Efficient Energy Management with Emphasis on EV Charging/Discharging Strategy

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ABSTRACT

Leveraging the Vehicle-to-Grid (V2G) concept, this research explores how a decentralized energy reserve from hybrid electric vehicles can enhance the power system, particularly in large-scale implementations. The study introduces a V2G solution designed for effective microgrid frequency control over a full day. Targeting a scenario with minimal usage, typically in spring or fall, the microgrid is scaled to represent a community of 2000 homes. This is exemplified by integrating 500 Electric Vehicles (EVs) based on a 1:4 vehicle-to-household ratio, reflecting a plausible future scenario. The research conducts a comprehensive examination of the microgrid's voltage, current, and active power. By synchronizing the management of diesel and Renewable Energy Source (RES) generation, power transactions, and EV generation, the microgrid's frequency is effectively regulated through V2G devices adjusting load demand. The implemented V2G-enriched microgrid demonstrates improved energy management and mitigates the inconsistencies and fluctuations inherent in RES power generation, showing notable performance enhancements. In various operational contexts, system parameter fluctuations have been analyzed, revealing that deviations are maintained below a 5% threshold.

Keywords-Vehicle-to-Grid (V2G); power system enhancement; energy management optimization; Renewable Energy Source (RES); microgrid

I. INTRODUCTION

EVs are increasingly recognized for their potential to address climate change. While they emit no greenhouse gases directly, their charging largely depends on an energy mix that includes fossil fuel-based power plants [1]. The energy consumed in EV manufacturing also factors into their overall CO_2 emissions. This dependence means the net CO2 reduction potential of EVs varies with the type of power generation, especially in coal-reliant systems [2]. Consequently, the integration of RESs alongside EVs is critical for genuinely diminishing CO_2 emissions. In line with this, the Saudi Standards, Metrology, and Quality Organization (SASO) introduced regulations for EV usage in January 2018, and by June 2020, the Saudi Press Agency confirmed the official approval for importing and using EVs as per these guidelines. Vision 2030 in Saudi Arabia includes an objective to "Reduce All Types of Pollution," aiming to decrease air pollution from various residential and industrial activities [3]. CO_2 emissions in Saudi Arabia have notably increased, rising from 200 million tons in 1996 to 600 million tons in 2014, with the transportation sector contributing 20% of this amount [4]. EVs, emitting zero direct emissions, are poised to play a significant role in reducing transportation emissions, thereby enhancing air quality and public health, and lessening environmental impacts. Research by KAPSARC has shown that realistic scenarios of EV integration could lead to a significant decrease in CO_2 emissions [4]. As Plug-in Hybrid Electric Vehicles (PHEV) increasingly integrate into the power grid, a potential rise in peak electricity demands is observed. However, PHEVs also present an opportunity for implementing energy storage and peak-shaving technologies.

The proliferation of EVs, while reducing oil consumption in transportation, leads to a surge in electricity demand for EV charging [5-6], increasing the daily load profile significantly, creating additional peak demands, intensifying existing peak loads, and escalating overall electricity requirements. A notable consequence of high EV penetration includes transformer overloads and distribution feeder congestions. Addressing these challenges, Demand Response (DR) strategies are employed in residential distribution networks to manage load effectively. This approach allows consumers to selectively control their loads, enhancing their comfort. A case study conducted in the Virginia Tech Electric Service area, considering varying levels and types of EVs along with diverse charging profiles, illustrates an increase in peak loads and potential violations of consumer comfort indices with increased EV penetration [7-8].

By 2030, it is expected that the EV fleet will grow by 10%, adding further strain to the electric system and necessitating increased power generation [9]. Projections indicate that global EV charging could demand about 2500 TWh of electricity by 2050 [10], with the National Renewable Energy Lab forecasting a 38% increase in electricity demand attributable to EVs by the same year [11-12]. In 2018, SASO established regulations for EV usage in Saudi Arabia [12-13] and in 2019, the Saudi Press Agency announced the official permission for EV importation and usage in the Kingdom as per these regulations. In 2021, Saudi Arabia launched its green initiative to combat the effects of climate change, including a project to increase Riyadh's EV presence to 30% of total vehicles [13-14].

The aim of this paper is to provide a detailed overview and simulation of an integrated microgrid system that incorporates V2G technology, specifically designed for a 24-hour MATLAB simulation catering to a community of 2000 households. It encompasses a diesel generator for reliable backup power, renewable energy contributions from wind and photovoltaic farms, and the innovative V2G system, which allows EVs to both draw from and contribute to the grid. The simulation showcases a modern energy management approach that leverages a mix of traditional and renewable sources, ensuring efficient power distribution and promoting energy independence. The system demonstrates the potential for localized energy production and consumption, aiming to reduce transmission losses and carbon footprint, while providing a resilient and flexible power network capable of adapting to varying load demands of residential and industrial consumers. This comprehensive microgrid model emphasizes advanced grid management and the integration of renewable energy sources, reflecting a progressive shift towards sustainable and self-sufficient energy ecosystems.

II. STRUCTURE OF THE PROPOSED V2G INTEGRATED MICROGRID SYSTEM

Figure 1 offers a concise overview of a projected microgrid system that integrates a V2G technology. This system is designed for simulation in MATLAB, focusing on a 24-hour operation. Key components include a diesel generator, a combination of photovoltaic (PV) and wind power sources, and the V2G setup. It is tailored for a community with 2000 households, with a significant emphasis on the integration of renewable energy sources and advanced grid management, ensuring balance and efficiency in power distribution and utilization. At the core, a Diesel Generator with a 15 MW capacity acts as the primary power source, flanked by a 8 MW PV farm and a 4.5 MW wind farm. The microgrid is designed to cater to both residential and industrial loads, with a substantial 10 MW allocated for residential consumption and 0.16 MVA for industrial use. In this energy ecosystem, the V2G component is dual-functional, contributing 4 MW as either an additional load or a power source, depending on the grid's demand. The system's energy balance is regulated through a phasor model operating at 60 Hz, ensuring a stable supply against the variable load demands over time, which is tracked by an integrated clock marking the simulation hours. The microgrid acts as a nexus point, distributing generated electricity to meet the demands of different load profiles, specifically residential and industrial loads. Residential load refers to the energy consumption by households, which typically includes lighting, heating, cooling, and electronics. On the other hand, the industrial load represents the power drawn by factories and industrial plants, which is generally significant and constant. At the forefront of this energy ecosystem is the V2G component, where EVs are depicted as both consumers and potential suppliers of energy. V2G technology allows for bidirectional energy flow, enabling not only the charging of the EVs, but also the provision of the stored energy back to the grid when needed, e.g. during peak demand or when the generation from other sources is low. This integrated system showcases a modern approach to energy management, where flexibility and sustainability are paramount. It leverages both traditional and renewable energy sources, alongside innovative technologies like V2G, to create a resilient and adaptive power network.

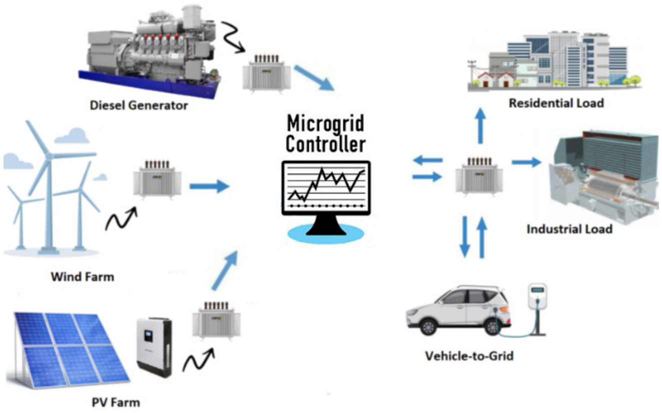

Fig. 1. Integrated microgrid system with V2G connectivity.

The infrastructure displayed in Figure 1 highlights the potential for localized energy production and consumption, minimizing transmission losses and promoting energy independence.

The flowchart in Figure 2 describes a process for managing V2G interactions, focusing on charge conditions and plug states. It differentiates between charging and regulation modes based on whether the cars are plugged in. For cars in the charge state, the V2G charging power is divided by the number of cars charging. For regulation, the V2G power is divided by the number of cars available for regulation. The plug state determines if a constant value is set to "1" (plugged in) or "0" (not plugged in), which affects the efficiency adjustments for discharging or charging. The State of Charge (SoC) is calculated by integrating the initial values, and based on this, the system either enters regulation or charge mode. This flowchart is instrumental in estimating the percentage state of charge for the vehicles in profile 1, optimizing the microgrid's performance.

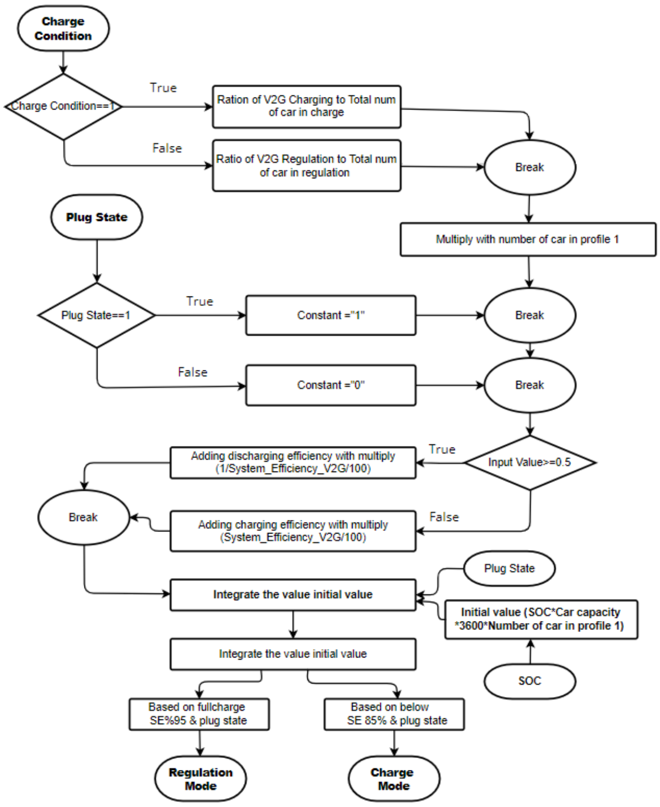

Fig. 2. Flowchart for V2G charge and regulation.

Figure 3 encapsulates the operation of V2G technology explored in this research, delineating its functional architecture. Central to managing the frequency of PHEVs is an aggregator that diligently oversees the EV network integrated with the grid. The potential for energy provision to this network hinges on the number of V2G-capable vehicles. Operators communicate with the aggregator, who then orchestrates the fleet's energy contribution, thus facilitating strategic capacity regulation and optimal bid selection. The V2G system, through its control unit, manages charging and discharging activities based on battery status and grid demands, with the Battery Management System (BMS) ensuring the battery's optimal SoC. Control mechanisms detailed in [20] underpin the study's operational analysis**.** The EVs' charging behavior is characterized using SoC and connection duration. Figure 3 delineates the methodology to discern EVs' charging or grid support engagement. Within the SoC control framework, dual constraints are applied to mitigate fluctuations caused by connection status and SoC at the onset. Figure 3 details the operational flow for V2G's charging and regulation actions. Notably, the charger control operates with distinctive criteria: it ceases charging beyond 95% SoC to maintain power quality and activates charging below 85% SOC, with the range in-between reserved for regulation activities.

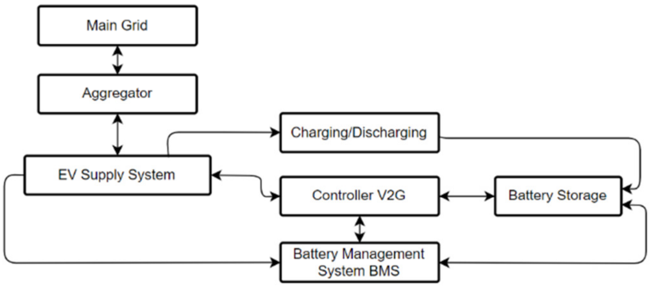

Fig. 3. V2G system operations.

III. RESULTS AND DISCUSSION

The simulation results were generated using Matlab/Simulink 2022 across a full day, totaling 86,400 s. The simulation adopted a variable step size and employed the Ode23tb solver, which is well-suited for stiff problems. This method effectively managed the complex behavior of a microgrid system comprising diverse power generation units, namely a diesel generator, a wind farm, a PV farm, and the bidirectional energy flows characteristic of V2G technology, in addition to meeting significant residential and industrial load demands. Figure 4 provides insight into the active power output of the PV RES throughout the day. It clearly illustrates the relationship between solar irradiance and power production, with a peak corresponding to the highest sun intensity. The graph presents a pronounced dip at around 12.1 hours, attributed to partial shading on the solar panels, effectively demonstrating the sensitivity of PV output to changes in solar conditions. This visualization serves as an effective tool for understanding the dynamics of solar energy contribution to the grid. Figure 5 presents the active power contribution of the wind farm to the electrical grid, with output levels fluctuating in tandem with wind speed variations. Higher wind speeds result in the wind turbines generating an increased amount of energy for grid supply. Conversely, a decline in wind speed leads to reduced capacity for active power transmission from the wind turbines to the grid. Therefore, wind speed variations are pivotal in determining the active power output from the wind generators.

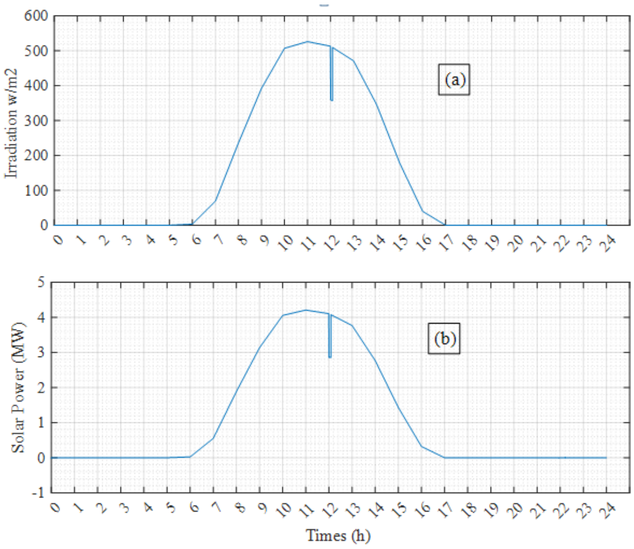

Fig. 4. PV power generator.

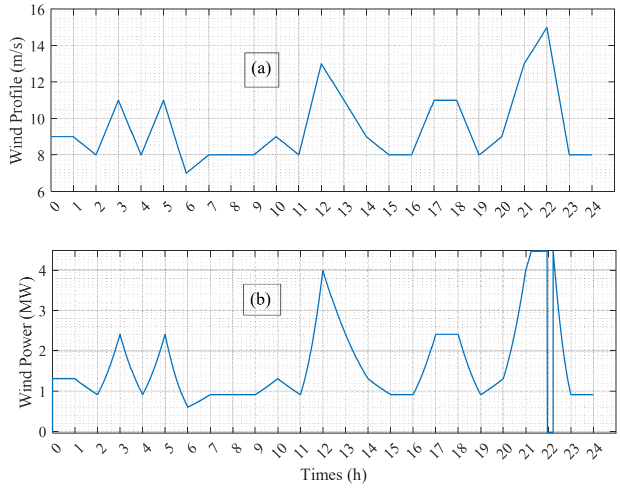

Fig. 5. Wind power generator.

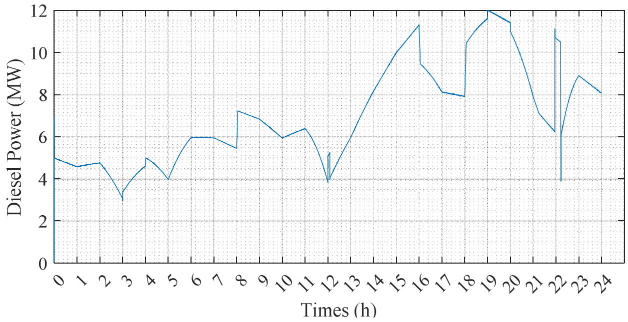

Fig. 6. Active power of the diesel generator.

Figure 6 illustrates the distribution of active power from the Diesel Generator to the grid. The active power output is contingent upon the generation levels from wind and PV farms, as well as the power transacted via the V2G system. Figure 7 depicts the active power consumption by the residential load from the microgrid. It is observed that the load draws active power ranging between 5 MW and 10 MW. Notably, there are significant variations in load demand during specific intervals (11.9 to 12.1 and 21.8 to 22.4), indicating periods of abrupt changes in power requirements. Figure 8 showcases the active power consumption of the Asynchronous Machine (ASM) from the grid. Upon activation, the ASM demonstrates a significant initial draw of active power, followed by a consistent consumption of 0.321 MW. Additionally, there are notable fluctuations in active power usage, particularly during the intervals of 11.9 to 12.1 hours and 21.9 to 22.3 hours.

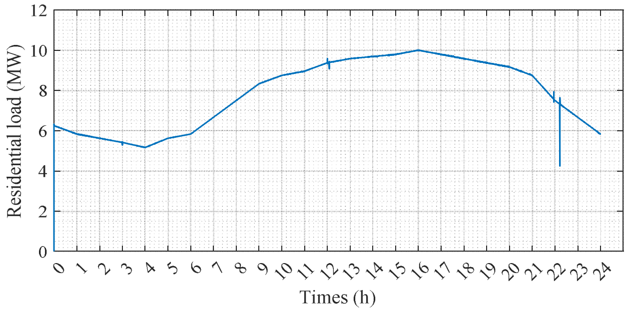

Fig. 7. Active power of residential load.

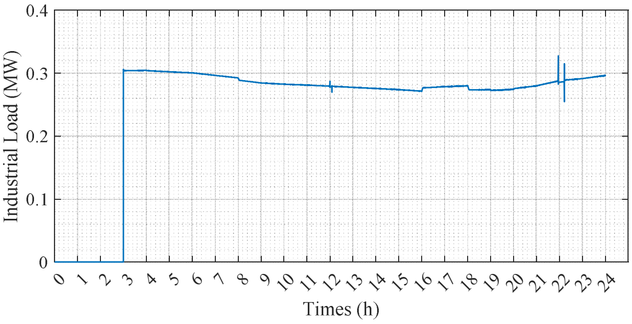

Fig. 8. Active power of industrial load.

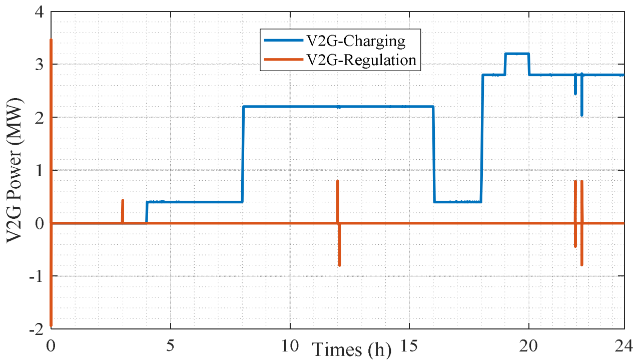

Fig. 9. Power flow characteristic of V2G.

Figure 9 illustrates the active power measurements during the charging and regulation mode of vehicles via the V2G system. Power consumption from the grid is denoted as negative, indicating that during four specific time periods, the batteries are utilizing grid power for charging. During the intervals of 11.9 to 12.1 hours and 21.9 to 22.3 hours, the vehicles are observed to draw reactive power from the grid for battery charging purposes. Figures 10 and 11 exhibit the microgrid's active and reactive power distributions. Figure 10 indicates the active power with a significant event at 22:00, where the total power sharply drops from around 10 MW due to the wind generation disconnecting, triggering the diesel generator to supply upwards 5 MW to compensate for the shortfall, highlighting the grid's adaptive response mechanisms. Figure 11 shows the reactive power fluctuating, peaking just above 6 MVar, which could suggest increased demand or decreased supply during peak solar hours, possibly due to partial shading.

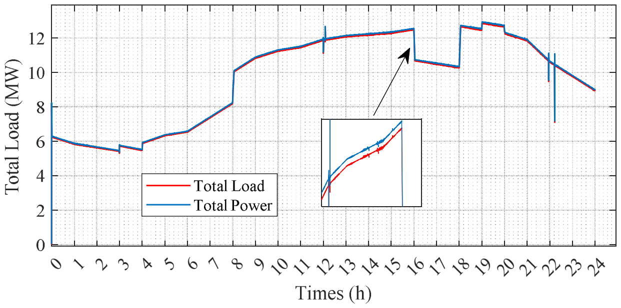

Fig. 10. Total power flow of the micro grid.

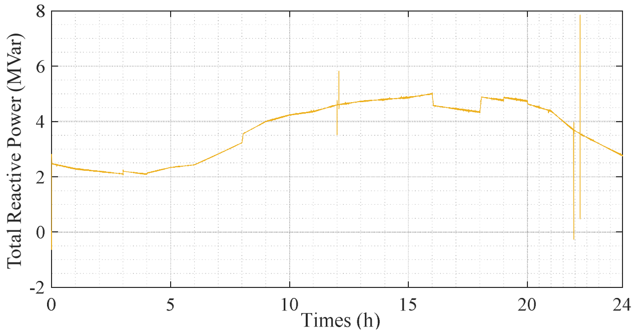

Fig. 11. Total power flow of the micro grid.

IV. CONCLUSION

This research significantly advances sustainable energy systems, showcasing an innovative microgrid model that integrates Vehicle-to-Grid (V2G) technology with traditional and renewable sources. It highlights the microgrid's capability in balancing energy through Matlab/Simulink simulations, under various conditions. The study emphasizes V2G's role in grid efficiency and stability, offering insights for future microgrid designs, especially in managing fluctuating renewable sources. Overall, it sets a foundational framework for integrated microgrids, pivotal in evolving energy management towards resilience and efficiency in the renewable energy era.

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