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Distribution Transformers Overloading Mitigation Using Smart Coordination Between PV Generation, Battery Energy Storage and EV Charging

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SUMMARY

The modern power grid has undergone a remarkable transformation with the integration of new and sustainable resources, namely photovoltaic (PV) solar panels, electric vehicles (EVs), and battery energy storage systems (BESSs). The integration of these resources into the power grid presents several challenges for distribution transformers. The charging and discharging cycles of EVs and BESS can result in sudden load changes, potentially causing transformer overheating and reduced lifespan. Additionally, the increased adoption of these technologies can lead to higher demand on transformers, requiring upgrades or replacements to handle the greater load. An alternative to costly replacement or upgrade can be smart energy management of these resources.

To handle increased EV charging and its impact on transformers, utility companies can proactively implement smart grid management technologies like demand-response programs and load balancing. By influencing EV charging timing and rate, they can balance the load and avoid peak demand periods, reducing strain on transformers. Advanced monitoring and control systems enable real-time data analysis to identify overloading scenarios and take proactive measures. Integrating renewable energy sources and energy storage enhances grid resilience and provides alternative power supply during high EV charging demand.

A comprehensive approach combining efficient charging practices, grid management, and sustainable energy solutions ensures smooth EV integration while protecting transformers and extending their lifespan. Our paper explores two charging management approaches, centralized and distributed, with their respective benefits for mitigating transformer aging and failures. Coordination between PV, BESS, and EV charging proves to be a beneficial solution for transformer risk mitigation. This approach also accommodates customer's need for a convenient charging options. The study uses Monte Carlo simulation to quantify the benefits of this coordination. The findings in this paper are the result of a comprehensive study on future grid developments, specifically focusing on EVs, PV Systems, and BESSs undertaken during recent large-scale project funded by DOE and Indian government involving several partners from the two countries.

KEYWORDS

Electric vehicles, PV systems, battery energy storage systems, distribution transformers, ageing, risk.

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1. Introduction

The rising adoption of electric vehicles (EVs) has brought about a positive shift in the transportation sector, contributing to reduced greenhouse gas emissions and environmental sustainability. Nevertheless, this transformative transition to electric mobility has not been without its challenges, particularly concerning the impact on electrical infrastructure and distribution transformers (DTs). As more EVs are being charged, the load on local power distribution networks is increased resulting in frequent and fluctuating power demands on distribution transformers. These variations in load and subsequent thermal stress can hasten the aging process of transformers, leading to premature deterioration of crucial components and a shortened operational lifespan.

The continuous heating and cooling cycles experienced during peak charging times can accelerate insulation breakdown, increase winding resistance, and trigger internal faults, ultimately compromising the reliability of the power grid. To mitigate the detrimental effects on transformers, utility companies and stakeholders must proactively address this issue. Implementing smart grid management technologies, such as demand-response programs and load balancing, can help optimize power distribution and reduce the strain on transformers.

To address these challenges, regular health assessments of DTs are essential. Utilities must proactively monitor transformer conditions, implement smart grid management technologies, and conduct preventive maintenance to identify and rectify potential issues before they escalate. By taking proactive measures, utility companies can ensure the reliable operation of DTs, minimize downtime, and enhance the overall resilience and resilience of the electricity distribution system. At the distribution level, a good estimate of the DT state of health is its loss of life (LOL). It is the time taken by a transformer to reach a critical condition, such as a winding hot-spot temperature that exceeds the insulation's thermal limit. LOL can be estimated using several methods, including:

- Thermal analysis: This method uses the transformer's load, ambient temperature, and other parameters to calculate the winding hot-spot temperature.
- Accelerated aging testing: This method exposes transformers to accelerated aging conditions, such as high temperatures and humidity, to determine their LOL.
- Statistical method: This method uses historical data on transformer failures to estimate LOL.

One potential solution to prevent DT overloading is the installation of solar PV and BESS (Battery Energy Storage System) on the consumer-side. By dispatching power from these sources during peak demand periods, consumers can meet their local energy demands, thereby alleviating the strain on the DT. Various coordinated dispatch strategies for solar PV, and BESS have been proposed in the literature [1]-[9]. The impact of PV and BESS on LOL is due to several factors, including: *(i)* The capacity of PV and BESS installed, *(ii)* the load profile of the distribution system, *(iii)* the ambient temperature, and *(iv)* the transformer's thermal design. Due to lack of real-time monitoring of DT, their loading patterns are generally not strictly monitored. Therefore, EVs charging at home or public charging stations, in a particular region, can cause DT overloading that may go unnoticed for longer periods which may lead to failure of DT [10], [11]. Repeatedly overloading condition of DT can lead to outages and financial burden on the utilities in terms of DT higher maintenance cost or replacement cost. The risk of DT failure increases when it continuously operates in overloading conditions for longer time periods, as a result transformer life reduced drastically [12]. The impact of PV and BESS on LOL is a complex issue, and the results of studies can vary depending on the scenarios considered. Nevertheless, it is well established that the addition of PV and BESS can significantly reduce LOL, which can extend the lifespan of DTs and yield cost savings for utilities by deferred investments. Besides making sure that the transformers are not overloaded, and the risk of failures is taken into account, the DT asset management strategy has to accommodate customer’s EV charging needs.

2. TRANSFORMER LOSS OF LIFE AND PROBABILITY OF FAILURE

2.1.Hot Spot Temperature Calculation

Many factors in the transformer can cause a rise in temperature in very complex and uneven distributed location inside the transformer. This non-uniformity in temperature raise location can create the maximum ageing at a particular area which is called hot spot temperature. Measuring the hotspot temperature is very expensive and complex and often requires special sensors or lasers which make measuring impractical for most of the DTs. Therefore, calculations of the hot spot temperature make it more viable for long-time in-service transformers. Rising hotspot temperature might reduce the dielectric strength of the transformer by increasing the risk of gas bubbles and expose the insulation leading to transformer failure.

The hot spot temperature is calculated as per IEEE C57.91 standards [13]. The standards provide hot spot temperature calculation based on load variation and provide guidance for calculation of transformer aging based on temperature rise and increase in load. The hot spot temperature depends on the ambient temperature as well as the top oil temperature rise over ambient temperature and conductor temperature rise over top oil which both are functions of transformer loading.

2.2. Transformer Ageing

Power transformer ageing is a natural process that occurs over time due to various factors, including thermal stresses, electrical loading, and environmental conditions. The Arrhenius model is commonly used to quantify the impact of temperature on transformer ageing [14]. According to the Arrhenius model, the rate of ageing is exponentially related to temperature, implying that higher operating temperatures accelerate the ageing process. The model is based on the Arrhenius equation, which describes the dependence of the reaction rate on temperature and material characteristics. In the context of power transformers, the Arrhenius model helps determine the loss of life of the transformer by considering the effect of temperature on the insulation materials and other components.

Primary and secondary coils are the key components in a transformer that performs the basic function of either step up or step down the voltage and current. A material is used to insulate the primary and secondary coils. The insulating material is one of the most critical and necessary elements of transformer for its safe operation. This insulation not only helps to isolate coils from one another or from core but also ensures transformer from accidental over voltages. The material of the paper has outstanding characteristics like excellent dielectric and mechanical properties made of lignin, hemicellulose and cellulose that ensure the safeguard of transformer [15].

When the insulating paper is exposed to water, oxygen, high temperature and acids, which are aging lead to chemical reaction and consequently the life span of insulating paper decreases. Each aging agent can affect degradation rate hence must be controlled individually. In the example shown in IEEE std., C57.12.00-2010 insulation life of the transformer used as a sample is 1800000 hours at 110 ℃ [16]. The rise in temperature mainly depends on load that brings effect on chemical reaction speed for insulation paper and is calculated based on Arrhenius equation. This equation describes the dependency on rate of speed of chemical reaction over temperature. Practically with increase in temperature, the aging rate increases exponentially.

2.3. Transformer Probability of Failure

Failure in distribution transformer can occur due to various reasons including operational stress, overload, harmonics, oil leakage and unbalance loading. If any of these conditions occur consistently and exceed the design and operational limits, this may lead to reduction in transformer service life or failure. There are many causes of transformer failure reported in literature, different test analyses are conducted to identify the root cause and to find the preventive measures to avoid breakdown. Transformer can fail due to combination of mechanical, thermal, or electrical factors and the mode of failure is difficult to determine. Mechanical Factor results in damage to the winding rupturing due to electromechanical forces or during shipping of transformer, conductor tipping, spiral tightening etc. Electrical factors include overvoltage/overcurrent conditions, overloading of transformers and lightning surge.

Over time the insulation of the transformer degrades due to heat generation and decreased the dielectric strength of the insulation, which happens due to thermal factors. Other reasons of DT failure due to thermal factor could be failure of cooling systems, overloading of DT for prolonged time period, operation of DT in high ambient temperature and operation of DT on nonlinear loads. Insulation degradation due to overheating makes loading of the transformer one of the most important factors in transformers early failure, and therefore, it is the main factor used in quantification of the probability of transformer failure as explained in [14].

3. Impacts of EV Charging on Transformer Ageing and Mitigation Techniques

Utility companies can influence the timing and rate of EV charging to balance the load and avoid peak demand periods, thus reducing the strain on transformers. Additionally, the deployment of advanced monitoring and control systems can enable real-time data analysis, helping operators identify potential overloading scenarios and take proactive measures to redistribute the load or initiate controlled charging processes. Furthermore, the integration of renewable energy sources and energy storage systems can enhance the overall grid resilience and provide alternative power supply during periods of high EV charging demand. A comprehensive approach that combines efficient charging practices, grid management, and sustainable energy solutions can ensure the seamless integration of electric vehicles while safeguarding transformers from overloading and extending their operational lifespan. EV charging management can be centralized with optimization performed by the distribution system operator or decentralized with all the controls performed by the local controller.

3.1. Centralized EV Charging Management for DT Risk Mitigation

In centralized charging management, the status of EVs as well as transformer loading and EV owners' preferences are communicated to the distribution system operator (DSO), and through solving an optimization problem, the DSO sends charging management signals back to EVs to postpone the charging of EVs. The schematic of such a control solution is shown in Figure 1. In this figure EV Participation Factor (EVPF) is used to represent EV owner preferences and EV battery status as defined in [17]

A smart fuzzy logic-based decision-making approach is used as the local controller to calculate EVPFs and control the charging of each EV. It factors in various parameters, including EV battery state of charge, required state of charge for the next trip, estimated time of EV departure, and customer comfort. The fuzzy system provides a performance index for the distribution system operator (DSO) and helps determine which EV charging should be postponed, incentivizing EV owners to participate in the mitigation program. Figure 2 shows the fuzzy controller that manages the charging of the EVs..

The centralized method involves communication between the DSO, EV owners, and transformer management system. Fuzzy logic is used to incorporate human judgment in the control process, allowing for better assessment of options, particularly considering customer comfort and time-of-use preferences. The fuzzy logic algorithm takes four main inputs: EV battery state of charge, required state of charge for the next trip, estimated time of EV departure, and customer comfort level. The distribution transformer loss of life and failure hazard are utilized in the decision support algorithm used by the distribution system operators. Required State of Charge (RSOC) and Departure Time are used to calculate the Charging Necessity Factor (CNF).

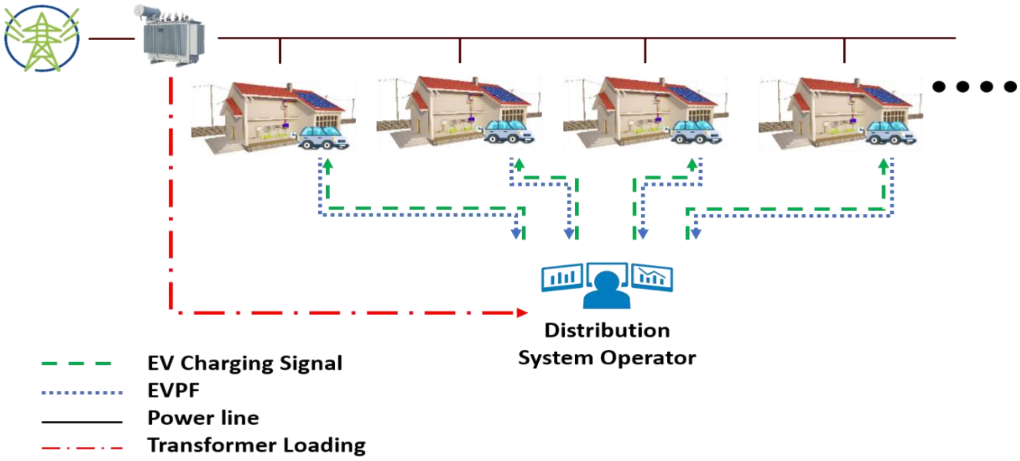

Figure 1. The schematic of centralized EV charging management for DT risk mitigation [17]

The EVPFs are communicated to the DSO and DSO's central decision-making algorithm determines whether the EV charging should be postponed. This approach utilizes the Arrhenius-Weibull model to quantify loss of life and failure hazard in transformers due to EV overloading. By combining loss of life and failure hazard in a cost function, DSO manages to optimize the EV charging.

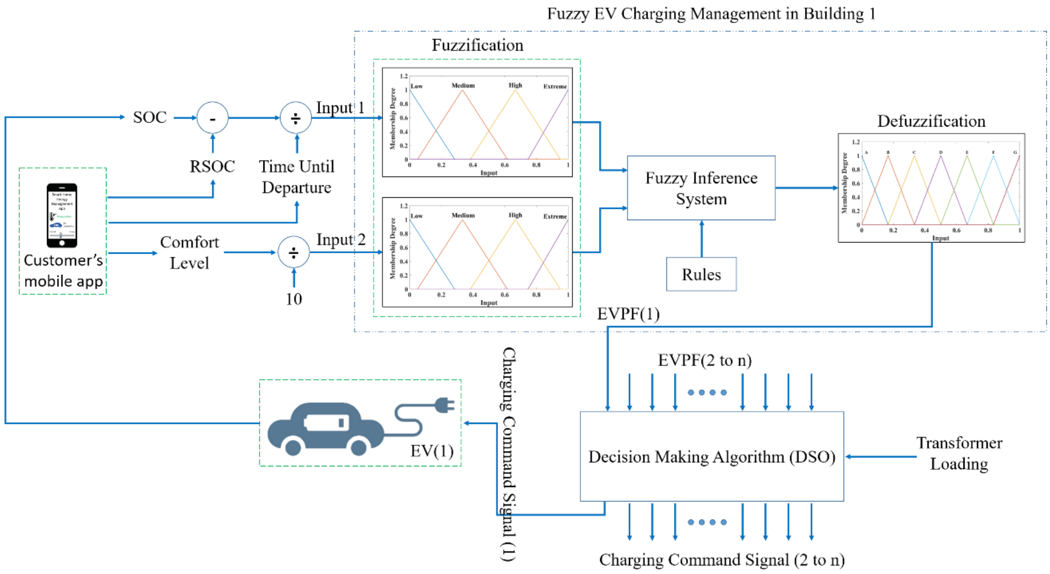

Figure 2. Local fuzzy controller in centralized EV charging management [17]

3.2. Distributed EV Charging Management for DT Risk Mitigation

This section explores the concept of distributed EV charging management, presenting it as an approach to optimizing charging infrastructure in terms of mitigating DTs ageing and risk of failure. Traditional centralized systems have limitations in scalability and energy utilization. In contrast, distributed control empowers individual EV owners and charging stations to make autonomous and intelligent decisions. EVs and charging stations can communicate directly, exchanging critical information that can be used in EV charging management.

Distributed EV charging management serves as a crucial strategy for mitigating electric transformer overloading in the context of rapidly expanding electric vehicle adoption. By implementing a distributed approach, individual EVs and charging stations can optimize their charging patterns in response to real-time data on transformer capacity and grid demand. Through a local controller, EVs can be directed to charge during off-peak hours or times when the transformer has spare capacity, thereby reducing the risk of overloading. This intelligent coordination ensures a balanced distribution of power demand, maximizing transformer efficiency, and minimizing the need for costly infrastructure upgrades.

In this approach, EV owners communicate with a local controller and provide their preferences and EV charging availability. The information exchanged are similar with the centralized approach with the difference that local controller runs a simplified algorithm for the limited number of EVs that use the charging station for EV charging and manages the charging of the EVs to mitigate the transformer ageing and risk of failure. The schematic of such a control is shown in Figure 3.

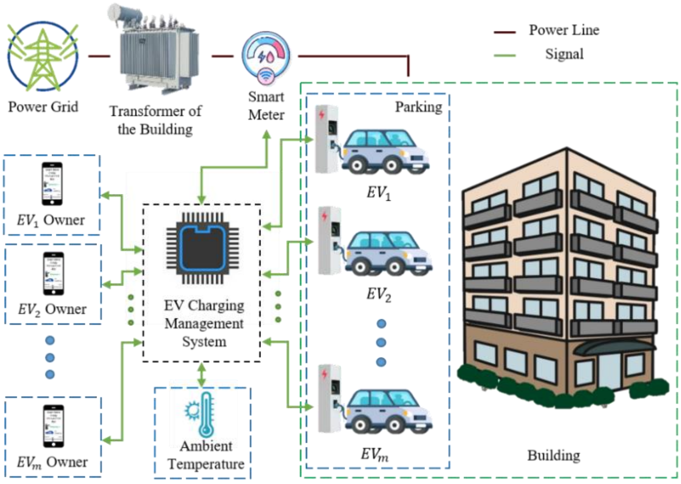

Figure 3. The schematic of decentralized EV charging management for DT risk mitigation [18].

EV Charging Management System calculates EVPFs for the EVs connected to the charging station and using the algorithm implemented in the charging controller. The transformer loading and ambient temperature are the other inputs given to the charging management system. The controller uses all the inputs to decide whether it is needed to postpone charging of an EV to mitigate the transformer overloading. The charging management system is shown in Figure 4.

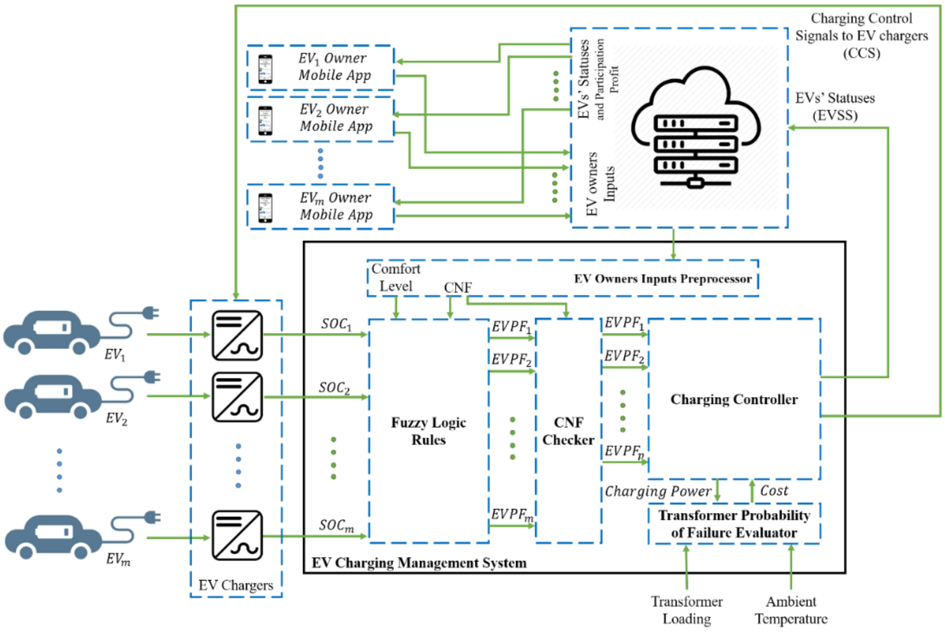

Figure 4. The distributed EV charging management system [18].

4. Impacts of EV Charging on Transformer Ageing and Mitigation Techniques

Coordinating Photovoltaic (PV) systems, Battery Energy Storage Systems (BESS), and Electric Vehicle (EV) charging can be a powerful strategy to mitigate transformer overloading in a distributed energy environment. By integrating these technologies, it is possible to balance the grid's power flow and alleviate the strain on transformers.

PV systems can generate electricity during peak daylight hours, and by synchronizing their output with transformer load profiles, excess energy can be diverted to charge BESS and EV batteries. This process ensures that energy generated by PV systems is not wasted and is instead stored for later use or EV charging. During periods of high demand, when the transformer's capacity might be exceeded, the stored energy can be drawn from the BESS to offset the load on the transformer, reducing the risk of overloading.

In [3], we studied the economic impact of this coordination of resources and their analysis takes into account the costs of PV systems, BESS, and transformers. We calculate the Net Present Value (NPV) and payback period to evaluate the financial benefits of employing BESS and PV generation. The results indicate that including BESS and PV in the system can significantly extend the lifespan of transformers and lead to tangible financial benefits, making the approach economically viable and profitable.

We developed several optimization solutions for the coordination problem of these resources as explained in [1] and [4]. The optimization problems aim to schedule battery charging and discharging in a day-ahead manner to achieve peak load shaving. In [1], we use a genetic algorithm to solve the optimization problem efficiently. The demand of PEVs is modeled probabilistically based on variables like driving distance, arrival time, and PEV characteristics. The impact of PEVs on transformer aging is quantified using IEEE Standard C57.91, which considers factors like ambient temperature and loading. In [4], the interior point algorithm is used to solve the optimization problem. The case study in [1] and [4] are performed using the information and models shown in Figure 5.

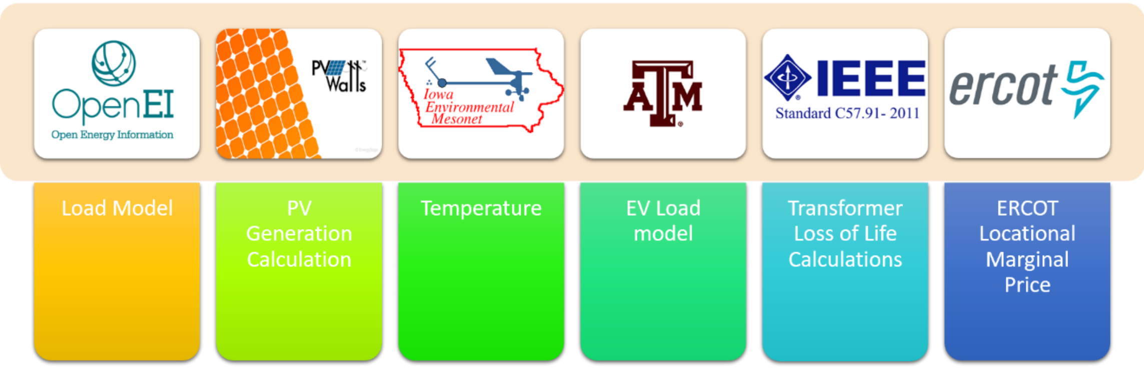

Figure 5. Utilized tools and models for case study.

5. Conclusion

This paper presents an overview of the challenges faced by distribution transformers due to the integration of EVs, BESSs, and PV systems, and proposes solutions through smart coordination of these resources to mitigate the impacts. The following conclusions are drawn:

- Centralized charging management of EVs by Distribution System Operators (DSOs) can effectively address transformer overloading and the risk of failure.
- Distributed charging management is a scalable solution, especially in scenarios with a high number of EVs where centralized management may be impractical and costly.

- Coordinating the operation of BESS and PV systems while considering EV loading can offer an economically viable solution to the problem of transformers aging and overloading.

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