Analyzing the Influence of Electric Vehicle Deployment on the Distribution Grid in the Presence of Demand-Responsive Loads

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Abstract:

In today's technologically advanced world, the evolution of sophisticated platforms has played a pivotal role in enabling the efficient deployment of smart grid systems. These technological innovations allow energy operators to more effectively monitor and control consumer energy usage patterns. A key aim of such advancements is to shift electricity demand from peak periods to off-peak hours, thereby improving the reliability and stability of the power network. This load shifting also alleviates grid congestion during high-demand intervals, delivering significant advantages to both consumers and energy providers. These benefits are realized through strategies known as responsive load management. In this research, responsive load management is applied to a standard 20-bus distribution system, consisting of 3,500 branches and capable of supporting up to 2,500 electric vehicles. The proposed approach focuses on reducing the collective energy consumption cost, while taking into account user-specific tolerances for electric vehicle charging delays. The impact of various electric vehicle penetration levels 15%, 40%, and 75% has been evaluated using a genetic algorithm for optimization. The analysis reveals that by designating 20% of the system's load as responsive, energy costs for consumers can be lowered by up to 36%. Moreover, this strategy significantly bolsters network reliability and reduces the likelihood of power outages by curbing energy use during peak demand periods. These findings highlight the potential of responsive load management in promoting a more sustainable and robust energy infrastructure

Keywords: responsive load, reliability, distribution network stability, electric vehicle, distribution network

Nomenclature

EC^{t}	Amount of energy consumed during time step t.
SD	Power transferred from peak hours to off-peak hours.
tar^{t}	Tariff rate during time step t.
tar_{p}	Tariff rate during the peak time period.
tar_{np}	Tariff rate during the off-peak period.
λ	Common satisfaction coefficient.

SD^{max} Maximum transferable demand.

L_t^{EV} Amount of electric vehicle charging during time step t.

q_{rated} Maximum instantaneous charging rate.

1. Interdiction

The increasing adoption of electric vehicles (EVs) poses both opportunities and challenges for existing distribution networks. With the growth of EV ownership, understanding the effects of their integration, particularly when coupled with responsive load, becomes critical for ensuring grid stability and reliability. The penetration of EVs in the distribution network can lead to a significant increase in overall electricity demand. Charging patterns can introduce variability, especially during peak hours, leading to potential overload situations. Since EV charging typically occurs in the evenings or during off-peak hours, there is a necessity for distribution network operators to manage peak loading scenarios effectively. The concentrated charging of EVs can result in voltage drops or fluctuations in the distribution network. These issues may necessitate upgrades to infrastructure, including transformers and voltage regulation equipment. Increased load can lead to higher energy losses in transformers and distribution lines. The effective management of these losses is crucial to maintaining efficiency within the distribution network. Responsive loads can help mitigate the impact of EV charging by shifting demand from peak periods to off-peak periods. Incorporating demand response systems can help balance the load and enhance overall grid reliability. Implementing dynamic pricing strategies for EV charging can incentivize users to charge during off-peak times, effectively flattening demand peaks and distributing loads more evenly throughout the day. By incorporating smart charging solutions, EV owners can respond to grid signals, shifting their charging times based on electricity availability and demand levels. The increasing adoption of electric vehicles (EVs) presents both opportunities and challenges for existing distribution networks. As EV ownership continues to grow, understanding the effects of their integration—particularly when coupled with responsive load management—becomes critical for ensuring grid stability and reliability. The penetration of EVs into the distribution network can lead to a significant increase in overall electricity demand. Charging patterns associated with EVs can introduce variability, especially during peak hours, potentially leading to overload situations within the grid. Typically, EV charging occurs in the evenings or during off-peak hours, necessitating that distribution network operators effectively manage peak loading scenarios. The concentrated charging of EVs can result in voltage drops or fluctuations within the distribution network. Such issues may require substantial upgrades to infrastructure, including transformers and voltage regulation equipment, to maintain optimal operational standards. Furthermore, increased load can lead to higher energy losses in transformers and distribution lines, making the effective management of these losses crucial for maintaining efficiency within the distribution network. Responsive load management strategies can help mitigate the impact of EV charging by shifting demand from peak periods to off-peak periods. Incorporating demand response systems can assist in balancing the load and enhancing overall grid reliability. Additionally, implementing dynamic pricing strategies for EV charging can incentivize users to charge during off-peak times, effectively flattening demand peaks and distributing loads more evenly throughout the day. By integrating smart charging solutions, EV owners can respond to grid signals, adjusting their charging times based on electricity availability and demand levels. This proactive approach not only aids in stabilizing the grid but also promotes a more sustainable energy ecosystem by optimizing resource utilization. Moreover, the successful integration of EVs into the distribution network can lead to the development of innovative business models and services. For instance, vehicle-to-grid (V2G) technology allows EVs to discharge electricity back into the grid during high demand periods, further enhancing grid resilience. As the energy landscape evolves, the collaboration between utility providers, EV manufacturers, and consumers will be essential in creating a robust framework that supports the seamless integration of electric vehicles into our energy infrastructure. Electric vehicles (EVs) significantly reduce carbon emissions and improve environmental quality in urban areas. As the adoption of electric vehicles accelerates, they are quickly becoming a substantial component of urban transportation systems. The use of conventional vehicles has been one of the main contributors to greenhouse gas (GHG) emissions, which is a critical factor driving changes in climatic conditions. These traditional vehicles operate on fossil fuels, emitting substantial amounts of carbon dioxide, nitrogen oxides, and other pollutants into the atmosphere, thereby exacerbating air quality issues and contributing to global warming. The adoption of electric vehicles represents a promising solution to significantly mitigate GHG emissions since they can emit up to 70% fewer emissions compared to conventional vehicles. This remarkable reduction in emissions is primarily attributable to the absence of tailpipe emissions in EVs; they do not emit any pollutants from the exhaust, making them inherently cleaner alternatives for urban transportation. Moreover, electric vehicles are generally more energy-efficient than traditional vehicles, as they convert a higher percentage of the electrical energy from the grid to power at the wheels. Furthermore, the electricity that powers EVs can be generated from renewable sources such as solar, wind, and hydroelectric power, which further reduces their environmental impact and dependency on fossil fuels. In its Announced Pledges Scenarios, the International Energy Agency (IEA) presumes that electric vehicle sales will increase to up to 30% of all vehicle sales globally. However, despite the optimism surrounding these projections, this figure is still significantly below the target of achieving a 60% market share by 2030 to facilitate net-zero CO_2 emissions by 2050[1]. Numerous impact studies on the power system have focused on various aspects of electric vehicle integration, examining how their widespread adoption affects energy demand and infrastructure requirements [2-12]. For developing countries, prioritizing the electrification of transportation is crucial. This strategic shift can help reduce their dependency on oil, which, in turn, supports economic growth and energy security. By transitioning to electric vehicles, these countries can anticipate significant long-term cost savings on fuel imports and improve their balance of trade. In the United States, the federal government has announced a proposal to enlarge the market share of zero-emission transportation to 50% by 2030, echoing the global push toward cleaner mobility solutions. According to a report by Bloomberg, electric vehicles are projected to account for 30% of all new car sales by 2030, a remarkable increase from just 3% in 2020[13], [14]. Nonetheless, it is widely recognized that electric vehicle charging can lead to abrupt spikes in instantaneous power requirements. The presence of a substantial number of electric vehicles necessitates meticulous planning within the electrical sector to ensure that future electricity requirements can be fulfilled without jeopardizing the stability of the power system and its economic sustainability. The charging behaviors of electric vehicles, coupled with the durability of the charging infrastructure, significantly impact peak power consumption, which, in turn, influences investment strategies within the energy industry. This situation implies that the distribution network could experience a wide range of severe adverse effects due to the increased demands generated by EVs. These effects may vary based on different factors, including electric vehicle battery characteristics, driving behaviors, fleet charging profiles, trip distances, and the implemented demand response strategies [16]. Heightened demand introduced by electric vehicles at the distribution network level may lead to voltage drops and exert excessive stress on transformers and power cables, ultimately risking the reliability and efficiency of the power supply. To address these challenges, it is imperative for utilities and policymakers to collaborate and develop comprehensive strategies that not only encourage the adoption of EVs but also ensure the electrical grid can support this transition. Enhanced infrastructure, smart grid technology, and proactive demand management techniques will be crucial in mitigating the impact of increased electric vehicle integration on power systems. By integrating innovative solutions, the transition to electric vehicles can be executed in a manner that maximizes environmental benefits while maintaining an efficient and stable energy supply. Minimizing energy losses, optimizing power distribution within the network, and maximizing the efficient use of generation capacity are crucial considerations in modern energy management. Furthermore, load response mechanisms can enhance system reliability. The careful implementation of these programs can significantly compensate for the limitations of generation and transmission capacity during peak demand periods [15][16]. Conversely, in emergencies or when the system's reserve levels are low, consumer participation becomes invaluable in preventing excessive flow and maintaining system availability. In fact, the voluntary participation of consumers in balancing generation and consumption during emergencies is generally more cost-effective and appropriate than implementing mandatory power cuts on their demand [17]. One practical method to facilitate this is the application of multi-time tariffs. This approach establishes that the cost of energy consumption during peak hours is higher than during off-peak hours, thereby encouraging subscribers to shift their load to reduce energy consumption costs. In this context, reference [18] presents a strategy for controlling the charging and discharging of electric vehicles (EVs) to function as responsive loads, while also considering the economic benefits associated with utilizing their batteries. Additionally, reference [19] introduces a distributed framework for implementing demand response programs, demonstrating that information regarding energy tariff rates can be instrumental in modifying peak loads. As long as the capacity of controllable loads remains low, the use of time-varying tariff rates is somewhat effective. However, with the increasing participation of electric vehicles, subscribers gain enhanced flexibility to alter their consumption patterns. In this scenario, the management of flexible load participation to harness their potential for improving power quality indicators warrants comprehensive study. In other words, evaluating the behavior of electric vehicles, their capacity, and power consumption is essential to determine the quality of this participation, particularly given their substantial potential for involvement in load response programs. For instance, it is projected that the electric energy consumption of plug-in hybrid vehicles will account for up to 5% of total energy consumption in Belgium by 2030[20]. If the electric range of these vehicles is increased to 60 miles (100 km), their energy consumption could rise to 8%. Traditional vehicles with internal combustion engines contribute significantly to greenhouse gas emissions and environmental pollutants, such as nitrogen oxides [21]. Although the current sales of electric vehicles may not be economically justified due to factors such as battery performance, maintenance costs, and technical challenges, a different future can be envisioned with the implementation of incentive policies by governments. Such policies could stimulate demand for electric vehicles, fostering a transition to cleaner transportation options.

Furthermore, while the adoption of electric vehicles is a primary solution to the environmental challenges posed by conventional vehicles, from the perspective of distribution network operators, the management of power consumption during battery charging is essential to prevent the overloading of transformers and network feeders. The widespread integration of electric vehicles into the power grid introduces substantial electrical loads, which may lead to serious disruptions in the utilization of distribution network capacity. To address these challenges, smart scheduling methods can facilitate the seamless integration of electric vehicles into the power grid without necessitating significant structural changes. By employing smart home controllers, electric vehicle charging intervals can be optimized based on consumer preferences and energy tariff rates. This approach ensures that common costs are reduced while preventing additional load from being introduced into the network during peak hours. Moreover, the implementation of smart grid technologies can further enhance the efficiency of electric vehicle integration. These technologies enable real-time monitoring and management of energy flows, allowing for more responsive adjustments to changing demand patterns. Additionally, the use of vehicle-to-grid (V2G) systems can empower electric vehicles to discharge energy back into the grid during peak periods, thereby providing additional support to the power system and enhancing overall grid reliability. In conclusion, the transition to electric vehicles presents both opportunities and challenges for the energy sector. By optimizing load response mechanisms, implementing multi-time tariffs, and utilizing smart scheduling techniques, it is possible to manage the integration of electric vehicles effectively. This not only enhances system reliability and efficiency but also contributes to the broader goals of reducing greenhouse gas emissions and promoting sustainable energy practices. Several researchers have studied the implementation of load response schemes and have designed various objective functions, such as minimizing energy costs for household subscribers or maximizing their welfare levels to achieve a flat electric load profile based on dynamic pricing. In reference [22], Garcia and Rad employed a linear programming approach to model the optimal management of charging and discharging for electric vehicles. This study also investigated multi-time and step-wise tariff rates, highlighting their impact on consumer behavior. Similarly, the authors in reference [23] utilized a convex programming method to evaluate the implementation of load response strategies for controllable electrical equipment within residential households. Furthermore, Bradley and Davis [19] introduced a novel decision-making approach to assess the effects of multi-temporal tariffs on electric vehicle charging patterns. Despite these advancements, a comprehensive study has yet to be conducted that plans for consumers' electric vehicle charging while considering their satisfaction levels and modeling consumers' elastic behavior in response to changes in tariff rates. This gap in the literature underscores the need for more nuanced research that integrates consumer preferences with load response strategies. In this context, the most significant contributions of the present paper can be articulated as follows:

1) Development of a comprehensive framework for planning electric vehicle charging that prioritizes consumer satisfaction.
2) Analysis of consumer elasticity in relation to varying tariff rates, providing insights into behavioral responses.

This study involves comparing the amount of energy consumed and the costs associated with charging electric vehicles under two modes: normal and planned. The analysis is conducted across three different scenarios, specifically focusing on penetration rates of 15%, 40%, and 75%. Additionally, the research includes a mathematical modeling of subscribers' elasticity in response to changes in the two-time tariff rates. It also considers varying elasticity coefficients for different types of residential and industrial loads. Furthermore, the satisfaction coefficient is incorporated to enhance subscriber welfare, which helps determine the optimal charging times for electric vehicles. This approach aims to improve reliability and sustainability while reducing emissions.

In this paper, a standard IEEE distribution network consisting of 20 buses was utilized, which closely resembles a segment of an island distribution network in the United States. In this network, each bus, with the exception of buses 4 and 5, accommodates 70 residential houses, resulting in a total of 250 electric vehicles considered for the entire distribution network, as illustrated in Figure 1. The load data is derived from reports published by the American Institute of Electrical Engineers, specifically focusing on winter days, as shown in Table 1 [24]. In 2010, it was reported that 29% of home heating systems in the United States were powered by electricity. This transition to electric heating is significant in understanding the overall energy demands on the distribution network. According to reference [25], in a residential house equipped with an electric heating system, the average electricity consumption ranges between 1.1 and 1.4 kW. Conversely, the average consumption of other subscribers is approximately 0.6 to 1 kW. These figures underscore the increasing demand placed on the electric grid during winter months, particularly as more households turn to electrical heating solutions. The integration of electric vehicles into this network further complicates load management, necessitating careful planning and optimization of the distribution system to ensure reliability and sustainability.

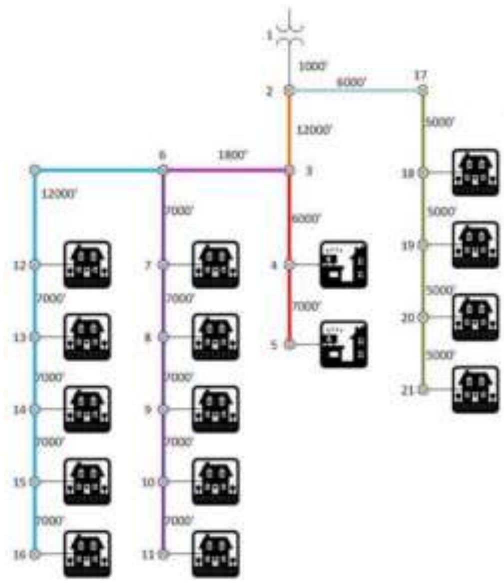

Figure 1: structure distribution network

Table 1: Maximum power consumption per hour in the distribution network structure

Hours	Load (MW)	Hours	Load (MW)	Hours	Load (MW)
1	65	9	105	17	120
2	60	10	111	18	125
3	59	11	115	19	110
4	56	12	110	20	130
5	58	13	100	21	135
6	65	14	108	22	135
7	77	15	121	23	120
8	85	16	112	24	115

Minimizing the cost of energy consumption and the waiting time for charging electric vehicles (1) is a primary objective of this study. The first and second terms in this equation represent the costs associated with energy consumption by household appliances during peak and off-peak hours, respectively. These terms are crucial for understanding how time-of-use pricing impacts consumer behavior and energy costs. The third term is a linear function that models the consumer satisfaction coefficient associated with initiating the electric vehicle charging process. This coefficient reflects the importance of user experience in the charging process. In this context, the waiting time for electric vehicle charging is defined according to equation (2):

$$F = \min \sum_{t \in p} (EC^t - SD).tar_p^t + \sum_{t \in np} (EC^t + SD).tar_{np}^t + \sum_{EV \in N} (1 + \lambda w^{EV}).L_{EV}^t.tar^t \tag{1}$$

$$W^{EV} = t - t_0^{EV} \tag{2}$$

The expected time to initiate the electric vehicle (EV) charging process is set for 18:00. Consequently, the waiting vector (W) is calculated and presented in Table (2) for reference.

Table 2: Waiting vector for charging the studied electric vehicle

$\mathbf{W^{EV}}$	0	1	2
T	18	19	20

The determination of tariff rates reflects consumers' responses to the variations in rates between peak and off-peak hours. In this project, this elastic behavior is mathematically modeled using equations (3) and (4) specifically for peak and off-peak periods, respectively, enabling a detailed analysis of consumer engagement and energy consumption patterns based on pricing.

$$SD_{(j)} - \left(\frac{1}{1+e^{-a_{(j,p)}\left(\mathrm{T\,a\,r}_{cons(j,p)} - \mathrm{Tf}\right)}} - 0.5\right) SD_{(j)}^{max} = 0 \tag{3}$$

$$SD_{(j)} - \left(\frac{1}{1+e^{-a_{(j,np)}\left(\mathrm{T\,a\,r}_{cons(j,np)} - \mathrm{Tf}\right)}} - 0.5\right) SD_{(j)}^{max} = 0 \tag{4}$$

The charging of an electric vehicle is subject to specific limitations and cannot exceed a predetermined value. Equation (6) illustrates that if the vehicle is not present in the parking lot, the charging rate is effectively zero. This condition emphasizes the importance of vehicle availability for optimizing the charging process.

$$0 \le L_t^{EV} \le q_{rated}^{EV} \quad , \quad t \in [t_0^{EV}, t_1^{EV}] \tag{5}$$

$$L_t^{EV} = 0 \quad , \quad t \in T \setminus [t_0^{EV}, t_1^{EV}] \tag{6}$$

The genetic algorithm has successfully determined the optimal values for the movable loads in accordance with the two-time tariff rate structure. Table (3) presents the elasticity coefficients that have been considered for various types of subscribers. As illustrated, five distinct consumer categories have been employed in this modeling framework, four of which pertain to residential consumers, while the fifth category is dedicated to industrial users. This differentiation allows for a nuanced analysis of load response behavior across different consumer segments.

Table 3: Price Elasticity Coefficients for Various Types of Subscribers

Type	Bus No.	$\mathbf{a_p}$(**kWh/$**)	(**kWh/$**)$\mathbf{a_{np}}$
Res.1	12-13-14-15-16	7	-25.5
Res.2	7-8-9-10-11	5	-24
Res.3	18-19-20-21-22-23	5.5	-24.5
Res.4	24-25-26	6	-26
Ind. 1	4-5	7	-27

2. Discussions

Scenario 1: 15% In this segment, 20% of the residential homes in the network have an electric vehicle (a total of 500 electric vehicles). The result obtained in this case is shown in Figure 2.

Scenario 2 :40% In this scenario, 40% of subscribers own an electric vehicle. Figure (3) shows the amount of power consumed. In this situation, more than 35% of charging costs are reduced.

Scenario 3: In this scenario, 75% of consumers own an electric vehicle. Figure (4) .shows the amount of power transferred.

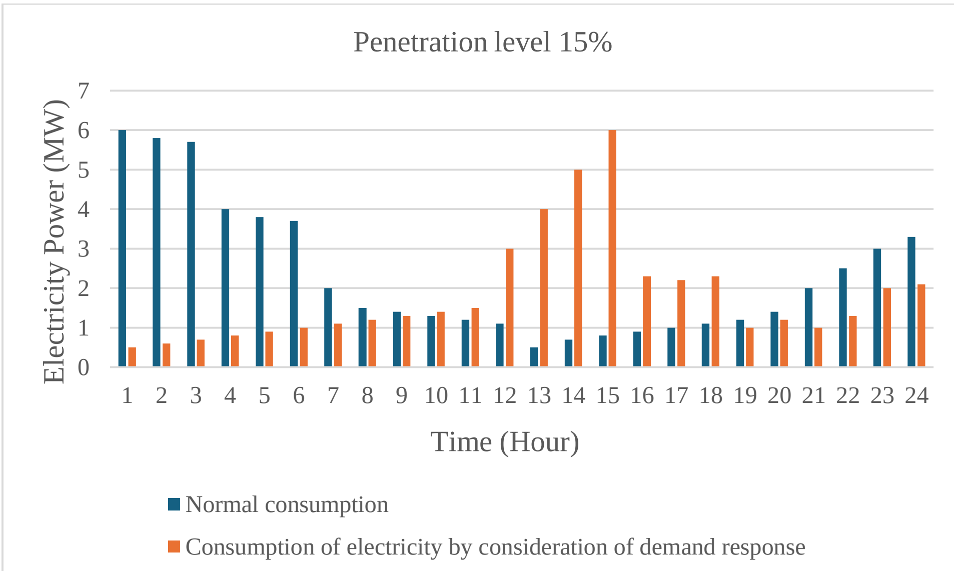

Figure 2: Comparison of energy consumption (penetration level: 15%)

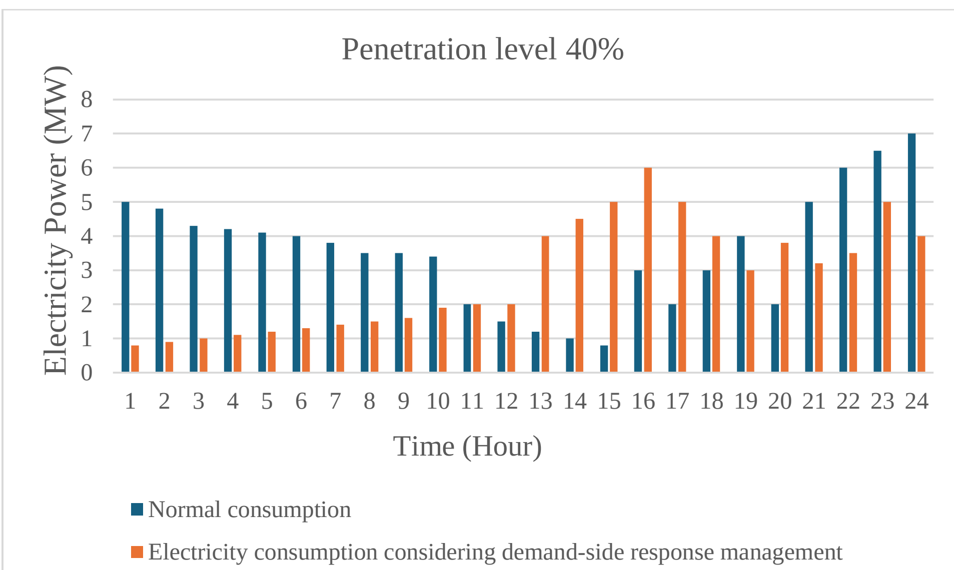

Figure 3: Comparison of energy consumption (penetration level: 40%)

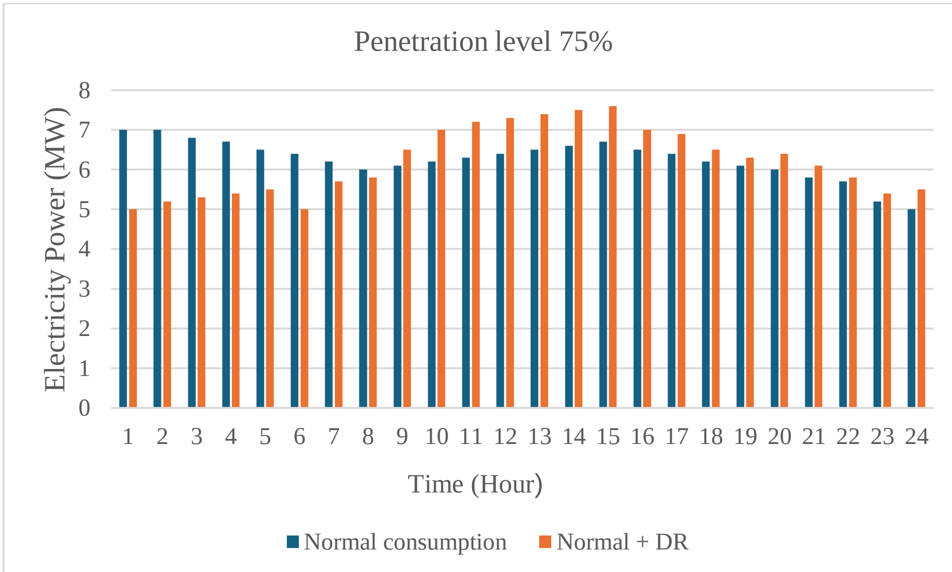

Figure 4: Comparison of energy consumption (penetration level: 75%)

A comparison of various levels of electric vehicle penetration reveals a significant reduction in energy costs for subscribers as the penetration percentage increases. According to the results obtained, at penetration percentages of 15%, 40%, and 75%, the cost of charging with scheduling is consistently higher than the cost of charging without scheduling. While this may initially seem counterintuitive, the use of scheduled charging offers substantial benefits, including cost reductions for subscribers and improved operational efficiency for electricity companies. Such scheduling enables utilities to better manage demand, thereby enhancing the stability of the electrical grid. Consequently, the integration of electric vehicles through scheduled charging practices can significantly contribute to overall network resilience. Detailed results supporting these findings are presented in Table (4).

Table 4: Charging Cost at Different Levels of Penetration Percentage

Penetration Percentage (%)	Scheduling Type	Charging Cost ($)	Total Cost ($)
15	With Scheduling	23460	36060
	Without Scheduling	12600	
40	With Scheduling	42060	68522
	Without Scheduling	26462	
75	With Scheduling	59842	98583
	Without Scheduling	38741	

The data presented in the table illustrate the impact of scheduling on the charging costs and total costs associated with electric vehicle (EV) charging across three distinct penetration percentages: 15%, 40%, and 75%. At a penetration percentage of 15%, charging costs with scheduling amount to $23,460, while without scheduling, they are significantly lower at $12,600. This trend continues as penetration increases to 40%, where scheduled charging costs rise to $42,060 compared to $26,462 without scheduling, emphasizing how scheduled charging may accommodate larger energy loads and potentially higher costs. When penetration reaches 75%, the difference becomes even more pronounced, with scheduled charging costs soaring to $59,842, while unscheduled costs rise to

$38,741. The total costs, incorporating both charging costs and other associated expenses, are notably higher when scheduling is utilized, highlighting the complexity and potential benefits of managing energy loads effectively. The increased costs associated with scheduling at higher penetration levels suggest that while scheduling aids in managing demand, it may also lead to elevated operational expenses. Therefore, this analysis indicates a trade-off between the advantages of organized charging processes and the overall costs, necessitating careful consideration in future planning and implementation of electric vehicle charging infrastructure.

3. Conclusion

In traditional power networks, the generating capacity of power plants must be increased to meet maximum demand levels. However, in the restructured environment of smart distribution networks, a portion of the demand capacity can be managed effectively. By shifting the load to off-peak hours during critical periods, network congestion can be alleviated, and the required generation capacity can be significantly reduced. This innovative approach is particularly vital as peak load times in the network do not follow a strictly defined schedule. Therefore, it is essential to design consumption management plans with the necessary flexibility to adapt to varying demand patterns. In this paper, we introduce a novel approach to energy management in residential buildings that not only reduces energy costs by shifting consumption loads from peak to off-peak hours but also enhances consumer comfort. This is achieved by defining an index known as the satisfaction level specifically for electric vehicle (EV) owners. This index measures the level of comfort and satisfaction that consumers experience when participating in load management schedules, ensuring that their needs are taken into account. To evaluate the load response capacity, we utilized a 20-bus IEEE standard network comprising 3,500 branches and accommodating a maximum of 2,500 electric vehicles. By implementing a demand pull model with a two-time tariff rate, we studied the effects of electric vehicle charging at penetration levels of 15%, 40%, and 75%. The genetic algorithm was employed to optimize the scheduling and management of these loads. According to the results obtained from this analysis, it was determined that by designating 28% of the load capacity as the response capacity, energy bill costs could be reduced by an impressive 36%. The penetration of electric vehicles in the distribution network presents both significant challenges and opportunities. By considering responsive load and implementing effective demand response strategies, utilities can manage the impact of EVs on their infrastructure more effectively. This approach not only enhances grid stability but also aligns with broader environmental goals by promoting cleaner energy usage. Furthermore, comprehensive planning and collaboration among stakeholders are essential for optimizing EV integration while ensuring a resilient and efficient distribution network. It is crucial to foster collaboration between utility operators, policymakers, and EV manufacturers to create a cohesive strategy for managing load impacts. This collaborative approach can facilitate the development of innovative solutions that address the unique challenges posed by the increasing presence of electric vehicles in our electricity distribution networks. In conclusion, this assessment underscores the need for a proactive approach to managing the growing integration of electric vehicles. By leveraging advanced energy management strategies and fostering stakeholder collaboration, we can create a sustainable and efficient energy ecosystem that benefits consumers and utilities alike. This proactive stance will not only help in managing the complexities associated with electric vehicle charging but also contribute to the overall stability and sustainability of our energy systems. As we move forward, it is imperative to continue exploring new technologies and strategies that can further enhance the integration of electric vehicles into the existing power infrastructure, ensuring a cleaner and more reliable energy future for all.

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