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Energy Management Of Grid-Connected/Islanded Microgrid Integrated With Electric Vehicles

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Microgrids, which are small energy networks that may function in either grid-connected or islanded modes, have proliferated in response to the growing need for clean, dependable, and decentralized energy systems. One potential way to improve microgrids' energy flexibility, storage capacity, and system resilience is to include electric vehicles (EVs). For the purpose of microgrid power management when electric vehicles are installed, this study suggests a charging/discharging algorithm. By optimizing the usage of solar (PV) electricity and using EVs as energy storage systems (ESSs), while minimizing the maintenance cost and grid reliance, MG is optimized using a multi-objective approach. Our method takes into account both the base load and the PV power generation simultaneously for power management, which helps to reduce imbalances between the two and maximize the value of EV discharging power. Compared to conventional EV scheduling and no scheduling at all, the suggested EV scheduling method considerably reduces power expenditures, according to simulation findings based on a 90-EV parking station. The approach also improves the use of renewable energy sources while decreasing grid stress during peak loads, which helps smart energy systems remain sustainable from an economic and environmental perspective.

Keywords: Electric vehicle, Microgrid, Power management, Energy cost, Charging/discharging.

I. INTRODUCTION

The global energy sector is undergoing significant transformation due to several disruptive technologies and the imperative to save the environment. Significant advancements encompass the rapid ascent of electric mobility, the expansion of smart grid technology, and the extensive use of renewable energy sources (RES) such as solar photovoltaic (PV) and wind energy. Microgrids are pivotal to this transformation. They are compact, intelligent energy systems capable of operating alone (islanded) or in conjunction with the primary utility grid (grid-connected). An increasing number of individuals perceive microgrids as a sustainable, decentralized solution to address the rising demand for power and the urgent necessity to reduce carbon emissions. Electric vehicles (EVs) are increasingly favored not just for their environmental benefits but also as versatile, transportable energy storage assets that may enhance the adaptability and resilience of microgrids in response to fluctuating conditions.

The integration of electric vehicles into microgrids synergizes the energy and mobility sectors, yielding mutual advantages. Electric vehicles (EVs) utilize electricity as a load while charging, although they may also function as distributed energy resources (DERs) using technologies such as vehicle-to-grid (V2G) and vehicle-to-home/building (V2H/V2B). This enables them to return stored energy to the grid or supply it to local need. This bidirectional energy exchange alters our perspective on energy management. It enables electric vehicles (EVs) to maintain grid stability, support critical loads during outages, and enhance the overall efficiency of the energy system for both the economy and the environment. Overseeing the intricacies of a hybrid system, particularly in microgrids that must transition seamlessly between grid-connected and islanded modes, is challenging. It necessitates sophisticated energy management systems (EMS) that include technological constraints, user behavior, and economic variables.

When a microgrid is interconnected with the grid, it collaborates with the central utility system to import or export power as required. This mode offers advantages such as enhanced reliability, support for ancillary services, and financial savings through energy trading and demand-side management. For instance, during periods of elevated demand or peak pricing, the microgrid may supply power from its renewable sources or electric vehicle batteries to the grid. This generates revenue and alleviates the burden on centralized infrastructure. In islanded mode, the microgrid is restricted to utilizing its own generation, storage, and load balancing capabilities. This frequently occurs in remote areas disconnected from the grid or during grid outages due to maintenance, natural disasters, or system failures. Transitioning between these two operational modes, referred to as mode switching, requires meticulous control to maintain voltage and frequency stability, particularly in the presence of dynamic and unforeseen variables such as renewable energy sources and electric vehicle operations.

Incorporating electric vehicles into an already intricate infrastructure further exacerbates its complexity. Electric vehicles are difficult to predict due to their reliance on user behavior, which fluctuates based on charging and discharging patterns. They may function as loads when charging and as energy sources during discharging, indicating they possess two distinct forms of value. Participation in energy exchanges is contingent upon the appropriate state of charge (SoC), battery health, user choices, energy pricing, and grid conditions. To effectively manage energy in microgrids including electric cars, it is essential to coordinate scheduling, implement optimal dispatch mechanisms, and utilize real-time management algorithms that can adjust to fluctuations in supply and demand while maintaining system stability and cost efficiency.

By enabling electric vehicles (EVs) to actively participate in microgrid operations, technologies such as V2G and V2H/V2B facilitate their more comprehensive integration. V2G enables electric cars to perform beneficial functions such as maintaining frequency stability, sustaining voltage levels, reducing peak demand, and providing backup power during grid outages. Smart charging systems provide flexibility by regulating the timing and speed of electric car charging in accordance with grid conditions, renewable energy supply, and fluctuating price signals. For example, during periods of high solar power generation, electric vehicles may be charged to accumulate surplus energy. During periods of elevated demand, they may be released to help equilibrate the load. The unpredictability of renewable energy supply and the erratic behavior of EV users create significant ambiguity. To address these issues, we must employ robust forecasting instruments, predictive analytics, and adaptive control systems capable of managing uncertainty and optimizing energy flows in real time.

The increasing utilization of renewable energy sources in microgrids amplifies the demand for effective energy management. Although solar and wind energy are environmentally beneficial and abundant, they are not consistently accessible and cannot be dispatched on demand. To mitigate fluctuations and provide a consistent power supply, the integration of energy storage systems (ESS), including stationary batteries and electric vehicle batteries, is essential. Consequently, the EMS must synchronize the operation of renewables, storage systems, and EVs to ensure optimal generation, storage, and utilization of energy. This entails considering several elements, including state of charge limitations, battery deterioration rates, user timetables, renewable energy generation forecasts, and power pricing.

Advancements in digital technologies, like as the Internet of Things (IoT), artificial intelligence (AI), and improved communication protocols, are facilitating the development of next-generation smart microgrids. These systems are equipped with sensors, actuators, and data analytics platforms that enable real-time monitoring, control, and optimization. Local controllers may independently manage distributed energy resources (DERs) and electric vehicles (EVs) within hierarchical and decentralized control frameworks, collaborating with higher-level supervisory systems. This process is referred to as dispersed decision-making. AI-driven techniques like as machine learning and reinforcement learning are increasingly employed for load prediction, generation forecasting, and optimum energy dispatch. Simultaneously, blockchain technology and transactive energy models provide secure and efficient energy trading among individuals, enabling compensation for utilizing grid services. However, these novel concepts also introduce challenges related to interoperability, data privacy, and cybersecurity, particularly in geographically dispersed regions with diverse populations.

The integration of electric vehicles with microgrids will significantly influence the economy, society, and the environment. It reduces greenhouse gas emissions by facilitating the use of sustainable energy and substituting fossil-fuel-based mobility. It can benefit the economy by reducing expenses, postponing infrastructure initiatives, and generating new revenue streams through engagement in associated markets. It enhances energy equity and resilience, particularly in regions that are underserved or prone to calamities. For utility operators and regulators, the simultaneous management of electric vehicles (EVs) and distributed energy resources (DERs) facilitates demand-side flexibility, reduces dependence on centralized systems, and enhances grid resilience against disturbances.

However, several issues must be addressed prior to the construction of grid-connected or islanded microgrids including electric vehicles. Elevated expenses, ambiguous regulations, a deficiency in standardized communication protocols, and uncertainty over the operation and charging of electric vehicles continue to hinder their adoption. The accuracy of real-time data, the accessibility of historical data for algorithm training, and the computing efficiency of optimization models are crucial for the success of EMS systems. To overcome these challenges, power systems engineers, control theorists, data scientists, urban planners, and policymakers must collaborate across disciplines. Public engagement and education are equally essential. Users must comprehend and employ these tools responsibly.

Incorporating electric vehicles (EVs) into microgrids, irrespective of their connection to the grid, represents a significant advancement for modern energy systems. It demonstrates the effective synergy between localized renewable energy generation and sustainable mobility. To maximize the benefits of this integration, it is essential to develop intelligent, flexible, and robust energy management frameworks capable of addressing the many challenges arising from unpredictability, uncertainty, and user behavior. As governments strive for a future devoid of carbon emissions, the integration of electric vehicles (EVs) with microgrids is essential for the advancement of sustainable, resilient, and efficient power networks in the 21st century.

II. REVIEW OF LITERATURE

Raya-Armenta, J. et al., (2022) For off-grid systems and distant places, island microgrids (IMGs) offer a sustainable and dependable energy source. Operating IMGs efficiently, reliably, robustly, resiliently, and self-sufficiently is no easy feat; it requires coordinating a wide range of distributed energy supplies and loads, many of which are intermittent in nature. Regarding this, IMGs' energy management systems (EMS) have been getting a lot of attention recently, particularly from an economic and emissions perspective. This study summarizes the state of the art in the EMS optimization problem for IMGs by methodically reviewing the leading research in the field. The current state of the art is that there are six primary components necessary for optimizing IMG energy management: design, time-frame, uncertainty handling strategy, optimizer, goal function, and constraints. There includes an in-depth analysis of each of these factors, as well as a current and future trends overview of the EMSs for IMGs. The following are some of the upcoming trends: better models, more sophisticated data analytics and forecasting methods, evaluation of real-time EMS performance across the entire MG control hierarchy, completely functional decentralized EMSs, enhanced cyber security and communication systems, and validations in real-world settings. Also included are detailed descriptions of the most popular heuristic optimization approaches, how they are applied to IMG EMSs, and the pros and cons of each. With any luck, this study will serve as a springboard for other investigations on how to enhance the EMS of IMGs.

Bagheri-Sanjareh, Mehrdad et al., (2020) In order to keep the demand-supply balance in the Micrgorid (MG) island operation, it is crucial to establish an energy storage system (ESS). In this article, the demand-supply balance in a residential MG is continuously maintained using lithium-ion batteries (LIBs), which are among the most popular ESS technologies for grid-based applications. A new energy management method that is based on frequency is suggested for this objective. During peak-load periods, a LIB ESS is used to regulate energy and frequency, while microturbines and fuel cells, which are dispatchable distributed generators, provide the base load. A large portion of the home load profile is accounted for by the air-conditioning TCLs, particularly in the middle of summer. Thermal energy storage systems

(TESSs) have the ability to store thermal energy for later use, in contrast to TCLs that immediately employ the thermal energy they create to regulate interior temperatures. Reducing power usage of a home Microgrid (MG) in islanded mode is achieved in this article by using TESSs instead of TCLs. Doing so reduces the necessary LIBESSs capacity by 70% compared to using TCLs for interior temperature management. There is a 63.7 percent drop in the overall cost of thermal and electrical storage when TESSs are used in place of ACs and EHPs.

Manandhar, Ujjal et al., (2019) DC-coupled microgrids are straightforward since they do not necessitate synchronization when incorporating various distributed energy sources. Nonetheless, the regulation and energy management strategy between renewable energy sources and energy storage systems across various operational modes is a formidable challenge. This research proposes a novel energy management approach for grid-connected hybrid energy storage systems incorporating batteries and supercapacitors under various operating modes. The primary benefits of the proposed energy management system include efficient power distribution among various energy storage systems, expedited DC link voltage regulation in response to generation and load disturbances, dynamic power allocation between the battery and the grid contingent on the battery's state of charge, diminished charge/discharge rates of battery current during both steady-state and transient power fluctuations, enhanced power quality characteristics in the AC grid, and smooth transitions between operational modes. The efficacy of the suggested strategy is corroborated by both simulation and experimental investigations.

Singh, Shakti et al., (2018) The significant integration of renewable energy sources (RESs) in microgrids has resulted in several voltage-related challenges, including voltage swings within the power system. These variations can be regulated using power electronics (PE) interfaces with energy storage systems (ESSs). Nonetheless, the installation of traditional Energy Storage Systems is an expensive endeavor. Recent advancements in electric vehicle (EV) technology have positioned EVs as viable substitutes for conventional storage systems. This study offers an islanded microgrid linked with electric vehicles to enhance energy storage and provide voltage regulation support. A voltage controller utilizing an active power/voltage, or P/V droop characteristic has been developed to manage voltage by either injecting or extracting active power from the electric vehicle charging station. The requisite active power regulation is attained by the regulated charging and discharging of electric vehicles to concurrently meet the demands of the microgrid and the vehicles. A control method has been devised for the allocation of electricity among each electric vehicle, taking into account their specific charging and discharging needs. The proposed control system has been simulated on a microgrid, confirming that the controller improves the dependability and stability of the microgrid in question.

Khalid, M.S. et al., (2015) An imbalance in the load, as a result of more and more electric cars (EVs) on the road, can have negative effects on power quality (such as voltage deterioration) and, if not handled correctly, might cause equipment damage. In order to keep the power grid stable when operating in vehicle-to-grid mode, this article gives a comprehensive overview of energy supply and management together with load synchronization via EVs, which helps to preserve transient voltage stability. At many levels, the energy management system is taken into account, including residential and commercial building feeders, stand-alone EV parking lots, stand-alone PV, wind, and battery storage. To begin, we suggested an algorithm for energy management that would reduce the maximum power that electric vehicles might take from the microgrid's distributed energy resources, freeing up more power for devices that are short on power. During times of increased power prices, the cars with higher priority still need resources and may continue operating without interruption since the EVs negotiate according to their need, priority, and the available electrical resources. Reducing peak demand and increasing system efficiency are both aided by the movement of electrical resources from one load device to another. To further evaluate EVs' potential to deliver and store energy for the grid, we secondly suggested the transient voltage stability margin index (TVSMI). At the DIgSILENT Power factory, we model the controls and management of energy use.

Zhang, Mingrui & Chen, Jie. (2014) This study proposes a smart microgrid-based regional energy management system to address the impacts on the utility grid caused by the uncoordinated charging of electric cars (EVs) and battery swapping stations (BSS). The system would also include optimum operation methods for these systems. A management approach is developed using a price-incentive model to coordinate the charging of EVs and BSS in grid-connected mode, with the goal of minimizing the overall cost of EVs and maximizing the profit of BSS. In island mode, the electric vehicle's service fee is determined by its current battery charge using the fuzzy control approach, which is based on the power balance between renewable energy sources and loads. Optimizing the energy management and dispatch of EVs and BSS, in conjunction with interruptible-load scheduling, minimizes operating cost and maximizes the advantage of islanded microgrid. In A Modeling Language for Mathematical Programming, the primary optimization issues are expressed as two separate problems: one that maximizes profits and one that minimizes costs. Results from real-world scenarios prove that the suggested methods for optimizing EV and BSS operations work. With the rapid growth of electric vehicles, this paper's methodology also offers suggestions for how a future smart grid could best accommodate these vehicles.

Jiang, Quanyuan et al., (2013) Microgrids operate in two modes: grid-connected mode and stand-alone mode. A microgrid often remains linked to the main grid for the bulk of its operation, functioning in grid-connected mode. In stand-alone mode, a microgrid operates independently from the main grid; its primary objective is to ensure a dependable power supply for consumers rather than to prioritize economic advantages. The aims and energy management tactics differ between the two regimes. This work proposes a unique double-layer coordinated control strategy for microgrid energy management, including a scheduling layer and a dispatch layer. The scheduling layer derives an economic operating strategy from forecasting data, and the dispatch layer allocates power from controllable units using real-time data. Discrepancies between forecasted and actual data are mitigated by the coordinated management of the two levels by conserving sufficient active power in the scheduling layer, then distributing that reserve in the dispatch layer to address the uncertainty of uncontrolled units. A standard microgrid configuration is examined as a case study, and simulation outcomes are provided to illustrate the efficacy of the proposed double-layer coordination control mechanism in both grid-connected and stand-alone modes.

III. SIMULATION SETUP

The goal of this paper's power management system for electric vehicles in residential parking garages is to reduce the grid-connected mode maintenance cost of the MG as much as possible. Data on the base load, PV power generation, SMP, and DR program are received by the MGCC. Using this data, we can learn how each EV is performing at any given moment.

Proposed Power Management for EV Parking Station

To mitigate negative impacts like capacity fades caused by intermittent charging and discharging, the charging and discharging switching functions are designed independently for each EV. Equation (1) defines the MG's base load and PV power generation, and each EV is assigned to the charging or discharging operation according to this comparison.

$$\begin{cases} O_{Ch}^{i,t} = +1 \text{ if } P_{load}^{t} - P_{PV}^{t} < P^{flag} \text{ and } SoC_{EV}^{i,t} < SoC_{max} \\ O_{Dch}^{i,t} = +1 \text{ if } P_{load}^{t} - P_{PV}^{t} \geq P^{flag} \text{ and } SoC_{EV}^{i,t} > SoC_{min} \end{cases} \quad (1)$$

Where $O_{Ch}^{i,t}$ and $O_{Dch}^{i,t}$ denote the switching functions of the i-th electric vehicle, representing charging and discharging operations, respectively, and P^{t}_{load} and P^{t}_{PV} signify the base load and photovoltaic power generation during the t-th time interval. The pflag denotes the flag parameter utilized to determine the duration for which electric vehicle (EV) charging or discharging is enabled, while $SoC^{i,t}_{EV}$ represents the state of charge (SoC) of the i-th EV, with SoC_{min} and SoC_{max} indicating the minimum and maximum permissible SoC for the i-th EV, respectively. In the suggested technique, if the disparity between the base load and PV power generation is less than P^{flag} and the EV's state of charge (SoC) is below SoC_{max}, then $O_{Ch}^{i,t}$ is assigned a value of +1 (indicating charging). If it exceeds P_{flag} and EV's SoC surpasses SoC_{min}, then $O_{Dch}^{i,t}$ is assigned a value of +1 (discharge).

Multi-objective optimization for power management of MG

1. Minimization of electricity cost

The primary objective function is to decrease the overall power expenditure of the microgrid. The power expense is diminished with the strategic timing of EV charging and discharging as outlined below:

$$\text{Electricity cost} = \pi_{grid}^{t} \times \left(P_{grid-load}^{t} \times O_{grid-load}^{t} + P_{grid-EV}^{t} \times O_{grid-EV}^{t}\right) + \pi_{PV}^{t} \times \left(P_{PV-load}^{t} \times O_{PV-load}^{t} + P_{PV-EV}^{t} \times O_{PV-EV}^{t} - \sum_{i=1}^{N} P_{Dch}^{i} \times O_{Dch}^{i,t}\right) \quad (2)$$

Where π^{t}_{grid} and π^{t}_{PV} represent the electricity rates from the utility grid and photovoltaic (PV) system, adhering to the demand response (DR) program and system marginal price (SMP), respectively. Furthermore, $P^{t}_{grid\text{-}load}$ and $P^{t}_{grid\text{-}EV}$ denote the electric power supplied to the base load and charging demand from the utility grid, respectively, while $P^{t}_{PV\text{-}load}$ and $P^{t}_{PV\text{-}EV}$ indicate the electric power provided to the base load and charging demand from the PV system, respectively. Additionally, $O^{t}_{grid\text{-}load}$, $O^{t}_{grid\text{-}EV}$, $O^{t}_{PV\text{-}load}$, and $O^{t}_{PV\text{-}EV}$ are the switching functions corresponding to Ptgrid-load, Ptgrid-EV, PtPV-load, and PtPV-EV, respectively. Lastly, P^i_{Ch} and P^i_{Dch} signify the charging and discharging power of the i-th electric vehicle (EV), respectively. The charging and discharging power of each electric vehicle is allocated based on the owner's information. The discharging power of the EVs is sold to KEPCO at the SMP rate, therefore reducing energy consumption from the utility grid.

2. Minimization of grid dependency

Minimizing grid power usage for both base load and EV charging load is the second objective function that is being examined. As the electrical system grows more unstable because to an excessive growth in grid power demand, the use of RESs becomes increasingly important. The following measures can be taken to reduce electricity consumption from the grid:

$$\text{Grid Power Consumption} = P^t_{grid-load} \times O^t_{grid-load} + P^t_{grid-EV} \times O^t_{grid-EV} \qquad (3)$$

3. Maximization of the PV power use

The PV system in the MG purchases power at the rate of SMP. It is possible to reduce the contribution of PV power to total load demand when the SMP exceeds the rate of the DR program. The following goal function can be used to make better use of PV electricity. Both the base load and the EV charging load consume PV electricity, which is included in this.

$$\text{PV power use} = -P^t_{PV-load} \times O^t_{PV-load} - P^t_{PV-EV} \times O^t_{PV-EV} \qquad (4)$$

IV. RESULTS AND DISCUSSION

It is expected that the electric vehicle parking station has a capacity of 90 electric vehicles. In addition, the daily base load as well as the PV power generation of the MG are depicted in Figure 1. The 'PV-system+proposed-EV-scheduling' approach is responsible for the use of power management in conjunction with the proposed EV scheduling. This method incorporates both the PV system and the EV discharging. In the 'PV-system+EV-scheduling' technique, power management is done in conjunction with a normal EV scheduling. This method incorporates a PV system, but it does not incorporate EV discharging. Within the framework of the 'no-PV-system+no-EV-scheduling' technique, the power management and EV scheduling are not implemented on the MG, and the PV system does not exist.

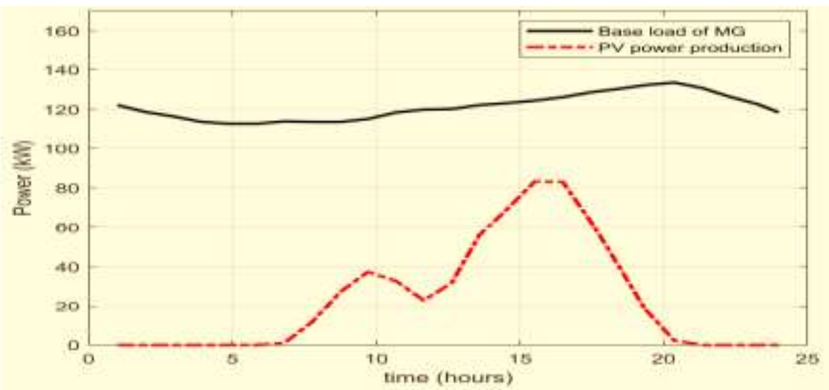

Figure 1: Temporal Changes in Base Load Demand and PV Power Production

Power management schemes affect grid power use, as seen in Figure 2. Since electric vehicles usually begin charging as soon as they are parked, the 'no- PV-system+no- EV-scheduling' technique shows high grid power demand without limits of maximum grid power usage between 0:00 and 5:00. Since EV charging is scheduled, the 'PV-system+EV-scheduling' and 'PV-system+proposed- EV-scheduling' methods result in lower grid power usage from 0:00 to 5:00. During the hours of 8:00-18:00, when PV power is generated, grid power usage reduces because the 'PV-system+EV-scheduling' and 'PV-system+proposed-EV-scheduling' methods allocate the bought PV power to the base load and EV charging load, respectively. The 'no-PV-system+no-EV-scheduling' technique uses less grid power between 19:00 and 23:00 hours since EV charging is done early on. In contrast, charging electric vehicles to their desired state of charge (SoC) between the hours of 19:00 and 23:00 using the "PV-system+proposed-EV-scheduling" approach results in increased grid power usage.

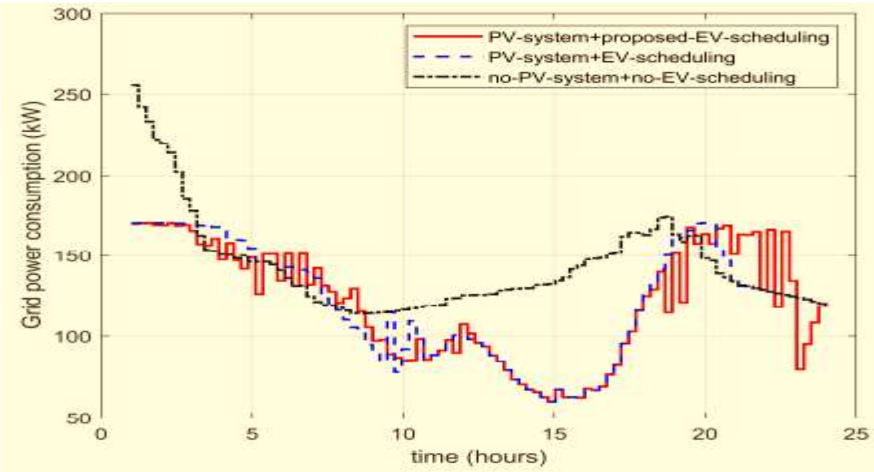

Figure 2: Impact of Power Management Strategies on Grid Electricity Usage

The residential parking station's EV charging and discharging load is depicted in Figure 3. To reduce the potential increase in grid power consumption caused by several EVs charging at once, the 'PV-system+proposed- EV-scheduling' technique schedules EV discharging to occur between the hours of 0:00 and 5:00. Although the base load is larger than other times, the most requests for EV charging occur between 18:00 and 24:00 hours. Active EV discharging happens throughout this time frame to reduce peak demand. Since EV discharging is not a part of the 'PV-system+EV-scheduling' technique, scheduling limits the need for charging loads. The 'no-PV-system+no-EV-scheduling' strategy results in a larger EV charging load from 0:00 to 3:00 hours since most parked EVs are charged independent of base load. Between the hours of 8:00 and 13:00, there is no electric vehicle charging demand at the parking station because it is situated in a residential neighborhood. In comparison to the 'PV-system+EV-scheduling' technique and the 'no-PV-system+no-EV-scheduling' approach, the 'PV-system+proposed-EV-scheduling' method decreases electricity costs by 6.7% and 18.14%, respectively.

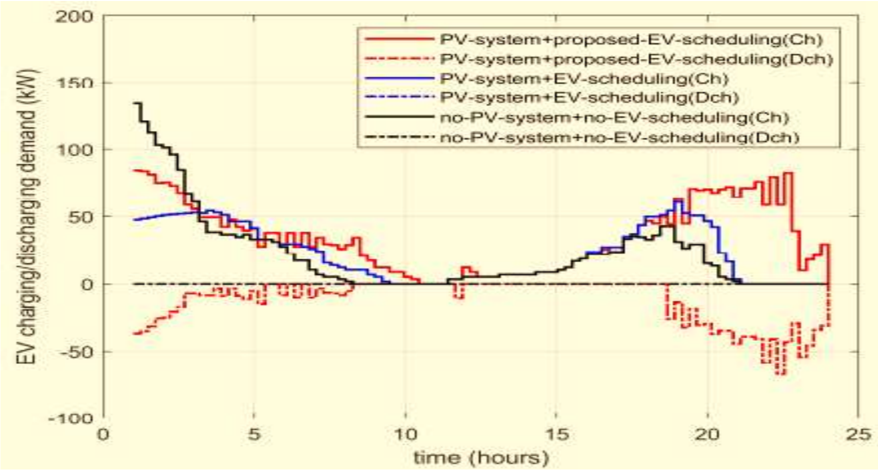

Figure 3: Temporal Distribution of EV Charging and Discharging Power Demand

V. CONCLUSION

An exciting new development in the field of grid-connected microgrid energy optimization is the power management framework that has been suggested for home EV parking stations. The system efficiently saves electricity costs, decreases reliance on the utility grid, and increases the use of renewable energy by intelligently scheduling EV charging and discharging operations based on real-time base load, PV generation, and market signals like SMP and DR programs. Electric vehicle (EV) battery life is extended and sustainable energy practices are supported by the implementation of a switching mechanism that guarantees efficient EV operation while protecting battery health. The suggested solution outperforms traditional scheduling methods in terms of cost savings and grid load reduction, as shown by the simulation results, which clearly verify its usefulness. Greener, more efficient, and more resilient energy ecosystems are the end goals of this strategy, which offers a strong and extensible answer for potential smart grid uses in the future.

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