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Advanced Grid Integration and Energy Management for Vehicle-to-Grid Systems with Hybrid Power Sources

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Abstract: This paper presents a hybrid-based grid integration system for Vehicle-to-Grid (V2G) applications, focusing on efficient energy management and renewable power utilization. The system integrates hybrid energy sources, such as solar and wind, with an electric vehicle (EV) battery through a bidirectional DC-DC converter to facilitate seamless power exchange. The inverter is employed to convert DC power from hybrid system and EV battery into AC power, which is then filtered using an LC filter before connecting to the grid. MATLAB 2018a software is used to simulate the entire system, ensuring optimal power flow, voltage regulation, and grid stability. The proposed architecture offers a sustainable solution for V2G systems by utilizing renewable energy sources to reduce grid dependency and enhance overall system performance. The simulation results demonstrate the system’s effectiveness in managing energy flow, supporting renewable integration, and improving grid resilience.

Keywords: Hybrid system, Electric vehicle, Battery, Bidirectional converter, Inverter, Filters, Micro grid

1. Introduction

The growing demand of energy has led to the overuse of non-RES such as coal, natural gas, and oil. These conventional energy sources are not only depleting rapidly but also contribute significantly to environmental pollution through greenhouse gas emissions. The heavy reliance on fossil fuels has raised concerns over global warming, climate change, and energy security. As a result, the need to transition towards cleaner and more sustainable energy solutions has become more critical than ever before [1].

RES such as solar and wind power have developed as promising alternatives to non-renewable energy, offering the advantages of sustainability, reduced carbon emissions, and an inexhaustible supply. Solar energy, harnessed from sunlight, and wind energy, derived from atmospheric airflows, have shown great potential in powering homes, industries, and transportation. However, [2-4] integrating these renewable sources into the grid has presented challenges due to their intermittent nature and variable power output. This led to various energy management strategies to stabilize the grid and optimize power flow [5].

Previous methods have typically integrated solar and wind energy separately into grid systems, each requiring dedicated converters and control systems. This separation has increased system complexity and costs, while also making it difficult to achieve an optimal energy management strategy [6,7]. Moreover, the lack of coordination between these renewable sources can lead to inefficiencies in power generation, underutilization of available resources, and challenges in grid stability. These limitations in existing methods underscore the need for more advanced and unified approaches to renewable energy integration [8-10].

This paper introduces a hybrid system that integrates both solar and wind power into a unified energy management framework for V2G applications. By leveraging the strengths of both energy sources, the hybrid system provides a more reliable and stable power supply. Utilizing a bidirectional DC-DC converter and an inverter, it efficiently controls power flow between electric vehicles and the grid. The proposed architecture is designed to decrease reliance on fossil fuels, improve energy efficiency, and enable the seamless integration of renewable energy sources into the grid.

The hybrid system presented in this study has several advantages over existing methods [14]. By combining solar and wind power, the system ensures continuous energy availability even when one source is underperforming due to weather conditions. The integration of an EV battery further enhances the system’s energy storage capabilities, enabling better load management and grid support. Additionally, the use of MATLAB 2018a for simulation provides insights into the system's performance, demonstrating improved grid stability, optimized energy management, and greater resilience compared to conventional methods. This paper targets to showcase the benefits of hybrid renewable energy integration for V2G systems and contribute to the development of sustainable energy infrastructures.

The following sections includes: Section I Introduction, which provides an overview of the study’s background and objectives; Section II System Description, detailing the components and architecture of the proposed electric vehicle system; Section III Proposed Method, outlining the integration of Hybrid systems technology.Section IV Results and Discussion, presenting and analysing the outcomes of the implementation and Simulations; and Section VI Conclusion, shows key outcomes and contributions of the study.

2. System Description

The proposed system integrates hybrid RES, namely solar and wind power, with a V2G system to achieve efficient energy management and grid integration [15]. The system is designed to facilitate bidirectional power interchange b/wEVs and grid while ensuring a reliable and sustainable energy supply by incorporating renewable energy [16, 17].

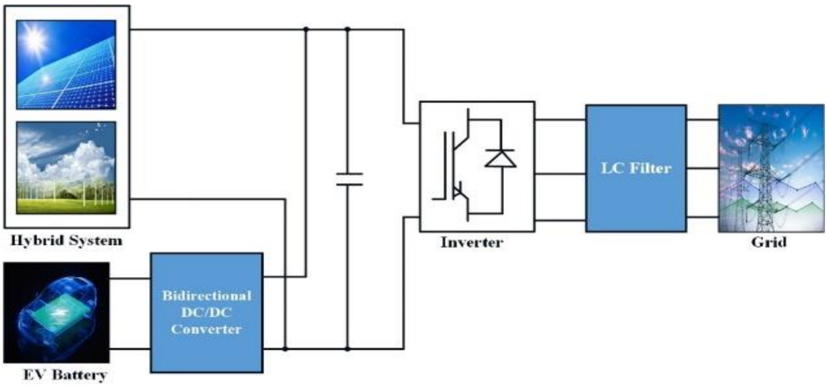

Fig.1 proposed block diagram

A) Hybrid Renewable Energy System: The hybrid system contains of solar and wind power generation units. Solar panels capture energy from sunlight, while wind turbines harness kinetic energy from the wind. These two sources complement each other; when solar energy is insufficient (e.g., during night time or cloudy conditions), wind power can contribute to maintaining a steady energy supply. The hybrid system thus provides a continuous source of renewable energy, reducing dependency on non-renewable sources and enhancing overall system efficiency.

Bi-directional DC-DC Converter: The energy generated by hybrid system and the energy stored in the EV battery are managed through a bi-directional DC-DC converter. This converter regulates the power flow between hybrid system and EV battery, allowing energy to be stored in the battery when surplus power is available or drawn from the battery when additional power is required by the grid. The bidirectional nature of the converter ensures that power can flow in both directions, supporting the V2G system's capability of both charging the EV and discharging power back to the grid.

Inverter: The DC power generated by the hybrid RES and stored in EV battery needs to be converted into AC to be compatible with the grid. The inverter performs this conversion by turning DC power into AC. The inverter is a crucial component for ensuring the system's compatibility with the grid and other AC-powered devices. Additionally, it supports the synchronization of the power output with the grid frequency to ensure stability during power transmission.

LC Filter: Before connecting the power output to the grid, it passes through an LC filter, which consists of inductors (L) and capacitors (C). The purpose of the LC filter is to smooth the AC waveform generated by the inverter, removing any noise or harmonic distortions. This ensures that the power delivered to the grid meets the required quality standards and reduces any potential disturbances to grid operation.

Grid Integration: The final stage of the system connects the hybrid energy sources, managed through the bi-directional DC-DC converter and inverter, to grid. This bi-directional integration allows for energy to flow from the hybrid system and EV battery to grid when there is excess renewable generation, as well as from grid to EV battery when needed. The system is designed to improve grid stability, support renewable energy integration, and enable effective energy management through V2G technology.

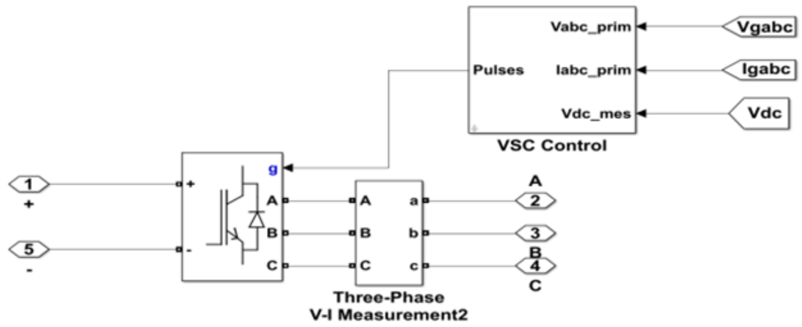

Fig.2 Voltage source converter controlling for the Inverter

Voltage Source Converter (VSC) Design for Inverter Control

The VSC plays a critical role in controlling the transformation of DC power from the hybrid renewable system and EV battery into AC power for grid integration. It generates PWM signals to regulate the switching of IGBTs or MOSFETs within the inverter. These switching signals enable precise control over the output voltage, frequency, and phase to ensure that the inverter's AC output is synchronized with the grid. The VSC uses a DC link capacitor to stabilize the input voltage and smooth out fluctuations in the DC supply, ensuring steady operation.

In the design process, the PWM controller inside the VSC compares the reference AC signal (which matches grid specifications) with a triangular carrier wave to produce the gating signals required for the inverter switches. The modulation index is carefully controlled to control the inverter's output voltage and maintains a correct power factor. By managing these switching events, the VSC allows for efficient bi-directional power flow, supporting both G2V and V2G operations, ensuring optimal energy transfer and grid stability.

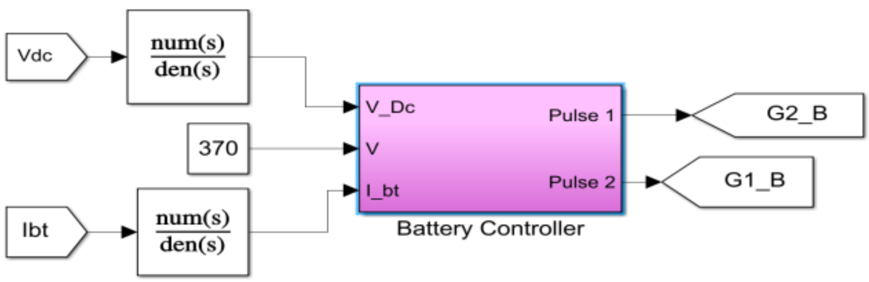

Fig.3 controlling of the bidirectional converter

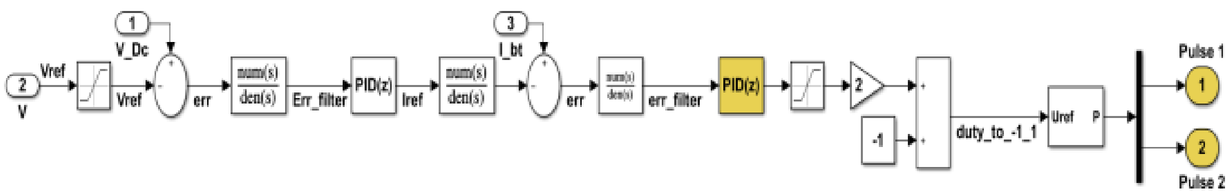

Fig.4 controlling of battery controller

The control approach for bi-directional DC-DC converter in electric vehicle system starts by monitoring key variables, namely the DC bus voltage (Vdc) and battery current (Ibt). The DC bus voltage is compared to a reference voltage (Vref), producing an error signal that reflects the difference b/w the actual and target voltage values. This error signal is then filtered to eliminate noise and processed through a PID controller. The PID controller is essential in fine-tuning the system's voltage, working to reduce the voltage error by dynamically adjusting the reference current (Iref), which is later applied in the current control loop.

In current control loop, the reference current (Iref), derived from the voltage loop, is compared with the sensed battery current (Ibt). This comparison generates another error signal, indicating the difference between the target and actual battery current levels. Similar to the previous step, this error is filtered and processed through a second PID controller, which fine-tunes the system to achieve the desired current levels. The output from this PID controller is transformed into a duty cycle, which is carefully constrained between -1 and 1 to ensure safe and efficient operation of the converter.

Finally, the computed duty cycle is converted into PWM signals, producing Pulse 1 and Pulse 2 for the bidirectional converter. These pulses are critical for managing the power flow b/wEVs battery and DC bus, enabling seamless energy transfer whether the system is in charging or discharging mode. This comprehensive control strategy facilitates precise regulation of both voltage and current, ensuring stable performance and optimizing the energy management of the electric vehicle system.

Table-1 Parameter Values

S.no	Parameter name	Parameter value
1	PV Voltage	350V
2	PV Current	50A
3	Nominal Voltage	220V
4	Rated capacity	5.4Ah
5	SOC%	50
6	WEC Voltage	350V
7	WEC Current	10.5
8	DC link voltage (Vdc)	350V
9	Grid output voltage	230V
10	Grid output Current	10A

3. Proposed Method

The proposed method introduces a hybrid RES that combines solar and wind power to improve energy generation efficiency and reliability.

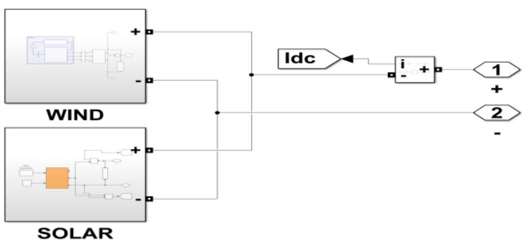

Fig.5 Hybrid system

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Unlike traditional systems that rely solely on either solar or wind energy, this hybrid approach takes advantage of the complementary characteristics of both sources. Solar power production generally peaks during daylight hours, while wind energy can be generated at different times, including at night or under cloudy conditions. By integrating these two sources, the hybrid system delivers a more stable and consistent power output, effectively mitigating the intermittency challenges typically faced by standalone solar or wind systems.

In this system, solar panels and wind turbines operate together to generate electricity, which is managed by a smart controller that regulates power distribution to the grid and battery storage. This setup permits extra energy produced during topmost generation periods to be stored for future usage, reducing reliance on non-renewable energy sources during times of low solar or wind activity. The integration of battery storage is essential for maintaining a continuous power supply, enabling the hybrid system to store surplus energy and release it when renewable generation is insufficient, ensuring a stable and reliable power output.

The proposed hybrid system also utilizes advanced control algorithms that optimize energy generation and distribution. These algorithms adjust for changes in solar irradiance, wind speed, and grid demand, ensuring efficient energy management. Additionally, the hybrid system helps lower greenhouse gas emissions by reducing dependency on fossil fuels, supporting global initiatives for cleaner energy and sustainable practices. Overall, this hybrid system enhances energy resilienceand promotes greater sustainability compared to conventional RES.

4. Results and Discussion

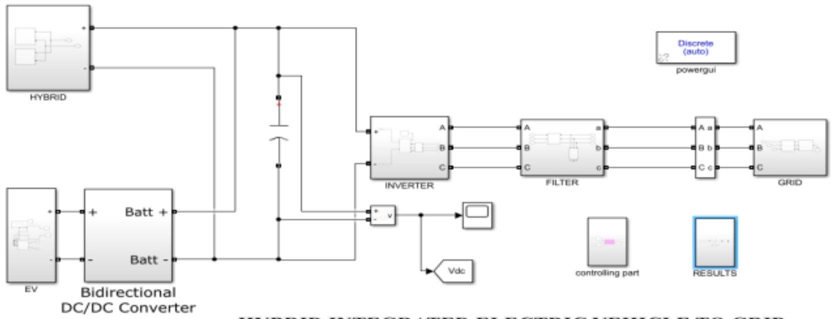


Fig: 6 Simulation Diagram of Proposed Hybrid integration System with vehicle to grid configuration

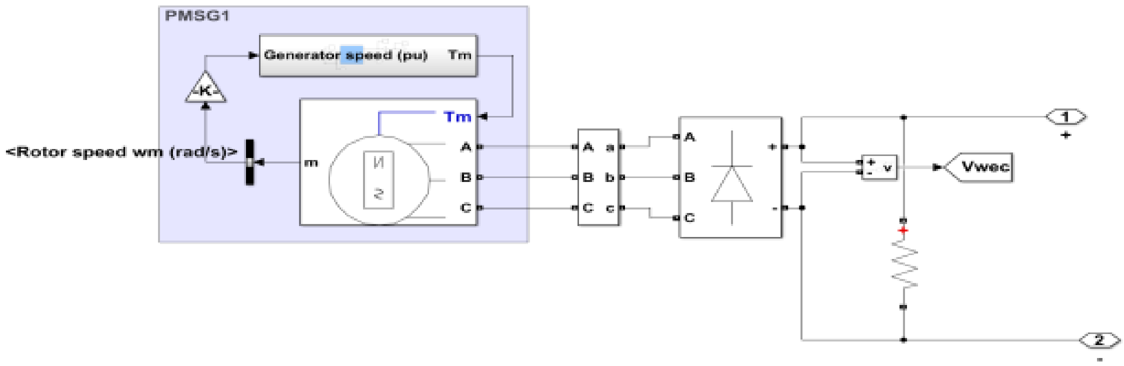


Fig.7 simulation model of wind

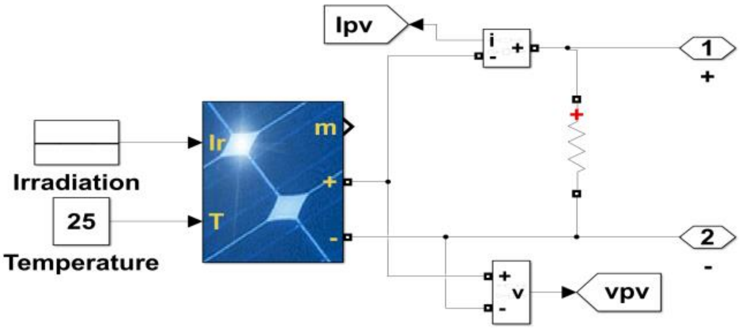
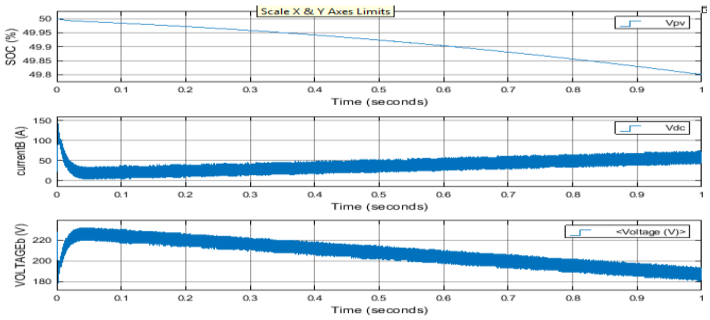


Fig.8 simulation model of solar

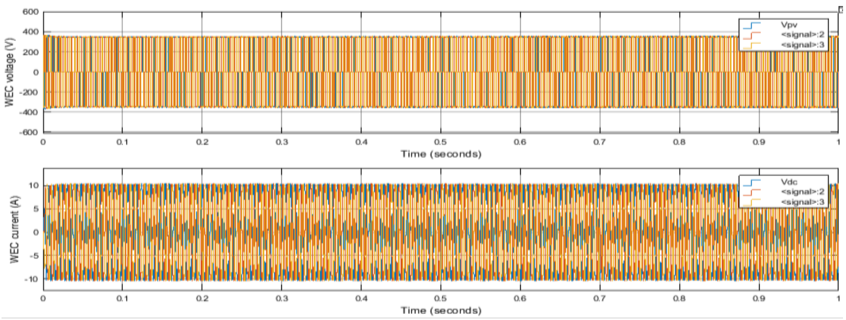
Figure 6 illustrates a simulation of integrating a hybrid wind and solar system with a V2G setup through an inverter. This setup enables bi-directional power flow b/w the grid, hybrid sources, and electric vehicles. Surplus hybrid power can be used to charge EVs during low demand and discharge energy back to grid when required. An inverter plays a key role in managing power flow and ensuring system compatibility, enhancing renewable energy utilization and promoting grid stability.

Vehicle to Grid Operation under Hybrid Integrated System (Solar, Wind)

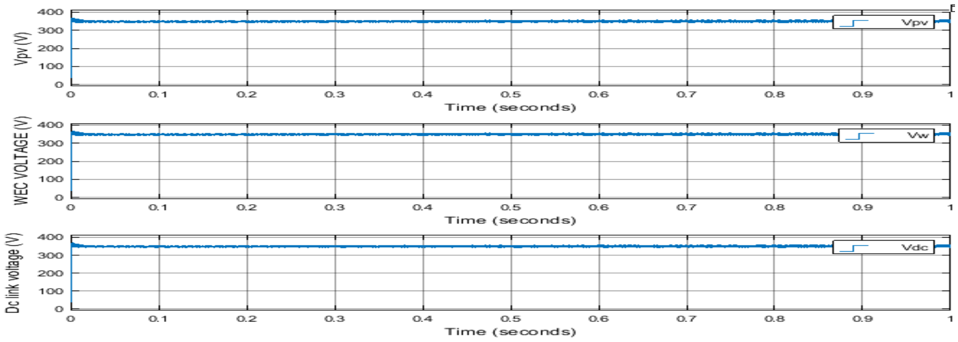
The proposed V2G operation is tested within a hybrid integrated system. The overall system results include battery voltage, current, battery power, and %SOC, as well as wind side voltage, wind power, and current. Additionally, solar side voltage (Vpv), solar power, and DC link voltage are examined. Furthermore, inverter side voltage, inverter active power, and current are evaluated, along with grid side voltage, current, and grid active power. Analysing these responses facilitates a deeper understanding of the system's behaviour within a hybrid setup integrated with vehicle-to-grid functionality.



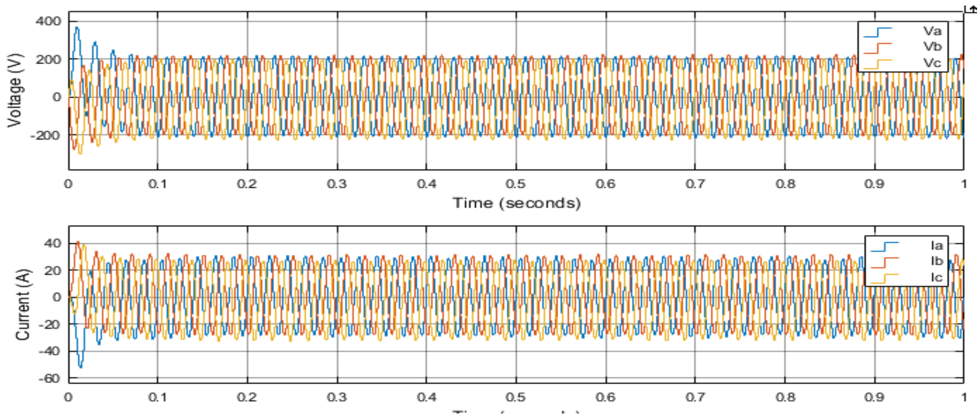
A) Battery voltage, current and SOC



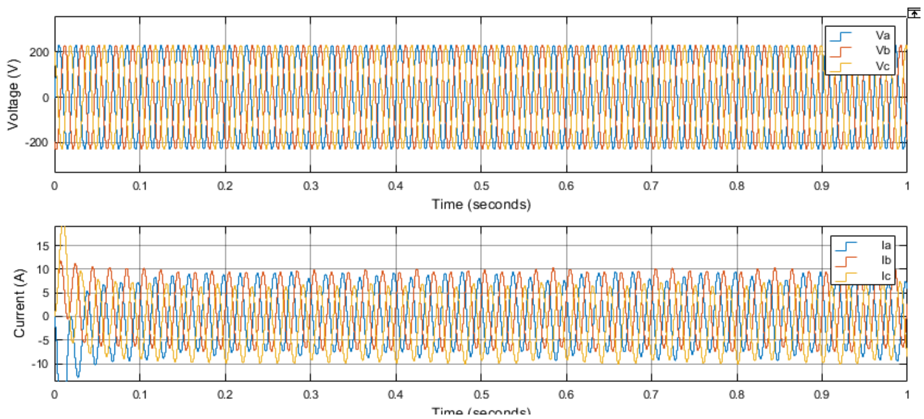
B) Wind side voltage and current



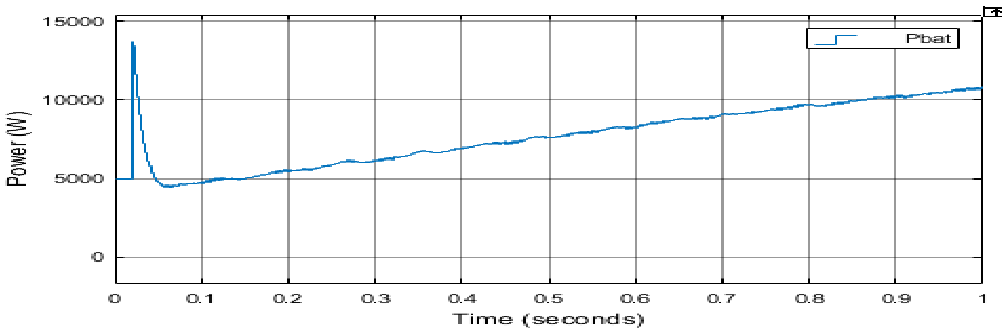
C). Voltage of wind, Voltage of solar and Voltage of dc link



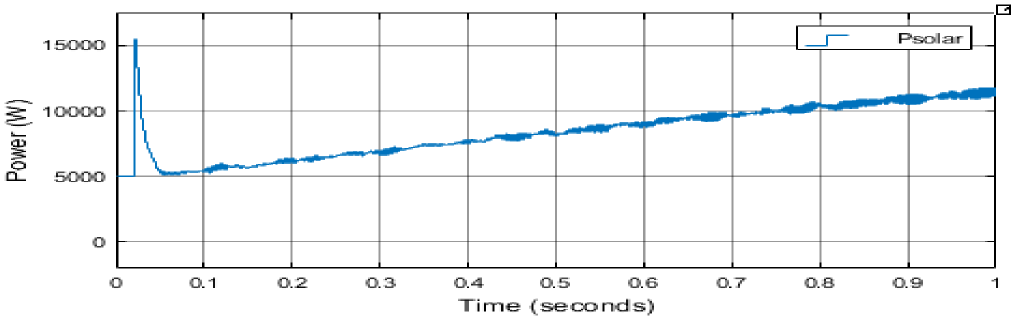
D).Inverter side voltage and current



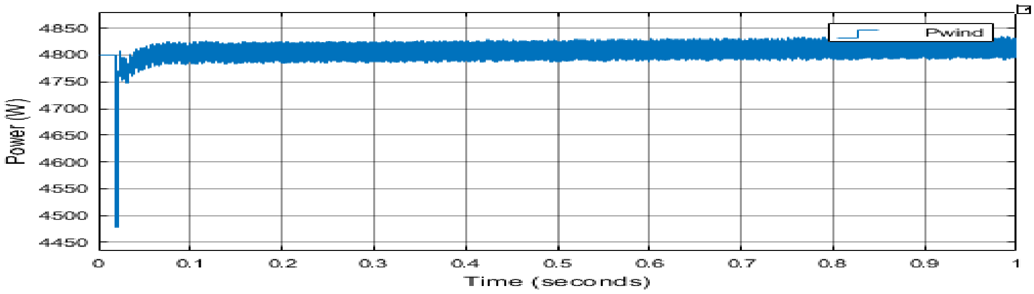
E). voltage and current of Grid side



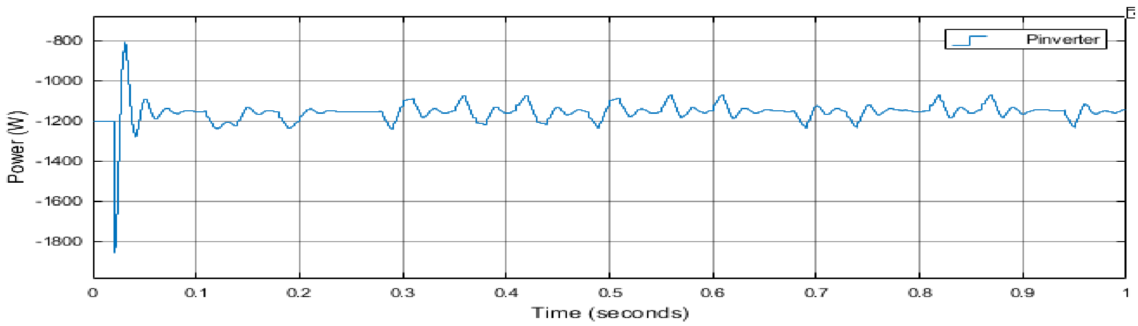
F).Battery power



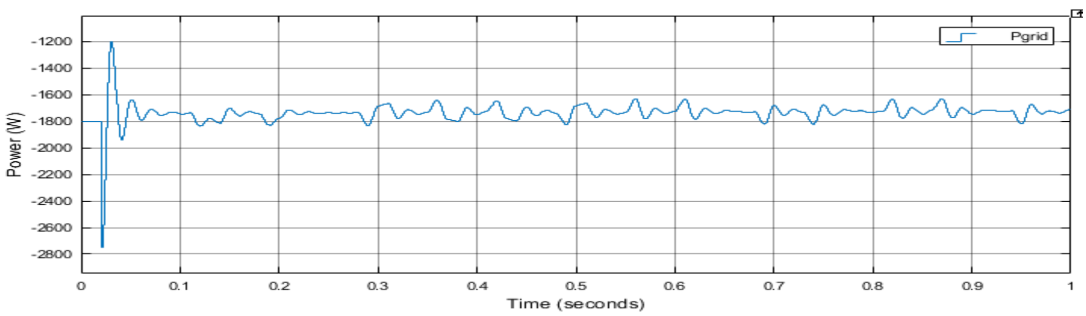
G).Solar power



H).Wind power



I).Inverter active power

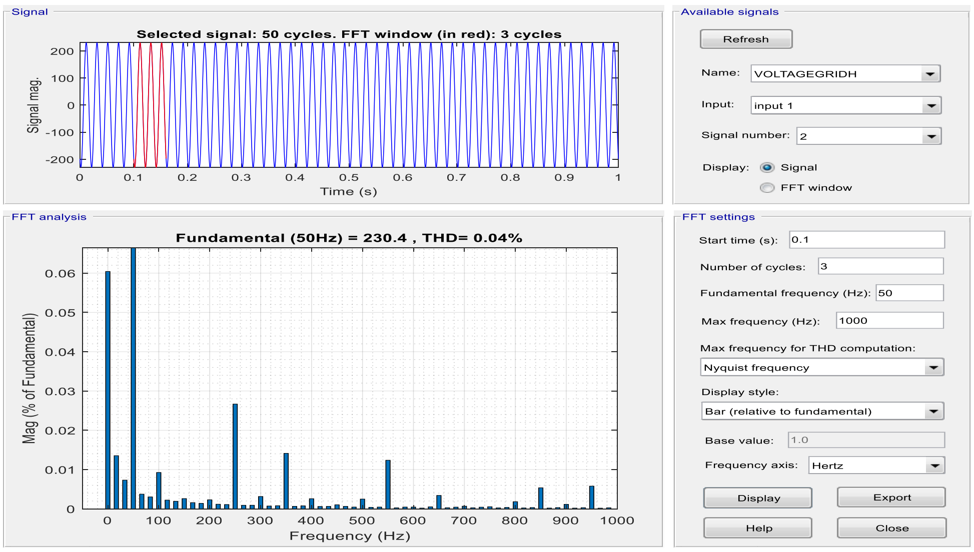


J). Grid active power

Figure 9: Results of proposed hybrid system with Vehicle to grid A) Battery current, voltage, and state of charge (SOC). B) Wind side voltage and current. C) Wind side voltage (WECV), solar side voltage (Vpv), and DC link voltage. D) Inverter side voltage and current. E) Voltage and current of Grid side. F) Battery power. G) Solar power. H) Wind power. I) Inverter active power. J) Grid active power.

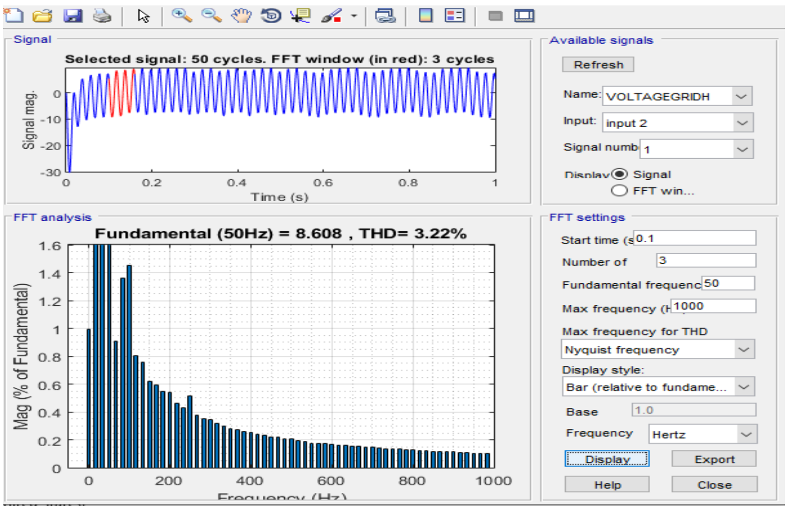
The hybrid system is connected to the V2G setup. The results shown in Figure 9 illustrate the simulation outcomes from the operation of this system.

Fig 9A: It illustrates the behaviour of the electric vehicle battery
Fig 9B: It shows the behaviour of the wind system
Fig 9C: It demonstrates the behaviour of the wind, solar, and DC link voltages
Fig 9D: It displays the behaviour of the inverter voltage and current
Fig 9E: It exhibits the behaviour of the grid voltage and current
Fig 9F: It presents the electric vehicle battery power
Fig 9G: It showcases the solar power
Fig 9H: It reveals the wind power
Fig 9I: It indicates the inverter active power
Fig 9J: It demonstrates the grid active power

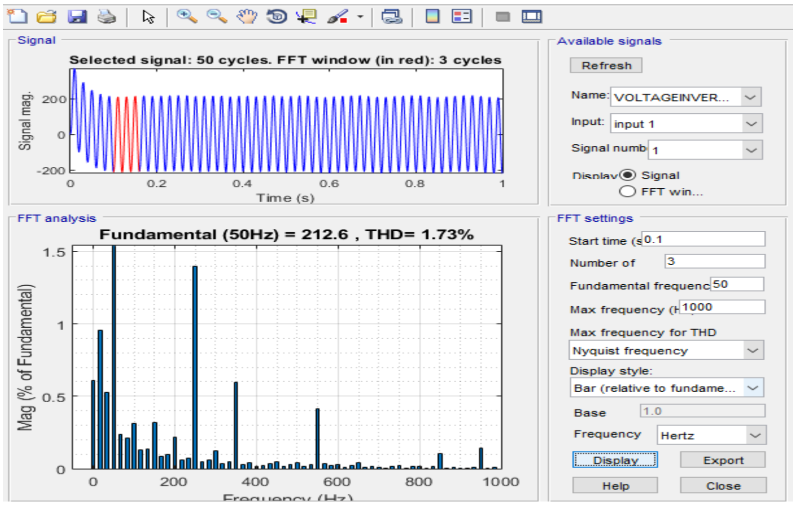


A) THD of Grid Voltage

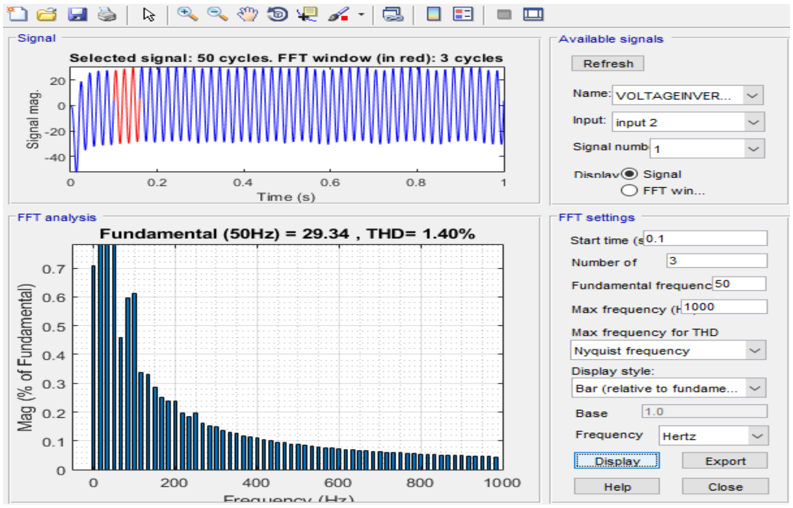
B)



B) THD of Grid Current



C) Inverter Voltage THD



D) THD of Inverter Current

Figure 10: presents the THD analysis of the grid and inverter current and voltage.

Analysing these results provides valuable insights into the behaviour and performance of hybrid system within the context of vehicle-to-grid integration, aiding in optimizing system operation and enhancing overall efficiency.

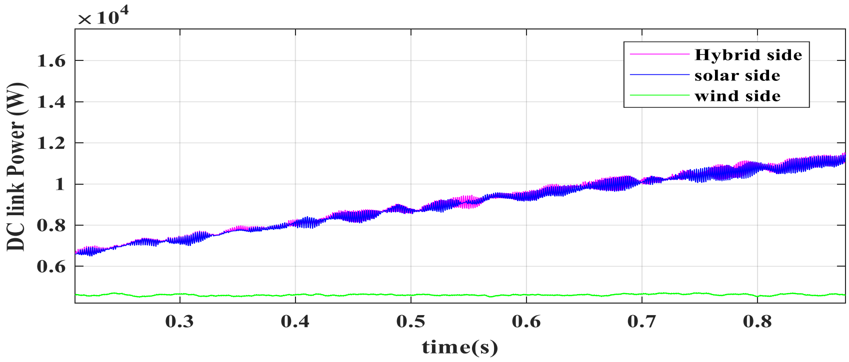
Total Harmonic Distortion (THD) Analysis

THD analysis involves assessing the level of harmonic distortion present in a system. It measures the extent to which the harmonics of a waveform deviate from its fundamental frequency. THD analysis is crucial in various applications, including power systems, audio engineering, and telecommunications, as excessive harmonic distortion can degrade performance and cause interference.

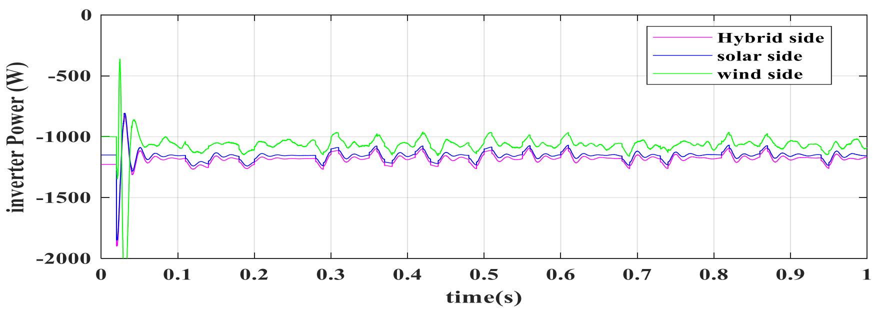
Figure 10A depicts the percentage of THD in grid voltage when the hybrid system is integrated with V2G technology. In Figure 10B, we observe the percentage of THD in grid current under the same integration scenario. Moving to Figure 10C, it shows the THD percentage in inverter voltage with the hybrid system integrated into V2G technology. Lastly, Figure 10D illustrates the percentage of THD in inverter current under the same conditions of hybrid system integration with V2G technology. These analyses provide insights into the quality of voltage and current signals in the grid and inverter, aiding in the assessment of system performance and stability.

Comparison of the Power generated by wind, solar and hybrid integration Vehicle to grid condition:

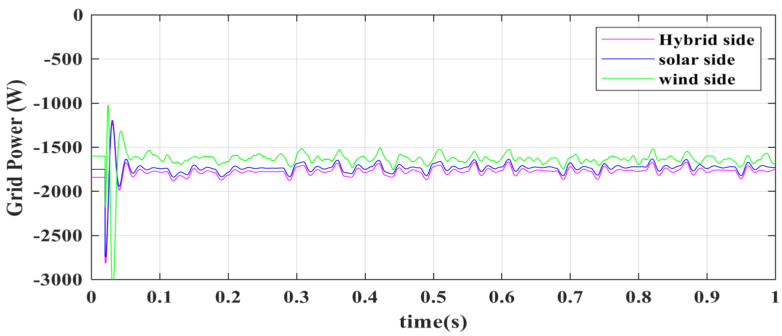
The power generation values for three vehicle-to-grid conditions—wind integration, solar integration, and hybrid integration of the system are presented in proposed method. It outlines the power generated at the DC link, inverter, and grid.



a) Dc link power



b) Inverter power



c). Grid power

Figure 11 illustrates a comparison of the power generated by wind, solar, and hybrid integration, depicting: a) DC link power, b) inverter output power, and c) grid power.

In Figure 11a, the DC link powers obtained from wind, solar, and hybrid systems integrated into the vehicle-to-grid system are depicted. Figure 11b displays the inverter powers obtained from these systems, while Figure 10c illustrates the grid power obtained from wind, solar, and hybrid systems. These figures provide insights into the power generation capabilities of each integration scenario within the vehicle-to-grid system.

Comparison table: 2

configuration/parameter	Solar integrated	Wind integrated	Hybrid integrated
Inverter side voltage	1.57	1.85	1.73
Inverter side current	1.45	0.67	1.40
Grid side voltage	0.04	0.09	0.04
Grid side current	3.25	3.51	3.22

Power Comparison table: 3

parameter	Solar integrated	Wind integrated	Hybrid integrated
Dc link power	5700	4500	5750
Inverter power	1120	1050	1165
Grid power	1720	1625	1750

The above comparison Table 2, displays the THD values for three vehicle-to-grid conditions: wind integration, solar integration, and hybrid integration of the system. It showcases various THD percentages for inverter side voltage and current, as well as grid side current and voltage.
The above comparison Table 3, illustrates the power generation values for three vehicle-to-grid conditions: wind integration, solar integration, and hybrid integration of the system. It presents the power generated at the DC link, converted by the inverter, and distributed to the grid.

5. Conclusion

The conclusion of this paper emphasizes the effectiveness of integrating hybrid RES, such as solar and wind power, with V2G technology. The proposed system, which incorporates a bidirectional DC/DC converter and an inverter, enhances grid stability by ensuring efficient energy management and seamless power exchange between the electric vehicle and the grid. The hybrid approach reduces dependency on non-renewable energy sources and provides a consistent power supply, addressing the intermittency challenges of renewable energy. Simulation results demonstrate the system's ability to optimize power flow, improve grid resilience, and contribute to overall energy efficiency. The integration of solar and wind energy, along with advanced control strategies, makes the proposed system a sustainable solution for future smart grid infrastructures, supporting renewable energy adoption and reducing greenhouse gas emissions.

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