasing load, with harmonic distortion appearing as the load increased. Figures 9,10,11 and 12 illustrate the current waveform and spectrum of transformer T3 under different load conditions and types.

Table 4: Harmonic results for scenarios 1 and 2 with IEEE 6 pulse 1.

Load ing	T3 Primary (Load)		T3 Secondary (Load)		T3 Primary (EV)		T3 Secondary (EV)	
	THDV (%)	THDI (%)	THDV (%)	THDI (%)	THDV (%)	THDI (%)	THDV (%)	THDI (%)
5%	0.16	12.75	2.4	12.75	0.157	12.75	2.4	12.75
%10	0.279	11.79	3.8	11.79	0.338	7.39	3.94	7.39
20%	0.464	10.37	5.62	10.37	0.509	8.94	8.38	8.94
30%	0.605	9.29	6.86	9.29	0.773	8.94	12.85	8.94
40%	0.715	8.42	7.79	8.42	1.04	8.94	17.54	8.94
50%	0.804	7.7	8.54	7.7	1.32	8.94	22.46	8.94
60%	0.875	7.08	9.15	7.08	1.61	8.94	27.65	8.94
70%	0.934	6.55	9.65	6.55	1.91	8.94	33.12	8.94
80%	0.982	6.1	10.08	6.1	2.21	8.94	38.91	8.94
90%	1.02	5.69	10.45	5.69	2.53	8.94	45.07	8.94
100 %	1.06	5.34	10.76	5.34	2.86	8.94	51.63	8.94

Figure 9 shows the variation of the transformer current (T3) over time under three different load conditions (5%, 50%, and 100%) over a single cycle. It is noticeable that the current increases significantly with increasing load ratio, representing a direct relationship between the load and the current drawn from the transformer. The waves at full load (100%) also exhibit significant distortion compared to low load, indicating nonlinear effects such as core magnetic saturation or the presence of harmonic components resulting from the nature of the load. Furthermore, sharp peaks and rapid current changes emerge at certain points, more pronounced under high load conditions. This can cause thermal and magnetic stress on the transformer windings, reducing efficiency. These results highlight the importance of controlling load levels to avoid distortions and minimize negative effects on the performance and life of electrical transformers.

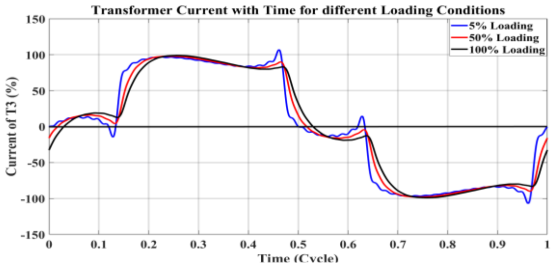

Fig. 9 Waveform of transformer (T3) current with cycles of the residential network for load with IEEE 6 Pulse 1 harmonic source for different loading conditions.

The figure 10 shows the harmonic spectrum of the current in transformer T3 under three loading levels (5%, 50%, and 100%). Prominent individual harmonic components, such as the 3rd, 5th, 7th, 11th, and 13th orders, are observed, with the 5th harmonic clearly dominating as the highest component after the fundamental. The intensity of the harmonics increases with higher loading, especially at lower orders, indicating that higher loads cause greater distortion of the current shape and result in higher harmonic content. This is an indication of the negative impact of high loads on power quality, which can lead to additional heating in the transformer, loss of efficiency, and reduced operating life of the associated equipment.

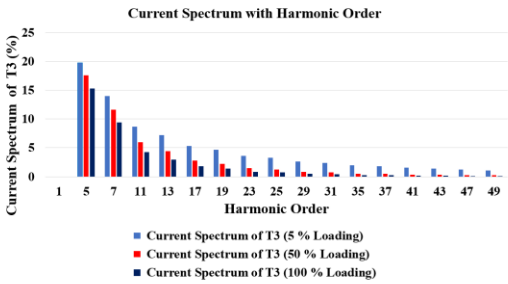

Fig. 10 Spectrum of transformer T3 with Harmonic Order of the residential network for load with IEEE 6 Pulse 1 harmonic source for different loading conditions.

The figure 11 shows the phase current variation of transformer T3 over time under various loading conditions, including normal loads and electric vehicle (EV) charging loads. It is observed that the current increases significantly with the introduction of EV charging, especially at full load (100% EV), where sharp peaks and pronounced distortions appear in the waveform compared to the 5% normal load. The combination of normal load and EV charging (e.g., 50% load + EV) results in a more distorted, complex current waveform, reflecting the nonlinear impact of EV loads on the distribution system. These distortions indicate the potential for electrical and thermal stress on transformers, negatively impacting operational efficiency.

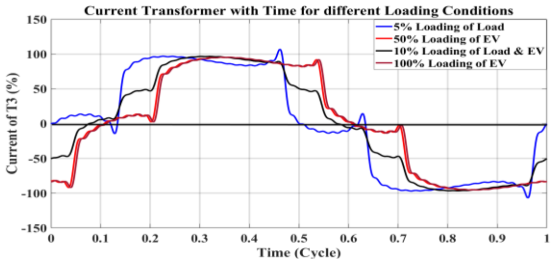

Fig. 11 Waveform of transformer (T3) current with cycles of the residential network for EV with IEEE 6 Pulse 1 harmonic source for different loading conditions.

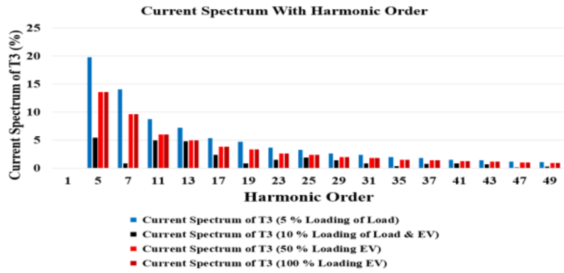

Fig. 12 Spectrum of transformer (T3) current with cycles of the residential network for EV with IEEE 6 Pulse 1 harmonic source for different loading conditions.

Figure 12 shows the harmonic spectrum of the current in transformer T3 at three different load levels (5%, 10%, 50%, and 100%). Prominent individual harmonics are observed, such as the third, fifth, seventh, eleventh, and thirteenth harmonics, with the fifth harmonic appearing as the largest harmonic component after the fundamental frequency. The figure also shows that the harmonic amplitudes increase significantly with increasing load levels, particularly for low-order harmonics. This indicates that higher loads lead to increased current distortion and higher harmonic content. This is indicative of the negative impact of high loads on power quality, as they cause increased heat losses within the transformer, reduced efficiency, and a shorter service life for the transformer and its associated equipment.

Harmonic flow in the electrical network was analyzed for the base case, with an IEEE 12 Pulse harmonic source and the load level gradually varying from 10% to 100% of the transformer's full capacity. Table 5 shows the detailed results of the harmonic analysis for all the load levels mentioned. The results showed that, in the presence of an IEEE 12 Pulse 1 harmonic source, the total harmonic distortion (THD) of the voltage increased with increasing load and was lower than in the presence of an IEEE 6 Pulse 1 harmonic source. Meanwhile, the current total harmonic distortion (THD) decreased with increasing load and was significantly lower than in the presence of an IEEE 6 Pulse 1 harmonic source. It was also observed that harmonic distortion increased with increasing load.

Table 5: Harmonic results for scenario 1&2 with IEEE 12 pulse 1.

Loading	T3 Primary (Load)		T3 Secondary (Load)		T3 Primary (EV)		T3 Secondary (EV)	
	THD V(%)	THD I(%)	THD V(%)	THD I(%)	THD V(%)	THD I(%)	THD V(%)	THD I(%)
5%	0.212	28.61	3.27	28.61	0.21	28.61	3.27	28.61
%10	0.374	27.61	5.26	27.61	0.395	9.78	5.64	9.78
20%	0.634	26.07	7.96	26.07	0.681	19.85	11.27	19.85
30%	0.844	24.83	9.9	24.83	1.03	19.85	17.3	19.85
40%	1.02	23.74	11.47	23.74	1.4	19.85	23.61	19.85
50%	1.17	22.77	12.79	22.77	1.77	19.85	30.23	19.85
60%	1.31	21.88	13.93	21.88	2.15	19.85	37.21	19.85
70%	1.42	21.05	14.94	21.05	2.55	19.85	44.57	19.85
80%	1.52	20.29	15.85	20.29	2.96	19.85	52.37	19.85
90%	1.62	19.57	16.67	19.57	3.38	19.85	60.65	19.85
100%	1.7	18.9	17.41	18.9	3.82	19.85	69.48	19.85

Figures 13,14,15 and 16 illustrate the current waveform and spectrum of transformer T3 under different load conditions and Types.

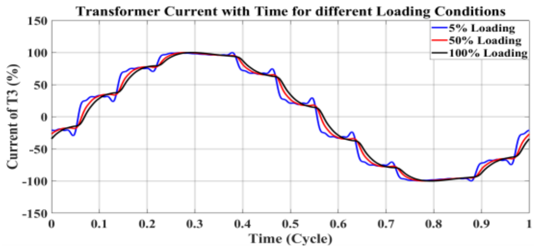

Fig. 13 Waveform of transformer (T3) current with cycles of the residential network for load with IEEE 12 Pulse 1 harmonic source for different loading conditions.

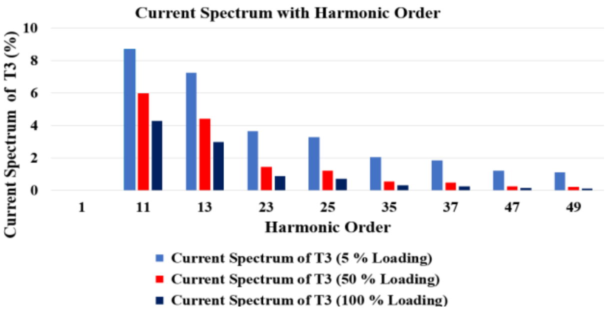

Fig. 14 Spectrum of transformer T3 with Harmonic Order of the residential network for load with IEEE 12 Pulse 1 harmonic source for different loading conditions.

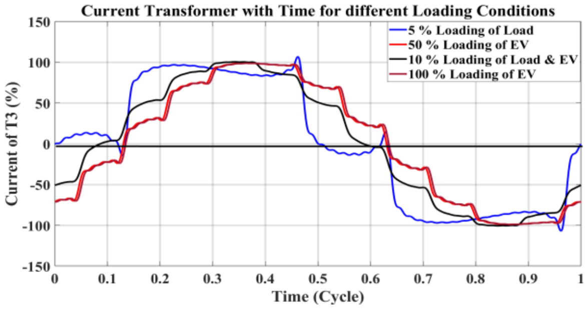

Fig. 15 Waveform of transformer (T3) current with cycles of the residential network for EV with IEEE 12 Pulse 1 harmonic source for different loading conditions.

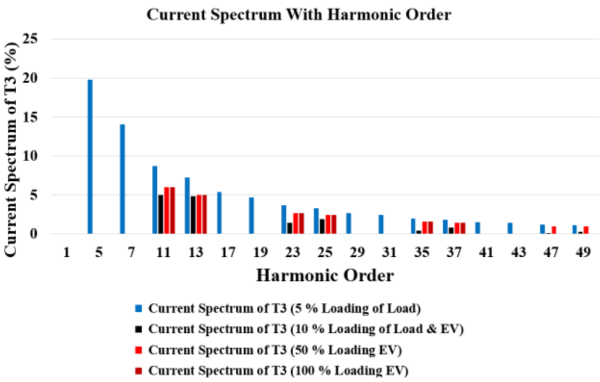

Fig. 16 Spectrum of transformer (T3) current with cycles of the residential network for EV with IEEE 12 Pulse 1 harmonic source for different loading conditions.

In this scenario, Electric Vehicles are connected to the home grid, with the load distributed between home consumption and the electric charger at ratios ranging from 10% to 50% of the full capacity of the distribution transformer T3. It is assumed that approximately 50% of households own and use electric vehicles at this balanced rate. Harmonic flow in the electrical network was conducted in the case of electric vehicle deployment and load changes. The load level for electric vehicles and the load were gradually increased from 10% to 50% of the transformer T3's full capacity. The results showed that in the case of a resistive load and the absence of harmonic sources, no harmonic distortion occurred with increasing load.

Analysis of the harmonic flow in the electrical network was conducted for an electrical load with electric vehicle deployment and an IEEE 6-Pulse 1 harmonic source. The load level was gradually changed from 10% to 50% of the full capacity of transformer T3. Table 6 presents the detailed results of the harmonic analysis for all the aforementioned load levels. The results showed that, for an electric vehicle load and an IEEE 6-Pulse 1 harmonic source, the harmonic voltage distortion (THDV) ratio increased with increasing load. The harmonic current distortion ratio (THDI) decreased with increasing load. A clear distortion in the harmonics appeared as the load increased.

Table 6: Harmonics results for the case of electric vehicles with household load with IEEE 6 pulse 1

Loading	T3 Primary		T3 Secondary	
	THDV(%)	THDI(%)	THDV(%)	THDI(%)
5%	0.177	7.65	2.13	7.65
%10	0.338	7.39	3.94	7.39
20%	0.621	6.92	6.9	6.92
30%	0.865	6.49	9.32	6.49
40%	1.08	6.1	11.42	6.1
50%	1.26	5.75	13.31	5.75

Fig. 17 and Fig.18 show the current waveform and frequency spectrum of transformer T3 under different loading conditions.

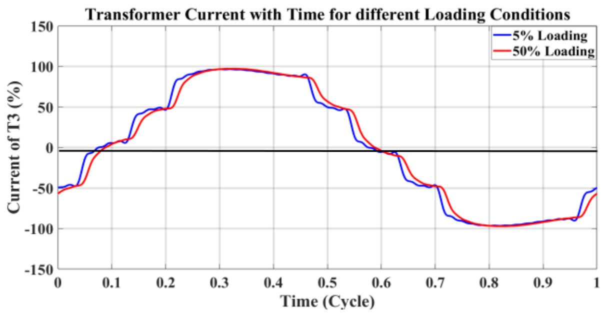

Fig. 17 Waveform of transformer (T3) current with cycles of the residential network for load & EV with IEEE 6 Pulse 1 harmonic source for different loading conditions.

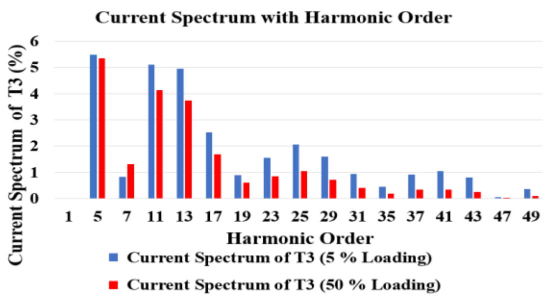

Fig. 18 Spectrum of transformer T3 with Harmonic Order of the residential network for load & EV with IEEE 6 Pulse 1 harmonic source for different loading conditions.

Harmonic flows in the electrical network were conducted under the presence of an electric vehicle load, in addition to an IEEE 12-Pulse 1 harmonic source. The load level was gradually varied from 10% to 50% of the full capacity of transformer T3. Table 7 shows the detailed results of the harmonic analysis for all the load levels studied. The results showed that, in the presence of a combined load with electric vehicles and a harmonic source, the total harmonic distortion of voltage (THDV) increased with increasing load level and was lower than in the presence of an IEEE 6 Pulse 1 harmonic source. Meanwhile, the total harmonic distortion of current (THD) decreased with increasing load, and its value was significantly lower than in the presence of an IEEE 6 Pulse 1 harmonic source. It was also observed that harmonic distortion increased with increasing load.

Table 7: Harmonic results for the electric vehicle case with household load with IEEE 12 pulse1.

Loading	T3 Primary		T3 Secondary	
	THDV(%)	THDI(%)	THDV(%)	THDI(%)
5%	0.211	10.07	3.13	10.07
%10	0.395	9.78	5.64	9.78
20%	0.709	9.28	9.47	9.28
30%	0.974	8.86	12.42	8.86
40%	1.2	8.51	14.91	8.51
50%	1.41	8.22	17.13	8.22

Fig. 19 and Fig. 20 show the current waveform and spectrum of transformer T3 under different load levels.

The graph shows the variation of the three-phase distribution transformer's current (percentage) over time under two different load conditions: no load (0%) and 80% load. The figure shows that the current at full load exhibits greater distortion than at no load, with sharper peaks and troughs and a less smooth waveform. This indicates harmonic content caused by non-linear loads such as electric vehicle charging stations. In contrast, the waveform at no load is closer to a perfect sinusoid, an indicator of stable electrical performance. This figure clearly highlights the effect of increasing loads on the quality of the transformer's output current and serves as an effective visual representation for comparing transformer behavior under different operating conditions.

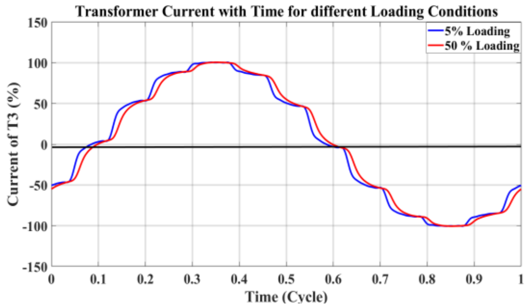

Fig. 19 Waveform of transformer (T3) current with cycles of the residential network for load & EV with IEEE 12 Pulse 1 harmonic source for different loading conditions.

The figure displays the harmonic spectrum of the current output from the T3 distribution transformer at 5% and 50% load, showing the proportion of each harmonic order relative to the total current. It is noticeable that odd-order harmonics, particularly the 11th and 13th orders, show a significant increase in the 50% load condition compared to the 5% load condition, indicating that the increased load leads to an increase in harmonic distortions in the current. Higher harmonics (such as orders 23 and 25 and above) appear in small proportions, which is positive because it indicates that most of the distortion is confined to lower harmonics, which are easily managed by filters. The figure provides a clear comparison between the two load conditions, helping to assess the impact of charging stations on power quality and accurately analyze transformer performance.

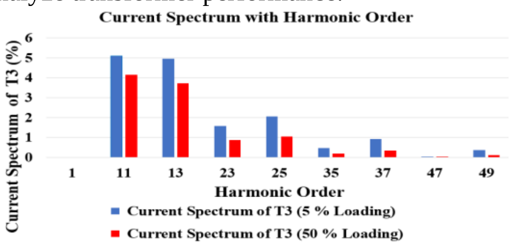

Fig. 20 Spectrum of transformer T3 with Harmonic Order of the residential network for load & EV with IEEE 12 Pulse 1 harmonic source for different loading conditions.

According to the IEEE C57.91 standards, every 6–7°C increase in hotspot temperature reduces the transformer's service life by half. This means that continued overloading could reduce the transformer's service life by 50% or more unless cooling is improved or the load is reduced. Furthermore, the nonlinear currents generated by electric vehicle chargers contain third-, fifth-, and seventh-order harmonics, which lead to additional losses in the windings (such as eddy currents and scattered losses) and in the iron core components, increasing total losses by 10–20% or more, depending on the THD value. It is noted that the IEEE 6 Pulse source produces lower-order harmonics (such as the 5th and 7th), which have the greatest impact on heating and power loss. In comparison, the IEEE 12 Pulse source produces higher-order harmonics (such as the 11th and 13th), which have a relatively lower thermal impact but still negatively impact transformer performance and internal insulation.

THDV should not exceed 5% in low- and medium-voltage networks. Results showed that THDV values remain within the permissible limits at low loads (≤10%), but exceed the limit starting at 20%, reaching more than 10% for conventional loads and more than 50% for electric vehicles at full load, clearly exceeding the standards. According to IEEE/IEC, THDI permissible values depend on the short-circuit current-to-load current ratio (Isc/IL), but in most low-voltage distribution applications, the acceptable level is considered to be 8–12%. IEEE 519, Voltage THD usually ≤ 5% (general case for LV and MV). IEC, Voltage THD limit around 5–8% depending on class.

In this study, values ranged from 5–12%, which is relatively acceptable at most load levels but close to the recommended upper limits. Thus, it is clear that integrating electric vehicles leads to a sharp increase in voltage distortions beyond the permissible limits, while current distortions remain within limits but may pose additional thermal hazards to transformers at high penetration ratios.

4. VALIDATE THE RESULTS

The results showed that the THD reached 55.71% when using an IEEE 6 Pulse source, and 40.53% when using an IEEE 12 Pulse source, compared to the IEEE 519-2014 standard. The maximum allowable total harmonic distortion (THD) at low distribution voltages (<1 kV) is only 5%. That is, the calculated values in the research exceed the standard limit by 8 to 11 times, indicating significant deterioration in power quality and a clear violation of the standards. The Voltage Drop reached to 12.40% at full load.

The general standard (according to IEEE, IEC, and power distribution standards) typically allows a voltage drop of no more than ±5% under normal operating conditions, with up to ±10% acceptable in extreme cases. Therefore, the calculated 12.4% drop also exceeds the acceptable limits, indicating that the system's performance is outside the standard range. According to IEEE C57.91, Guide for Loading Mineral-Oil-Immersed Transformers, the overload condition of transformer T3 exceeds the permissible operating limits for safe operation. Continuous operation of the transformer above its rated power without thermal control results in excessively high hotspot temperatures, accelerating insulation aging, and reducing the transformer's operational life. Although this study did not directly calculate the hotspot temperature, the analysis results indicate a loading condition that exceeds the thermal limits specified in IEEE C57.91.

In [9] THD values were low (<5%), within the permissible limits of the IEEE 519-2014 standard, especially on the medium-voltage side.

▪ This is because the study relied on small charging capacities (16 kW) and a limited number of charging units.

▪ The increase in THD remained gradual (from 2.11% to 3.45%) when the number of charging stations doubled.

In the current study, THD values reached 40–55%, which is ten times higher than the standard limit. This indicates that the charging system in the study has very high nonlinear loads, resulting in significant power-quality degradation. In terms of voltage drop, [9] showed that the voltage drops to less than 0.95 pu at loads exceeding 1000 kW, i.e., a drop of about 5%, which is close to the acceptable limit. While in my research, the drop was 12.4%, which is outside the allowable range (±5–10%). My research found that electric vehicle charging stations significantly affect the performance of 11/0.4 kV distribution transformers in residential networks. The voltage drop reached 12.40% at full load for transformer T3, and a high total harmonic distortion (THD) of 55.71% was recorded with an IEEE 6-Pulse harmonic source and 40.53% with an IEEE 12-Pulse source. Compared to the results of [11], the THD values ranged from 3% to 10%, and the voltage drop remained below 5% in most cases, even as the number of vehicles per feeding point increased. This indicates that the charging system studied in my research has a more severe impact on power quality than [11], with the current values exceeding the limits of IEEE 519-2014 (which specifies a maximum permissible THD of 5%), as well as the recommendations of IEEE C57.91 for safe load and temperature limits for transformers.

5. CONCLUSION

This study demonstrates that electric vehicle charging stations significantly impact the performance of 11/0.4 kV three-phase distribution transformers in residential networks. Simulation results using MATLAB and ETAP demonstrate that overloading, voltage imbalances, and harmonic distortions caused by non-linear loads from electric vehicle chargers reduce transformer efficiency and increase total losses. Power flow analysis showed a 12.40% voltage drop at full load when transformer T3 was overloaded. Harmonic load flow analysis also revealed a high total harmonic distortion (THD) of 55.71% on the secondary side of transformer T3 when using an IEEE 6 Pulse harmonic source and 40.53% when using an IEEE 12 Pulse source, indicating a significant negative impact on power quality. It's worth noting that each electrical transformer is designed to carry a specific load, known as the "rated load." Continuous operation above this load increases the load current and, consequently, the copper losses (I^2R) and the hotspot temperature within the transformer, accelerating the rate of insulation degradation. We recommended designing an active/passive harmonic filter or a load management strategy (demand-side management/coordinated charging) as the preferred solution, while clarifying the basic design criteria and addressing critical variables (such as the harmonic cutoff frequency, filter capacity, and time-based control mechanisms for vehicle charging).

6. FORWARD-LOOKING PERSPECTIVES

To address (e.g., AI-based load management, integration with renewables) challenges and ensure the safe and sustainable integration of electric vehicles into residential grids, the following trends can be considered:

AI-based Load Management: AI and machine learning can predict and dynamically adjust charging patterns to mitigate peak demand and reduce transformer stress.

RES Integration: Connecting electric vehicle charging stations to clean energy sources such as solar and wind power relieves pressure on the distribution grid and reduces reliance on the traditional grid.

Smart Charging and V2G Technologies: Implementing smart charging strategies, along with vehicle-to-grid (V2G) technology, can transform electric vehicles into flexible energy storage that supports grid stability rather than burdening it.

Harmonic Mitigation Solutions: Using active and passive harmonic filters to improve power quality and reduce thermal losses within transformers.

Designing improved future inverters: Developing more efficient inverters specifically designed to handle the non-linear loads associated with electric vehicle charging.

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