Vehicle-to-Grid (V2G) Charging of Electric Vehicles and its Influence on Microgrid Operations, from the Perspective of Electric Vehicle Utilization

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Abstract: This work deals with a general description of the functioning of the vehicle-to-grid system, which can be used in the operation of electric vehicles within a microgrid network. To describe the impact of electric vehicle operation, a residential network with installed renewable sources, in the form of photovoltaic power plants, was chosen. Important input data for the simulation included the initial and final states of charge (SoC) of the vehicles and the daily load profile applied within the residential area. The simulation of microgrid behavior, with six different deployment scenarios of sources and loads in terms of energy supply and consumption confirmed the significant impact of energy-supplying vehicles, on the overall power balance of the microgrid. Based on the simulation, threshold states were identified where the production of the PV system and vehicles in V2G mode, was significant enough to cover the entire consumption of the studied network. Consequently, further investigation into the influence of such connected vehicles, is necessary for the optimal operation of microgrids.

Keywords: vehicle 2 grid; EV charging; smartgrid; vehicle 2 everything

1 Introduction

The rise of electric vehicles (EVs) has revolutionized the transportation industry and paved the way for a cleaner and more sustainable future. However, the benefits of EVs extend beyond emission reduction and fuel efficiency. Vehicle-to-Grid (V2G) charging, a groundbreaking technology, is poised to transform the way we think about energy distribution and microgrid operation. V2G charging refers to the bi-directional flow of electricity between EVs and the power grid. Traditionally, EVs have been viewed as energy consumers, drawing power from the grid to charge their batteries. V2G technology, on the other hand, allows EVs to not only draw electricity from the grid but also return excess energy back to it when needed. This two-way energy flow enables EVs to function as mobile energy storage units, unlocking a plethora of possibilities for optimizing energy management within microgrids. [1] [2]

1.1 General Definition of Microgrids

As shown on figure 1, microgrids are localized energy systems that can operate independently or in conjunction with the main power grid [3]. They are often found in remote areas, military bases, hospitals, or other critical infrastructure. In this era, when there is massive deployment of renewable energy sources on the household level, a group of such households can be considered as a microgrid. Microgrids offer numerous advantages, including enhanced energy reliability, resilience, and the integration of renewable energy sources. V2G charging can further enhance the performance and efficiency of microgrids by leveraging the battery capacity of EVs.

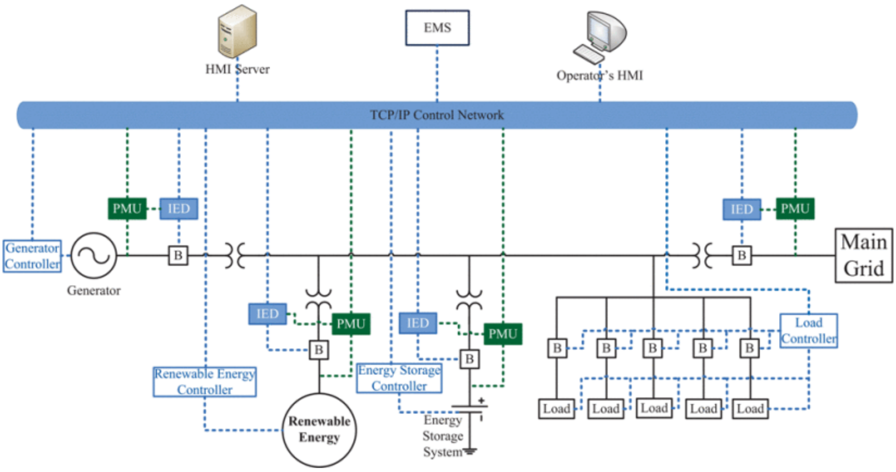


Figure 1

Topology of microgrids [3]

1.2 Vehicle-to-Grid (V2G), as a Part of Modern Microgrid

One of the significant influences of V2G charging on microgrid operation is the ability to support peak load management. During periods of high electricity demand, when the grid is under stress, V2G-enabled EVs can inject surplus power back into the grid, alleviating strain on the system. This dynamic load balancing helps stabilize the grid and reduce the need for expensive infrastructure upgrades. Additionally, V2G charging allows microgrids to tap into the distributed energy storage capacity of EVs, thus improving their ability to handle fluctuations in renewable energy generation. Furthermore, V2G technology enables microgrids to integrate a higher share of renewable energy sources. As intermittent sources such as solar and wind become more prevalent, the challenge of balancing energy supply and demand increases. EVs, when connected to microgrids through V2G charging, can absorb excess renewable energy during periods of oversupply and release it during peak demand, effectively acting as a buffer and enhancing grid stability. This synergy between EVs and microgrids promotes the integration of clean energy sources and accelerates the transition towards a sustainable energy future. In addition to grid support, V2G charging offers economic benefits to EV owners and grid operators. A crucial aspect of operating electric vehicles in the vehicle-to-grid mode is understanding the specific utilization patterns of these vehicles and accurately modeling the anticipated battery charge levels in relation to the distance covered and the elevation profile of the route. This information plays a significant role in determining the feasibility and efficiency of integrating electric vehicles into the grid.

1.2.1 Initial State of Charge as Significant Simulation Parameter

To properly simulate and assess the impact of vehicle-to-grid operations, it is essential to establish the initial charge states of the vehicles based on predefined routes. These initial charge states serve as the starting point for the simulation, enabling researchers and operators to evaluate the performance, energy consumption, and potential grid interactions of electric vehicles in a controlled environment [4]. By considering the length and elevation profile of the route, it becomes possible to estimate the energy consumption and battery usage during the journey accurately. For example, routes with steep inclines or long distances may require more battery power, resulting in a higher discharge rate and potentially affecting the vehicle's remaining charge at the end of the trip [5] [6].

Furthermore, the utilization mode of electric vehicles is a critical factor to consider. It involves analyzing how the vehicle is used throughout the day, including periods of driving, parking, and grid interaction. Understanding the usage patterns allows for the identification of opportunities for vehicle-to-grid interactions, such as charging during periods of low electricity demand or discharging excess energy back to the grid when it is most needed. [7] [8] Accurate modeling of the anticipated battery charge levels and utilization patterns is vital for optimizing the operation of vehicle-to-grid systems. It enables the prediction of energy availability, the scheduling of charging and discharging activities, and the overall integration of electric vehicles into the grid. By establishing the correct initial charge states based on predefined routes, simulations can provide valuable insights into the performance and feasibility of vehicle-to-grid operations, helping stakeholders make informed decisions regarding the deployment and management of electric vehicle fleets.

2 Investigated Microgrid - Description

Our investigated microgrid is a decentralized energy system that involves integrating various energy sources such as solar panels, batteries (in our case also batteries in EVs, connected as V2G), and possible other renewable energy sources. This microgrid system can operate independently or be connected to the main power grid, providing flexibility and independence from traditional centrally controlled energy sources. The main objective of the investigated microgrid system is to optimize energy production, distribution, and consumption to maximize efficiency, minimize costs, and reduce negative environmental impacts. This system enables balancing energy production and consumption by managing the flow of energy between different sources and consumers within the microgrid. An important aspect of studying the microgrid system is the analysis and optimization of energy storage management, particularly battery storage (Battery energy storage systems and battery of EVs). This aspect is of utmost importance, for ensuring operational stability, within a microgrid. Microgrids, with their limited scale and local energy generation and consumption, are more susceptible to fluctuations in both electricity production and demand (in our case is supplying of microgrid provided by two 1600kVA distribution transformers). These fluctuations can result from various factors, such as intermittent renewable energy sources (like solar and wind), varying load patterns, or unexpected changes in energy usage. [9] [10]

The potential risks associated with these fluctuations include not only instability but also the compromised quality of electricity supply. Voltage and frequency variations, as well as the presence of higher harmonics, can lead to voltage sags, surges, or frequency deviations, affecting the performance of electrical equipment and causing disruptions in power delivery. [11] To mitigate these risks and ensure stable and reliable operation, the interface between the microgrid and the distribution grid, which acts as the higher-level system, becomes crucial. This interface serves as a point where the flow of energy needs to be carefully examined and managed. It involves analyzing and coordinating the contributions of all energy sources and loads within the microgrid, considering their collective impact on the overall energy balance. [12] [13]

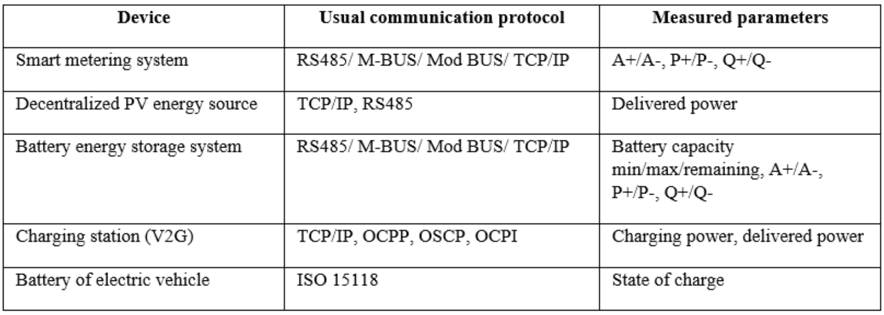
By studying the energy flow at this interface, it becomes possible to optimize the coordination of electricity generation, consumption, and storage within the microgrid. This allows for effective load balancing, efficient utilization of available energy resources, and enhanced grid stability. Understanding the dynamics of energy exchange between the microgrid and the distribution grid helps ensure the seamless integration of the microgrid into the larger power system while maintaining grid stability and the quality of electricity supply.

BESS and EVs batteries which were mentioned before are used to accumulate excess energy from renewable sources when production exceeds consumption and provide it later when consumption exceeds production. [14] Managing this energy storage is crucial to ensure the stability and reliability of the microgrid system. Another aspect of the study is the analysis of the efficiency and reliability of energy transmission within the microgrid. This system often involves a distribution network with various points of energy production and consumption, making it important to analyze and optimize energy transfer between these points. It is also necessary to examine various factors that can affect transmission reliability, such as the impact of weather conditions on solar and wind energy production. The study of the microgrid system also includes the evaluation and management of dynamic energy demand within the network. This involves analyzing and optimizing various methods of managing energy consumption, such as time-shifting energy demands, efficient appliance control, and implementing smart grids. Overall, studying the microgrid system aims to create an energy-efficient, reliable, and sustainable system that utilizes renewable energy sources and maximizes the utilization of available energy through optimal management, storage, and distribution of energy. [15]

Given the need for communication between devices in terms of mutual monitoring of production and consumption, it is important to define these communication interfaces [16]. Micro grids, commonly found in residential areas, consist of several key components. These include a smart electricity meter that interfaces with the distribution network, a decentralized renewable energy source (typically photovoltaics operating in hybrid mode), battery storage system - BESS (often utilizing LiFePO4 technology), an optional charging station with vehicle-to-grid (V2G) capabilities, and an electric vehicle connected to the grid. Standard Communication protocols are mentioned below:

Table 1

Standard used components and communication protocols



Device	Usual communication protocol	Measured parameters
Smart metering system	RS485/ M-BUS/ Mod BUS/ TCP/IP	A+/A-, P+/P-, Q+/Q-
Decentralized PV energy source	TCP/IP, RS485	Delivered power
Battery energy storage system	RS485/ M-BUS/ Mod BUS/ TCP/IP	Battery capacity min/max/remaining, A+/A-, P+/P-, Q+/Q-
Charging station (V2G)	TCP/IP, OCPP, OSCP, OCPI	Charging power, delivered power
Battery of electric vehicle	ISO 15118	State of charge

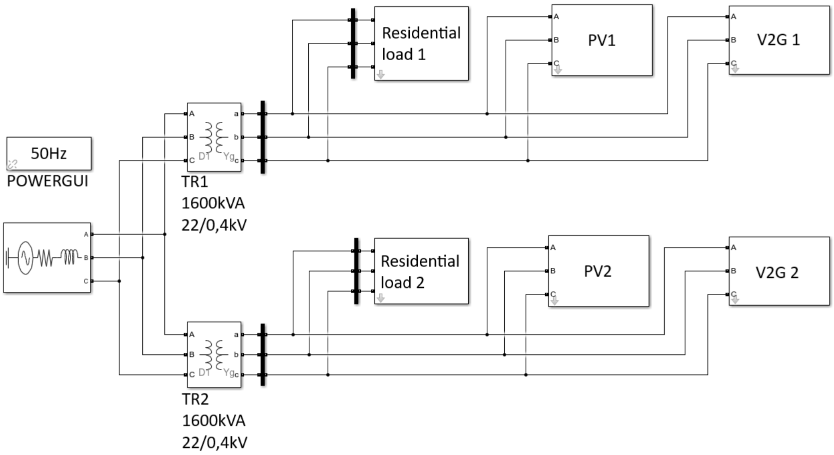
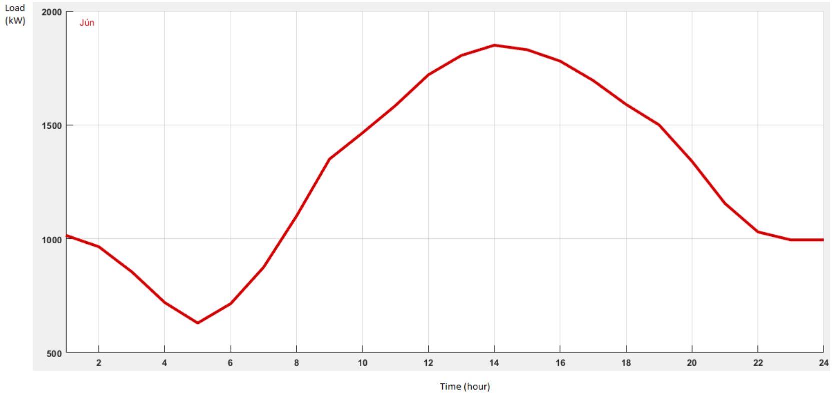


Figure 2
Schematic of modelled microgrid

The schematic diagram of the examined microgrid is depicted in figure number 2. Our microgrid configuration comprises two identical sections, each consisting of a distribution transformer with a capacity of 1600 kVA. These transformers are connected to a 22 kV distribution network, which serves as the power source for a residential area of a specified size. In our case, this corresponds to approximately 200 households. To accurately model and analyze the energy dynamics within the microgrid, specific daily load profiles have been defined for these households. These load profiles, illustrated in figures 2 and 3, were established to represent typical energy consumption patterns during both summer and winter seasons. By considering the distinctive characteristics of each season, such as varying temperature conditions and corresponding shifts in electricity usage, a comprehensive assessment of the microgrid's performance under different scenarios can be obtained. The utilization of such load profiles enables a more



detailed investigation of the microgrid's operational behavior and its ability to efficiently meet the energy demands of the connected residential area. By examining the variations in load patterns throughout the day and across different seasons, valuable insights can be gained regarding the overall system performance, energy management strategies, and the potential for optimizing energy generation and storage resources. This comprehensive analysis of the microgrid, considering the defined load profiles and its interaction with the distribution network, plays a crucial role in assessing the system's stability, reliability, and overall effectiveness. It provides a foundation for making informed decisions and implementing measures that enhance the microgrid's performance, energy efficiency, and ultimately, the satisfaction of the residents it serves.

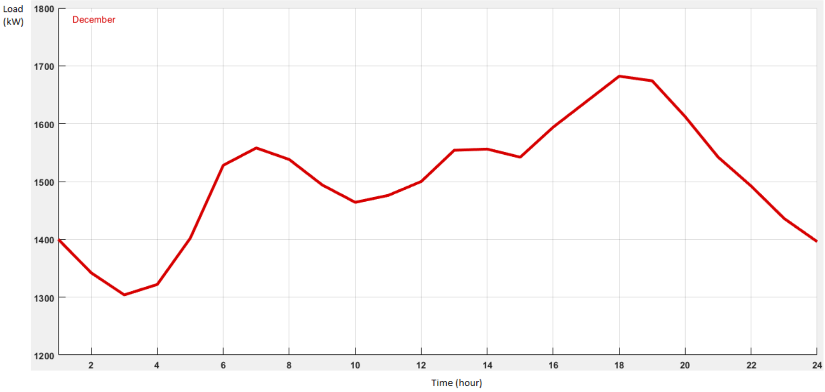


Figure 3

Mentioned daily load diagram for both scenarios

In the case of the microgrid's energy sources, we have a photovoltaic power plant with an installed capacity of 250 kWp. For simulation purposes, it is not crucial whether this source is divided into smaller distributed units or concentrated as a single entity. The crucial parameter, however, is the irradiance level, which ranges from Irmax 220 W/m^2 to 725 W/m^2. The photovoltaic power plant plays a significant role in the microgrid, harnessing solar energy and converting it into electricity. Its installed capacity of 250 kWp represents the maximum power output it can generate under optimal irradiance conditions. The actual output of the photovoltaic system depends on the prevailing solar irradiance, which can vary throughout the day and across different seasons. The range of irradiance levels mentioned, from I_{rmax} 220 W/m^2 to 725 W/m^2, reflects the variability in solar radiation that the photovoltaic panels receive. This variability can be influenced by factors such as weather conditions, time of day, and geographical location. The microgrid simulation takes into account these varying irradiance levels to accurately model the performance of the photovoltaic power plant.

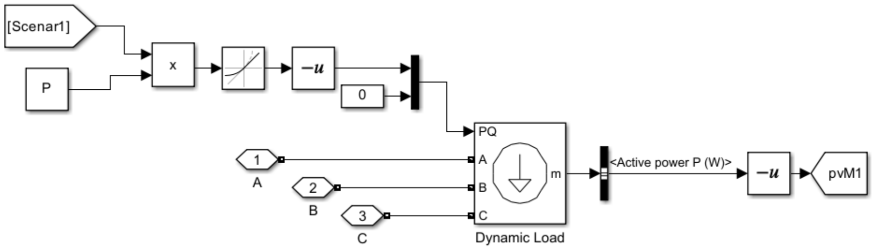


Figure 4
Wiring of a photovoltaic power plant in the Simulink environment

By considering the irradiance as a key parameter, the simulation captures the real-world conditions and enables an assessment of the photovoltaic system's output and its contribution to the microgrid's overall energy generation. This information is crucial for evaluating the system's reliability, energy balance, and its ability to meet the electricity demand of the connected residential area. Moreover, the simulation allows for studying different scenarios and evaluating the impact of changing irradiance levels on the microgrid's performance. This analysis aids in optimizing the energy management strategies, ensuring efficient utilization of available solar resources, and enhancing the microgrid's overall operational efficiency. Thus, the accurate representation of irradiance in the microgrid simulation plays a significant role in understanding the system's behavior, optimizing its’ performance, and facilitating informed decision-making for achieving sustainable and reliable energy supply within the microgrid.

2.1 Installed EV Chargers in General

The interface between the electric vehicle and the distribution network, or microgrid, is facilitated by a charging station. AC charging using the vehicle's on-board charger is the most common method. This involves using wall chargers with a power capacity of up to approximately 22 kW. External chargers powered from 230 V sockets can also be used for AC charging. However, the charging capacity is limited by the vehicle's on-board charger, typically up to 22 kW for fully electric vehicles and up to 3.6 kW for hybrid vehicles. One potential issue with these chargers is their configuration, which can load only one phase, leading to load asymmetry and posing a risk to the electrical grid or the electrical installation of a household with a renewable energy source such as a photovoltaic power plant. In household AC charging installations, another problematic factor can be the use of power management in the charging station, which considers the maximum reserved capacity of the electrical delivery point defined by the main circuit breaker. With controlled charging in multiple households, this may require a higher-rated fuse element at the distribution substation level. Hence, this phenomenon should be taken into account for future network development, as it significantly affects the value of the simultaneity coefficient β. Vehicle-to-grid (V2G) mode is less commonly used for AC charging, as it requires direct support from the vehicle's on-board charger. In contrast, DC charging rectifies alternating current and directly charges the vehicle battery at power levels ranging from approximately 50 kW to 350 kW [17]. Unlike AC charging, DC charging is typically a symmetrical load. The charging process itself is controlled primarily by battery thermal management to minimize wear and tear and achieve faster charging times. Efficiency of power supply from the battery depends on its temperature, as depicted in Figure 4. Ideally, the temperature range should be around 0°C to 40°C, but achieving this throughout the year is challenging.

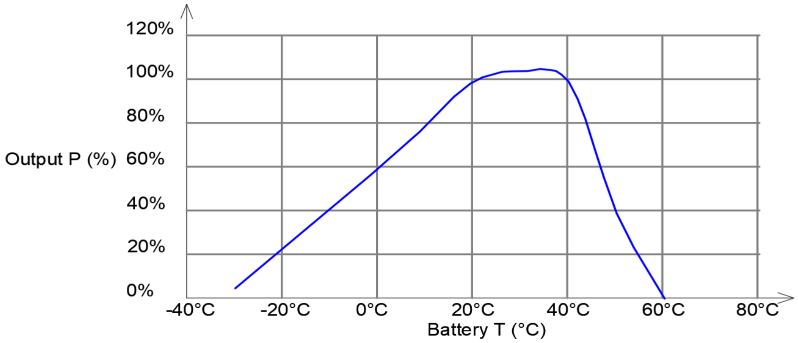


Figure 4
Estimated dependence of battery power by temperature

Increasing the battery temperature externally is possible but not economically viable for the overall efficiency of the nanogrid. Battery temperature also affects charging performance, imposing limitations that can be managed through thermal management systems in electric vehicles [18]. Since DC charging is concentrated at charging hubs, managing the load and rate of energy flow in the grid becomes crucial. Installing battery storage enables better energy flow management between the distribution grid and batteries, optimizing available capacity at specific grid points. Charging points are strategically located in places with high demand for fast charging, such as transit routes and near highways. However, these locations often impose limits on the installation of devices with high performance along with the simultaneity coefficient β of 0.8-0.9. Energy management options, apart from battery storage, include vehicle-to-grid (V2G) and vehicle-to-vehicle (V2V) systems. Implementing these technologies typically requires smart grids that enable communication between elements in the distribution grid. This communication allows for reverse power flow from electric vehicle batteries to compensate for insufficient capacity at specific points. Understanding the behavioral models of individual cars connected to the distribution grid is crucial for the effective utilization of available energy in vehicle batteries. Additionally, considering the "vehicle-to-everything" (V2X) model holds promise, as it facilitates data sharing for energy flow control and can be applied to traffic management, parking, and other functions.

2.2 Overview of Possible Charging Methods Used in Microgrid

2.2.1 Unmanaged Charging

Electric vehicles (EVs) are connected to a charging station of any type (AC and DC), and electricity is supplied from the grid to the vehicle at a steady rate. During this charging process, EVs typically do not consider factors such as the cost of electricity or the impact on the microgrid. This means that EVs charge without actively adjusting their charging behavior based on electricity prices or grid conditions. However, it is important to note that charging patterns that disregard these factors can have implications for both the cost of charging and the overall stability of the grid. To ensure more efficient and sustainable charging practices, advanced charging strategies and technologies are being developed. These aim to optimize charging schedules based on electricity pricing, grid load, and renewable energy availability, ultimately promoting cost savings and reducing the strain on the grid. By implementing smarter charging solutions, the charging process of EVs can be better aligned with grid conditions, contributing to a more balanced and economically viable electricity ecosystem. [19] [20]

2.2.2 V1G Unidirectional Smart Charging

Electricity is supplied from the grid to the vehicle, with the charging process carefully managed to address several important objectives. One of the key goals is to mitigate any potential negative impacts on the grid. By implementing intelligent charging strategies, the charging rate and timing can be optimized to avoid overloading the grid during peak demand periods. This helps maintain grid stability and prevents disruptions in the electricity supply. Additionally, managing the charging process allows for the minimization of costs, both for consumers and utilities. Charging can be scheduled during off-peak hours when electricity prices are typically lower, enabling consumers to take advantage of reduced rates. This not only reduces the financial burden on consumers but also promotes more efficient use of grid resources. Moreover, the management of charging can also support renewable energy generation. By aligning the charging schedule with periods of high renewable energy production, such as during sunny or windy conditions, EV charging can contribute to the integration of renewable sources into the grid. This not only reduces reliance on fossil fuels but also helps maximize the utilization of clean energy resources. Overall, by actively managing the charging process, it becomes possible to achieve multiple benefits simultaneously. It ensures grid stability, reduces costs for both consumers and utilities, and supports the transition towards a more sustainable and renewable energy future. Through advanced technologies and smart charging solutions, electricity can be effectively utilized to meet the growing demand for electric vehicles while optimizing the operation of the grid. [21] [22]

2.2.3 V2G Bidirectional Smart Charging

The vehicle-to-grid (V2G) system encompasses all aspects of vehicle-to-grid interaction, including the ability for the vehicle to discharge electricity back to the grid in a strategic manner. This two-way flow of electricity enables the vehicle to not only consume power from the grid but also serve as a potential source of electricity, offering flexibility and additional benefits to the grid operators and energy system as a whole. By intelligently managing the bi-directional energy exchange, V2G systems contribute to grid stability, load balancing, peak demand management, and the integration of renewable energy resources.

2.2.4 Scenarios for Charging Electric Vehicles and Delivering Electricity to the Grid

For the purpose of simulation, we have chosen three distinct scenarios for electric vehicle charging and three different scenarios for grid-to-vehicle (V2G) power delivery. For each scenario, the connection of twenty electric vehicles was considered, with the state of charge indicated in table No. 2. To accurately represent the battery's thermal management influence, we have selected specific charging profiles as depicted in Figure 6. In the case of power delivery to the grid, discharge profiles have also been carefully chosen, with a maximum power consideration of 11 kW. These selected scenarios offer a comprehensive range of charging and delivery patterns, allowing us to analyze and evaluate various aspects of the system's performance. By incorporating different charging strategies and grid interaction scenarios, we can gain valuable insights into the behavior of electric vehicle charging and its impact on the power grid. The charging profiles, defined by the charging curves in Figure 6, capture the dynamic nature of the battery charging process. These curves outline the power levels at different time intervals, taking into account the battery's thermal constraints and ensuring efficient and safe charging. [23] The chosen curves represent realistic charging scenarios that reflect typical user behavior and charging infrastructure capabilities. Similarly, the discharge profiles for grid delivery follow a carefully planned strategy. These profiles consider the power limits imposed by the grid and aim to maximize the utilization of available energy while maintaining stability and reliability. The maximum power level of 11 kW serves as an upper threshold for the considered discharge scenarios.

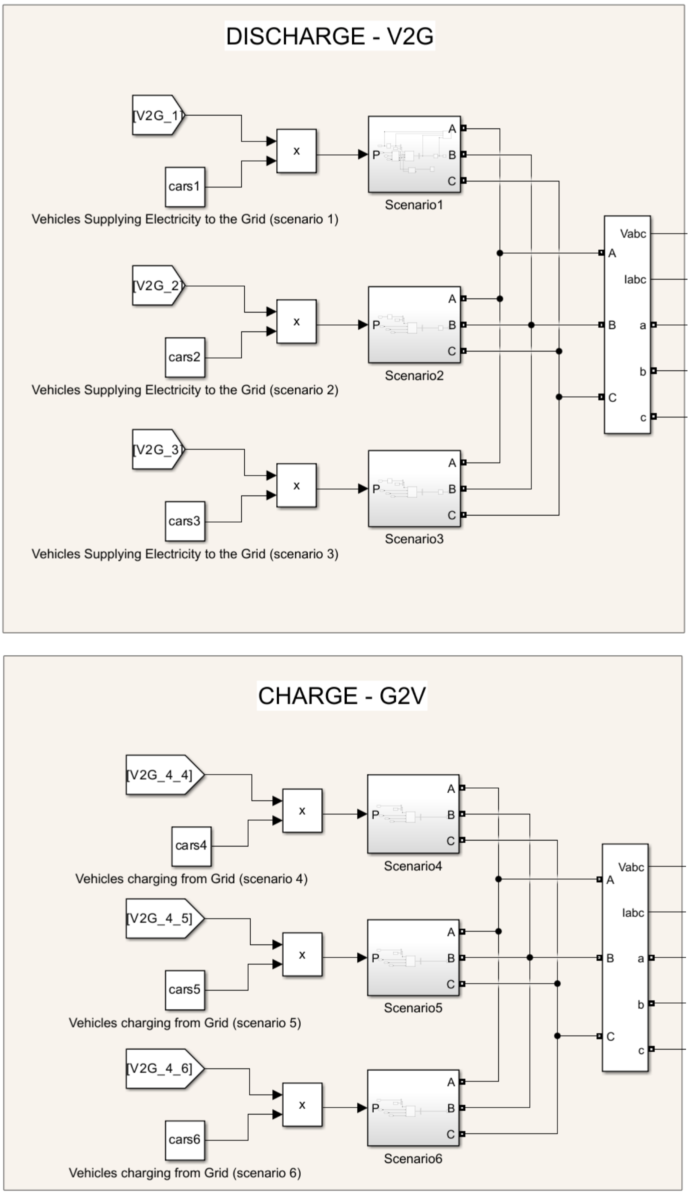


Figure 5

Power system of simulated microgrid V2G chargers - Scenarios

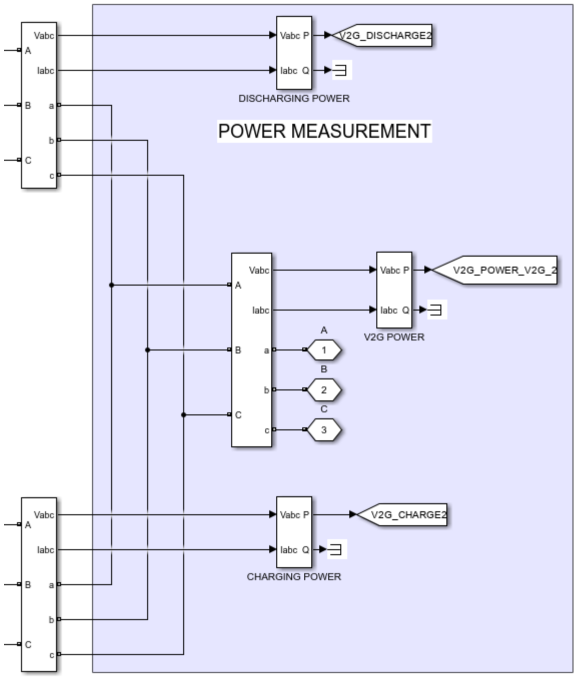


Figure 6
Power system of simulated microgrid V2G chargers – Power measurements

Scenario	Full Battery Capacity (kWh)	Initial State of Charge (kWh)	Desired State of Charge (%)	Charged Capacity (kWh)	Discharged Capacity (kWh)
1	85.0	21.2	80	46.8	
2	85.0	39.8	80	28.2	
3	85.0	24.0	80	44.0	
4	85.0	85.0	0		83.75
5	85.0	85.0	0		78.55
6	85.0	68.0	10		45.20

Table 2
Standard used components and communication protocols

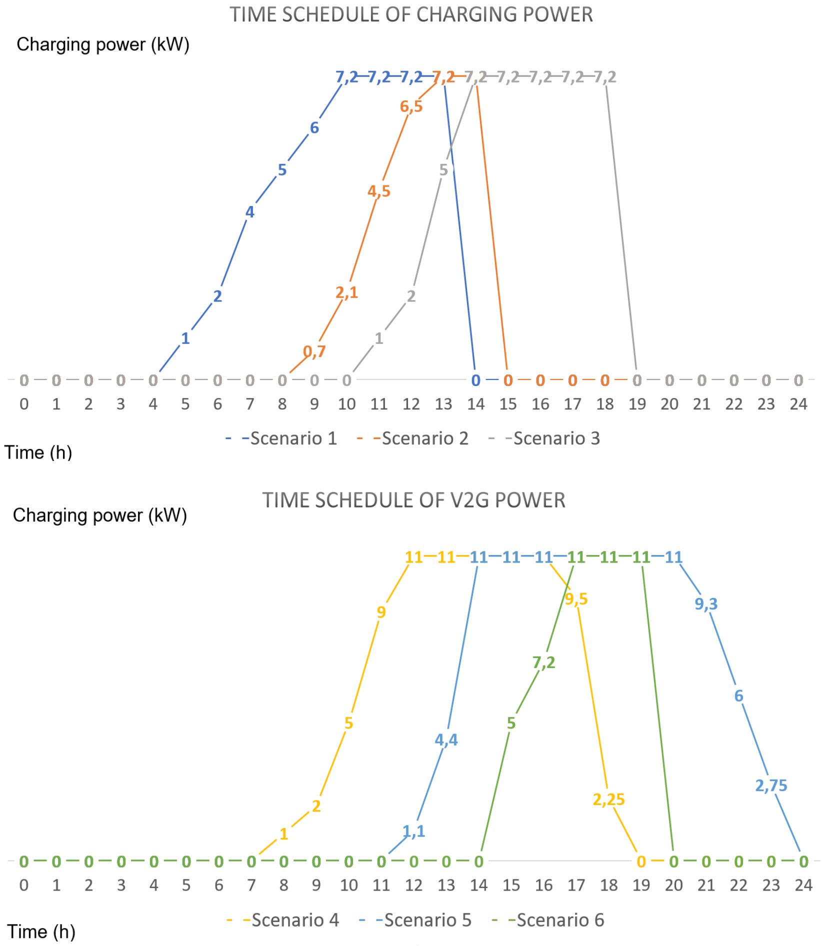


Figure 7
Time schedule of connected vehicles

3 Simulation Results

In the initial scenario, a microgrid was simulated in isolation, without the presence of any electric vehicles. As depicted in Figure 7, the primary contributor to the power balance of the system was a photovoltaic (PV) source. This simulation underlines the capacity of solar energy as a standalone power source within a microgrid, highlighting its capability to meet the system's power demand effectively. It's important to understand this baseline operation to gauge the changes introduced with the integration of electric vehicles. Shifting focus to the second scenario, this is where the complexity of the microgrid takes a leap with the addition of 60 electric vehicles. The charging pattern, depicted in figure 8, outlines how the vehicles draw power from the grid. With an initial state of charge indicated in Table 2, and a targeted charging level at 80%, the energy demand from the vehicles poses an additional load on the microgrid. This scenario allows for the evaluation of how such an increase in load affects the operational dynamics of the microgrid. It underscores the challenges of peak demand management and the need for load balancing strategies within the grid. The last scenario introduces another layer of complexity by transforming the electric vehicles into active grid participants through a V2G mode. This implies that electric vehicles are no longer just consumers of electricity; they become temporary energy storage units that can feed electricity back into the grid when necessary. Here, it's assumed that the vehicle batteries could be discharged down to a 0% limit. The purpose behind this setup is to test the maximum potential contribution of these vehicles to the microgrid's energy supply. Given the substantial size of electric vehicle batteries, their collective energy storage and supply potential can have a significant impact on the grid's stability and resilience.

Each of these scenarios reveals the multi-faceted relationship between electric vehicles and the power grid. The first scenario provides a baseline understanding of a PV-powered microgrid. The second demonstrates the impact of introducing electric vehicles and their associated power demands. The final scenario illuminates the potential benefits and challenges of V2G systems, underscoring the dual role of electric vehicles as both consumers and suppliers of electricity. It's evident that managing these complex interactions efficiently will be a critical component of future grid management strategies.

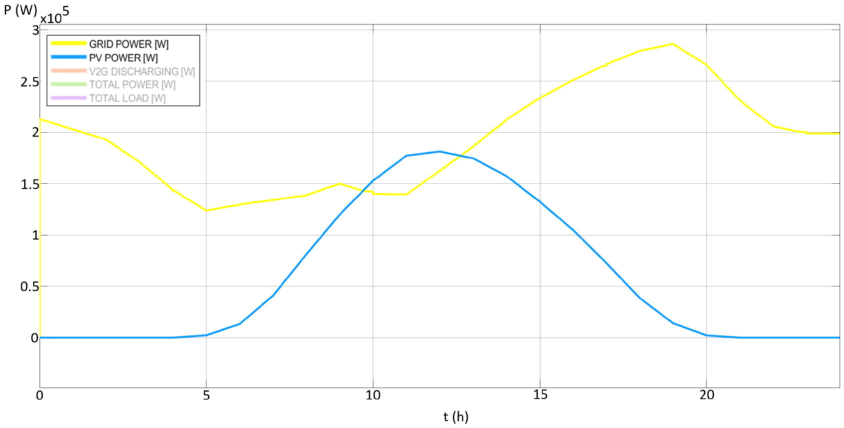


Figure 8

Time dependency of network power without connected electric vehicles

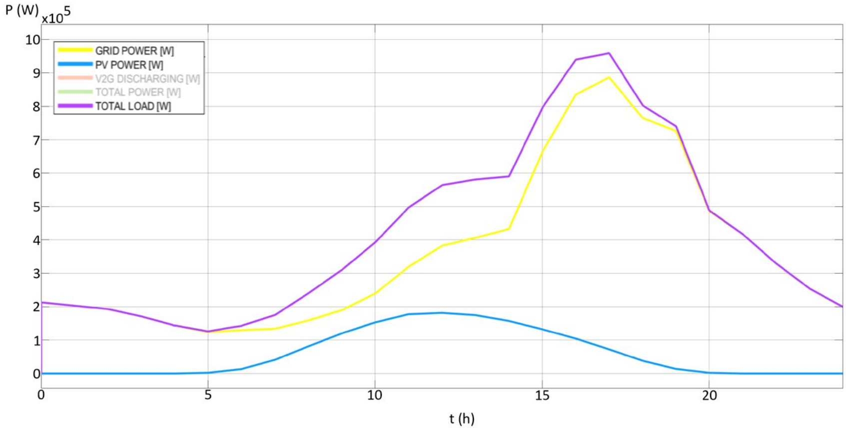


Figure 9

Time dependency of network power with 60 charging electric vehicles in defined time schedule

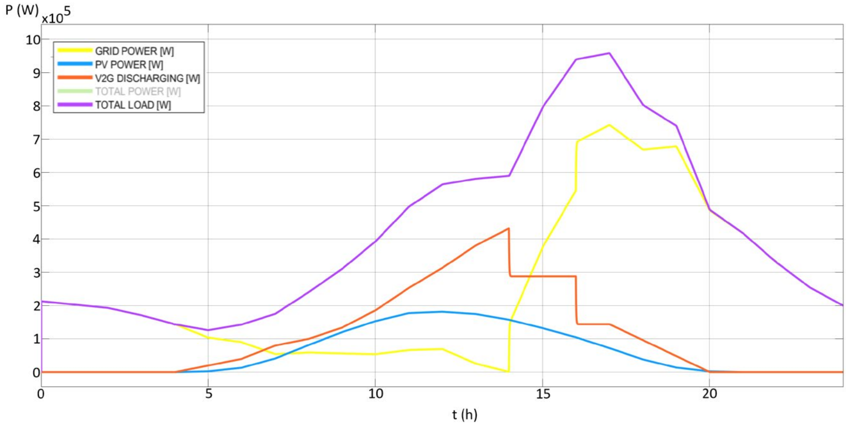


Figure 10

Time dependency of network power with 60 electric vehicles in V2G mode and 60 charging vehicles

4 Discussion

The findings discussed provide valuable insights into the complex interactions between electric vehicles (EVs) and microgrids, offering a deeper understanding of the challenges and opportunities involved in their integration. In the first scenario, the dominance of solar energy highlights its effectiveness as a primary energy source in microgrids. This serves as an essential baseline, emphasizing the reliability of renewable energy in meeting energy demands within such systems. This foundational understanding is crucial for accurately assessing the impacts of introducing EVs into the microgrid environment. Moving to the second scenario, the inclusion of EVs adds a new layer of complexity to the microgrid. The observed charging patterns illustrate the additional load imposed by the vehicles, highlighting the importance of effective load management strategies. Managing peak demand becomes a critical consideration, necessitating the development of robust mechanisms to balance loads and maintain grid stability and reliability. In the final scenario, the introduction of Vehicle-to-Grid (V2G) technology transforms EVs into active participants in the energy ecosystem. Allowing EVs to both consume and supply electricity to the grid presents opportunities to enhance grid resilience and flexibility. However, this also poses challenges, particularly in battery management and grid regulation. The assumption of discharging vehicle batteries to a 0% limit underscores the need for careful monitoring and control to preserve battery health and vehicle performance. Overall, these scenarios highlight the intricate relationship between EVs and microgrids, emphasizing the importance of efficient management strategies. As EV adoption continues to increase, integrating these vehicles into the grid effectively will be crucial for ensuring energy sustainability and resilience. This requires ongoing research and innovation in areas, such as demand response, smart charging and V2G technology, to maximize the benefits of EV-microgrid integration, while minimizing potential drawbacks. Addressing these complexities will pave the way for a more resilient and sustainable energy future.

Conclusions

Drawing from the insights gleaned through the simulations herein, it's clear that a crucial factor for microgrids employing V2G enabled vehicles, will be managing the initial and target charging levels of these vehicles, along with coordinating the availability of energy from on-site renewable sources. This will directly impact the cost-effective allocation and use of different energy resources, throughout the day. An interesting proposition, particularly in the context of reusing electric vehicle batteries, involves leveraging them in battery energy storage systems (BESS). Much like the V2G vehicles, these systems could facilitate load balancing during peak energy demand periods, which is particularly pertinent in a community-based energy ecosystem and shared utilization of regionally installed resources within the microgrid.

As previously mentioned, a critical aspect of future microgrid evolution lies in the seamless integration and efficient intercommunication of devices within the network. Equally significant is the capability to forecast individual consumer behaviors and habits, potentially through the application of a variety of mathematical models.

Acknowledgements

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