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# Optimizing Hybrid Smart Grids Through V2G: Bidirectional Power Flow for Improved Load Balancing and Stability

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***Abstract***— This research investigates the integration of Vehicle- to-Grid (V2G) technology into smart grids as a strategic approach to address the challenges posed by increasing renewable energy penetration. By utilizing electric vehicle (EV) batteries as decentralized, bidirectional storage units, V2G enhances grid stability, facilitates demand-side management, and optimizes renewable energy consumption. Through detailed simulation models, the study demonstrates how EVs can actively contribute to load balancing, frequency regulation, and smoothing the intermittency of wind and solar power sources. The findings highlight that large-scale deployment of V2G can significantly improve energy system resilience and efficiency while providing economic incentives for EV owners. Additionally, the research discusses critical technical, economic, and policy considerations necessary for successful implementation, emphasizing the importance of supportive regulatory frameworks, technological advancements, and consumer engagement. Overall, the results underscore V2G's promising role in advancing a sustainable and reliable energy future, leveraging the growing fleet of electric vehicles as a key asset in modern power systems.

**Keywords**— *Smart Grid, Vehicle-to-Grid (V2G), Renewable Energy, Load Balancing, Energy Storage.*

## I. INTRODUCTION

The modern electrical grid is facing unprecedented challenges driven by the escalation of energy demand, the integration of renewable energy sources, and the rise of electric vehicles (EVs). Globally, electricity consumption continues to grow at an exponential rate, propelled by expanding urbanization, technological proliferation, and increased reliance on electronic devices. In accordance with the International Energy Agency (IEA), global electricity demand is istemated to increase around 2.4% annually through 2040, signaling an urgent need for power systems that are more flexible, efficient, and sustainable [1].

Traditional power systems were originally designed for unidirectional energy flow—power generated centrally, transmitted over long distances, and delivered to consumers. Such systems are increasingly inadéquate given the variability of renewable resources, the emergence of prosumers, and the necessity for grid resilience against disruptions. Moreover, they exhibit inefficiencies, with approximately 8-10% of generated power lost during transmission and distribution [2]. These inefficiencies necessitate innovative approaches focused on energy quality, demand response, and decentralization.

To deal with these challenges, the concept of smart grids has gained prominence globally. Smart grids leverage advanced communication, automation, and information technologies to facilitate real-time monitoring, control, and optimization of electricity flows [3]. These grids support features such as distributed generation, demand-side management, and bidirectional energy flow,enabling a more resilient and efficient energy infrastructure (see Fig. 1).

One of the most promising advances in this field is Vehicle-to-Grid (V2G) technology. Electric vehicles, thanks to their large on-board energy storage capacity, can serve as mobile energy reservoirs contributing to the stability of the electrical grid. By systematically coordinating charge and discharge cycles, V2G systems can mitigate the variability of renewable energy, reduce consumption peaks, and provide ancillary services such as frequency regulation [4]. Vehicles typically remain stationary more than 95% of the time, representing a substantial and largely underutilized energy storage resource that could be harnessed to balance supply and demand [5].

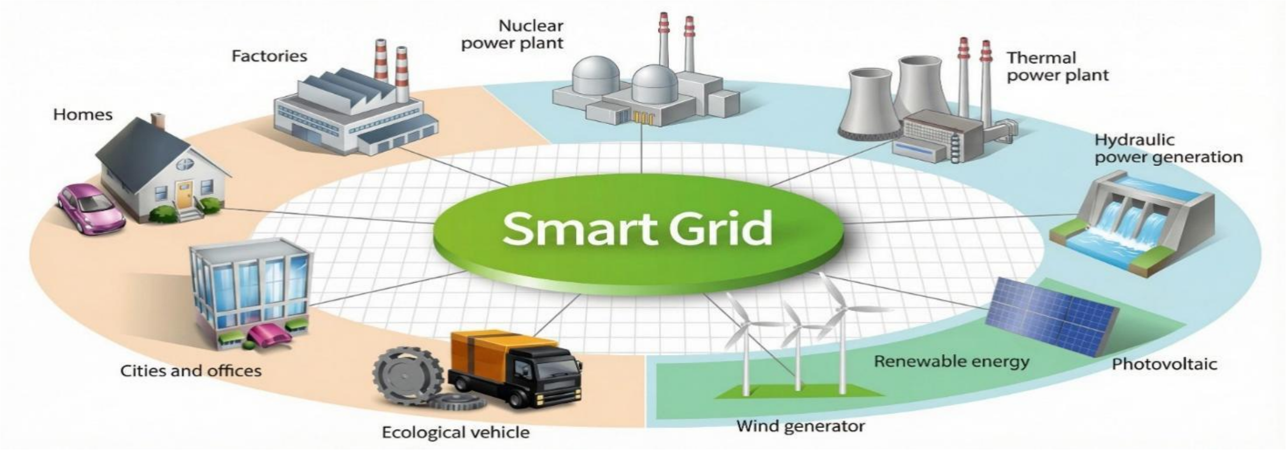

Fig.1. The architecture of Smart grid

Intégration V2G within smart grid architectures offers multiple benefits, including increased renewable energy utilization, reduced reliance on fossil fuel power plants, and economic incentives for EV owners. As the adoption of EVs accelerates—projected to reach 30% of new car sales globally by 2030 [6] —the potential for V2G to play a substantial role in energy management becomes critical.

However, integrating V2G systems faces several technical, economic, and regulatory challenges. Technical issues involve developing effective control algorithms, ensuring battery health, and managing grid stability. Economically, appropriate incentive mechanisms are required to motivate EV owners to participate actively in grid services. Regulatory frameworks need adaptation to support V2G markets and address cybersecurity concerns [7].

This research aims to develop comprehensive models of a hybrid smart grid integrating renewable energy sources (solar, wind), conventional generation, and EV-based energy storage through V2G technology. By simulating various operational scenarios, the study seeks to evaluate how V2G can contribute to grid stability, renewable energy integration, and demand-side management. Specific objectives include:

- Modeling the dynamic behavior of a small-scale hybrid smart grid incorporating renewable sources, conventional generators, and EVs with V2G capabilities.
- Analyzing the effectiveness of V2G in load leveling, peak demand reduction, and mitigating renewable intermittency.
- Assessing the economic feasibility and operational control strategies required for large-scale deployment.
- Identifying barriers to implementation and proposing policy frameworks to facilitate adoption.

The transition to smart grids aligns with global decarbonization goals established under agreements like the Paris accord. Countries are investing heavily in grid modernization; for instance, the European Union plans to allocate 20 billion toward smart grid development by 2030 [8]. The proliferation of EVs is orthogonally significant; the global EV stock surpassed 10 million units in 2022, with projections indicating exponential growth [9].

Research has demonstrated that V2G can enhance grid flexibility by providing ancillary services such as frequency regulation, voltage support, and congestion management [10]. Control strategies that optimize the charging/discharging schedule based on grid needs, market signals, and user preferences are actively being developed. These include predictive algorithms, game-theoretic approaches, and machine learning techniques tailored for real-time operation [11].

## II. METHODOLOGY

### A. System description

The study's system description involves modeling, simulating, and analyzing a microgrid that combines renewable energy sources with Vehicle-to-Grid (V2G) technology to improve load balancing and grid stability. The process begins with designing the system components such as a diesel generator (15 MW), photovoltaic (PV) arrays (8 MW), wind turbines (4.5 MW), and electric vehicles (EVs) equipped with bidirectional chargers— based on typical operating conditions and future projections. Using MATLAB/Simulink, a detailed mathematical and behavioral model is developed to capture the dynamic interactions among energy sources, storage, and loads over a 24-hour period, focusing on control strategies for EV charging/discharging based on grid frequency, electricity prices, and demand. The renewable energy components include:

#### 1) Photovoltaic (PV) system

A solar photovoltaic (PV) park represents an installation comprising photovoltaic panels that exploit solar energy to produce electrical power. This operation employs the use of 'photovoltaic cells'. Electricity travels towards the network in consumption areas eventually reaching everyone's homes [12]. production energy proportional to three factors:

a. The size of the area covered by the photovoltaic farm.
b. The efficiency of solar panels.
c. It's the radiation data.

Production fluctuates due to changes in solar insolation throughout the day.

*2) Wind turbines (WT)*

Converting wind kinetic energy into electricity via synchronous or asynchronous generators, often associated with energy storage or diesel engines to mitigate intermittency, with installations onshore or offshore [12].A simplified model of a wind farm power follows varies linearly with wind speed. When the wind reaches a nominal value, the wind farm produces rated power. The wind turbine automatically disconnects from the network when the wind speed exceeds the maximum value and reconnects once the wind returns to this level.

*3)* The renewable energy integration

into the smart grid allows for better management of the intermittent and unpredictable nature of sources like wind and solar. Smart grid technologies, including smart meters and demand response, enable real-time adjustment of consumption to match generation, shifting loads outside peak hours and optimizing demand response to enhance efficiency.

Demand management algorithms are incorporated, considering EV battery states, user preferences, and system priorities, to schedule EV charging and discharging optimally. The simulation evaluates V2G’s effectiveness in balancing load, regulating frequency, utilizing renewable energy, and maintaining stability under various scenarios, including high renewable variability and peak demand, with metrics validated through multiple runs to ensure robustness.

*4) Integrating renewable energy into the grid*

The smart grids are based on an information system that allows for short- and long-term level of production and consumption. Renewable energy that works often intermittently and in an unpredictable way (e.g. wind) can be better managed.

*5) The load in the smart grid*

Smart grids enhance traditional power systems by using advanced technologies like smart meters and demand management to better match electricity consumption with real-time production, especially from intermittent renewable sources such as wind and solar. By shaping demand, shifting loads outside peak hours and optimizing EV charging schedules based on battery status and user preferences, these grids reduce peak demand and lower the need for maximum capacity. Simulations incorporating renewable variability and demand response algorithms evaluate system stability, frequency regulation, and renewable integration, validating effectiveness across various scenarios. The insights guide control strategies and policies, facilitating the practical deployment of V2G technology to improve grid resilience, efficiency, and renewable utilization.

*6) Electric vehicles*

The transport sector is a major contributor to greenhouse gas emissions in the European Union, as it relies heavily on fossil fuels, making emission reduction efforts both challenging and costly. Electric vehicles (EVs), whether battery-powered or hybrid, represent a promising solution for reducing carbon dioxide ($CO_2$) emissions. The advancement *of* smart grid technologies, particularly vehicle-to-grid (V2G) systems, enables bidirectional communication between EVs and the electricity grid. This capability allows EVs to supply stored energy to the grid during periods of high demand or to recharge during low-demand periods, thereby transforming EV batteries into mobile energy storage units that enhance grid stability and promote sustainable and cleaner transportation.

*7) Véhicule-to-Grid (V2G) Application*

V2G technology's key application is providing frequency control services, which help balance electricity and enable the integration of renewable energy sources into the grid.

By increasing reserve capacity, V2G can support the long-term removal of high-carbon power plants used during peak demand days and improve environmental conditions. Overall, V2G enhances grid stability and efficiency through smart grid developments, transforming it into a crucial tool for managing electricity flow and supporting sustainable energy goals.

Electric vehicles (EVs), unused 95% of the time, can serve as valuable energy storage resources for the grid, providing additional capacity if economically and technically viable. However, utilizing EV batteries for storage requires rapid and frequent charging and discharging cycles, along with high energy density. Moreover, the grid's current state must be considered to optimize charging and discharging times, such as avoiding peak periods to prevent additional strain during high demand times like winter evenings. difficulty for the balance of the electric system.

An advanced energy counting system, or smart meter, uses communicative meters that can store energy measurement data and facilitate quick, reliable data transfer between users, network operators, and suppliers. Equipped with two-way communication, these meters enable remote reading and control of energy supply, enhancing grid management and efficiency.

*8) The Rule-based energy management:*

The system uses rule-based management to operate based on generation, storage state, and load demand following main rules:

- The diesel generator is to balance the power produced with the power consumed to maintain constant frequency.
- Photovoltaic and wind energy are mainly used to supply the loads.
- Electric vehicles (EVs) are charged during periods of low electricity prices or surplus renewable generation and provide vehicle-to-grid (V2G) support during demand peaks, ensuring continuous load supply.

### *B. Simulation*

The microgrid comprises a 10 MW variable load, a 15 MW diesel generator, 8 MW PV and 4.5 MW wind turbines, and a V2G system, serving roughly 1,000 homes on a low-consumption day (Fig. 2).

The basic model includes 100 electric vehicles, corresponding to a 1:10 ratio between vehicles and households. This scenario represents a plausible projection for the near

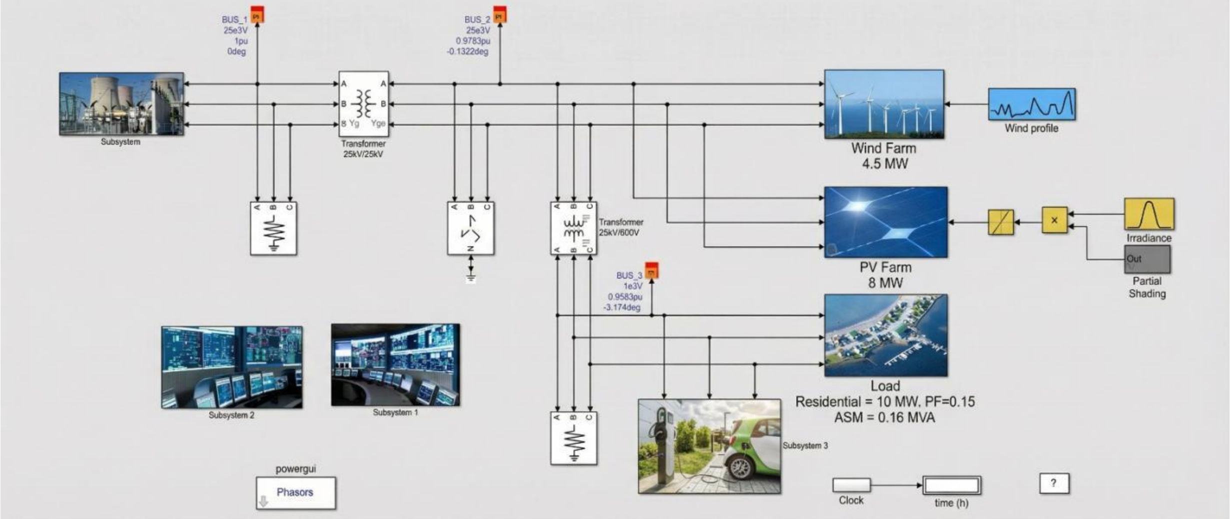

Fig.2. MATLAB simulation of Smart-Grid system (Matlab/Simulink)

TABLE I. MICROGRID PARAMETERS

| Symbol | Description | Value |
|---|---|---|
| $D_g$ | Diesel generator | 15 MW |
| $P_{PV}$ | Photovoltaic power | 8 MW |
| $P_{WT}$ | Wind turbine power | 4.5 MW |
| $P_L$ | Load power | 10 MW |

Based on the Simulink results, various system signals and rotor speed behavior were observed. The simulation lasts 24 hours in real time, equivalent to 3 minutes in phase mode.

The solar intensity follows a normal distribution, reaching its maximum at noon, while wind conditions vary throughout the day, showing multiple peaks and fluctuations.

**First Scenario:** A peak of power consumption (Overconsumption) which occurred at 3 o'clock in the morning is greater than 12MW due to high power demand.

**Second Scenario:** A partial midday cloud affecting solar energy production.

**Third Scenario:** At 22:00, a farm wind will be closed if the wind exceeds the maximum power permitted by the wind turbine.

For simplicity, this paper utilizes an AC dynamic load model based on a daily load curve representing a community with residences and small industries. The model includes an asynchronous machine to simulate the effects of an inductive industrial load like ventilation. The load profile reflects variations from factors such as time, weather, and economic conditions.

*Energy management:*

The energy management system applies predefined rules to manage generation, storage, and load in order to optimize power balance. The established ruleset is based on the following main rule:

- The diesel generator regulates the balance between power generation and demand to ensure frequency stability within the microgrid.
- Photovoltaic and wind energy systems constitute the primary sources for supplying the load.
- Electric vehicles (EVs) are scheduled to charge during periods of low electricity prices or when surplus energy from renewable sources is available.
- During peak load conditions or in response to fluctuations in renewable generation, EVs can operate in vehicle-to-grid (V2G) mode to inject power back into the grid.
- Consequently, the load demand is supplied through a coordinated contribution of photovoltaic systems, wind turbines, the diesel generator, and EVs operating in V2G mode.

## III. RESULTS AND DESCUSSION

Through the Simulink simulation, we can observe various signals in the model field and the changes in the rotor speed. The Oscilloscope and Power Measurement subsystems allow us to access information from various nodes. This subsystem also provides the charge status of each vehicle. A negative charge status indicates that the vehicle is driving or disconnected.

The simulation results show the impact and contribution of V2G technology loads on grid stability and efficiency, as well as the impact on real-time generation and consumption balance management.

The simulation uses typical residential electricity prices for electricity trading. The role of the V2G technology load manager in regulating the microgrid and changes in generation and consumption is studied.

By executing the simulation in Simulink, various signals within the model can be analyzed, including the rotor speed dynamics. Accessing the Scopes and Power Measurements subsystems allows the extraction of data from multiple network nodes. In addition, the state of charge (SoC) associated with each electric vehicle profile is available within this subsystem. A negative SoC value indicates that the vehicle is in operation (on the road) or not connected to the system.

The simulation results demonstrate the impact and contribution of vehicle-to-grid (V2G) technology on grid stability, operational efficiency, and real-time balancing between power generation and consumption. The simulations are conducted using representative residential electricity tariffs for both electricity purchasing and selling. The results highlight the role of V2G-based load management in microgrid regulation, as well as its influence on variations in power generation and consumption.

The V2G module incorporates five distinct electric vehicle user profiles:

**Profile 01**: represents a workplace equipped with charging infrastructure serving 35 employees who use electric vehicles. These employees undertake daily commutes totaling four hours, occurring between 6:00–8:00 AM and 4:00–6:00 PM. During commuting periods, the vehicles are disconnected from the grid, resulting in negative state-of-charge values that reflect vehicle operation. Outside these commuting intervals, all vehicles remain connected to the charging stations, as illustrated in (Figure 3).

**Profile 02:** Twenty-five employees with electric vehicles charge near the workplace. They need extra time to reach charging locations, extending travel periods to 5:00-8:00 AM and 4:00-7:00 PM. During these hours, charge levels go negative as vehicles operate. Outside travel times, all vehicles connect to charging stations (Figure 4).

**Profile 03:** Ten employees drive electric cars but cannot charge at work . They follow the same commuting schedule, keeping vehicles in operation from 6:00 AM to 6:00 PM with charge levels consistently below zero (Figure 5).

**Profile 04:** Twenty people own electric vehicles but remain home all day. Since no one travels, all vehicles stay connected to charging stations continuously. Fig. (6) shows a slight voltage oscillation of 0.002V throughout the day.

**Profile 05:** Ten employees work night shifts from 8:00 PM to 4:00 AM without vehicle charging access during work hours (Figure 7). These night workers cannot charge their electric vehicles while at work due to their different schedule.

Figure (8) shows all profiles with their usage periods, which concentrate primarily at the beginning and end of the day, with minimal activity at night.

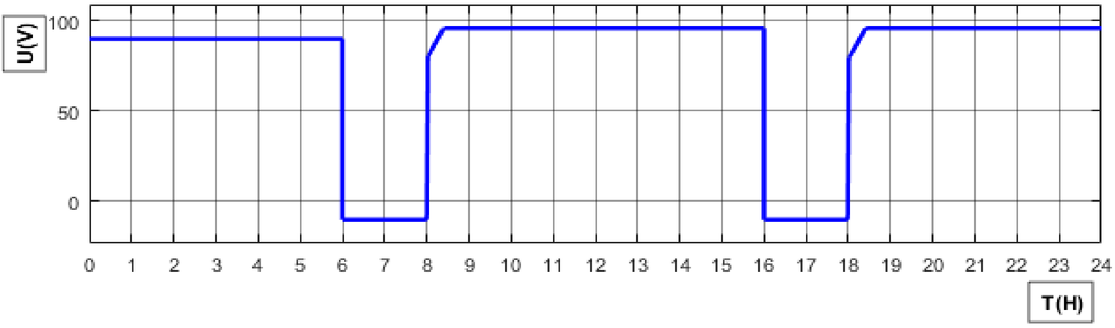

Fig.3. The voltage of battery in profile 01

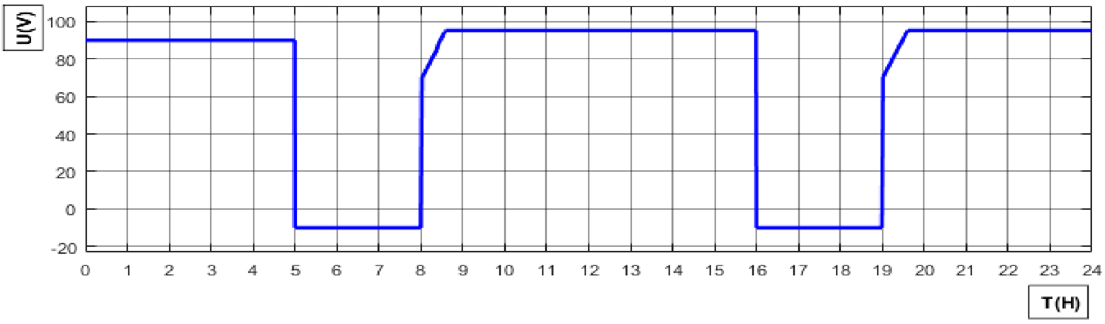

Fig.4. The voltage of battery in profile 02

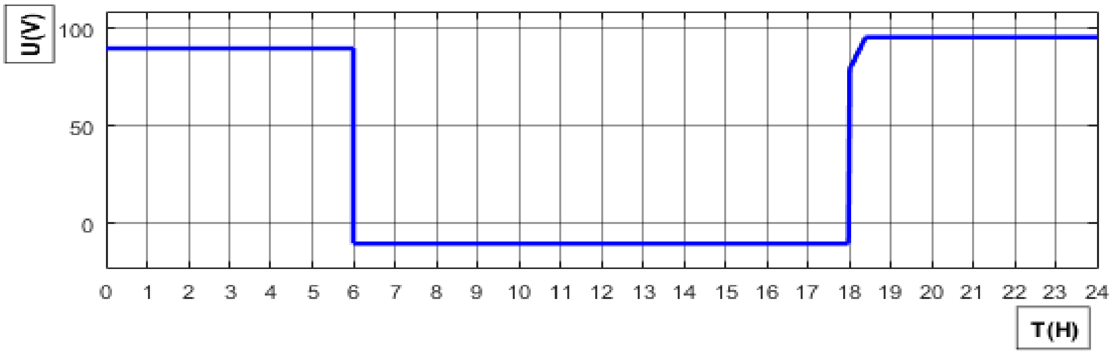

Fig.5. The voltage of battery in profile 03

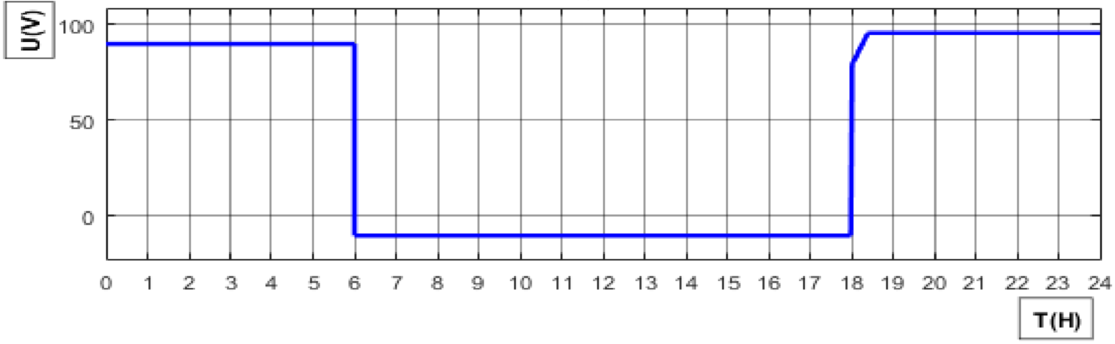

Fig.5. The voltage of battery in profile 03

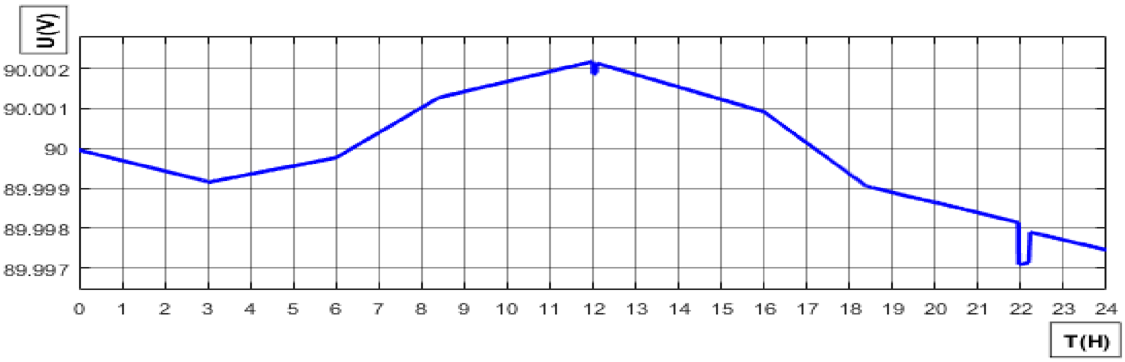

Fig.6. The voltage of battery in profile 04

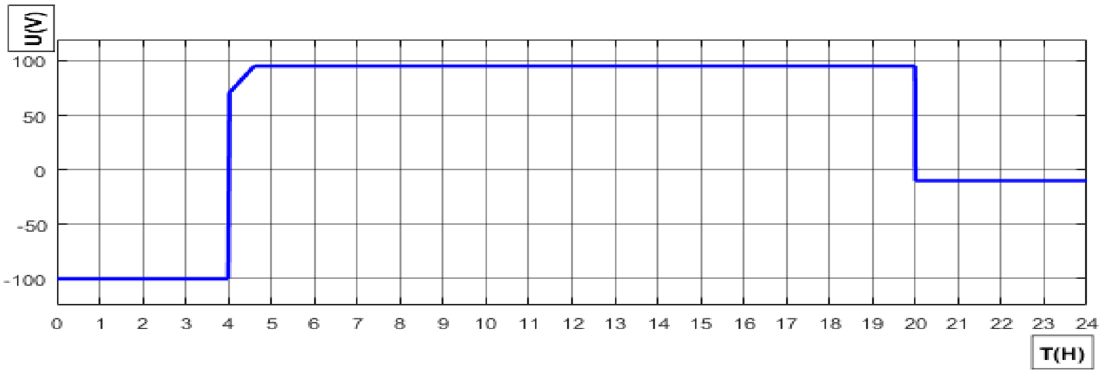

Fig.7. The voltage of battery in profile 05

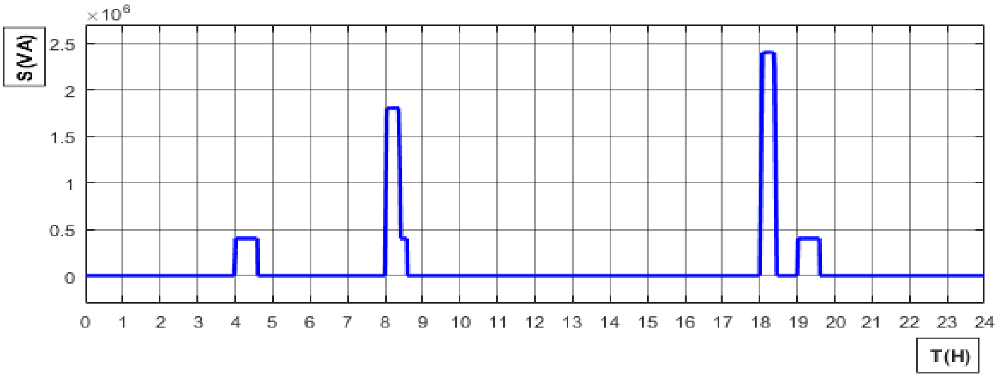

Fig.8. Charging status of all profiles

In (Figure 9), simulation results show the power generated by diesel generator, wind, photovoltaic fields and load consumption.

Power variations from different sources remain minimal during the first two hours, in the third hour a production peak appears due to high consumption from asynchronous motor startups, with significant wind production variation. From hour six, sunrise gradually increases photovoltaic production alongside household consumption. A production peak occurs from 08:00-09:00 AM due to high consumption. At noon, partial cloud cover affects solar energy production.

Out of 100 daily transfers, each lasting from a few seconds to a minute, we selected 90 transfers lasting 30 seconds each. Vehicles cannot participate in all transfers due to their usage patterns.

The grid automatically draws power from EV batteries during critical overload moments. Three main periods demonstrate V2G technology's importance:

- The asynchronous motor starts at 3:00 AM, with Profiles 1–4 injecting power into the smart grid.
- Cloud interference disrupting solar production - Profiles 1-3 and 5 compensate for reduced photovoltaic output
- Excessive wind speeds halting turbines - Power injections stabilize the network when wind generation stops

In each critical moment, available EV profiles automatically supply power to maintain grid stability (Figure 10).

Another consumption peak (overconsumption) exceeding 12MW occurred at 3:00 AM due to high power demand (Figure 11).

During system fluctuations, the diesel generator increases its output to compensate for power deficits (Figure 11), while connected electric vehicles instantly inject power. The network automatically draws energy from the batteries of electric vehicles during critical overloads. Four main periods show V2G technology's importance (Figure 12). Since V2G operates during peak tariff periods, charging station profits increase automatically.

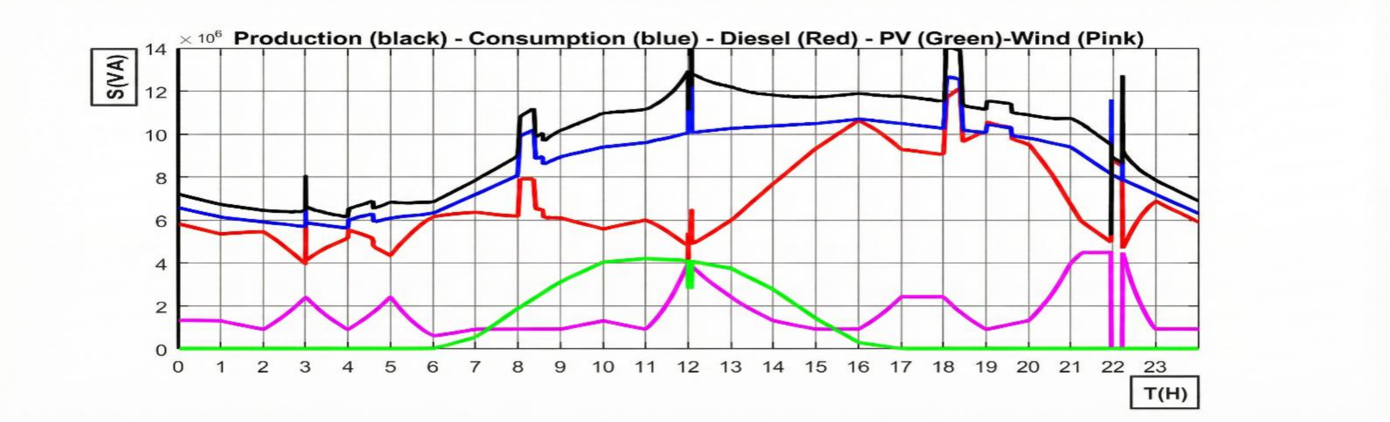

Fig. 9. Power variation Microgrid during a day

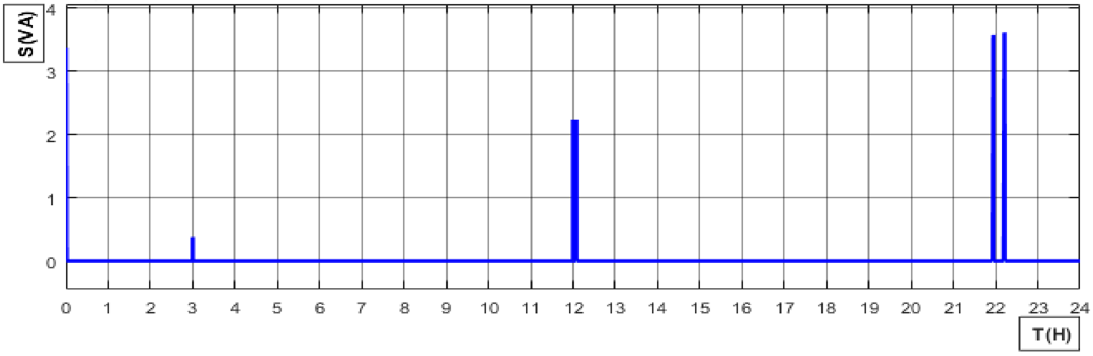

Fig.10. V2G's contribution to load balancing

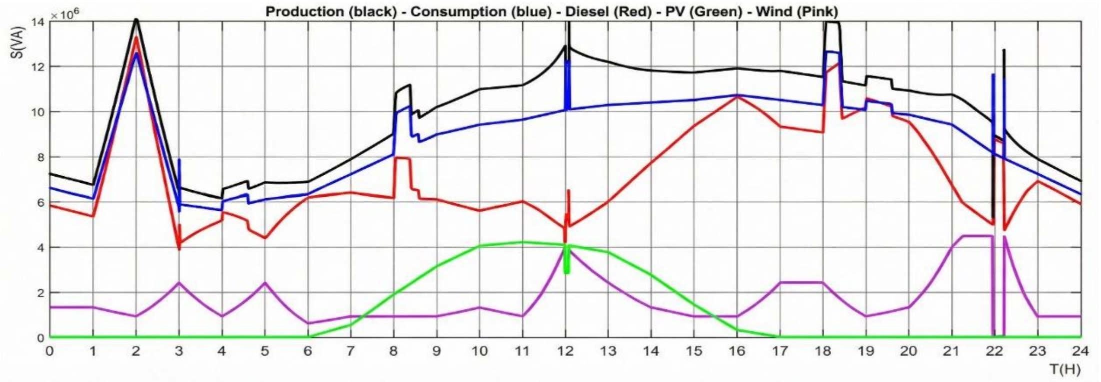

Fig.11. Power variation Microgrid during a day

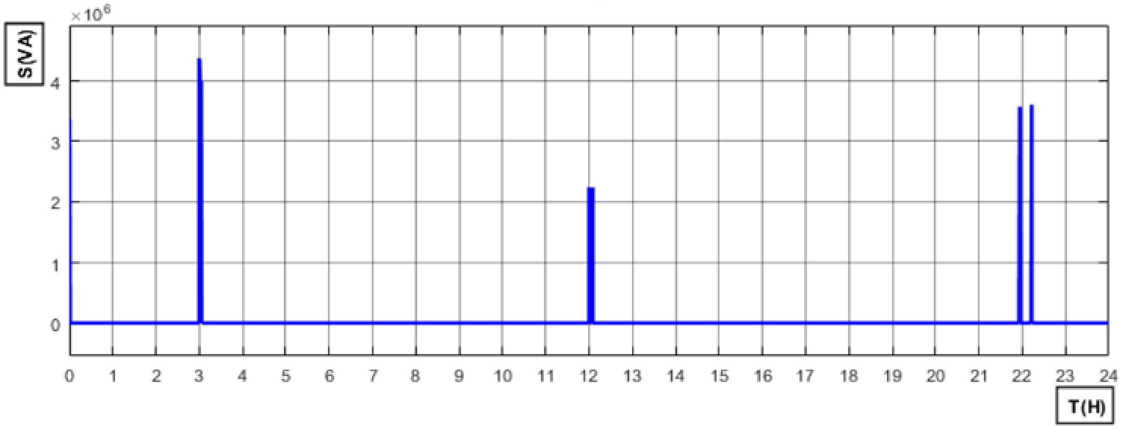

Fig.12. V2G's contribution to load balancing

The rapid growth of electric vehicles drives increased grid investment needs. EVs can generate power during peak hours, injecting stored energy to stabilize voltage and frequency while providing spinning reserve. V2G buffers renewable energy by storing excess power and delivering it during peak demand, reducing wind and solar intermittency.

This methodology significantly reduces peak loads while using excess renewable energy for off-peak vehicle charging, creating economic benefits. V2G offers profitable incentives for participants through management programs

## IV. CONCLUSION

This paper focuses on vehicle-to-grid (V2G) load technologies in smart grids. We examined smart grid components and V2G's bidirectional switching between injection and withdrawal modes based on real-time grid needs. Simulation demonstrated V2G's effectiveness in balancing electricity generation and control systems, improving energy efficiency, and providing grid flexibility during outages and supply-demand fluctuations. Load management has become crucial in smart grids, transforming from a concern into a major solution. We presented V2G as an example of this load-oriented approach, using EV batteries as energy storage that feeds back into the grid during high demand periods. This alleviates production fluctuations and reduces reliance on carbon-emitting thermal plants. EV batteries serve as distributed clean energy storage, supplementing the grid during peak usage while maximizing renewable energy use. Since vehicles are idle 96% of the time, energy transfer between EV batteries and other sources improves microgrid management and renewable integration through flexible energy storage and transfer. Customers have gone from being simple consumers to active consumers

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