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Assessment of Electric Vehicle Charging On Distribution Transformer Aging, Aswan City as a Case Study

Mostafa Ali [1,2], Omar Abdel-Rahim [1,*], Mahmoud Gaafar[1], Mustafa Dardeer[1] ,Mohamed Orabi[1], Alattar Ali[1]

[1]APEARC, Faculty of Engineering, Aswan University, Aswan, Egypt

[2]Upper Egypt Electricity Distribution Company, Aswan, Egypt

Abstract. The objective of this study is to assess the readiness of the distribution system in Aswan City, Egypt, to accommodate the increasing penetration of electric vehicles (EVs). The focus is on evaluating the potential overloading of the existing infrastructure, particularly transformers, and understanding the impact of EV charging patterns on the distribution system. This study specifically investigates the distribution system in Aswan City, which is known for its high temperatures, making it a challenging environment for EV operation. Real data from consumers and transformer statistics are used to simulate and analyze the impact of EVs on the distribution system. The study employs different scenarios to represent the variations in ambient temperature throughout the year, ranging from 48 degrees Celsius in summer to 11 degrees Celsius in winter. These scenarios are further categorized into daily, weekly, and annual loading scenarios, taking into account the charging patterns of EVs in different locations within Aswan City. The analysis of the distribution system reveals that the current infrastructure might face challenges with the anticipated increase in EV penetration. The study identifies potential overloading of old transformers due to the additional load imposed by EV charging. It highlights the need for rescaling and upgrading the distribution system to ensure its stability and avoid system collapse Aswan City's distribution system needs careful planning and modifications to accommodate the expected surge in EVs. The study emphasizes the importance of considering EV penetration when designing and operating distribution systems to prevent any disruptions in power supply. Upgrading the infrastructure and implementing smart grid technologies are crucial to effectively manage the growing number of EVs and ensure the sustainable integration of clean transportation into the electrical grid.

Keywords: Electric Vehicles, Distribution System, EV Penetration, System Collapse, electrical infrastructure, Transformer aging, Grid rescaling.

1 INTRODUCTION

The charging infrastructure market on a global scale is expected to grow well in the coming years. In 2022 alone, the market for EV charging stations was valued at USD 7.9 billion, based on market research conducted by Apollo Research Reports. This number is forecast to grow to USD 32.2 billion by 2032. The increasing popularity of electric vehicles (EVs) poses a significant challenge to electricity distribution networks. With the continuous development and a global push to reduce carbon emissions in the transportation sector, the need for EVs as a suitable alternative is becoming more urgent [1]-[5]. Experts predict that the number of electric cars worldwide will exceed 250 million by 2035, compared to the current five million[6].

To accommodate the rise in EVs, many countries are adopting ambitious strategies to increase EV reliance, resulting in progress being made each year. However, this rapid increase in EVs presents several challenges for distribution networks. The existing infrastructure, designed without considering such high EV penetration, can lead to voltage violations, power quality problems, and transformers loading issues[7]-[11].

Minimizing the adverse effects of overloading, especially during car charging, requires realistic solutions. Extensive research has focused on studying and understanding the impact of EV charging on transformer health. Overnight charging operations, where car owners plug in their vehicles at residential outlets, have been observed to determine transformer overload and its effects[12]. Therefore, it is essential to thoroughly consider industry standards, grid impacts, and technical policy issues

[*]Corresponding author E-mail: omar.mohamed27@gmail.com

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before implementing a complex EV charging infrastructure. Addressing these challenges will ensure the stability and reliability of distribution networks while enabling the seamless integration of EVs. By finding effective solutions to mitigate overloading effects and carefully planning for increased EV adoption, an efficient electric mobility ecosystem can be created. Utilities prioritize the protection of transformers and ensuring their reliability, leading to substantial investments in this field. A thorough review of numerous studies on the impact of electric vehicle (EV) charging reveals that only a limited number of studies have specifically examined the effects of charging EVs on transformer aging and energy loss [13]-[18].

To investigate this further, a 25 kVA transformer was utilized in a study involving a small number of electric vehicles [13]. The study employed a thermodynamic model that predicted the transformer's temperature based on power load and ambient temperature data. However, it is advisable to conduct research with a larger number of vehicles and transformers of greater capacity to obtain more comprehensive insights.

Another study highlights the significant impact of unbalanced EV charging networks on distribution, with a focus on residential areas experiencing substantial losses [16]. Various models have been developed to monitor the remaining vehicle charge and estimate arrival time. However, it is crucial to emphasize that this model may not be applicable to every EV loading scenario. Controlled EV charging should consider factors such as geographic location, ambient temperature, transformer rating, and EV penetration.

The charging of Plug-in Hybrid Electric Vehicles (PHEVs) on distribution networks has also been investigated [18]. The study analyzed the effects of charging different types of electric vehicle batteries on distribution transformer performance. However, simulation results do not precisely determine the percentage of decreased expected lifespan of transformers.

Furthermore, an analysis of EV charging patterns, including different electric car charging periods and power generation from solar panels, was conducted [19]. The study considered the performance, efficiency, and resilience of distribution transformers in light of varying solar panel generation rates. The initial findings indicated that the integration of solar energy generation can minimize the expected lifespan of transformers. However, these results do not indicate the actual overload conditions experienced by electric utilities.

To address transformer overload, simplified mathematical methods and EV to-network strategies have been proposed [20]. These approaches effectively mitigate overloads on distribution transformers. However, it is essential to note that the optimization was carried out for a specific region and may not yield the same results for other areas with a similar number of electric cars. Factors such as battery size and charging requirements vary among regions. The suggested mathematical methods were applied in a Canadian province during a cold winter when electrical energy consumption was higher. Consequently, the obtained results may not be applicable to regions experiencing peak demand during different seasons, such as summer

The determination of optimal charging station locations involved the application of optimal solution analytical methods along with the hierarchical process and order preference technique by likeness [21]. By using Ankara, the capital of Turkey, as a case study, the proposed methodology demonstrated that alternative sites outperformed the current sites of the 12 proposed Electric Vehicle Charging Stations (EVCS) based on the studied criteria. When determining the exact EVCS location, additional technical parameters such as power lines, transient stability, and power distribution devices must be taken into consideration.

Extensive research is needed, as mentioned in [22], to investigate the interaction between electric vehicle drivers, charging sites, and network operators, as well as how information and communication technologies systems can enhance scheduling, charging, and discharging processes. Finding compatibility between energy systems and communication systems will greatly improve the operation and control of advanced energy management systems.

A superior design and optimization system for EVCS powered by renewable energy sources has been introduced in[23], resulting in reduced air emissions and operating costs. This system utilizes hybrid solar cells with storage units, allowing any surplus power generated by the solar panels to be stored in the battery system.

In a low voltage distribution grid case study conducted in New Toshka city, Aswan, Egypt, various charging scenarios were investigated to assess the impact of EV charging on the distribution grid [24]. Two scenarios, namely uncontrolled charging and delayed charging, were examined, and the results confirmed that uncontrolled charging had a significant impact on the low-voltage network compared to delayed charging. However, caution must be exercised as uncontrolled charging may lead to a second peak in off-peak hours.

Additionally, a survey on the aging of distribution transformers was conducted in [25], focusing on the effect of rapid charging of electric vehicles from residential transformers. The research revealed that increasing the load of solar cells by more than 50% accelerated the deterioration rate of the transformer's lifespan. However, at lower load rates, the rate of deterioration remained within the normal limit. It should be noted that the proposed solution presented in the study to address transformer aging is costly.

In [26], several scenarios for charging electric cars were analyzed in detail for the distribution system. The study demonstrated that the suggested charging/discharging technique for plug-in controlled electric vehicles offers greater benefits to the distribution system compared to other techniques.

A standardized research method is employed within the European Union to assess the impacts on components of low voltage distribution networks, such as transformers and feeders [27]. The study investigates the effect of charging electric vehicles on a standard low-voltage network with varying levels of penetration. The analysis reveals that higher levels of EV loading can be accommodated, especially through automated indirect charging, without the need for network component updates or increases. The study focuses on transformers, as well as residential and industrial feeders, to assess their ability to handle power demand in different scenarios without additional load.

In terms of controlling the integration of vehicles and networks in radial power distribution systems, a strategy is proposed [28]. At the distribution grid level, a voltage compensation algorithm is designed to address voltage violations at distribution nodes, although further enhancements are required. At the micro level, the available power capacity for EV charging is optimized to meet the evolving needs of electric vehicles.

The fundamentals of electric vehicles (EVs) and EV charging technology are discussed, along with future research topics and charging methods for EVs [29]. The study investigates the ineffective outcomes resulting from unautomated EV charging on electric power systems and explores how effective results can be achieved through controlled charging processes.

The consequences of uncoordinated charging are extensively examined in [30], where researchers utilize active and reactive power measurements obtained from a local distribution station. Their objective is to quantitatively evaluate the impact of EV charging on distribution transformers, particularly in terms of grid voltage asymmetry. However, conducting such analyses poses challenges due to the requirement of obtaining realistic load and EV profiles [31].

In another study [32], a combination of smart meter data and a mixed technique is utilized to construct a model of residential load. This model serves as a basis for incorporating probabilistic EV charging profiles in a random manner, enabling researchers to investigate the implications of EV charging. To estimate temperature and loss of life, the researchers utilize the load profile of the transformer, which is obtained from actual meter data or power flow studies [33]-[34].

According to the findings reported in [35], approximately 80% of plug-in electric vehicle (EV) charging instances occur at residential dwellings, while 15-20% occur at workplace charging stations for EV owners. It is important to note that residential homes in Europe are commonly connected to power distribution systems (PDSs), which are linked to distribution transformers. When loads exceed the rated power capacity of a transformer, it results in an increase in temperature across various components such as windings, taps, insulation, and oil. These elevated temperature levels can reach undesirable values, posing a significant risk. Additionally, the excessive load causes an escalation in the scattering magnetic flux, leading to increased eddy currents that generate heat within the metallic parts of the transformer. Consequently, there is a potential for damage associated with the current magnitude and temperature, ultimately resulting in a reduced service life [36].

The nonlinearity of certain loads during EV battery charging causes an increase in temperature and associated losses in transformers, leading to a decrease in their overall lifespan. This nonlinearity introduces total harmonic distortion (THD) into the charging current, which has an impact on the power quality of the distribution network [37]-[38].

This particular study focuses on the impact of EV penetration on distribution transformers and is based on real loading profiles in Aswan, Egypt. Various penetration levels are considered to assess the capacity of the current distribution system to handle widespread EV usage, the flow chart of the proposed strategy of study is shown in Figure. 1. The main findings of the study include:

- Demonstrating how the number of EVs charging at a site can be increased without overloading the electrical infrastructure.
- Characterizing and studying the effects of electric charging using a large dataset of real transformer data.
- Analyzing daily, weekly, and annual loading scenarios of EVs.
- Assessing the impact of transformer insulation system parameters on transformer health.
- Examining the effect of transformer aging in the context of electric charging strategies.

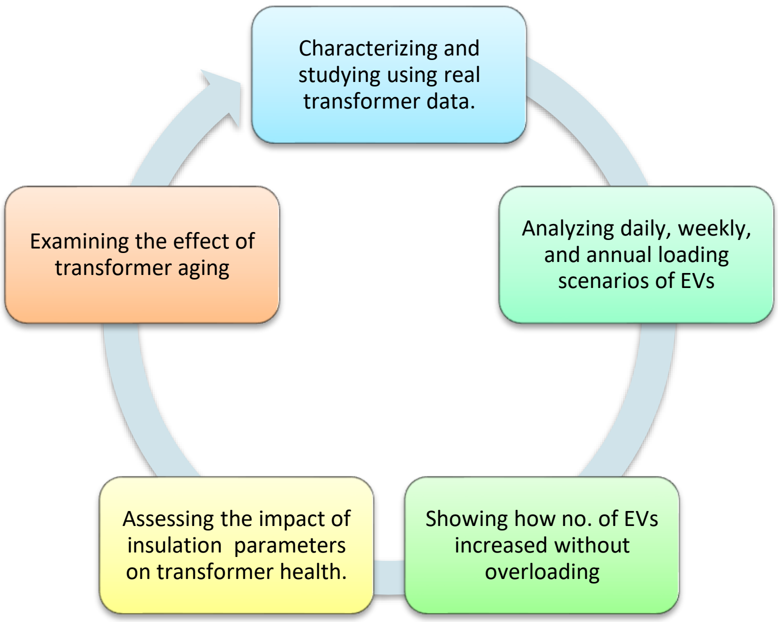

Fig. 1. *Flow chart of the proposed strategy of study*

1.1 Thermal Aging

The aging of a transformer's insulation, which directly affects its lifespan, is influenced by the highest temperature reached in its windings. Organizations like *IEEE* have established standards that offer guidelines for predicting the temperature of this critical spot and its associated aging process [39].

At a specific period time t, the highest spot temperature T_H, can be determined as a rise of the ambient temperature Ta, as describe in [12], where:

$$T_H^t = T_a^t + \Delta T_H^t \quad (1)$$

$$\Delta T_H^t = K_1 (LL^{t-1})^{2n} + K_2 \Delta T_H^{t-1} \quad (2)$$

The calculation involves the utilization of LL to represent the total load, with K_1, K_2, and n being coefficients derived from transformer characteristics and temperature modeling. For the sake of simplicity, it is assumed that the constants in K_1 and K_2 remain relatively unchanged even with variations in temperature. Reference [40] defines the Arrhenius equation, which establishes a relationship between elevated temperatures in transformer insulation and the acceleration of aging, capturing this effect.

The equation incorporates constants d and e, which are unique to each transformer and are specified by the IEEE Guide. These constants are determined based on the type of insulation system and materials employed in the transformer insulation, as indicated in reference [41].

$$EX = d\ exponential\left(\frac{e}{T_H + 273.15}\right) \quad (3)$$

EX is a function of T_H, and it determines the rate of accelerated aging, by comparing to a normal transformer lifetime:

The resulting value, EX, represents the anticipated lifespan of the transformer in hours when operated continuously at the temperature T_H. The values of a and b are determined according to the type of insulation system and materials utilized in the transformer insulation, as specified in the IEEE Guide.

EX is a function dependent on TH, and it determines the rate of accelerated aging, R_{aa}^t, by comparing it to the normal lifespan of a transformer.

$$R_{aa}^{t} = \frac{EX_{Normal}}{EX^{t}} \quad (4)$$

The cumulative loss of lifespan within a specified time frame is determined by integrating the aging factor, along with the equivalent aging factor referred to as Frequency. By considering the frequency, one can calculate the revised anticipated lifespan.

$$R_{eqa}^{t} = \left(\frac{\sum_{t=1}^{T} y^{t} F_{aa}^{t}}{\sum_{t=1}^{n} y^{t}} \right) \quad (5)$$

$$EX = \frac{EX_{Normal}}{F_{eqa}} \quad (6)$$

The lifespan of a transformer is subject to various factors, including overloading and aging, as described in Equation 6. This equation quantifies the aging process of the transformer, but it should be noted that it accounts for only one type of failure pattern. To provide a comprehensive assessment of life expectancy, other potential failure modes should also be considered. The degradation of a transformer's insulation plays a crucial role in reducing its lifespan. This degradation is influenced by the maximum temperature reached in the windings of the transformer, which is determined by the temperature rise above the ambient temperature. The Arrhenius relationship is employed to describe the impact of temperature on aging, with the constants a and b determined by the specific insulation system and materials utilized in the transformer.

2 Charging power levels and infrastructure

Developers play a pivotal role in ensuring the growth and enhancement of electric vehicle (EV) charging equipment and infrastructure. They must carefully consider various factors, including delivery logistics, distribution strategies, charging station demand policies, and regulatory steps, in order to foster the development of a robust and efficient charging network. For distribution system and network engineers, power levels of chargers provide crucial information regarding charging time, location, power capacity, cost, equipment specifications, and network impact. The availability and effectiveness of charging infrastructure can significantly impact the cost and energy storage requirements of EVs.

According to the Electric Power Research Institute (EPRI) [42], the majority of EV owners have the convenience of charging their vehicles overnight at home. In this context, Level 1 (L1) and Level 2 (L2) charging equipment are commonly utilized [43]. Level 1 chargers typically operate at power ratings ranging from 3 to 6 kW, suitable for home or workplace charging, while Level 2 chargers are typically found in public areas and offer higher power capacity, ranging from 7 to 22 kW.

An essential component that simplifies the EV charging process is the electric recharging point, also known as EV supply equipment (EVSE) [44]. The EVSE facilitates the transfer of electricity from the power grid to the charger, providing a vital link in the charging infrastructure. This connection is established through a plug and outlet mechanism [45]. It is worth noting that different countries may have specific requirements concerning electrical grid connection, frequency, voltage, and transmission standards.

To ensure a seamless and efficient charging experience, standardization of manufacturing processes and fostering collaboration among stakeholders are crucial. This approach helps mitigate potential shortages in component supply and promotes interoperability across various types of EV battery chargers and connectors, which may differ among companies and countries.

In the European Union and the UK, four main types of chargers are prevalent, including slow chargers (L1), fast chargers (L2), rapid chargers, and Tesla's supercharger [46]. Slow chargers (L1), with power ratings ranging from 3 to 6 kW, are suitable for home or workplace use. Fast chargers (L2), ranging from 7 to 22 kW, are commonly found in public areas. Rapid chargers, characterized by power ratings exceeding 43 kW and equipped with the rapid charging standard, are primarily located at gas stations and service areas designated for EVs. Parameters of electric vehicles in European Union are illustrated in **Table 1**.

By addressing these considerations and leveraging the insights provided by cited references, developers can contribute to the effective growth and improvement of EV charging equipment and infrastructure, fostering the widespread adoption of electric vehicles.

Table 1 *Parameters of electric vehicles in European Union [46]*

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Kind of charging	kilowatt Rating	Period of charging (hour)	Connector Type
Slow Charger	3-6	8-10	Three-Pin Type-one Type-two Commando
Fast Charger	7/11/22	3-4	Three-Pin Type-one Type-two Commando
Rapid Charger	43/50/100-350	0.5-1	Type-two CHAdeMo/CCS CHAdeMo/CCS

Battery chargers play a critical role in the advancement of electric vehicles (EVs), with factors like battery life and charging time significantly influencing charger design. An ideal battery charger should possess attributes such as cost-effectiveness, compactness, lightweight construction, and high power density. The development of high-performance EV chargers is essential to ensure a linear load in the power system, minimizing distortions in the current drawn and maximizing the real power extracted from the power outlet. Compliance with established standards, including IEEE1547 [47], IEC61000-3-2 [48], and NEC 690 [49], is crucial to maintain power quality within acceptable limits.

Manufacturers of electric vehicle battery chargers are required to adhere to these standards, ensuring the quality and reliability of their products. The implementation of interleaving techniques has been proposed as a solution to reduce battery charging current ripple and diminish the size of inductors used in chargers [50].

Studies have indicated an increased mid-range for battery electric vehicle (BEV) models, as documented in relevant literature [51]. **Table 2** presents examples of higher-capacity BEVs, showcasing data obtained from existing BEV manufacturers, which verifies that the battery capacity adequately supports the average daily driving range of these vehicles.

As the EV market becomes increasingly competitive, EV manufacturers are striving to gain a global market share by offering competitive pricing. Consequently, differences in charger technologies are expected to converge towards a few standard types [52].

By considering these factors and incorporating insights from the cited references, manufacturers can effectively address the challenges and opportunities related to EV battery chargers, fostering the continued progress and widespread adoption of electric vehicles.

Table 2 *Some BEVs having high range [53].*

Manufacture charging	Size of battery [kWh]	Consu-mption [Wh/mi]	Range [mi]
ID.Three Pro S -Volkswagen	77	0.275	280
ID.Three-Volkswagen	77	0.31	245
Kona Electric- Hyundai	64	0.26	245
EQC 400-Mercedes	80	0.345	230
Polestar- Two	75	0.305	245
Sportback –Audi	86.5	0.375	230
Model Three - Performance – Tesla	76	0.265	285
Model Three -Long Range- Tesla	70	0.245	285
Taycan 4S Plus –Porsche	83.7	0.31	270
Taycan Turbo –Porsche	83.7	0.31	245

Power system always faces high and low disturbances, Power system distinguished with uncertainty, nonlinearity and large number of variables. Solving power system problems is complicated. System stability issue is of great importance to maintain service availability to all consumers [54].

Depending on the use of renewable energy systems, which may have positive effects that support energy systems [55]:

• Minimizing loss

• Increase the flexibility of utility systems

• Improve power quality and voltage support

• Launching transmission and distribution capacity. The modernization of the transmission and distribution system has been postponed.

• Due to the standardized, ready-made components, installation is simple and convenient.

• Save costs by eliminating long-distance high voltage transmission.

• Since renewable resources are used, it is environmentally friendly.

3 RESULTS AND DISCUSSIONS

A matlab algorithm uses as input data the network configuration and load data for all consumers, given as an active load profile. The loading profile used in the study is based on real data, with EV loading estimated for a duration of one year and finds the relation between lifetime of 1000 kVA transformer & number of charging cars.

The algorithm was written on Matlab® (version: R2021a) - Open DSS (version: 8.4.1.1) co-simulation environment and executed on a processor with Intel Core i7-7700HQ with 32 GB RAM running at 3.4 GHz.

The study findings provide valuable insights into the impact of the increasing use of electric vehicles (EVs) on the lifespan of distribution transformers. Specifically, the research focuses on a 1000 kVA, three-phase, 11000/400V Dyn11 vector group transformer as shown in figure 2, that supplies power to 150 apartments in the El-Akaad area of Aswan, Egypt. The loading profile used in the study is based on real data, with EV loading estimated for a duration of one year. To assess the impact at various levels, different penetration levels of EVs were considered. Key transformer parameters are provided in Table 3, including its specifications as an oil natural air natural (ONAN) cooling system. The transformer operates at a primary voltage of 11kV and a secondary voltage of 400Y/220. Relevant sample study data is presented in Table 4, offering further insights into the research analysis.

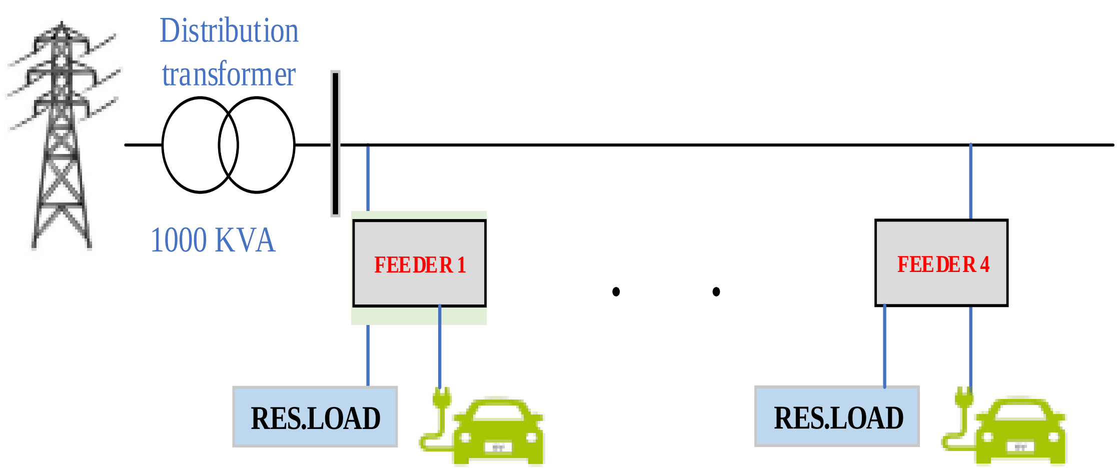


Fig. 2. *One-line diagram of the studied 1000KVA transformer in Aswan distribution network.*

Table 3 *Transformer specifications.*

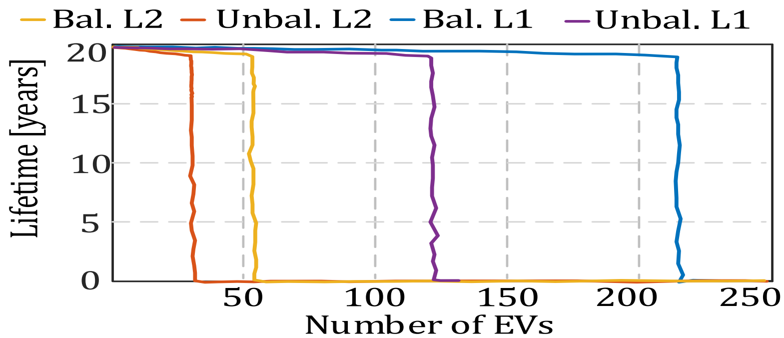
Parameter	Name	Rating
S	Rated power	1000 kVA
$\Delta T_{H,R}$	Temperature rate	55-60°C
n	Essential parameters	0.8
δ_t	Period	15 min
C_{tc}	Quantity of heat	180 W-min/°C
P_r	Copper loss	9450 W
Θ_e	Core temperature	25°C
lnd	Aging constant 1	− 22.082
e	Aging constant 2	16515

Table 4 *Sample of study date*

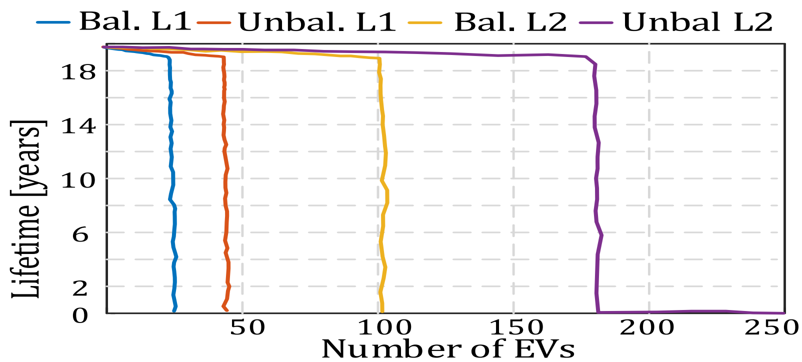
Date/ Time	Avg-V Ph-A	Avg-V Ph-B	Avg-I Ph-A	Avg-I Ph-B	Avg-P Ph-A	Avg-P Ph-B	Avg-Q Ph-A	Avg-Q Ph-B	$P.F_A$	$P.F_B$	$P.F_C$
14/06/2021 12:30	222.45	222.68	572.94	690.73	144.6	147.8	317.5	40.5	0.97	0.96	0.96
14/06/2021 13:00	223.39	223.49	659.08	830.68	162.2	178.2	398.6	47.2	0.96	0.96	0.96
14/06/2021 13:30	224.18	224.18	224.62	681.69	827.51	169	365.7	43.2	0.97	0.97	0.97
14/06/2021 14:00	224.89	224.89	224.96	767.43	961.87	194.2	512.1	59.6	0.95	0.95	0.95
14/06/2021 14:30	225.59	225.59	225.75	844.42	1024.61	204.2	555.3	63.8	0.95	0.95	0.95
14/06/2021 15:00	226.74	226.74	226.77	904.5	1111.86	220.6	664.5	78	0.94	0.94	0.94
14/06/2021 15:30	229.46	229.46	229.53	946.72	1149.84	220.3	689.8	80.5	0.95	0.94	0.94
14/06/2021 16:00	231.68	231.68	231.65	999.1	1218.23	231.2	777.7	91	0.94	0.93	0.94
14/06/2021 16:30	231.9	231.9	231.74	1010.67	1217.49	242.1	810.6	94.9	0.94	0.93	0.93
14/06/2021 17:00	231.84	231.84	231.44	1072.31	1278.81	254.3	896.5	104.8	0.93	0.92	0.93
14/06/2021 17:30	231	231	230.17	1080.74	1340.39	262.1	936.3	109.2	0.92	0.92	0.93
14/06/2021 18:00	230.32	230.32	229.77	1104.34	1344.45	257.7	942.7	108.2	0.93	0.92	0.93
14/06/2021 18:30	229.22	229.22	228.74	1128.05	1376.17	261.3	950.9	107.7	0.93	0.92	0.93

3.1. Transformer Lifetime Results

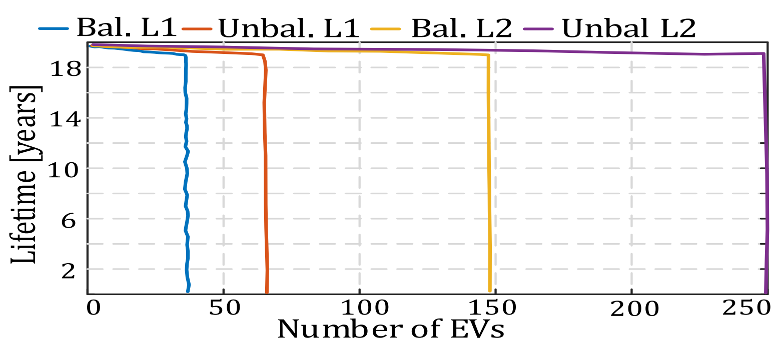
The relation between lifetime of 1000 kVA transformer & number of charging cars for phase A, B and C is shown in figure 3, as it was exposed to compound loads that include residential loads and electrical vehicle loads, with different numbers per day. The x axis represents the age of the transformers, while the y axis represents the number of cars that visit the car park each day. The results confirm that the transformer supports the load regardless of the charging scheme, but as the penetration increases, the lifetime decreases respectively from L1 balanced charge(Bal.L1), L1 unbalanced(Unbal.L1), L2 balanced (Bal.L2)and L2 unbalanced(Unbal.L1) with different values of time failure.



(a)



(b)



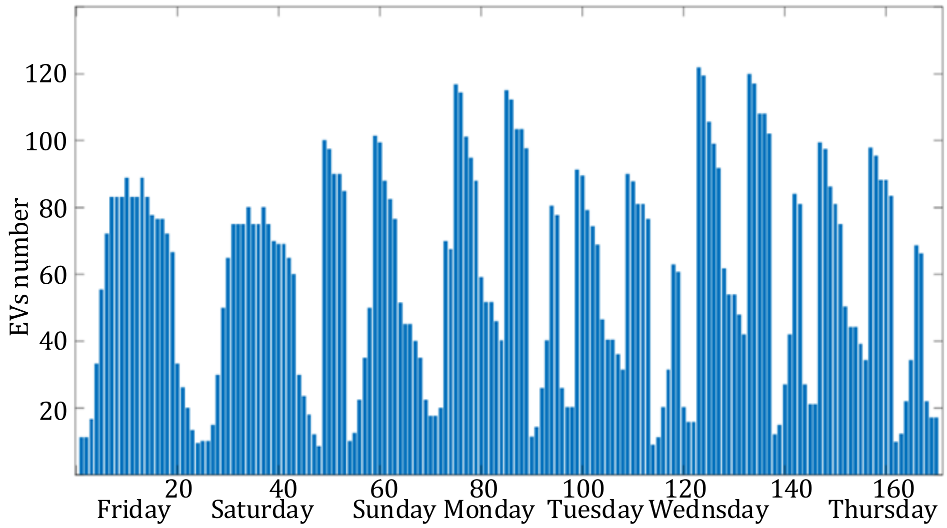
(c)

Fig. 3. Expected lifetime of transformer versus number of Evs for phase A (a), B(b) and C(c).

3.2. Weekly Loading of EVs

The analysis of the second case, involving a 1000 kVA distribution transformer, is depicted in Figure 4. This figure illustrates the relationship between the transformer's load over a week during the summer season, when the load tends to increase, and the overall load of the transformer represented as a percentage. The findings reveal that the demand for electricity related to electric cars exhibits peak periods on a weekly basis. Although the peaks may not align perfectly, the repeated occurrence of high-demand periods within a week puts significant stress on the distribution network, particularly during peak hours.

It is observed that the transformer's maximum load is exceeded during peak hours on weekdays, except for Saturdays. To ensure the safe operation of the transformer, it is essential to keep the daily peaks below 100% of its maximum load. One effective approach to reducing this load is to avoid charging electric vehicles during peak hours. By doing so, the load profiles can be leveled out, resulting in reduced daily expansion and contraction of the transformer. This practice is highly advantageous for prolonging the lifespan of the transformer.



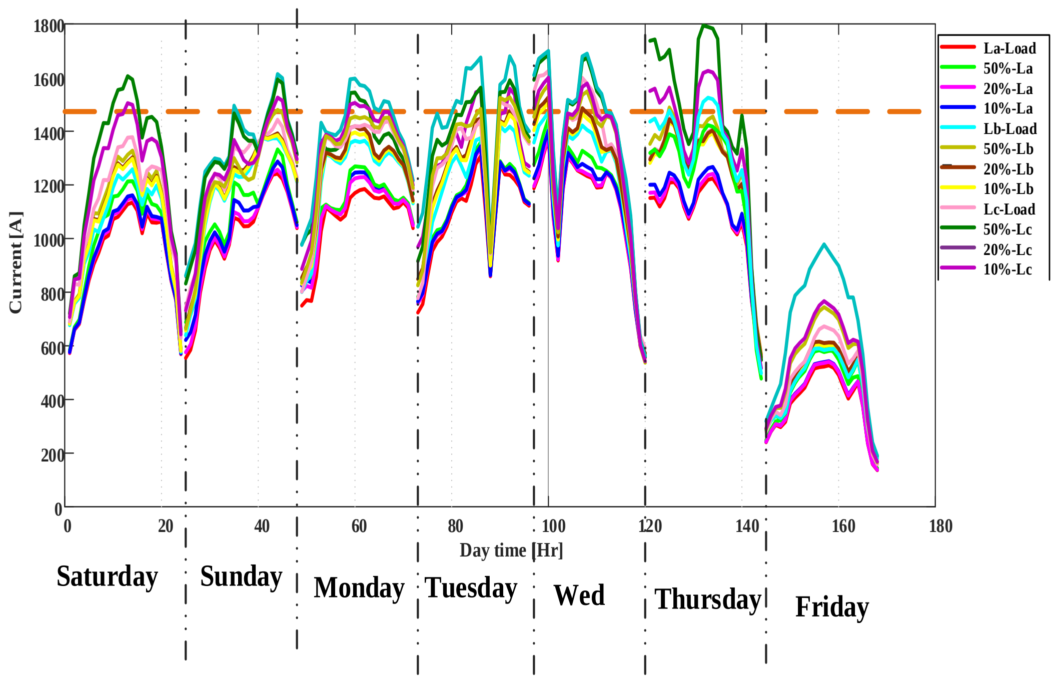


Fig. 4. Different Penetration level for one week in summer, Aswan, Egypt.

3.3 Different Daily Loading Results

While conducting this research, the loading on the transformer was analyzed throughout the entire year. During the winter, autumn and spring, the transformer is not at maximum capacity and has the ability to provide the necessary charging power. Summer, however, is a different story due to the hot weather and increased usage of air conditioners, so only summer results will be taken into account.

3.3.1 Impact of 53 EVs charging

To evaluate the impact of EVs on transformer loading, this study examines one day during the summer. The real loading profile is used, with varying levels of transformer phases a, b, and c considered both with and without EVs, including both Type I and Type II charging. The results are obtained by running the algorithm multiple times and taking the average of the outcomes.

3.3.1.1 Case 1 of transformer loading

In the initial scenario of transformer loading, phase b was assigned 60% of the electric vehicle load, while phases a and c had a load of 20% each. This configuration resulted in the highest loading curve during peak hours compared to the other phases. The loading curve gradually decreased for each phase based on the vehicle load and base load, as depicted in Figure 5.

Figure 5 illustrates the total power demand throughout a summer day. In phase b, the total load increased to 340 kW, which is 40 kW higher than the base case load of 300 kW, at 16:00 Hr. Similarly, in phase c, the total load increased to 330 kW, 10 kW higher than the base case load of 320 kW at the same time. In phase a, the total load remained relatively stable at approximately 270 kW, comparable to the base case load.

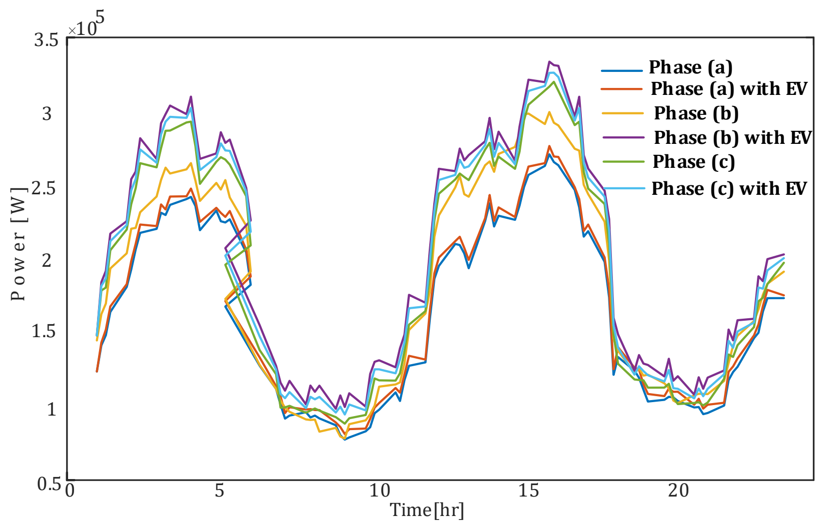


Fig. 5. Daily Loading level in summer, Aswan, Egypt, Phase a,b and c are load with 33% of EV

3.3.1.2 Case 2 of transformer loading

The second approach to transformer loading involved distributing the load evenly among the three phases, allocating 33% of the load to electric vehicles (EVs) in each phase. This scenario aimed to examine the impact of the base load on the loading curve for EVs, particularly during peak hours. The results showed a distinct increase in the loading curve for phase c with EV loading, followed by a gradual decrease in the curves for phases b and a, based on the base load. This is illustrated in Figure 6.

Figure 6 clearly demonstrates that the transformer loading reached a peak load of 330 kW in phase c when EVs were present, while it reached 320 kW in the same phase without EVs. Moreover, the loading values were lower in phases b and a, with and without EVs. The transformer loading increased with higher EV penetration, but it remained within safe limits.

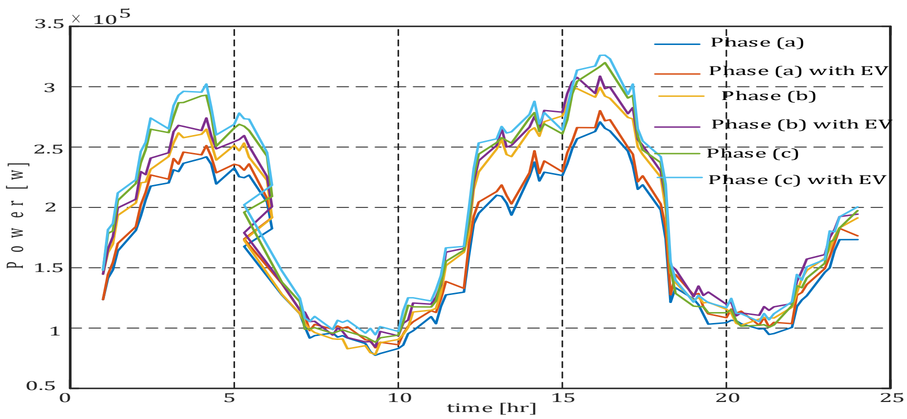


Fig. 6. Daily Loading level in summer, Aswan, Egypt, Phase a,c are load with 20% of EV and c are load with 60% of EV

3.3.1.3 Case 3 of transformer loading

The final scenario involved considering the average load of the three phases before and after incorporating the electric vehicle (EV) load. In this case, the impact of the EV load was greater than the base load throughout the load curve, particularly during peak hours, as depicted in Figure 7.

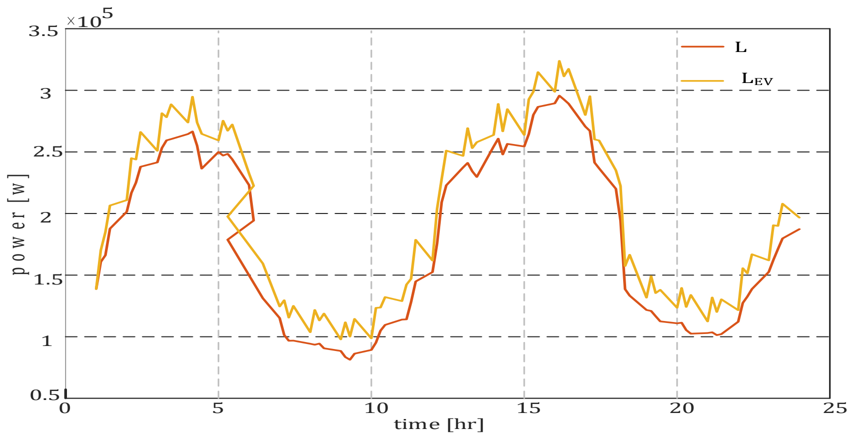


Fig. 7 Daily Loading level in summer, Aswan, Egypt, the average of the three phase before and after EVs

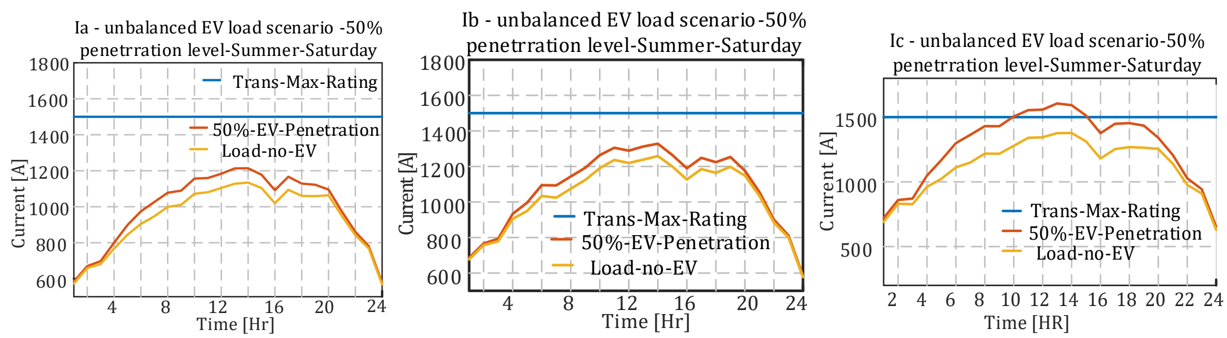
3.3.2 Impact of 80 EVs charging

The performance of the transformer is observed when it is loaded in varying proportions from 80 charging cars (50%, 25%, 10%) during a summer day during the unbalanced load of the transformer.

3.3.2.1 50 % penetration rate case of study

In Figure 8, the transformer loads exhibit an imbalance when there is a 50% penetration of EV charging. It is evident that there is a significant increase in the load for the first and second phases (a, b), although it does not reach the transformer's design load.

However, in the third phase (c), when the penetration of EV charging is added, the load exceeds the transformer's design capacity. This situation poses a considerable risk to the transformer and may lead to damage.

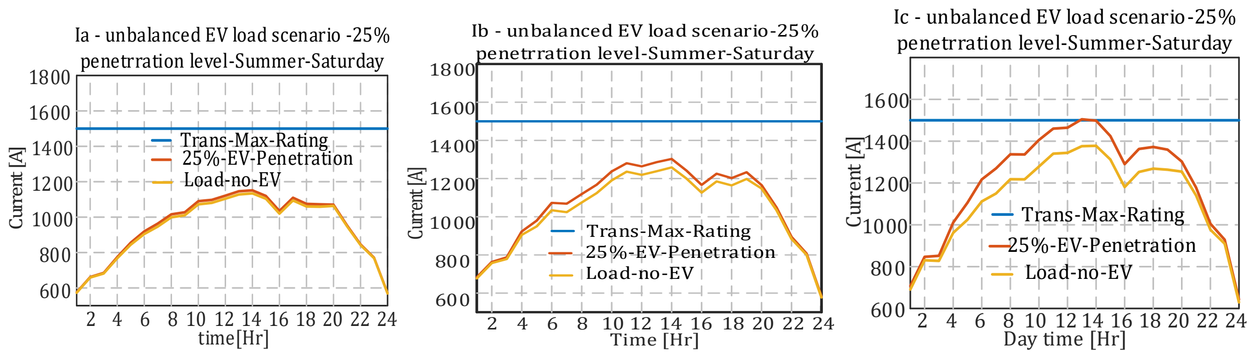


a) (b) (c)

Fig. 8. 50% EV Loading Summer, Saturday, (a) Phase a, (b) phase b, (c) Phase c

3.3.2.2 25 % penetration rate case of study

In Figure 9, when the EV penetration decreases to 25% under the same previous conditions, there is no significant impact on the load variation for phases a and b, as the changes remain within permissible limits. However, in the third phase (c), with the addition of penetration, the load approaches the design capacity of the transformer, presenting an immediate hazard. Nonetheless, the potential damage is comparatively less severe than in the previous scenario.

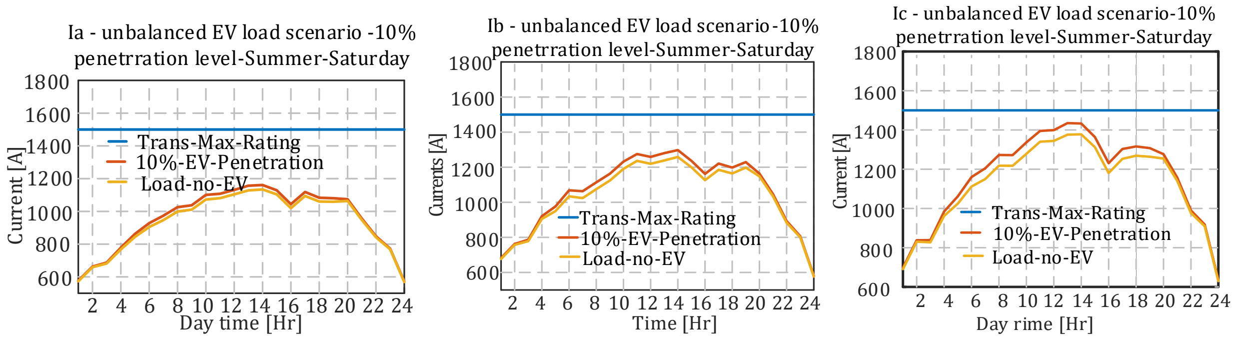


(a) (b) (c)

Fig. 9. 25% EV loading Summer, Saturday, (a) Phase a, (b) phase b, (c) Phase c

3.3.2.3 10 % penetration rate case of study

In Figure 10, the maximum loading of the transformer in phase c before connecting EVs is observed at 90% capacity at 14:00. After connecting EVs, the maximum loading during the time period of 13:00-14:00 also reaches 90%. This indicates that a 10% penetration of EVs has a relatively small effect on the transformer compared to the previous cases where the total load was closer to the base load.

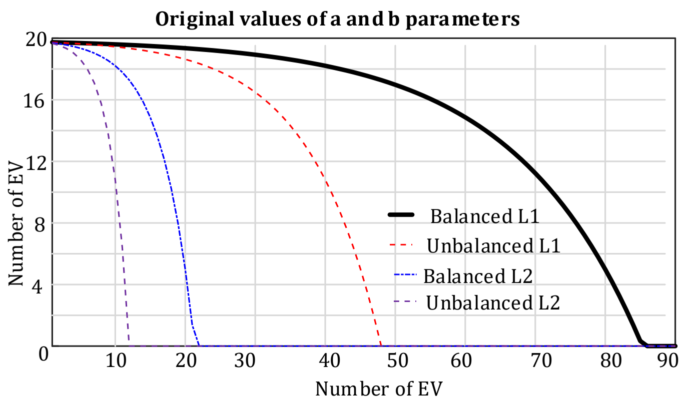


(a) (b) (c)

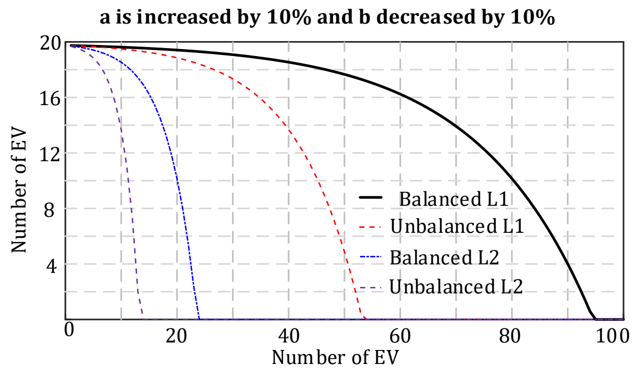
Fig. 10.10% EV loading Summer, Saturday, (a) Phase a, (b) phase b, (c) Phase c

3.4 Aging Sensitivity to Transformer Parameters

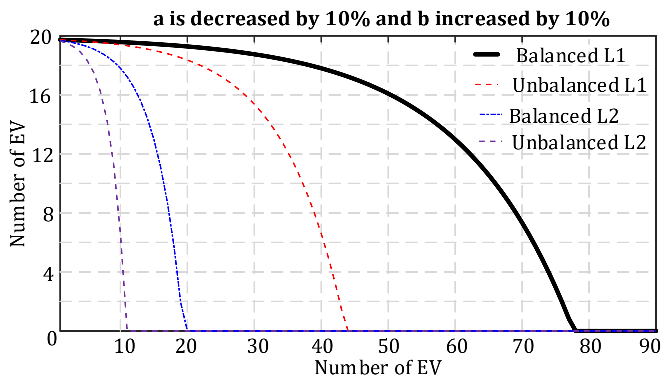
The aging results of transformers are highly sensitive to variations in parameters a and b, which are determined by the type of insulation system and materials used. The lifespan of the transformer is directly proportional to parameter a and exponentially related to parameter b as stated in equation 3. The impact of modifying these parameters by 10% is illustrated in Figure 11. Moving from figure 11(a) to figure 11(c) , the first case represents the original values of both parameters. The second case shows a 10% increase in parameter a while parameter b is decreased by 10%. The third case demonstrates a 10% decrease in parameter a accompanied by a 10% increase in parameter b.These two cases are emphasized due to their greater influence compared to when both parameters change in the same direction. Consequently, they result in a noticeable shift in the location of the drop in lifetime along the x-axis.



(a)



(b)



(c)

Fig. 11. Transformer lifetime regarding to transformer parameters variation

4 CONCLUSIONS

This study provides a comprehensive analysis of the impact of electric vehicle (EV) penetration on a 1000kVA transformer located in El-Akaad, Aswan, Egypt. The objectives were to evaluate the effects of EV charging under various scenarios and loading conditions, assess the stress on the grid during peak hours, and investigate the sensitivity of the transformer's lifetime to parameters a and b.

Based on the analysis of data from different EV penetration levels (ranging from 53 to 80 EVs) and charging scenarios (day, week, year), several key findings emerged. The weekly EV electricity demand profile showed significant peaks during weekdays, increasing the overall stress on the grid throughout the week, particularly during peak hours. This highlights the importance of managing daily peaks to ensure the transformer operates within safe limits.

The study also revealed that unbalanced transformer loading was more affected by increasing EV penetration, especially during the summer season. The lifetime of the transformer was found to be sensitive to parameters a and b, emphasizing the need to carefully manage the number of EVs connected to the grid to prevent overloading and potential damage.

Furthermore, the study highlighted the untapped potential of leveraging EV fleets to provide ancillary services and support the integration of renewable energy sources. This aspect warrants further exploration and utilization in future research.

The findings of this study lay a solid foundation for future investigations into EV integration, ancillary services, grid infrastructure, and charging management. However, it is important to note that further testing and calibration are required to determine the exact number of cars at which the lifetime of the transformer starts to decline for specific sites. Nonetheless, the consistent relationship observed between charging options and improvement through managed charging provides valuable insights and directions for future studies.

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6 **Conflict of Interest:** The authors declare that they have no conflict of interest.

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