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Exploring the Sustainability Impact of Fuzzy Logic Replacement Models in Bus Charging Systems

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The innovative replacement models of fuzzy logic in electric bus charging can enhance the efficiency and environmental advantages of electric public transportation systems. This study examines the utilization of fuzzy logic models to enhance charging schedules, battery management, and energy consumption in electric buses. The integration of such a model reduces energy waste, enhances battery longevity, and decreases greenhouse gas emissions that could otherwise pollute the clean urban environment. Fuzzy logic-based solutions achieve adaptability across many operational situations and real-time data, thus providing a more responsive and efficient charging infrastructure. This progressive strategy enables the implementation of sustainable urban mobility while concurrently enhancing economic returns through reductions in operational expenses and an extended lifespan for electric buses. Optimal expression is achieved by balancing power demand across grid, commercial, and residential activities, without allocating places for idle charging. Results indicate that vehicle categorization comprises 20% routine and 80% non-routine, hence demonstrating the system's prioritization of charging requirements. The power variation data verifies the grid's suitability for the system, enabling it to meet fluctuating demands with peak levels of 475 kW during the day, down to 418 kW at night.

Keywords: Fuzzy Logic, Electric Vehicle, Energy Wastage, Electric Bus Charging, Battery Management.

1. Introduction

Growing concerns about greenhouse gas emissions, impacts of global warming, and reliance on fossil fuels have driven the transportation sector to adopt Electric Vehicles (EVs). The industry is rapidly shifting towards an extensive use of EVs, covering both Battery Electric Vehicles (BEVs) and Plug-in Hybrid Electric Vehicles (PHEVs). Hybrid vehicles, such as the Prius, utilize energy from both the internal combustion engine and the electric battery. Furthermore, they can be recharged by an external power source and the onboard engine generator [1]. However, BEVs rely exclusively on electric batteries that require recharging from external power sources [2]. As both BEVs and PHEVs depend entirely on power infrastructure for charging, a substantial share of energy demand in transportation would move from fossil fuels to renewable energy sources [3].

EVs could not attain much popularity in the market initially at the beginning of the 20th century due to their high price and slow speed. However, this scenario has changed with the advancement in the 21st century as well as technological developments and rising environmental concerns as the desire for low-priced, high-speed, zero-emission, and long-range EVs is continuously increasing. Despite these improvements, one of the biggest challenges in India is the absence of sufficient charging infrastructure that prevents the diffusion of EVs [4]. A variety of approaches, such as pulse charging, Constant Power Mode (CPM), Constant Voltage Mode (CVM), and Constant Current Mode (CCM), can be used with EVs. Shorter charging periods and better control over the maximum battery voltage are some of the benefits that have been associated with the hybrid technique, which integrates CCM and CVM in charging Li-ion batteries in electric vehicles [5]. The use of such model has gained popularity in the discharge of EVs. One well-known example of a cyber-physical system is an EV charging network, which consists of hundreds of dispersed EVs and aggregators in charge of data management and charging regulation [6]. These modern sensing and communication technologies allow energy management systems to extract data from both the energy consumer as well as the power grid with high efficiency [7].

Fuzzy logic, established in 1965, is essential for enhancing the sustainability of electric bus charging systems via a flexible decision-making approach. This is due to the ability to generate intermediate values between common binary evaluations, such as true/false or high/low, which enables the usage of fuzzy logic to be more adept to uncertain conditions as it applies to electric bus charging [8]. Fuzzy logic is based on the concept of fuzzy sets, where X is the input space, and x represents its elements. A membership function, represented as μA(x), maps items to a value between 0 and 1, indicating the degree of membership of x in fuzzy set A. It can be expressed as:

$$A = \{x, \mu_A(x) \mid x \in X\} \qquad (1)$$

Consequently, the charging process of electric buses can be optimized by fuzzy logic models, leading to higher energy efficiency and superior load management with reduced battery degradation. This technique enhanced the sustainability of electric bus operations by decreasing energy usage, increasing battery lifespan, and minimizing emissions [9, 10].

The objective of this study is to improve the operational aspects of EV charging stations with a particular focus on the optimization of space allocation. The study addressed the challenges related to charging control using fuzzy logic functions, where information like arrival time, departure timings, and State of Charge (SoC) supplied by electric vehicle owners is essential to address scheduling in extensive parking facilities. EVs are categorized into regular usage and irregular usage to ensure that the system can adequately assist with the charging demands. The power grid, distribution infrastructure, baseload management, Distribution System Operators (DSOs), and communication networks are all vital elements that are required for the effective administration of EV charging.

The remaining parts of this work are structured as follows: Section 2 reviews the previous research on investigating the impact of fuzzy logic replacement model in EV bus charging.

Section 3 outlines the proposed approach used for this study. Section 4 presents the results, accompanied by a brief explanation to enhance understanding.

2. Related Work

This section presents a comprehensive review of related studies by various authors focused on the Sustainable impact of fuzzy logic replacement model in EV bus charging.

Ahmadi et al. (2023) [11] introduced a novel multi-objective optimization framework for Electric Vehicle Smart Charging (EVSC) with the Dynamic Hunting Leadership (DHL) approach. The findings illustrated that under certain operational constraints, this algorithm could effectively address trade-off requirements and improve the voltage distribution of the grid.

Du et al. (2023) [12] implemented an advanced Particle Swarm Optimization (PSO) method for optimal optimization of charging strategies for EVs. A PSO algorithm is employed to demonstrate the systematic charging method. The proposed systematic charging method lowered both charging costs and the disparity between peaks and troughs.

Raj et al., (2021) [13] implemented a solar-powered lithium-ion battery charging system that employed a Battery Management System (BMS) using fuzzy logic. The design and development were conducted on the MATLAB/Simulink platform to enhance the system's performance. The findings indicated that the proposed BMS attained an overall accuracy of 95.1%.

Hussain et al. (2020) [14] proposed a Fuzzy Logic Weight-Based Charging Scheme (FLWCS) to improve the Quality of Experience (QoE) via fuzzy logic. The research enhanced service quality for FLWSC concerning First-Come, First-Served queuing methodologies.

Chen et al. (2019) [15] created a decentralized infrastructure for EVs that run on FLC for charging and discharging. The findings showed that the average level of charge, random delay charging, and instantaneous charging systems were all less successful than the FLC strategy.

Park et al. (2019) [16] created an EV scheduling method that utilized fuzzy logic to enhance charging network performance. Based on simulations, it was found that the scheduling method enhanced smart charging networks.

Nienhueser et al. (2016) [17] investigated the benefits of using renewable energy sources to charge EVs at public Electric Vehicle Service Equipment (EVSE) from an environmental and financial standpoint. The findings suggested that charging using renewable energy might result in 433% rise in the usage of charging stations.

UI-Haq et al. (2015) [18] investigated the impact of EV charging stations on voltage imbalance in urban distribution networks. The findings indicated that an uneven EV charging scenario can generate voltage imbalances beyond the permissible 2% level.

3. Proposed Methodology

This section presents the structure of the proposed gradient rule-based fuzzy system.

System Model of Gradient Rule-Based Fuzzy Logic

A gradient rule-based fuzzy system is presented including the salient feature of the power grid, power distribution, and communication networks. The power grid deals with the generation of energy from nuclear and fossil fuel plants and sends it to DSOs through a High Voltage (HV) network. Then the Distribution System Operator (DSO) changes HV into Medium Voltage (MV) in some transforming stations and supplies the energy to business and habitation places. The low-voltage network supports Baseload (BL) for essential needs like lighting and air conditioning, as well as the Parking Lot (PL) load for EV charging. In a smart PL scenario, the study examines a PL where each parking space has a Charging Station (CS) with a J1772 connector for EVs, providing level 2 charging with 19.2 kWh of energy. A PL controller manages the system using gradient-based fuzzy logic, divided into three components, ensuring efficient overall operation [19].

- Data Aggregation And Charging Station Allocation.

EV owners must furnish the parking lot driver with necessary data upon their arrival, including their SoC, arrival time, and departure time. Upon initial processing of the data, any available CS is assigned to the just-arrived EV [20].

- Fuzzy Logic Controller

The issue of charging scheduling addressed in this study pertains to a substantial public parking lot where the simultaneous charging of all EVs during the current time slot would result in a significant charging burden. Electrical vehicles are divided into routine and non-routine categories according to the owner's behaviour. The daily commute consists of EVs travelling from their residences to their workplaces, with EVs also parked during duty hours. EVs that are not routine may be parked for extended or brief periods, contingent upon the nature of their owners' engagements, including visits to retail malls, movie theatres, medical appointments, or social gatherings. In the fuzzy logic controller, the operational data of EVs and the present condition of the power grid are crucial, depending on the kinds of EVs present in the parking lot [21].

- Charging Control And Power Distribution

It is feasible to manage the volume of charging operations and distribute electricity to the most appropriate EVs by employing the weight values obtained from the fuzzy inference mechanism, which are adjusted according to the power grid condition and electric car data. For consideration during the subsequent scheduling period, the updated state of charge (power utilization) of each EV and the current condition of the CSs are measured and reported.

- Proposed Algorithm

Step 1. Initialize each variable that the algorithm needs to perform computations. It requires the initialization of the charging capacity of the jth station, the number of charging stations, and the initial and maximal simulation times.

Step 2. Check for the new arrival of electrical bus users in the current slot time. The algorithm checks any of the new arrivals of the EV_i and the availability of a parking spot at a charging station.

Where t is the current slot time of the EV_i bus user.

EV_i: is the ith electrical vehicle bus user.

$$Spot_{ij} = \begin{cases} 1; & \text{if spot is available at charging station j} \\ 0; & \text{otherwise} \end{cases} \quad (2)$$

Where $Spot_{ij}$ is the availability of a parking spot at charging station j.

If a spot is located, then the new EV user should be registered, and their information should be stored at the charging station. After that, indicate that the charging station is in use.

Step 3. Calculate E_{demand}, AP and N_{EV}.

Where E_{demand}: Total Energy demand of the EV bus users, P: Available power on the jth charging station, N_{EV}: Total Number of EV bus users.

Step 4. After calculating the energy demand, check

$$E_{demand} > AP \quad (3)$$

then follow step 5.

where E_{demand} is the energy demand of the EV_i user and AP are the available power on the jth charging station.

Step 5. A fuzzy logic controller is activated when the energy demand exceeds the available power supply. The fuzzy logic controller initially entails the generation of the W_{EV} by calculating the W_{EVi} for each ith EV, based on the input data through the established fuzzy inference system. After calculating the weight, sort the vector of EVs in non-decreasing order according to the weight list.

Where W_{EV} is the weight vector of Evs, W_{EVi} is the weight vector of ith EV, N_{EV} is the sorted vector of EVs based on W_{EV}.

The proposed gradient fuzzy rule-based logic involves the concept of FCFS (first come, first serve) and the logic of left charging capacity. W_{EVi} of the ith EVs user. The algorithm takes the left charging of the ith EVs in the sorted vector. W_{EVi} Which provides from low to high charging capacity. The fuzzy inferences system takes the charging capacity as the input and applies the FCFS algorithm and priority scheduling logic. The FCFS algorithm used a concept of Queue data structure to track the record of the ith EVs owner to serve the concept of first come and first serve.

FCFS (W_{EVi}): First come, first serve.

The mathematical form of the priority scheduling algorithm is given below.

$$W_{EVi} \leq 30\% \quad (4)$$

and ith EVs user come first it would serve first. The proposed gradient fuzzy-based algorithm utilizes this concept of priority scheduling and decides to provide charging services for EV vehicles.

4. Results And Discussion

This section presents and discusses the study's results in detail.

Figure 1 represents a Mamdani-type fuzzy logic control system for EV charging with three inputs (SoC, Arrival Time, and Departure Time), one output (Charging Control), and four fuzzy logic rules. This system uses fuzzy logic to make decisions about charging control, providing an effective way to manage EV charging stations.

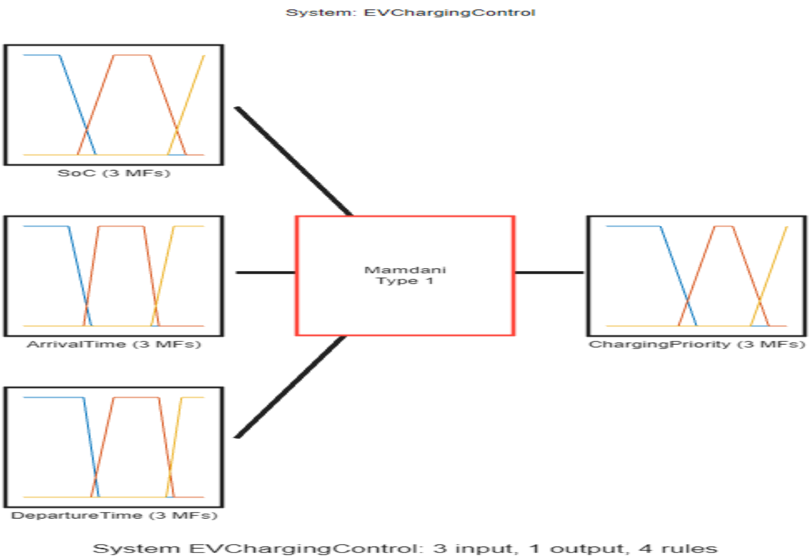

Figure 1. Fuzzy Logic Control System

Figure 2 illustrates the inference process in a fuzzy logic control system for EV charging, showing how input values affect the MFs and the application of fuzzy rules. Let's break down the components and explain the inference rules:

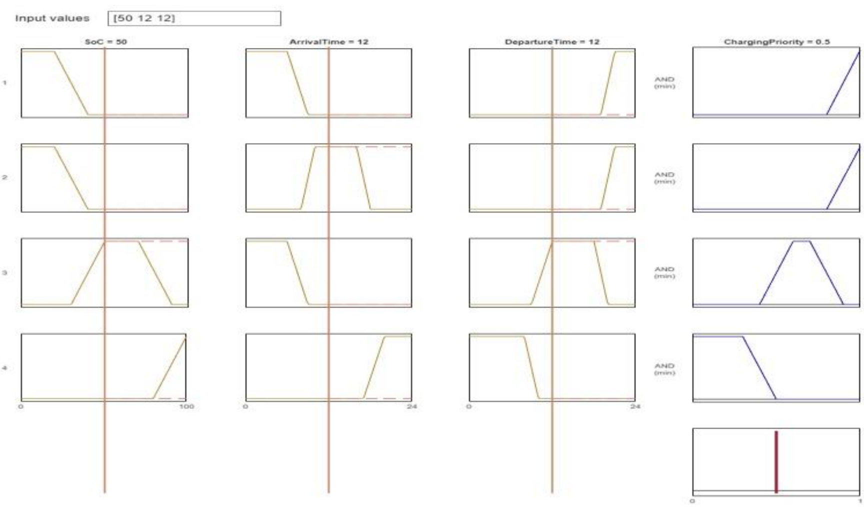

Figure 2. Inference rules for fuzzy logic control system

Based on the FCFS principle and considering the SoC, arrival, and departure times, vehicles are prioritized for charging (see Table 1). Routine vehicles are generally given higher priority, especially those arriving early and with lower SoC. Non-routine vehicles are prioritized based on their SoC and arrival times, with lower SoC and earlier arrivals being more urgent. The fuzzy logic system ensures an efficient and fair allocation of charging resources, optimizing the charging process and reducing wait times.

Table 1. Classification of vehicles using fuzzy logic system.

SoC	Arrival Time (in hours)	Departure Time (in hours)	Category
20	8	18	Routine
50	9	17	Non-Routine
30	7	19	Routine
40	10	20	Non-Routine
70	6	15	Non-Routine
80	12	22	Non-Routine
10	14	23	Non-Routine
60	16	18	Non-Routine
90	13	24	Non-Routine
25	11	21	Non-Routine

Figure 3 shows the variation of power (kW) across the grid, commercial and residential areas within 24 hours duration with power consideration starting from 6 AM. It shows that the grid power is always greater than the energy demand from commercial and residential areas, which is necessary to efficiently supply electricity to the EV parking units for meeting the charging needs. It also shows the voltage and current variation across the grid over the 24-hour duration with higher energy demand during daylight in comparison to nighttime.

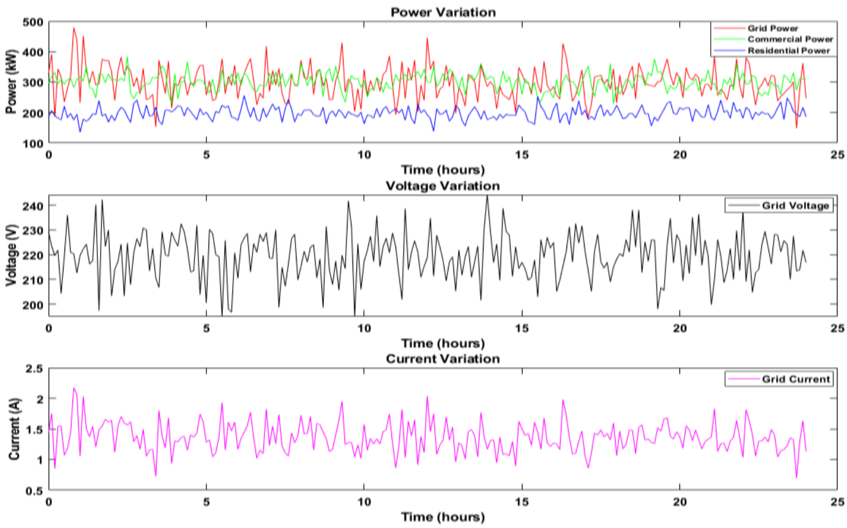

Figure 3. Power, voltage and current variation for Grid, Commercial and residential areas.

Figure 4 depicts the power consumption of a communication network over 24 hours, with power consideration starting from 6 AM. The x-axis represents time (in hrs), and the y-axis represents power usage in kilowatts (in kW). The graph reveals that the network's power consumption isn't constant throughout the day. It shows a trend of higher power consumption during daylight hours (between 12 PM and 9 PM) which lowers slightly during midnight.

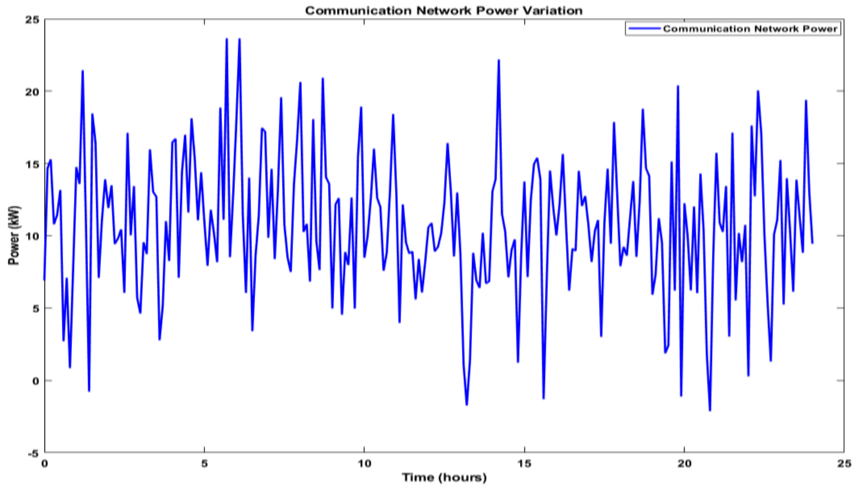

Figure 4. Communication Network Power consumption

Figure 5 depicts the power consumption taking place in EV parking units over 24 hours, with power consideration starting from 6 AM. The x-axis denotes time (in hours), while the y-axis indicates power consumption in kilowatts (in kW). The graph reveals that the EV parking power consumption isn't constant throughout the day. It shows a trend of higher power consumption during daylight hours (between 6 AM and 12 PM) as the EVs are engaged in working and transportation, which demands for charging decreases from 12 PM to 8 PM and again rises in the night time as more time is available for charging EVs while at rest.

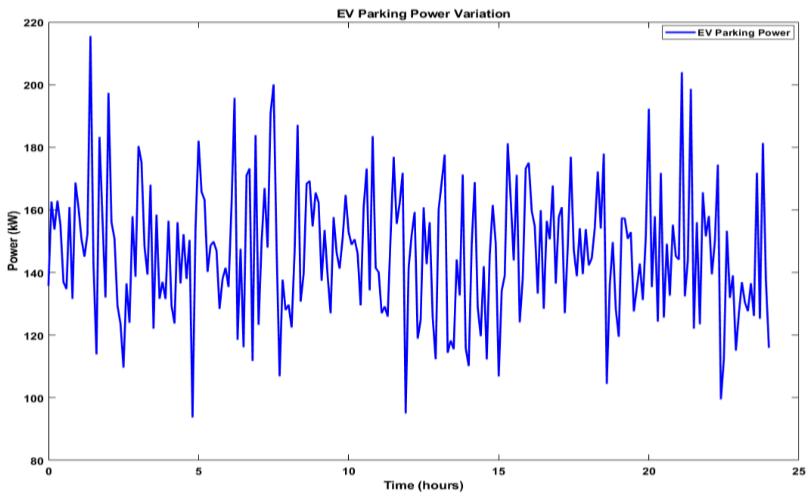

Figure 5. EV Parking Power Variation

Figure 6 shows the comparison between occupied and vacant spaces of EV charging for optimal allocation of free charging space after the application of a gradient rule-based fuzzy system. It shows that all the 10 EVs are properly placed, and no vacant space is left for charging depicting optimal resource and space allocation.

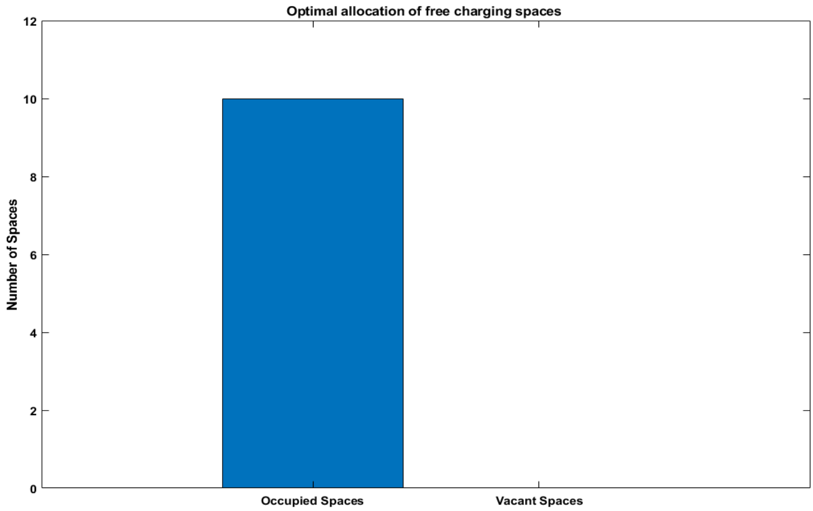

Figure 6. Optimal allocation of free charging space

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References

1. Geng, B.; Mills, J.K.; Sun, D. Two-stage energy management control of fuel cell plug-in hybrid electric vehicles considering fuel cell longevity. IEEE Trans. Veh. Technol. 2011, 61, 498–508.
2. Chan, C.C. The state of the art of electric, hybrid, and fuel cell vehicles. Proc. IEEE 2007, 95, 704–718.
3. Geng, B.; Mills, J.K.; Sun, D. Two-stage charging strategy for plug-in electric vehicles at the residential transformer level. IEEE Trans. Smart Grid 2013, 4, 1442–1452.
4. Hemavathi, S., and A. Shinisha. "A study on trends and developments in electric vehicle charging technologies." Journal of Energy Storage 52 (2022): 105013.
5. J. Y. Yong, V. K. Ramachandaramurthy, K. M. Tan, and N. Mithulananthan, "Bi-directional electric vehicle fast charging station with novel reactive power compensation for voltage regulation," Int. J. Elec. Power, vol. 64, pp. 300–310, Jan. 2015.
6. J. Zhong, L. He, C. Li, Y. Cao, J. Wang, B. Fang, L. Zeng, and G. Xiao, "Coordinated control for large-scale EV charging facilities and energy storage devices participating in frequency regulation," Appl. Energy, vol. 123, pp. 253–262, Jun. 2014.
7. Jin, Chenrui, Jian Tang, and Prasanta Ghosh. "Optimizing electric vehicle charging: A customer's

perspective." IEEE Transactions on Vehicular Technology 62, no. 7 (2013): 2919-2927.
8. L.A. Zadeh, Fuzzy Sets, Information and Control, 1965
9. Hellmann, Martin. "Fuzzy logic introduction." Université de Rennes 1, no. 1 (2001).
10. Kazeminezhad, M. H., A. Etemad-Shahidi, and S. J. Mousavi. "Application of fuzzy inference system in the prediction of wave parameters." Ocean Engineering 32, no. 14-15 (2005): 1709-1725.
11. Ahmadi, Bahman, and Elham Shirazi. "A Heuristic-Driven Charging Strategy of Electric Vehicle for Grids with High EV Penetration." Energies 16, no. 19 (2023): 6959.
12. Du, Wenyi, Juan Ma, and Wanjun Yin. "Orderly charging strategy of electric vehicle based on improved PSO algorithm." Energy 271 (2023): 127088.
13. Raj, P. Justin, V. Vasan Prabhu, and K. Premkumar. "Fuzzy logic-based battery management system for solar-powered Li-Ion battery in electric vehicle applications." Journal of Circuits, Systems and Computers 30, no. 03 (2021): 2150043.
14. Hussain, Shahid, Mohamed A. Ahmed, Ki-Beom Lee, and Young-Chon Kim. "Fuzzy logic weight-based charging scheme for optimal distribution of charging power among electric vehicles in a parking lot." Energies 13, no. 12 (2020): 3119.
15. Chen, Lidan, and Bo Chen. "Fuzzy logic-based electric vehicle charging management considering charging urgency." In 2019 IEEE Innovative Smart Grid Technologies-Asia (ISGT Asia), pp. 3441-3446. IEEE, 2019.
16. Park, Jinsol, Yujin Sim, Gangminh Lee, and Dong-Ho Cho. "A fuzzy logic-based electric vehicle scheduling in smart charging network." In 2019 16th IEEE Annual Consumer Communications & Networking Conference (CCNC), pp. 1-6. IEEE, 2019.
17. Nienhueser, Ian Andrew, and Yueming Qiu. "Economic and environmental impacts of providing renewable energy for electric vehicle charging–A choice experiment study." Applied Energy 180 (2016): 256-268.
18. Ul-Haq, Azhar, Carlo Cecati, Kai Strunz, and Ehsan Abbasi. "Impact of electric vehicle charging on voltage unbalance in an urban distribution network." Intelligent Industrial Systems 1 (2015): 51-60.
19. Hussain, Shahid, Mohamed A. Ahmed, Ki-Beom Lee, and Young-Chon Kim. "Fuzzy logic weight-based charging scheme for optimal distribution of charging power among electric vehicles in a parking lot." Energies 13, no. 12 (2020): 3119.
20. Nijhuis, M.; Gibescu, M.; Cobben, J. Valuation of measurement data for low voltage network expansion planning. Electr. Power Syst. Res. 2017, 151, 59–67.
21. Yagcitekin, B.; Uzunoglu, M. A double-layer smart charging strategy of electric vehicles taking routing and charge scheduling into account. Appl. Energy 2016, 167, 407–419.