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Optimizing Vehicle-to-Grid (V2G) Systems for Efficient Renewable Energy Integration and Management

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Abstract

This study investigates the optimization of Vehicle-to-Grid (V2G) systems and their role in energy management for integrating renewable power sources, specifically wind, solar, and hybrid energy. The research is structured around three key scenarios: wind power integration, solar power integration, and hybrid power integration. Each scenario is analyzed both with and without electric vehicles (EVs) to evaluate their impact on grid stability and power quality. In the wind power integration scenario, directly connecting wind energy to the grid without EVs leads to significant power fluctuations, increasing the risk of grid failures. However, incorporating EVs helps mitigate these issues by storing excess energy in batteries, ensuring a stable power supply during periods of low wind. Similarly, in the solar power integration scenario, surplus energy is stored in EV batteries, providing a continuous power supply even when sunlight is unavailable. The hybrid power integration scenario combines both wind and solar energy, leveraging their complementary characteristics to enhance power quality and reliability. Simulation results indicate that hybrid integration with EVs offers the most stable and high-quality power output, followed by solar and wind integrations. Furthermore, the implementation of DC-DC bidirectional converters and RLC filters improves power stability by regulating voltage fluctuations and minimizing harmonics. This comprehensive analysis underscores the potential of V2G systems to enhance the feasibility and reliability of renewable energy integration into the power grid.

Keywords: *EV, Vehicle-to-Grid (V2G), Solar system, Wind system, Hybrid resource.*

I. INTRODUCTION

The growing global concern over climate change and environmental degradation has prompted a significant shift towards renewable energy sources. This movement is driven by the necessity to reduce greenhouse gas emissions, decrease dependence on fossil fuels, and promote sustainable development. While renewable energy sources like wind and solar power offer clean, inexhaustible energy, they also present challenges due to their intermittent and variable nature. Effectively integrating these sources into existing power grids requires advanced energy management systems to maintain stability and reliability. One promising approach is the Vehicle-to-Grid (V2G) system, which utilizes electric vehicles (EVs) as mobile energy storage units[1]. V2G technology enables the bidirectional flow of electricity between EVs and the power grid, allowing EVs to not only draw power from the grid for charging but also feed stored energy back into the grid when needed. This capability effectively transforms EVs into distributed energy resources, and V2G systems have shown great potential in enhancing grid stability and facilitating the integration of renewable energy sources. Wind energy, one of the most established renewable technologies, has the potential to generate large amounts of electricity, particularly in areas with abundant wind resources. However, the variability of wind speeds leads to fluctuating power outputs, posing challenges for grid integration. Without effective energy management, these fluctuations can cause significant disturbances and potential grid instability. Research has shown that integrating wind power with V2G systems can address these issues. In scenarios where V2G is not utilized, direct wind power connection to the grid results in undesirable voltage, current, and power waveforms, leading to instability. However, by incorporating EVs, excess energy generated during high wind periods can be stored in EV batteries and released back into the grid during low wind periods, thereby smoothing power fluctuations and enhancing grid stability. Solar energy, derived from photovoltaic (PV) cells, is another crucial renewable resource [2]. Its reliance on solar radiation, which varies with weather conditions and time of day, presents challenges in maintaining a stable power supply when directly integrated into the grid. The integration of solar power with V2G systems offers a viable solution to these challenges. By storing surplus solar energy in EV batteries, the system can ensure a continuous power supply even during periods of low solar activity. Advanced control strategies, including PID controllers and DC-DC bidirectional converters, can regulate the variable DC supply from PV cells, ensuring a stable and reliable power output to the grid. This integration not only stabilizes the grid but also maximizes the use of solar energy, reducing reliance on fossil fuels. Combining wind and solar power in a hybrid system leverages the complementary nature of these resources, providing a more reliable and consistent power supply [3]. Hybrid systems are especially effective in regions with high wind and solar potential, ensuring a balanced power output. In hybrid power integration scenarios, energy from wind and solar sources is managed together, with EVs providing additional storage and buffering capabilities. DC-DC bidirectional converters play a critical role in regulating power flow, while RLC filters help reduce harmonics in the inverter output, resulting in improved power quality. This integrated approach enhances the reliability of the power supply and optimizes the use of renewable energy sources [4].

The integration of renewable energy sources into existing power grids presents several challenges, primarily due to the intermittent nature of wind and solar power, which can lead to variability in power output and grid instability. The lack of effective energy storage solutions further complicates these challenges, as excess energy generated during peak production periods cannot be efficiently stored and used during low production times. V2G systems offer a promising solution by providing dynamic and flexible energy storage. EVs, with their large battery capacities, can store surplus energy during periods of high renewable production and return it to the grid during low production periods. This bidirectional energy flow helps balance supply and demand, reducing the impact of variability and ensuring a stable power supply. The use of advanced power electronics, such as DC-DC bidirectional converters and RLC filters, enhances the effectiveness of V2G systems by regulating power flow, managing voltage fluctuations, and reducing harmonics, thereby contributing to overall grid stability and power quality[5]. The successful integration of V2G systems with renewable energy sources holds significant implications for future energy systems. By enhancing grid stability and improving the reliability of power supply, V2G systems can facilitate the large-scale deployment of renewable energy, supporting the transition to a sustainable and low-carbon energy future. Policymakers and industry stakeholders should prioritize the development and deployment of V2G infrastructure as a key strategy in achieving renewable energy goals. Future research should focus on optimizing V2G systems and exploring their integration with other renewable energy sources, such as tidal and geothermal energy[6-7]. Advancements in battery technology and energy storage solutions will also be crucial in enhancing the effectiveness of V2G systems, along with the development of smart grid technologies and real-time energy management systems to ensure efficient and reliable V2G operation.

II. VEHICLE-TO-GRID (V2G) OPTIMAL SCHEDULING FOR RENEWABLE POWER INTEGRATION

The optimal scheduling of the power system is analyzed through three different scenarios: Wind Power Integration, Solar Power Integration, and Hybrid Power Integration. Vehicle-to-Grid (V2G) technology allows energy to be transferred back to the power grid from the battery of an electric vehicle (EV). This system enables the charging and discharging of a car battery based on various signals, such as local energy production or consumption[8].

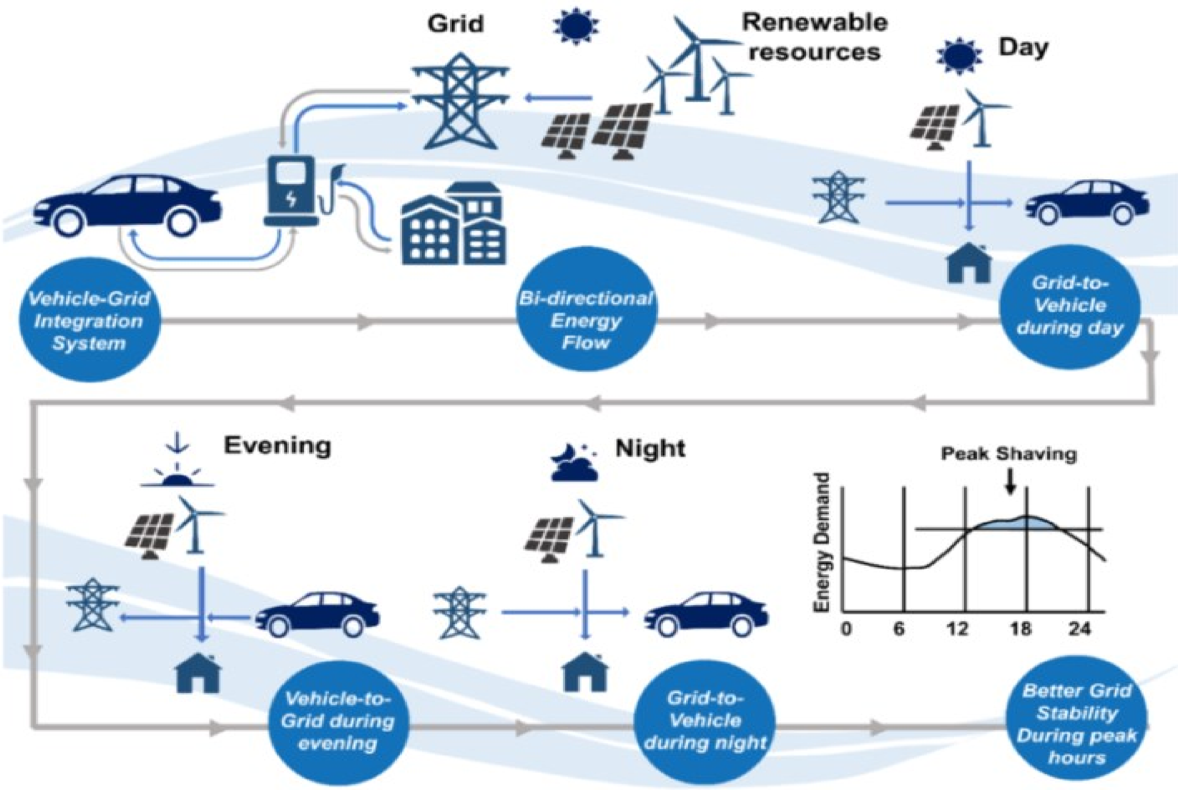

Fig.1 : Diagram of Vehicle to Grid (V2G) technology

The broader concept, known as Vehicle-to-Everything (V2X), includes several use cases like Vehicle-to-Home (V2H), Vehicle-to-Building (V2B), and Vehicle-to-Grid (V2G). The specific abbreviation used depends on whether the electricity from the EV battery is powering home appliances, building systems, or feeding back into the grid. This means that even when not connected to the grid, your vehicle can still offer value. The principle of V2G is similar to that of smart charging, or V1G charging, which allows for the controlled charging of electric vehicles with the ability to adjust charging power as necessary. V2G extends this concept by allowing the energy stored in car batteries to be returned to the grid, helping to balance fluctuations in energy supply and demand.

A. *Wind Power Integration with EV*

Integrating wind energy with electric vehicles (EVs) offers a promising solution to several challenges in both the energy and transportation sectors. This combination not only supports the adoption of renewable energy but also helps reduce greenhouse gas emissions and reliance on fossil fuels. In this context, we examine the advantages, challenges, and potential strategies for effectively integrating wind energy with electric vehicles. Power generation from wind energy is influenced by factors such as wind speed, generator speed, and pitch angle. Directly connecting wind-generated power to the grid can lead to grid instability due to fluctuations in these wind parameters. Low wind speeds and gusts can cause significant power variations, potentially leading to grid collapse. To address these fluctuations, integrating wind power with electric vehicles (EVs) provides a solution. When there is an excess or deficit in wind energy supply, EVs can store the energy in their batteries, thanks to the use of bidirectional converters. These converters regulate the power flow by switching between two modes: buck (for reducing voltage) and boost (for increasing voltage), ensuring a stable and consistent power supply[9].

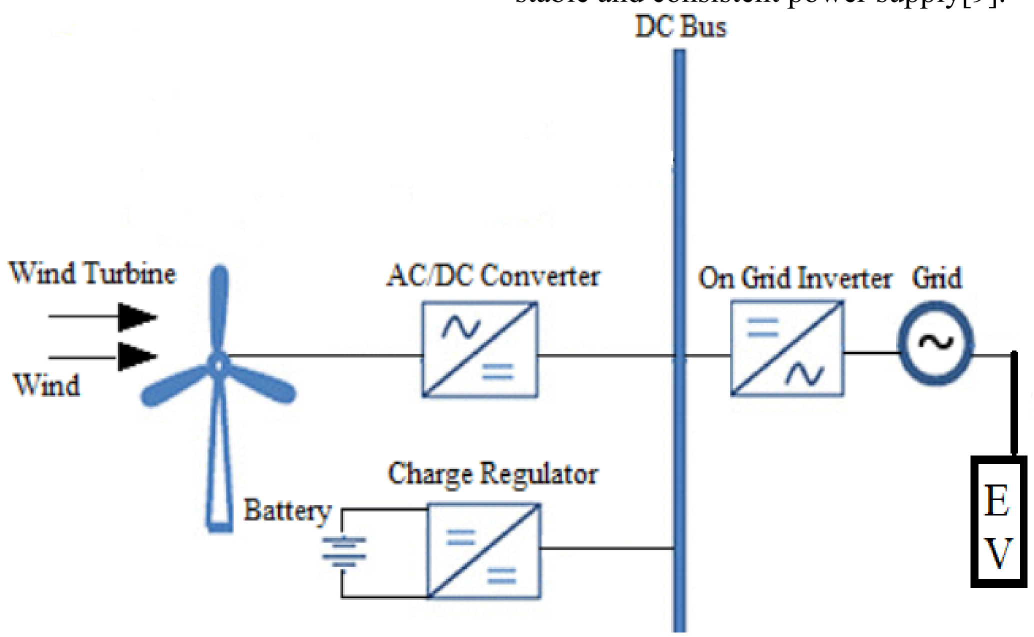

Fig.2 : Representation of Wind Power Integration with EV

When there is a high power output from wind energy, the excess power can be stored in the battery's supercapacitor, and only the necessary amount is sent to the

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grid. Conversely, when wind power supply is low, energy stored in the battery's capacitor can be drawn upon and supplied to the grid. Wind power generated through a permanent magnet synchronous generator (PMSG) produces AC power, which is then rectified to DC power as showin fig.2. This DC power is fed into a load-balancing storage device, specifically a DC link capacitor, to minimize voltage fluctuations. The DC supply is then converted back into AC power using inverters. However, this AC power may contain harmonics. To address this, RLC filters are employed to filter out and tune harmonics, removing any unwanted oscillations, noise, and distortions. The resulting smooth AC supply is then fed into the grid, which distributes it to consumers.

B. *Solar Integration with EV*

The PV source is composed of PV cells, which need to be modeled individually to create a PV module, and then combined into a PV array to achieve the desired power and voltage levels. Figure 3 illustrates the general equivalent circuit of a PV cell, which includes a current source paired with a reverse-blocking diode. The circuit also contains a photocurrent (Iph), which is influenced by temperature and irradiation. The series resistance represents the internal resistance through which the current (I) flows, while the shunt resistance accounts for the leakage current (Ish). The equations governing the load current, photocurrent, and other related parameters are provided below[10-11].

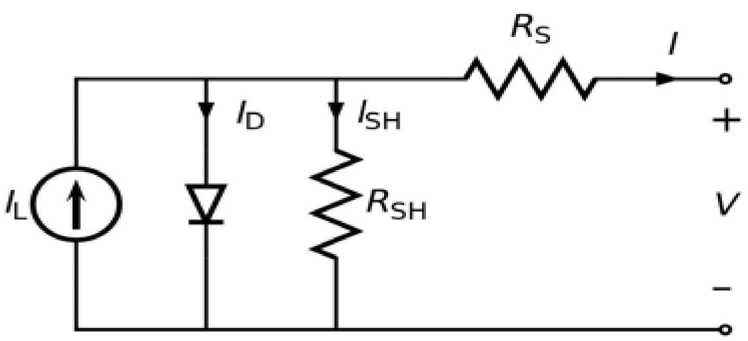

Fig.3 :Equivalent circuit of solar PV cell

$$I=I_{ph}-I_o-I_{sh}$$

$$I_{ph}=[I_{sc}+K_i(T_k-T)]\times\frac{G}{1000}$$

$$I_{RS}=\frac{Isc}{\exp\,(q\times Voc\div Ns\times K\times A\times T)-1}$$

$$I_o=I_{RS}\left[\frac{T}{Tr}\right]^3\exp\left[\frac{q\times E0}{Ak}\left\{\frac{1}{Tr}-\frac{1}{T}\right\}\right]$$

$$I_{pv}=N_p\times I_{ph}\times N_p\times I_0\left[\exp\left\{\frac{q\times Vpv+Ipv\times Rse}{Ns\times Akt}\right\}-1\right]$$

Where, Ipv is the solar cell module current in (A), Io is the reverse saturation current of diode in (A), Ish is the leakage current in (A), Vpv is the diode voltage in (V), Voc is the open circuit voltage in (V), Rse is the series resistance in (Ω), Rsh is the shunt resistance in (Ω), Isc is the short circuit current in (A), q is the electron charge, k is Boltzmann constant, A is the diode ideality factor, T is the temperature of the p-n junction in (Kelvin), IRS is the diode reverse current in (A), NP is number of cells connected in parallel and Ns is number of cells connected in series [17-18]. A solar cell, also known as a photovoltaic (PV) cell, is a device that converts light into electrical current through the photovoltaic effect, as illustrated in Figure 4. The first solar cell was developed by Charles Fritts in the 1880s. Ernst Werner von Siemens, a German industrialist, recognized the significance of this invention.

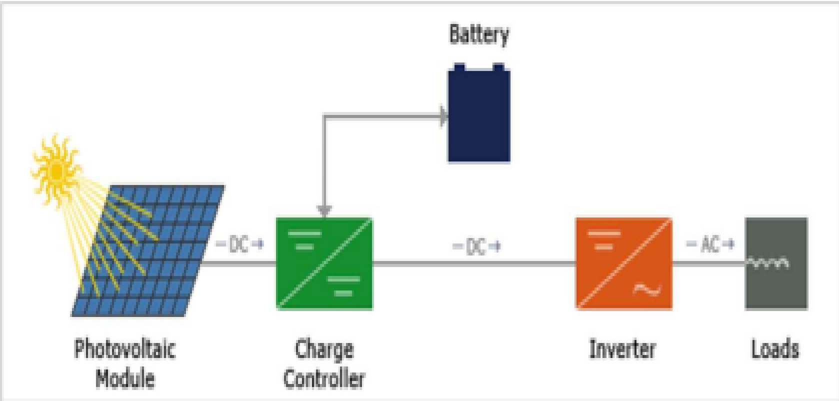

Fig.4 : Representation of solar Power Integration with EV

In 1931, German engineer Bruno Lange created a photocell using silver selenide instead of copper oxide, although the selenium-based cells at that time converted less than 1% of incoming light into electricity. Building on the work of Russell Ohl in the 1940s, researchers Gerald Pearson, Calvin Fuller, and Daryl Chapin developed the silicon solar cell in 1954. These early silicon solar cells had an efficiency of 4.5–6% and cost $286 per watt.

III. VEHICLE TO GRID TECHNOLOGY WITH HYBRID ENERGY STORAGE SYSTEM

V2G, or “vehicle to grid,” is a technology that allows energy to be transferred from an electric car’s battery back to the power grid. With vehicle-to-grid technology, also known as car-to-grid, a car battery can be charged or discharged based on various signals, such as local energy production or consumption[12-13].

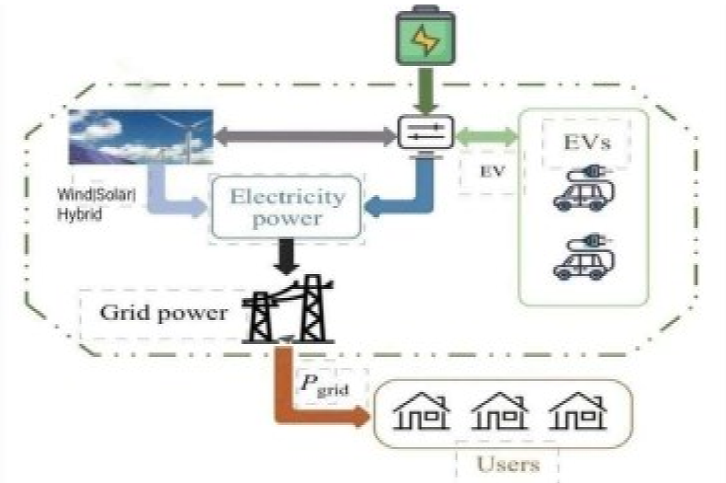

Fig.5: HESS's general framework for integrating renewable source power

In this work, the Hybrid Energy Storage System (HESS) incorporates clusters of electric vehicles (EVs) and supercapacitors (SCs). If EVs cannot fully compensate for fluctuations in renewable energy sources, the supercapacitor steps in to provide additional support. This approach also allows for a small degree of wind and solar curtailment. Figure 5 illustrates the general framework of the HESS for integrating renewable energy sources [14-15].

IV.SIMULATION RESULTS

The outcomes of optimizing the Vehicle-to-Grid (V2G) system and its energy management for renewable power integration are examined across three scenarios:

A. Wind Power Integration

B. Solar Power Integration

C. Hybrid Power Integration (wind & solar)

For Wind Power Integration, two specific scenarios are considered: one without the involvement of EVs and another with EV integration[16-17].

In Case 1, wind power integration is studied without incorporating EVs into the grid. Figure 6 presents the simulation block diagram for this scenario, illustrating wind integration without EV support[18].

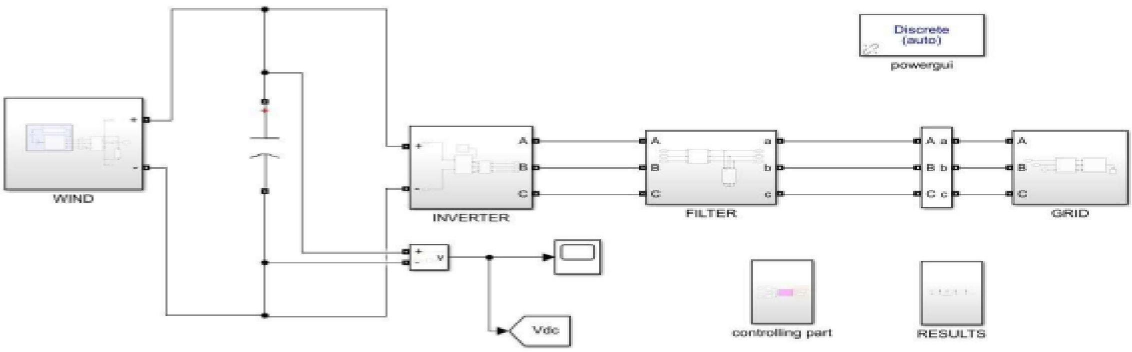

Fig.6: shows the simulation block diagram of wind integrated EV

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In the scenario where wind power is integrated directly into the grid without EV support, fluctuations in wind speed can cause significant issues in the power system. These variations, whether from high or low wind supply, result in unstable waveforms that are not suitable for reliable power delivery to the grid, potentially leading to grid failures. Figure 7 illustrates the resulting voltage and current waveforms from the wind supply, while Figure 8 depicts the voltage levels at the wind source and the DC link.

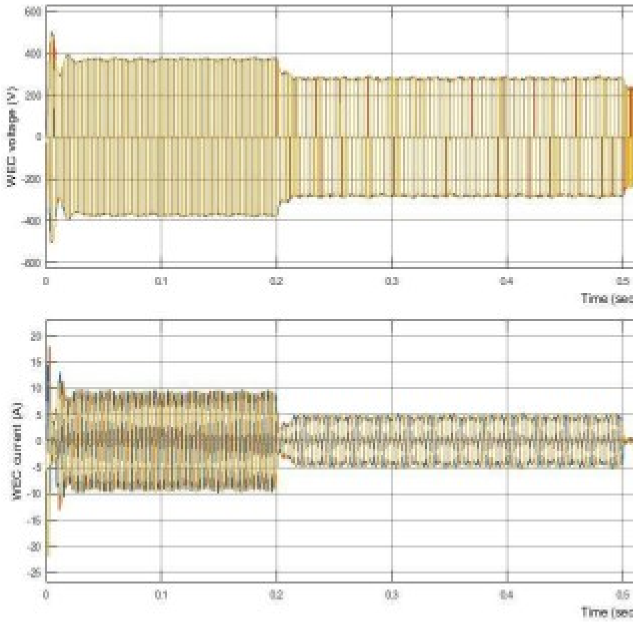

Fig.7: Waveforms of voltage and current at wind without EV

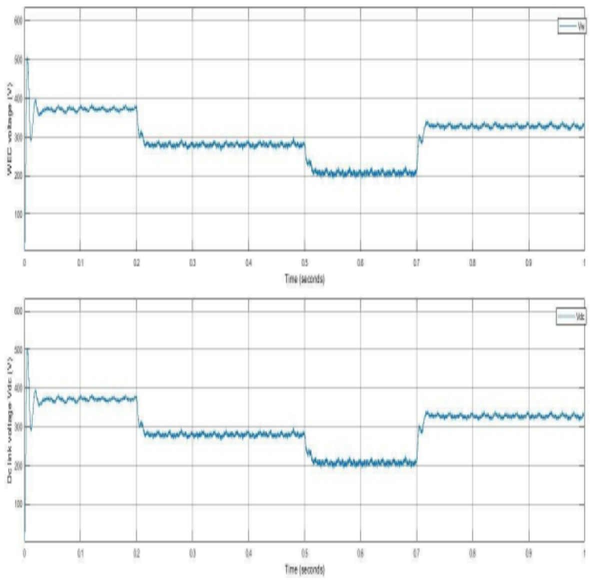

Fig. 8: Waveform of voltage at wind and DC link with EV

Case 2 studied the Solar Power Integration

In the study of solar power integration with electric vehicles (EVs) into the grid, we analyze how solar power combined with EVs can enhance energy management. The power generated from solar panels depends on factors such as solar radiation, the number of cells, series strings, parallel strings, open circuit voltage, short circuit current, maximum power point voltage, maximum power point current, and temperature. Excess energy produced by the PV cells is stored in battery supercapacitors[19]. When sunlight is unavailable or solar output fluctuates, the stored energy in these capacitors ensures a continuous supply. To manage high and low DC supply from the PV cells, PID controllers regulate the system. The DC-DC bidirectional converters, including buck and boost converters, play a crucial role in interfacing between the energy source and load, allowing energy to be stored in batteries. The DC supply is then directed to a DC link, which acts as a balancing storage device. This DC voltage is converted to AC power by an inverter. The resulting AC supply, which may contain harmonics, is filtered using RLC filters to ensure smooth operation. Finally, the inverter synchronizes with the grid, supplying utility electricity for both commercial and residential use. Figure 9 illustrates the block diagram of the solar power integration with EVs to the grid.

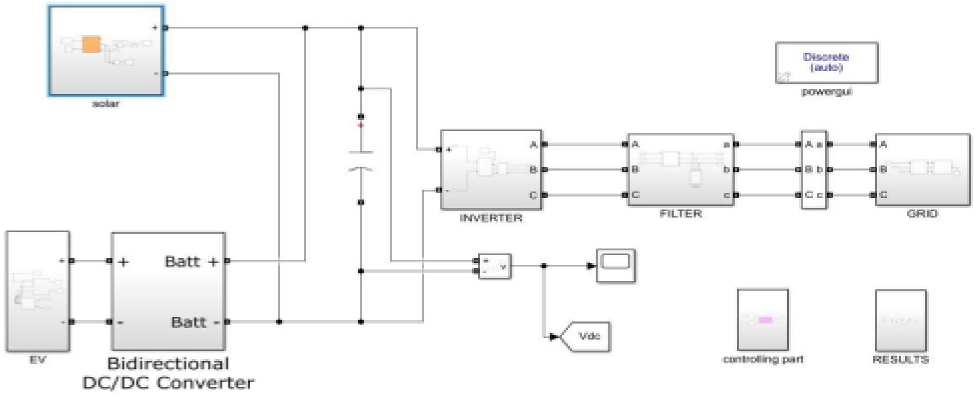

Fig.9: Block Diagram of solar integrated with EV to grid

Now Fig.10 shows the waveforms of voltage and current at solar with EV and

Fig.11shows the voltage waveforms at solar and DC link.

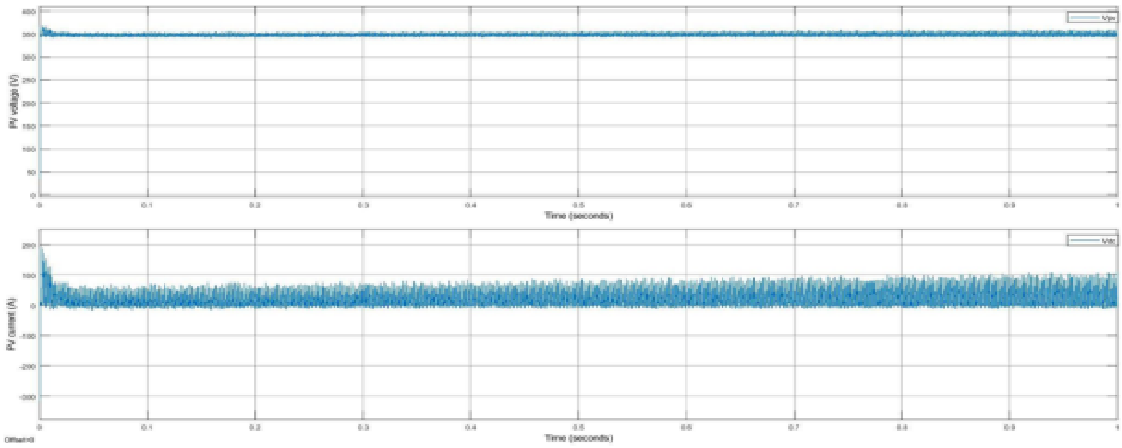

Fig.10 : Waveforms of voltage and current at solar with EV

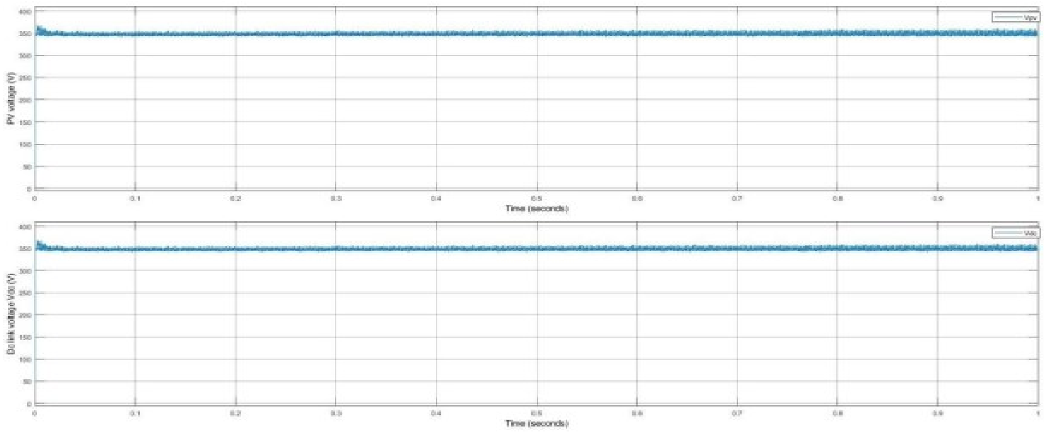

Fig.11: Waveform of voltages at solar

Case -3 studied Hybrid Power Integration

In hybrid power integration, combining wind and solar energy improves both power quality and continuity of supply. Power generated from both wind and solar sources is managed to ensure a stable supply. To prevent grid failures from direct power connections, the substantial power output is integrated with electric vehicles (EVs). The DC supply from this hybrid source is compared and regulated using buck and boost converters through DC-DC bidirectional converters, which store energy in the battery. The DC supply from the battery is then routed to a DC link, which stabilizes voltage and minimizes fluctuations, especially when the inverter requires significant current. The DC power is subsequently converted to AC by the inverter. Any harmonics present in the inverter output are mitigated using RLC filters. The inverter then synchronizes with the grid, providing the required output power for both domestic and commercial use. Figure 12 displays the block diagram of the hybrid power integration with EVs[20].

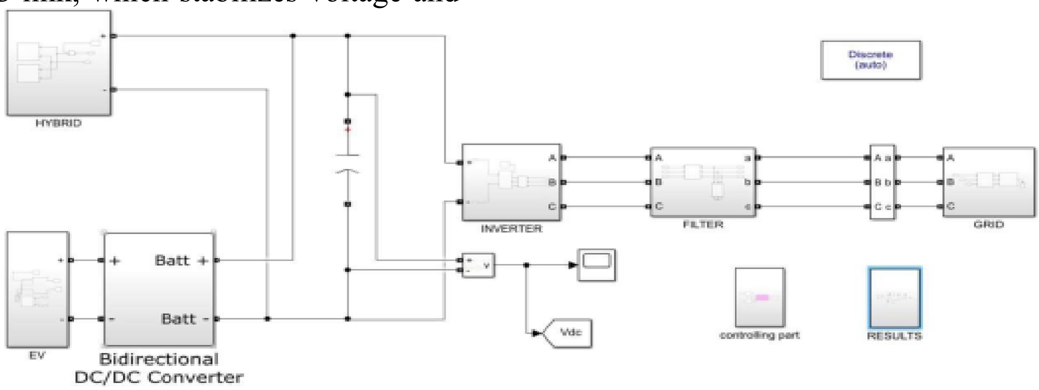

Fig.12: Block Diagram of hybrid integrated with EV to grid

Now, the Fig. 13 and 14 shows the voltage, current and power waveforms of the wind in hybrid integrated with EV to grid.

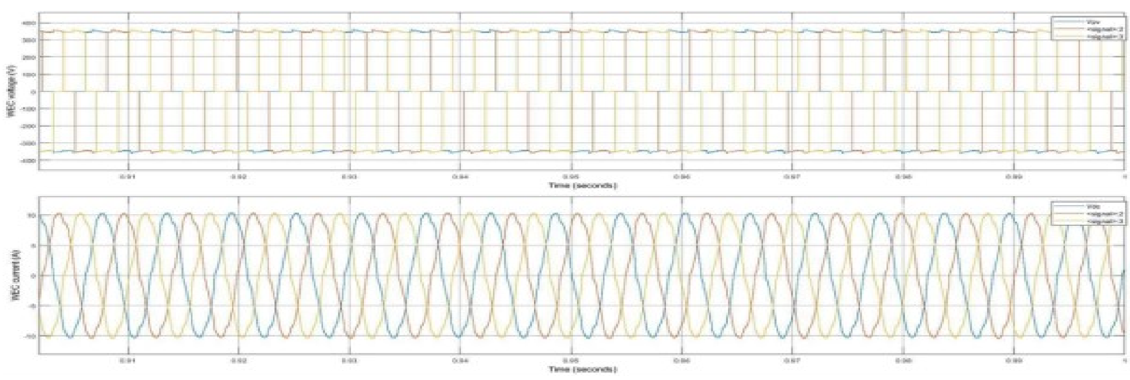

Fig. 13: Waveforms of voltage and current at wind in hybrid integrated with EV to grid.

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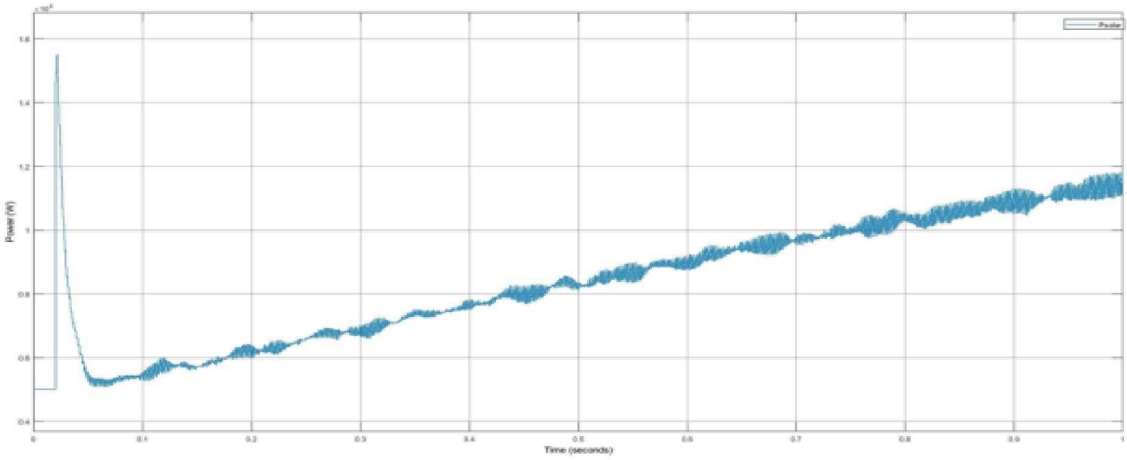

Fig. 14: Waveforms of power at solar in hybrid integrated with EV to grid

Conclusion:

The optimization of Vehicle-to-Grid (V2G) systems in conjunction with renewable power sources like wind, solar, and hybrid, demonstrates considerable benefits in managing energy resources and enhancing grid stability. Each scenario reveals distinct insights into how V2G technology can be leveraged to address challenges associated with renewable energy integration.

Wind Power Integration: Direct integration of wind power into the grid, without the support of electric vehicles (EVs), can lead to significant issues due to the inherent variability in wind speed. These fluctuations can result in unstable power outputs, potentially causing grid failures. However, incorporating EVs into the wind power system offers a practical solution. EVs can absorb excess energy generated during periods of high wind and release it when wind speeds are low, thereby stabilizing the grid and mitigating the adverse effects of power fluctuations.

Solar Power Integration: Solar power integration with EVs improves energy management by storing excess solar energy in battery supercapacitors. This stored energy can be used to provide a continuous and stable power supply during periods of low sunlight or fluctuating solar output. The use of PID controllers, DC-DC bidirectional converters, and RLC filters plays a crucial role in regulating and filtering the power, ensuring smooth integration with the grid. This setup facilitates reliable power delivery for both residential and commercial uses.

Hybrid Power Integration: Combining wind and solar energy with EV support enhances power quality and continuity. The hybrid system effectively manages and balances power supply by storing energy from both sources in batteries. This approach reduces the risk of grid failures and ensures a steady power supply. The use of buck and boost converters, DC links, inverters, and RLC filters optimizes the system by managing voltage fluctuations and reducing harmonics, leading to improved grid stability.

In summary, the integration of V2G systems with renewable energy sources offers a robust framework for addressing the challenges of energy variability and grid stability. These integrations not only enhance the efficiency and reliability of power systems but also contribute to a more sustainable energy future by reducing reliance on fossil fuels and supporting the transition to renewable energy. Continued advancements in technology and control mechanisms will further bolster the effectiveness of these systems, paving the way for a resilient and sustainable energy infrastructure.

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