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Assessing The Influence of Cost-Based Smart Electric Vehicle Charging 0n Urban Low-Voltage Power Distribution Networks

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Abstract: - *The surge in environmental and energy concerns has spurred the adoption of Electric Vehicles (EVs), which are rapidly advancing despite various challenges. Key obstacles include the need to improve driving range, battery longevity, and power capacity. To tackle these issues, this thesis investigates the performance of EVs equipped with a Hybrid Energy Storage System (HESS) that combines Li-ion batteries and Ultracapacitors (UCs). A comprehensive model of various system components for a 3-wheeled Electric Vehicle (EV), based on the Indian Driving Cycle (IDC), is presented to assist in sizing the Energy Storage System (ESS).*

Efficient energy management control is essential for regulating power flow according to the drive cycle's load requirements. This necessitates a robust control design capable of accommodating real-time load fluctuations by regulating power flow from hybrid sources. The thesis proposes a hybrid control strategy integrating filtering and fuzzy rule-based techniques for effective power flow regulation. Results regarding various performance metrics, including battery stress factor, UC state-of-charge (SOC) difference, energy consumption rate, system efficiency, and speed profile tracking, demonstrate the satisfactory performance of the proposed control strategy.

Voltage imbalance issues in series stacking of UCs are addressed by increasing the conversion gain of MMCC. The selection of conversion gain involves balancing UC capacitance, the number of parallel stacks, and cost considerations. The thesis provides detailed guidelines for determining the optimal voltage gain of MMCC, considering these factors. Additionally, a failure mode analysis of the MMCC converter highlights its performance under fault conditions.

A comprehensive comparative study of EVs employing Battery Energy Storage Systems (BESS) and hybrid energy storage systems is presented to elucidate the advantages of HESS. Economic feasibility assessments of BESS and HESS underscore the effectiveness of Li-ion battery/UC HESS.

Keywords: - Smart Charging, Electric Vehicles (EVs), Low-Voltage Power Distribution Networks, Cost-Based Charging, Grid Integration, Demand Response, Urban Mobility

I. INTRODUCTION

The rapid adoption of electric vehicles (EVs) presents both opportunities and challenges for urban power distribution networks. As urban areas strive to reduce carbon emissions and promote sustainable transportation, the integration of EVs into the existing infrastructure is crucial. However, the charging demand of these vehicles poses significant challenges to the low-voltage power distribution networks that predominantly serve residential and commercial areas.

One of the primary concerns is the impact of EV charging on the stability and reliability of power distribution networks. Unlike traditional fuel vehicles, EVs rely on electricity for operation, leading to increased demand on the power grid, especially during peak hours. This surge in demand can result in voltage drops, increased load on transformers, and potential overloading of distribution lines. Therefore, understanding and managing the impact of EV charging on power distribution networks is critical for maintaining grid stability and ensuring reliable power supply.

Cost-based smart charging systems have emerged as a promising solution to mitigate the adverse effects of EV charging on power distribution networks. These systems utilize dynamic pricing models and real-time data to optimize charging schedules, balancing the demand across different times of the day. By incentivizing off-peak charging through lower rates, cost-based smart charging can reduce the strain on the grid during peak hours, thereby enhancing the efficiency and reliability of power distribution.

This study aims to investigate the impact of cost-based smart EV charging on urban low-voltage power distribution networks. By analyzing various charging scenarios and their effects on the grid, this research seeks to provide insights into how smart charging strategies can be effectively implemented to support the growing number of EVs while maintaining grid stability. The study also examines the economic implications of smart charging, assessing how cost-based incentives can influence user behavior and overall energy consumption patterns.

The rise of electric vehicles (EVs) presents both opportunities and challenges for urban low-voltage power distribution networks. As EV adoption continues to grow, the demand for efficient and cost-effective charging solutions becomes increasingly critical. This study investigates the impact of cost-based smart charging strategies on urban power distribution systems, focusing on optimizing the balance between electricity demand and supply. By leveraging advanced algorithms and dynamic pricing models, smart charging can shift EV charging to off-peak hours, thereby reducing strain on the grid and enhancing its stability.

The research methodology integrates theoretical modeling with empirical data analysis to assess the potential benefits of smart charging. Data on EV charging patterns, electricity consumption, and grid load profiles in urban areas are collected and analyzed to identify peak demand periods and understand the strain on power distribution networks. Smart charging algorithms are then developed, utilizing real-time data and dynamic pricing to optimize charging schedules. These algorithms are designed to adapt to fluctuating electricity prices and grid conditions, ensuring a minimized impact on peak loads.

Simulation models are employed to test various EV charging scenarios, including unmanaged charging, time-of-use (TOU) pricing, and cost-based smart charging. The simulations evaluate the effects of each scenario on grid stability, voltage levels, and transformer loads. Additionally, the study explores the integration of renewable energy sources, such as solar and wind, into the smart charging framework. This integration aims to determine how renewable energy can offset peak loads and contribute to the efficiency of the power distribution network.

II. SMART ELECTRIC VEHICLE

A smart electric vehicle (smart EV) represents a significant advancement over traditional electric vehicles, integrating state-of-the-art technologies to enhance efficiency, connectivity, and user experience. These vehicles are designed with intelligent systems that optimize energy management, allowing for more effective charging and battery usage, thus extending battery life and improving overall vehicle performance. Connectivity is a key feature of smart EVs, enabling seamless communication with charging stations, other vehicles, and smart infrastructure through internet connections. This facilitates remote monitoring, diagnostics, software updates, and vehicle-to-everything (V2X) communication, enhancing both convenience and safety.

Smart charging capabilities in these vehicles allow them to interact with smart charging stations to schedule charging during off-peak hours or when renewable energy is most available, reducing charging costs and balancing the load on the power grid. Additionally, many smart EVs are equipped with autonomous driving features and advanced driver assistance systems (ADAS), utilizing sensors, cameras, and artificial intelligence to aid in driving tasks, collision avoidance, and traffic navigation, thereby significantly improving safety and convenience.

Furthermore, smart EVs can integrate with smart grids, supporting bidirectional energy flow. This means they can return energy to the grid during peak demand periods, acting as mobile energy storage units and contributing to a more stable and efficient energy system. Enhanced user interfaces, including touchscreens, voice control, and mobile apps, provide a more intuitive and interactive experience, allowing users to monitor vehicle performance, control settings, and plan routes efficiently.

III. METHOD

The proposed method for studying the impact of cost-based smart electric vehicle (EV) charging on urban low voltage power distribution networks involves a multi-faceted approach that integrates data analysis, simulation modeling, and optimization techniques. Here's a detailed outline of the proposed method:

Data Collection and Analysis:

Gather historical data on EV charging patterns, electricity consumption, and grid performance metrics from urban areas with significant EV adoption.

Analyze the data to identify trends, patterns, and correlations between EV charging behavior and grid dynamics, such as load profiles, voltage levels, and congestion points.

Smart Charging Algorithm Development:

Develop algorithms for smart EV charging scheduling that optimize charging patterns based on cost, grid constraints, and user preferences.

Consider factors such as time-of-use pricing, grid capacity limitations, renewable energy availability, and user demand patterns in the algorithm design.

Simulation Modeling:

Construct simulation models of urban low voltage power distribution networks using software tools like OpenDSS or MATLAB/Simulink.

Incorporate the developed smart charging algorithms into the simulation models to assess their impact on grid performance under various scenarios.

Performance Evaluation:

Evaluate the performance of the smart charging algorithms in terms of key metrics such as grid congestion reduction, load balancing, voltage stability, and energy cost savings.

Compare the performance of the proposed smart charging strategies against baseline scenarios with uncontrolled EV charging.

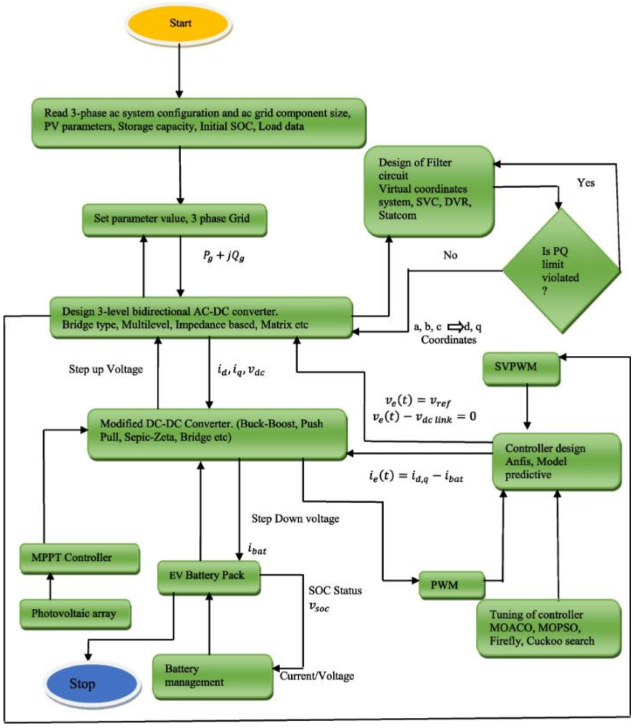

Figure 1 Proposed Flow

Optimization:

Use optimization techniques, such as linear programming or genetic algorithms, to fine-tune the smart charging algorithms and maximize their effectiveness.

Optimize parameters such as charging rates, scheduling priorities, and demand response strategies to achieve the desired balance between grid stability, cost efficiency, and user convenience.

Sensitivity Analysis:

Conduct sensitivity analysis to assess the robustness of the smart charging algorithms to variations in input parameters, such as electricity prices, EV penetration rates, and renewable energy generation levels.

Identify critical factors that influence the performance of the smart charging system and evaluate their impact on overall grid reliability and cost-effectiveness.

Proposed methodology is consists five step as show on figure 4.2

Low voltage power distribution network modeling

Low voltage power distribution network modeling involves the mathematical representation and simulation of electrical networks that deliver electricity from substations to end-users, such as residential, commercial, and industrial consumers. These networks typically operate at voltages below 1000 volts and form the final link in the electricity supply chain, distributing power to individual buildings and premises.

The modeling process encompasses several key aspects:

Network Topology: The physical layout of the distribution network, including substations, transformers, feeders, and distribution lines, is mapped out to establish the network topology. This involves identifying the connections and interconnections between various network components.

Load Modeling: Load modeling involves characterizing the electrical demand from consumers connected to the distribution network. This includes modeling the active (kW), reactive (kVAR), and apparent (kVA) power requirements of individual loads, as well as their voltage and current profiles over time.

Component Modeling: Each component of the distribution network, such as transformers, switches, capacitors, and voltage regulators, is represented using appropriate mathematical models. These models capture the electrical characteristics, performance parameters, and operational constraints of the components.

Circuit Analysis: Circuit analysis techniques, such as Kirchhoff's laws and nodal analysis, are employed to solve the electrical equations governing the behavior of the distribution network. These techniques help determine voltage profiles, power flows, and system losses under different operating conditions.

Steady-State and Dynamic Simulation: Steady-state simulation analyzes the behavior of the distribution network under balanced and quasi-steady conditions, considering factors such as load demand, voltage regulation, and power losses. Dynamic simulation, on the other hand, examines the network's response to transient events, such as switching operations, fault conditions, and load disturbances.

Voltage Regulation and Control: Voltage regulation strategies, such as tap-changing transformers, voltage regulators, and capacitor banks, are incorporated into the model to maintain voltage levels within acceptable limits and optimize network performance. Control algorithms and devices are designed to adjust voltage settings based on real-time measurements and system conditions.

Sensitivity Analysis: Sensitivity analysis is conducted to assess the impact of various factors, such as load variations, equipment failures, and network reconfigurations, on the performance of the distribution network. This helps identify vulnerabilities, reliability issues, and optimization opportunities.

Power Distribution Network (PDN) Modeling:

PDN modeling involves creating a mathematical representation of the low voltage power distribution network. This includes mapping out the physical layout of the network, identifying substations, transformers, feeders, and distribution lines.

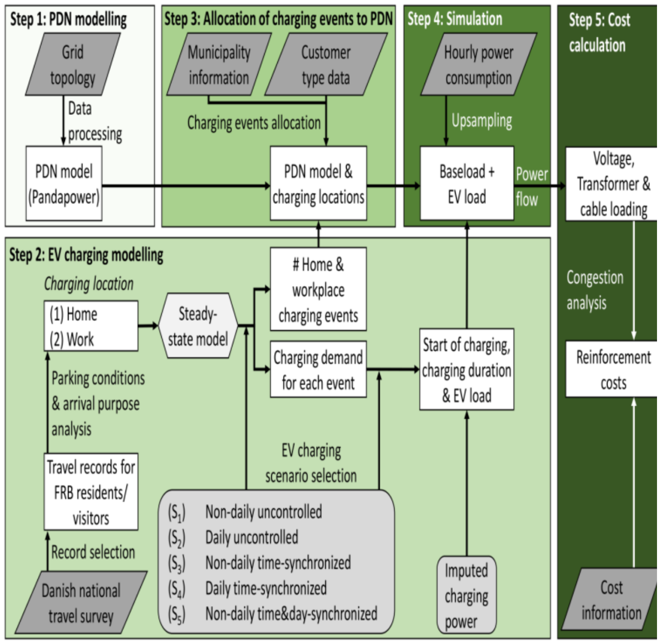

Figure 2 Grid Impact analysis Method

The topology of the network is established, indicating how different components are interconnected. Load characteristics, such as demand profiles and consumption patterns, are also incorporated into the model.

Electric Vehicle (EV) Charging Modeling:

EV charging modeling focuses on simulating the behavior and charging patterns of electric vehicles connected to the distribution network.

This involves characterizing various aspects of EV charging, such as charging rates, charging durations, and plug-in times.

Models may also consider different types of chargers (e.g., slow, fast, rapid), charging infrastructure availability, and user preferences.

Allocation of Charging Events in PDN:

Once the PDN and EV charging models are developed, the next step is to allocate charging events within the distribution network.

This involves determining the spatial and temporal distribution of EV charging activities across different locations and time periods.

Allocation methods may take into account factors such as charging demand, network constraints, and charging infrastructure capacity.

Simulation:

Simulation involves running computational models to analyze the behavior of the PDN under different scenarios and conditions.

The PDN, EV charging, and charging allocation models are integrated into a simulation environment.

Simulations are performed to evaluate the impact of EV charging on the distribution network, assess network performance metrics (e.g., voltage levels, power losses), and identify potential issues or challenges.

Cost Calculation:

Cost calculation involves estimating the economic implications of EV charging on the distribution network and associated infrastructure.

This may include evaluating the costs of network upgrades, infrastructure investments, energy losses, and operational expenses incurred due to EV charging.

Cost-benefit analysis techniques may be applied to assess the overall economic feasibility and sustainability of integrating EV charging into the distribution network.

By following these steps, researchers and practitioners can gain valuable insights into the implications of EV charging on urban low voltage power distribution networks, optimize charging strategies, and develop cost-effective solutions to support the widespread adoption of electric vehicles.

IV. RESULT

To commence, our focus shifts to the load modelling results, which serve as crucial inputs for the power flow simulations. The variation in total power load throughout the day in each grid. Several notable observations emerge from this analysis. Firstly, it is evident that the EV load exhibits greater volatility compared to the baseload, primarily due to the significant variation introduced by the multistep sampling approach.

A comprehensive summary of the sampling results for each step . The EV load in each grid demonstrates an upward trend with the increasing number of residential customers, accompanied by a corresponding increase in the baseload. Thirdly, there is a discernible risk of secondary peaks arising from cost-based charging, although this is contingent upon the specific characteristics of the LVDN and charging patterns. Table 4 provides a comparison of the peak load between scenarios S2–S4 and scenarios S0 and S1, respectively, along with the probability of introducing a new peak based on our 1000 simulations.

Table 1 The likelihood (%) of an increase in peak load in each LVDN for scenarios S2–S4 relative to the peak load in scenarios S0 or S1, respectively.

	LV1			LV2		
	S2	S3	S4	S2	S3	S4
S0	16	8.2	100	52	36	10
S1	0.3	0.1	100	1.4	0.5	10

The discrepancy in peak load arises from variations in the capacity factor (CF) and the level of baseload in each charging scenario. The CF of charging, representing the proportion of EVs charging at a given time relative to the total number of EVs, is depicted in Fig. 5.1. Uncontrolled charging exhibits the lowest CF across all scenarios, with medians below 4.5%. In contrast, scenarios S2 and S3 show a slight increase in CF due to charging synchronization during nighttime, with median CF during peak periods slightly above 11%. However, CF can rise up to 29% in rare instances for LV1. Scenario S4 introduces a significant change in the charging pattern, mandating all EVs to charge on the same day, resulting in a drastic increase in CF, with a maximum median exceeding 50%. Throughout the discussion, unless stated otherwise, results for LV1, LV2, and LV3 are represented in green, orange, and purple, respectively.

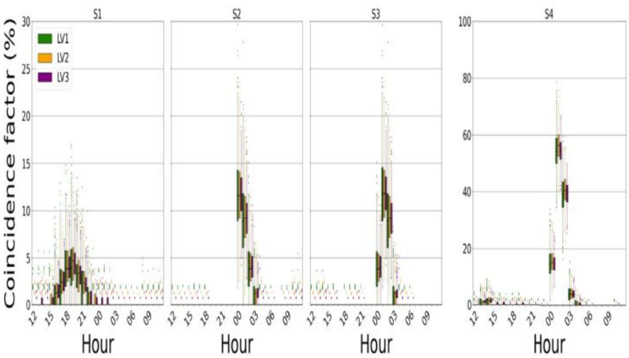

Figure 3 Coincidence factor (CF) of charging refers to the percentage of EVs charging at a given time compared to the total number of EVs.

To begin, we examine the transformer loading, which offers insights into grid utilization. Our analysis focuses on congestion (exceeding 100% loading) and adherence to the distribution system operator's (DSO) operational limit of 65%, ensuring N-1 security. While surpassing the critical operating load may not immediately require reinforcements, repeated violations prompt Radius to investigate demand reduction measures or timely reinforcement to sustain operation under component failure.

Fig. 4 illustrates the transformer load throughout the simulation period. In the left plot, distinct initial transformer loading conditions for each LVDN emerge from the interplay of customer numbers and transformer nominal power. LV1, with the fewest customers and a transformer rating of 620 kVA, consistently operates below 39% loading. LV2 and LV3, with the highest customer numbers and equally rated 510 kVA transformers, occasionally exceed the 65% threshold during evening peaks in rare outlier events, with a likelihood of less than 0.8% as indicated.

The figure depicts transformer loading for each Low Voltage Distribution Network (LVDN) and scenario, with S0–S4 arranged from left to right. Horizontal red lines denote the derated nominal load (solid) and N-1 redundancy limit (dashed). The color references in this figure legend can be interpreted via the web version of this article.

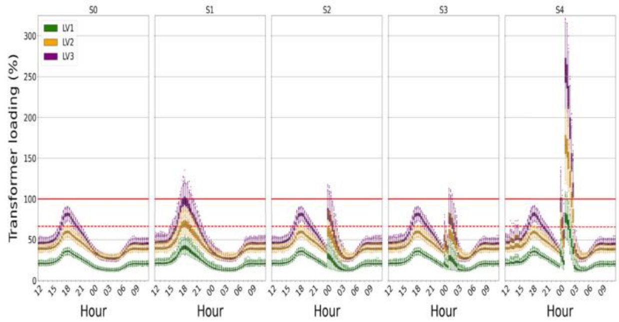

Figure 4 Transformer loading for Low Voltage Distribution Networks

Shifting our focus to the cables, we assess their performance under baseload conditions. Presently, the Distribution System Operator (DSO) doesn't actively monitor cable loading; instead, it relies on fuses installed at transformer interfaces to detect faults and prevent excessive overload events. However, due to the diversity of cable types, overloading is likely to occur without triggering fuses, especially for cables situated farther from the transformer, which typically have lower current-carrying capacities. With the fuse limits unspecified, we define overloading as cable loading surpassing 100%. Although cables may endure overload situations depending on various external factors, such conditions can hasten cable aging.

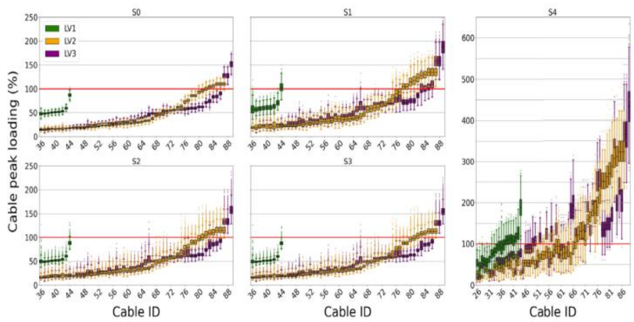

Figure 5 Peak Loading for Cable in LVDN

The voltage profile refers to the variation of voltage levels at different points within an electrical system, typically depicted graphically. In the context of electric vehicle (EV) charging, the voltage profile at the EV load location represents how the voltage fluctuates at the specific location where EVs are being charged. This information is crucial for assessing the impact of EV charging on the electrical distribution network, as voltage levels need to be maintained within acceptable limits to ensure the safe and efficient operation of electrical equipment and appliances.

Analyzing the voltage profile allows us to understand how EV charging activities affect the stability and reliability of the power distribution system. Voltage variations can indicate potential issues such as voltage drops or spikes, which may lead to operational problems or damage to electrical components if not properly managed. By examining the voltage profile at the EV load location, engineers and operators can identify areas of concern and implement appropriate measures to mitigate voltage-related issues and optimize the performance of the distribution network. as show figure 6.

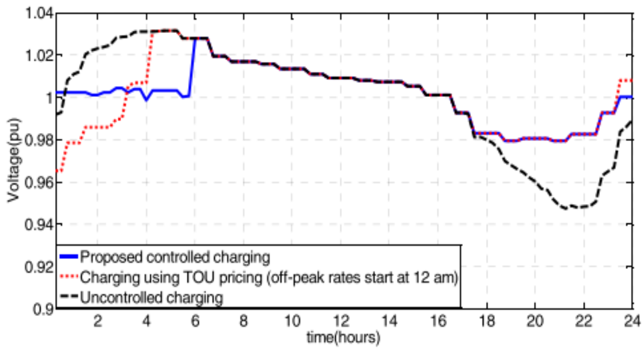

Figure 6 Voltage profile at the electric vehicle (EV) load site for each charging technique.

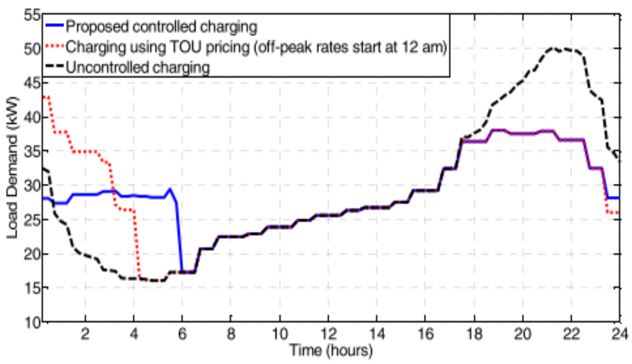

Figure 7 Load Demand Profile Every Day at LVDN

The daily load demand profile at the service transformer illustrates how the electrical load fluctuates over a typical day for each charging method. This profile provides valuable insights into the distribution of electricity consumption throughout the day, with specific emphasis on the impact of different EV charging strategies.

Analyzing the load demand profile allows us to understand the variations in power consumption and identify peak periods of demand. This information is essential for utilities and grid operators to effectively manage electricity generation, transmission, and distribution resources. By examining the load demand profile at the service transformer for each charging method, stakeholders can assess the overall impact of EV charging on the grid and make informed decisions about infrastructure upgrades, demand response initiatives, and energy management strategies as show figure 7.

V. CONCLUSION

Integrating smart charging technologies with cost-based incentives, it is possible to optimize the utilization of electricity infrastructure while accommodating the growing demand for EV charging. This approach not only helps to alleviate the strain on PDNs but also promotes efficient use of renewable energy sources and reduces greenhouse gas emissions associated with transportation.

The study employs a probabilistic methodology integrating smart meter data and a novel agent-based Electric Vehicle (EV) simulator named GAIA. It aims to model the fluctuations in both baseload and anticipated residential EV charging demand, assuming a scenario where 40% of vehicles are electric. In response to the current energy crisis and concerns regarding fluctuating electricity prices, the research proposes three cost-based charging methods (S2-S4) and evaluates their impact on Low Voltage Distribution Networks (LVDNs) compared to scenarios without EVs (S0) and with uncontrolled charging (S1). Through 1000 power flow simulations at 5-minute intervals over a typical weekday, the study analyzes the consequences on transformers, cables, and bus voltages for each LVDN and charging scenario.

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