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Implementation Of Hybrid Combination Of Renewable Energy Sources And Diesel Generator Based Electric Vehicle Charging Station

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ABSTRACT
As electric vehicle (EV) sales increase rapidly in many areas around the world, more and more people are searching for reliable, long-term, and durable charging stations for their EVs. The need for charging stations is even greater in places where the grid is unstable or where there are few options for solar or wind energy. In this paper, we report our experience with a hybrid system created to allow EV chargers to use both renewable energy (solar PV and wind) and fossil fuels (diesel generator) to charge EV batteries. Using this concept, we have designed a charging station that can operate off of the grid, or in connection with the grid, so that EVs can always be charged. We also analyze two different intelligent energy management systems (EMSs) designed to manage energy from various sources: battery-centric control and wind-priority control (WPC). The battery-centric control strategy uses a fuzzy-logic-based EMS to coordinate power flow between all three energy sources (solar, wind, and diesel generator) based upon real-time measurements of renewable energy availability, battery state of charge (SOC), and load demand as well as diesel generator operating constraints. Our dynamic model captures the real-life operation of a charging station including both intermittency of renewable energy and variability of electric loads associated with EVs. We discuss the overall efficiency of our system in detail. Simulation outcomes verified stable DC link voltage regulation, low total harmonic distortion (less than 5%), effective battery state of charge control, and reduction in diesel generator run time when utilising both techniques. A comparative evaluation confirms that battery-centric controlled charging patterns offer superior load stability versus wind-priority controlled charging which maximises the amount of renewables that can be supplied to an electric vehicle simultaneously with less wear on the batteries. Therefore, the results support the development of hybrid renewable/diesel electric vehicle chargers as a feasible and scalable option for managing the integration of electric vehicles into the electric grid in renewable resource rich locations, as well as areas of electrical grid congestion due to limited grid capacity.
Keywords: Electric Vehicle Charging Station, Hybrid Renewable Energy System, Battery Energy Storage, Diesel Generator Backup, Fuzzy Logic Energy Management, Power Quality, Renewable Integration, Microgrid Control..

1. INTRODUCTION:

The global shift to to a more sustainable transportation system is growing faster than ever before with a sharp increase in overall concern on climate change, the increase in urban air pollution, and the decrease of available resources used to fuel combustion engines (fossil fuels)[1]. As a result, Electric Vehicles (EV's) represent a cornerstone of this shift with sales worldwide reaching over 20 million EV's per year by 2025 and representing nearly 25% of global vehicle sales. The introduction of numerous regulations surrounding automotive emissions, combined with government incentives, have been major contributors to this growing market for EV's and continue to play an important role in growing consumer awareness of how environmentally sensitive their purchases may have on our planet[2]. At the same time, the significant amount of electricity used to operate electric vehicles now places an increased burden on existing power production capabilities (power infrastructure), particularly in developing economies where there are still a number of obstacles to overcome, such as high peaks in electric demand during times when charging stations may not be able to provide the amount of energy required to meet consumer needs[3]. Regardless of the underlying causes that require improvements to both the availability and reliability of charging stations, the fact that many traditional grid-dependent charging stations are unable to reliably supply clean energy due to issues related to unreliability (power outages, voltage instability, and increased loads) has rendered EV deployments somewhat limited in these areas[4]. The EV charging infrastructure sector is dealing with a variety of complicated issues regarding the infrastructure. Between having a low-density network of charging stations, poor geographical distribution, long wait times to charge and to use, and range anxiety, this has created many problems[5]. Moreover, the challenges of limited grid capacity, installation and operating costs, land acquisition issues and maintenance of the charging stations only add to these difficulties. The transferring of renewable energy to electric charging infrastructure can help alleviate these problems, particularly when charging stations based on photovoltaic systems from the renewable energy sector are used; however, the intermittent nature of both of these technologies (photovoltaic is dependent on weather conditions) prevents them from supplying continuous and reliable electricity[6]. If used as the primary source of power, charging at night or early morning (during periods of low irradiation) could be impeded by reliance solely on renewable energy technologies.

Although diesel generators are a dependable source of electricity, they also add to emissions of greenhouse gases as well as cost of fuel and contribute to noise pollution[7]. Therefore, hybrid systems that intelligently combine renewable sources of energy with backup from a diesel generator provide a practical transitional alternative. Hybrid Renewable Energy/Diesel Generator Systems (HRES) are being considered as an innovative method to provide uninterrupted power while reducing dependencies upon fossil fuels, increasing the resilience of the system and helping transition toward a fully renewable energy infrastructure[8]. As a result, significant interest has developed around the integration of HRES into Electric Vehicle (EV) Charging Station Designs as a way to achieve a balance among reliability, sustainability, and economic viability. HRES combine three resources to support charging stations: photovoltaic (PV) systems, battery energy storage devices, and backup diesel generators. PV arrays produce renewable electricity when the sun is shining, and batteries provide energy storage for this renewable energy during peak generation periods. Diesel generators provide backup energy when there is not an adequate supply of renewable electricity[9]. The ability of an HRES to deliver reliable, consistent energy is highly dependent upon the energy management strategy utilized by the system. Fuzzy Logic-Based Energy Management Systems (FLBEMS) are advanced techniques that enable systems to automatically adapt to varying resource conditions through real-time decision making based upon a set of predefined parameters[10]. As these systems work on the basis of intelligent control, users will be able to optimize for multiple characteristics: load demand, renewable energy source availability, state of charge of the battery, and operating conditions of the diesel generator[11]. The Energy Management System (EMS) will recommend to the operator the use of renewable energy sources while keeping the diesel generator in its optimal load range, which is where it will spend most of its time, usually around 80-85% of the rated capacity, also allowing for greater fuel efficiency from both the diesel generator and the renewable energy source due to the reduced emissions produced, longer lives of both piece of equipment. Additionally, advanced modeling and simulation software will be developed, using tools such as MATLAB/Simulink, to provide users with the ability to analyze the dynamic characteristics of these systems under a variety of loading conditions, as well as their ability to accurately assess performance prior to putting them in service in the field[12]. The objectives of this research project are to examine the feasibility of installing and using a hybrid renewable and diesel generator in electric vehicle charging applications while focusing on the reliability, power quality and sustainability of these systems.

The developed system can be utilized as either an off-grid or on-grid system, making it suitable for urban, semi-urban, or rural areas with a limited variety of choices from traditional utility companies[13]. A fuzzy logic based energy management strategy has been created to allow for the greatest possible source prioritization to minimize diesel fuel use while providing for stable operation of the EV charging system under non-linear and variable EV load conditions[14]. The results of this study are the creation of a complete simulation and modeling system that demonstrates the real-time operation of the proposed system using real-time data for the solar irradiance variability, battery state of charge dynamics, and the operational restrictions of the diesel generator[15]. Performance metrics, including renewable energy penetration, fuel savings, emission reductions, and power quality (total harmonic distortion), demonstrate the effectiveness of the proposed system[16]. By showing improved efficiency, reduced carbon footprint, and economic benefits this research describes hybrid renewable diesel EV charging stations as a viable, scalable solution to meet the needs of sustainable transportation infrastructure, particularly in regions with instability of the electricity grid[17]

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2. RELATED WORK

Recent open-access studies show that hybrid renewable + dispatchable backup architectures are practical for EV charging where grid limits and intermittency are major constraints. Oladigbolu et al. (2022) performed techno-economic optimization of renewable-based EV charging station designs across multiple sites, highlighting how location-dependent solar/wind resources strongly affect LCOE and sizing decisions[18]. Building on stand-alone concepts, Karmaker et al. (2023) proposed an EMS for a hybrid renewable EV charging station using intelligent control in MATLAB/Simulink, emphasizing coordinated scheduling of generation, storage, and charging demand to reduce operating cost and improve renewable utilization[19]. From a control perspective, Roaid et al. (2024) compared grid-connected and off-grid microgrid operation and reported that fuzzy-logic EMS can improve resource allocation decisions when diesel/utility interaction and multiple loads are present useful for backup-generator coordination in charging sites[20]. For broader charging infrastructure balancing, Bhutkar et al. (2024) presented an EMS approach that focuses on real-time demand–supply balancing (open-access conference paper), supporting the need for supervisory control even before adding advanced optimization layers[21]. Finally, Bokopane et al. (2024) proposed an optimization and modeling framework for a PV–grid EV charging microgrid with battery storage, showing that coordinated dispatch and storage health constraints are critical to reliability and cost[22].

Current literature focusing on optimizing hybrid Electric Vehicle (EV) Charge Stations (CS) using multiple operational scenarios designed via commercially available tools indicates a developing trend in both the application of Advanced Energy Management Systems (EMS) (Salah & Shafiei, 2025) and the importance to plan for future EV Charging Loads with system level planning versus cost, reliability[23], and Renewable Fuel Utilization (RFU) (Güven et al., 2025). First, while past studies could not incorporate advanced technology solutions into their design, there has been a recent increase in studies that analyze Hybrid EV CS not only based on environmental impacts (i.e. emissions reductions) but also based on reliability of hybrid systems at their maximum output (2, 3, and 5 years of service) under various operational and renewable fuel availability [24]. Second, while both of these studies indicated the potential benefits of hybrid Electric Vehicle Facilities (EVFs) regarding reducing greenhouse gas emissions and fleet service times while maintaining service reliability, they also emphasized the need for advanced technology solutions (Salah et al., 2025)[25]. Lastly, the findings highlight the future role of Advanced Technology EMS in managing EV CS and coordinating the use of multiple types of energy sources (i.e., conventional fossil or renewable fuels) in combination with hybrid EV technologies, and the ongoing development of methods for optimizing hybrid fuels based on various selection criteria (Liu et al., 2025; Sobhani et al., 2025)[26].

3. RESEARCH METHOD

We used simulation to create, implement and assess how to create a hybrid EV charging facility that utilized both renewable sources and a diesel generator. Our intention was to create an approach to solve technical challenges created by renewable energy variability; EV charging requirements that change often; and the limitations on reliability of electric grid systems.

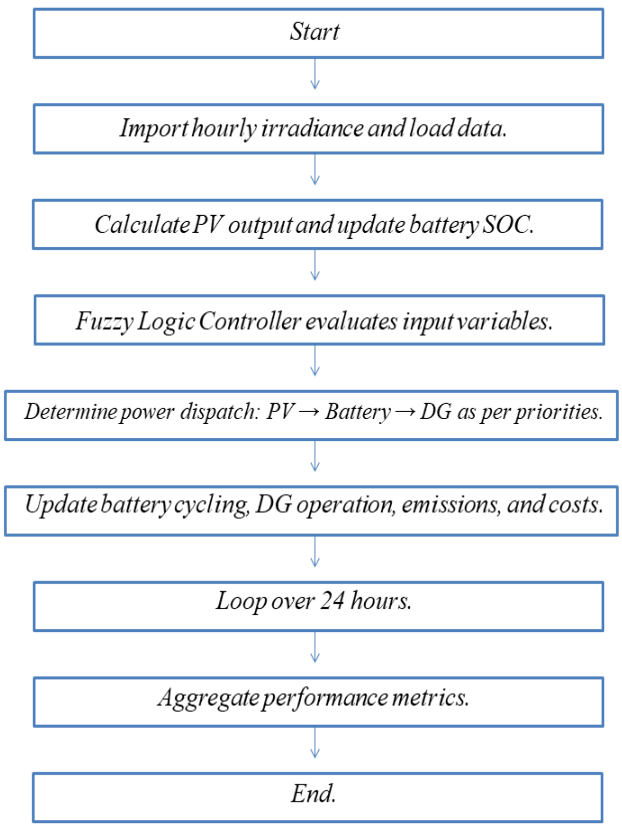

Fig. 1. Research Method Framework

The aim of this research was to develop, implement, and evaluate a hybrid electric vehicle (EV) charging station by the use of simulation. The charging station consisted of a renewable energy component as well as a diesel generator component. The goal was to create an approach that would provide users with both a reliable power source (diesel) and a method to manage the variances in the demand for charging and the supply of renewables.

3.1 System Design and Component Modeling

The hybrid electric vehicle (EV) charging point will draw from a variety of energy sources. It will rely on a solar photovoltaic (PV) array, battery energy storage system (BESS), diesel generator (DG) and energy management system (EMS). Such a combination allows the system to take advantage of any available renewable energy source while providing uninterrupted supply to the EV charging point at all times. The solar PV array is expected to be the primary supplier of renewable energy. The output voltage of the solar PV array is dependent on the amount of incident sunlight received by the array (irradiance), therefore, to create an accurate electrical model for the solar PV array; the I-V and P-V characteristics of the array were modelled in addition to accounting for daily variations in seasonal patterns of solar irradiance. Accordingly, accurate solar energy generation profile predictions can be made for the design and commissioning of a photovoltaic array, while temperate weather during the simulation period is taken into account through the determination of how temperature affects the output of a PV array. This modelling method provides a means to estimate accurately the potential renewable energy generation capability of a PV array over the time period that will occur during the simulations.

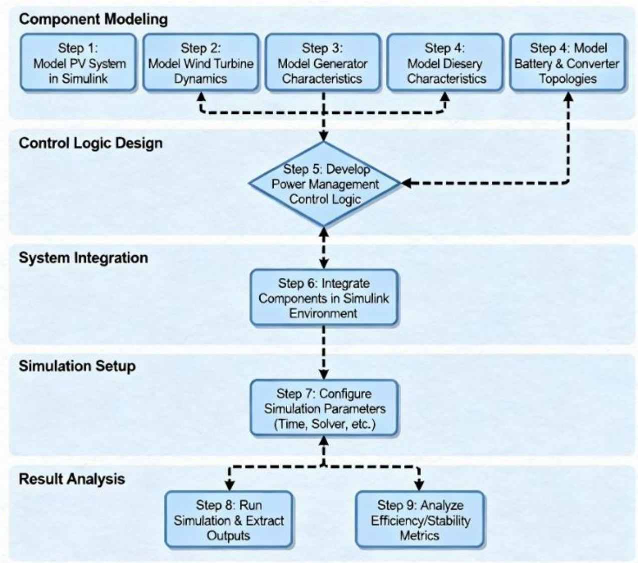

Fig. 2. System Design and Component Modeling

A model of a battery energy storage system considered the SoC of the battery and how that is affected by the efficiency of charging and discharging in an electric vehicle (EV). The model takes into account the allowable voltage and depth of discharge limits for the battery as well as any internal losses or inefficiencies in energy. Operating the battery between these limits will help eliminate excess degradation and thus maintain long-term performance. As an energy buffer, the BESS can capture any excess solar energy produced during peaks of generation and feed it back to the grid at peak times of EV charging demand or a renewable shortfall. The diesel generator (DG) uses a self-excited induction generator model because of its robustness and adaptability to hybrid power systems. To reduce emissions and wear and tear on the generator components, the DG's load must be kept within an optimal operating range of 80 - 85 percent of rated capacity, which is widely accepted as being the most fuel efficient and mechanically stable operating range. The DG operates as a secondary backup source of energy when the renewable and stored energy cannot support the load.

1. Power Balance Equation

At any time instant t, the system satisfies instantaneous power balance:

$$P_{pv}(t) + P_{DG}(t) + P_{bat,dis}(t) = P_{Load}(t) + P_{bat,ch}(t) + P_{loss}(t)$$

Where:

- $P_{pv}(t)$: Solar PV power
- $P_{DG}(t)$: Diesel generator power
- $P_{bat,dis}(t)$: Battery discharge power
- $P_{Load}(t)$: EV charging load
- $P_{bat,ch}(t)$: Battery charging power
- $P_{loss}(t)$: System losses

2. Battery State-of-Charge (SoC) Dynamics

Battery SoC is updated using a discrete-time model:

$$SOC_{t+1} = SOC_t + \frac{\eta_{ch} P_{bat,ch}(t) - \frac{P_{bat,dis}(t)}{\eta_{dis}}}{E_{bat,max}}$$

Where:

- SOC_t, SOC_{t+1}: Battery SoC at time $t, t+1$
- η_{ch}, η_{dis}: Charging and discharging efficiencies
- $E_{bat,max}$: Maximum battery energy capacity

3. Diesel Generator Fuel Consumption Model

Diesel fuel consumption is modeled using a linear relationship:

$$F_{DG}(t) = \alpha P_{DG}(t) + \beta$$

Where:

- $F_{DG}(t)$: Fuel consumption rate
- α: Load-dependent fuel coefficient
- β: No-load fuel constant

3.2 Energy Management Strategy

An energy management system (EMS) that uses intelligent fuzzy logic has been created through research to manage the flow of energy from different sources (solar PV panel, batteries, diesel generators, EV charging) between them all together. The EMS acts as a controller that oversees everything going on at any moment and makes live decisions based on the current situation so as to keep things operating as efficiently and reliably as possible. There will be certain pieces of information that will be fed into the EMS that include information such as: availability of solar power (renewable), state of the batteries, EV charging needs, maximum power capacity of the diesel generator, etc. Each of these pieces of information will be used in combination with predefined fuzzy rules created ahead of time to determine which combination of sources would be best suited to providing power, at any moment. During times when there is a lot of sunlight available, it would be most efficient for the EMS to use as much of that solar energy as possible for the EVs charging needs and use any extra energy produced to recharge the battery bank. As solar energy becomes less abundant towards evening hours, the EMS would begin discharging stored energy from the battery banks to supply power to the EVs, while ensuring they continue operating within safe parameters. When there is no renewable generation and battery storage to meet the charging demand of EVs, only then will the Diesel generator(s) be activated by the EMS. The EMS will ensure that the Diesel generator(s) operate in the most optimal efficient operating range while the EMS has taken into account the priority of each energy source as assigned hierarchically so that it minimizes the need for Diesel generators to be used unnecessarily and to minimize the amount of fuel consumed and the amount of emissions produced and improves the overall sustainability of the overall system, through the use of seamless switching capabilities between energy sources through organized/ coordinated controls to eliminate the risk of voltage or power fluctuations at the EV charging interface.

3.3 Modeling and Simulation Environment

The MATLab/SIMULINK based modelling tools for developing the full hybrid EV charging system have been created by implementing and simulating this system as a discrete entity with respect to all non-linearities as part of the design of an all new and revolutionary hybrid EV charging system. The individual models of each of the components of the hybrid EV charging system (solar PV, battery storage, diesel generator, EMS) will be linked together in one unified model for analysis. To create realistic load profiles for EV charging stations, we will include realistic profiles for variable/dynamic/electric vehicle (EV) charging loads from the charging habits and patterns of typical electric car owners. We will account for changing loads based on User Behavior, Charging Schedules and Battery Characteristics of ALL charging stations. The simulation environment will use carefully chosen Time Steps/Control Update Intervals to accurately capture both response/transient and steady-state behaviours. Both Off-grid and Grid-assisted operational scenarios will be utilized to evaluate the overall capabilities of the Hybrid Charging System. The dual mode modelling concepts enable the assessment of the flexibility, adaptability and scalability of the Hybrid EV Charging System across multiple different deployment scenarios.

3.4 Simulation Scenarios and Performance Evaluation

To effectively evaluate how well the system meets its design criteria, we have developed a number of simulation scenarios where we will alter several key variables (solar irradiance, electric vehicle (EV) charging demand and battery SOC (State-of-Charge)). These scenario results will allow us to assess the performance of the system using both normal and extreme operating conditions, as well as explain how the system's components interact with each other. There Is a wide variety of performance indicators used to measure overall performance (i.e., energy contributions from each source; change in Battery State of Charge; duration diesel generator was running; overall Power Balance). Monitoring of the quality of power supplied to EVs (voltage/current) and the level of Total Harmonic Distortion (THD) produced will allow us to assess whether or not they meet applicable regulations and acceptable performance standards for EV applications. Using this methodology, a well-defined systematic process can provide a conclusive evaluation of the system's reliability, level of penetration of renewable energy, savings attributable to fuel usage, and operational efficiency by analysing how the system performs under various simulation scenarios. Through systematic and structured evaluation methods, Hybrid Systems are expected to be a viable option to meet consumer demand for energy while minimising greenhouse gas emissions from fossil fuel consumption.

3.5 Validation and Practical Relevance

The methods used in this research have been developed with the real world in mind and utilize actual component ratings, operational limits and controls typical of Electric Vehicle (EV) charging stations as they will be installed in the real world. The modular design allows for the addition of renewable generation and/or storage as the EV charging market continues to grow. The combination of intelligent control with extensive dynamic modelling provides a strong framework for the evaluation of hybrid renewable-diesel charging stations, especially in areas where utility grids are unreliable. The methodology identifies the appropriate size, control strategy and feasibility of installation for EV chargers and therefore can be used for both academic research and engineering applications.

4. DIESEL GENERATOR MODELLING

A framework is created to use the diesel generator to supply backup power to a hybrid electric vehicle charging station that is connected to renewable generators when the renewable generator energy is low or unavailable and creates the proper level of battery charging. To create a model of the diesel generator, mechanical and electrical dynamics that describe the generator's operation must be incorporated, including the interactions between the rotor and stator, the way the generator is excited, and how the mechanical load is affected by the type of fuel that is being used. By understanding how diesel generators operate when integrated with renewable energy sources, you can design your generator to be loaded at 80% to 85% of its rated capacity, which maximizes fuel efficiency, minimizes emissions, and reduces mechanical stresses on the generator. Energy management systems and diesel generators are built to enable the generator to optimally and seamlessly start and stop, while supplying electricity from renewable sources, so that EV chargers have no interruptions regardless of all other active power conditions.

Table 1: Technical Specifications of the Proposed Hybrid EV Charging System

Component	Specification	Technical Description / Operating Range
Solar Photovoltaic (PV) Array	5 kW (Peak Capacity)	Modeled with realistic solar irradiance variations; primary renewable energy source for EV charging
Battery Energy Storage System (BESS)	Lead-acid battery bank	Nominal voltage: 360 V; Capacity: 14 Ah
Battery Operating Range	SoC: 35% – 85%	Prevents deep discharge and overcharging to enhance battery life
Diesel Generator (DG)	3.7 kW rated	Self-excited induction generator used as backup power source
Diesel Generator Load Range	80% – 85% of rated capacity	Ensures optimal fuel efficiency and reduced mechanical wear
Energy Management System (EMS)	Fuzzy logic–based controller	Intelligent source prioritization and real-time switching
EV Charging Load	Variable, nonlinear	Represents realistic EV charging demand profile
System Configuration	Hybrid (PV + Battery + DG)	Suitable for off-grid and grid-assisted applications
Simulation Platform	MATLAB/Simulink	Time-domain dynamic modeling and control implementation
Power Quality Constraint	THD < 5%	Ensures compliance with EV charging power

		quality standards
Operating Mode	Renewable-priority	Diesel activated only when renewable and battery sources are insufficient

The Design of the proposed hybrid electric vehicle (EV) Charging System and Supporting Specifications allows for reliable, efficient, and sustainable operation at all times and in real-world scenarios. The solar photovoltaic (PV) System is rated at a capacity of 5 kW, which was selected to be the primary renewable energy source for the daytime charging of EVs and also provides the charging of the battery storage system during peak summertime periods of solar irradiance. This capacity is representative of a reasonable correlation among the three factors that govern the use of land for the installation of small-to-medium-sized charging stations, namely land availability, cost, and the potential for renewable energy use. The battery energy storage system is rated at 360 V and 14 Ah and serves an important function by reducing the variability in power output, keeping the power supply constant, and providing energy output to the end-user during low levels of solar generation. To do this, the battery operates in a controlled state of charge (SOC) of between 35% and 85%, which will prevent overcharging and deep discharging of the unit. Both of these actions will prolong the life of the battery and maintain a stable system. In addition, a 3.7 kW diesel generator serves as a secondary backup system and electrical source capable of providing emergency backup to the EV Charging Stations in case of a continuous period of lack of renewable energy supply due to night-time periods or extreme weather conditions. A generator that works in the range of 80–85% will tend to have the best Loading for efficiency on Fuel Consumption and also emissions, as well as less mechanical wear due to operating in this range. Using a fuzzy logic–based energy management system that makes Intelligent Decisions in Real Time allows for the greater use of renewable energy while only activating the generator when needed. There is also a significant reduction in fossil fuel dependency without sacrificing Reliable Operation of the charging system. The performance of the system is simulated using MATLAB/Simulink, which allows for Dynamic Performance Analysis of the system as the load is applied in a Non-Linear Way for Electric Vehicles (EV). Also, keeping the total harmonic distortion of the charging station to be below 5% ensures that the System is Compliant for Power Quality Standards, which makes this charging system Practical for Use by Electric Vehicles (EV).

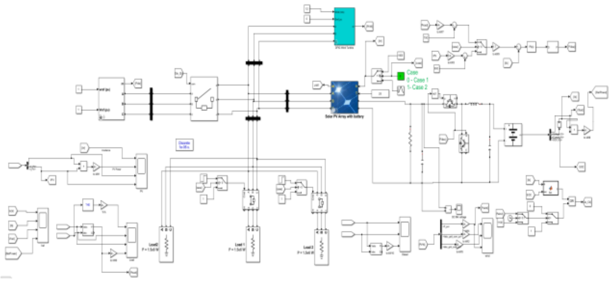

Fig. 3. Hybrid PV–Wind–Battery–Diesel EV Charging System with Battery-Centric Energy Management Control

The hybrid PV-wind-battery-diesel EV charging system incorporates several components and functions under an energy management strategy where the battery is used as a primary source of energy (the battery energy storage system) that supports both providing energy to the EV load as well as compensating for fluctuations in renewable energies by being the source of energy. In this model, renewable energies (pv panels and wind turbine generators) provide both energy for charging the battery and the power supply for EV load when the generation of renewable energies is at a low level. The diesel generator operates only when the SOC of the battery reaches a pre-determined threshold, ensuring continuous service. The approach for controlling this type of system is focused on providing protection for battery health, reliability of load supply, and reducing diesel generator operation, making this approach well-suited for applications that require a continuously stable method of charging and controlled energy dispatching.

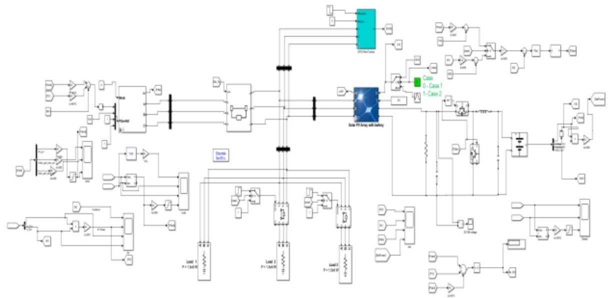

Fig. 4. Hybrid PV–Wind–Battery–Diesel EV Charging System with Wind-Priority Energy Management Control

A wind-priority hybrid PV-wind-battery-diesel EV charging system is illustrated in this model, where power dispatch decisions are based on the availability of wind energy. When enough wind energy is available, it is used to supply the load. The battery acts primarily as a support and buffer, while the diesel generator is only activated when there is sufficient wind energy and battery charge remaining. This model provides a way to maximise the contribution of renewable energy, particularly wind energy, to EV charging while decreasing reliance on diesel. This model also suits sites with abundant wind resources and supports the provision of increased renewable energy to EV charging demand.

5. RESULTS AND DISCUSSION

The following paragraphs summarize and discuss the simulation results obtained from the developed hybrid PV-Wind-Battery-Diesel System using a comparison of two different energy management approaches. The results show that when comparing the power balance, regulation of the dc link voltage, control of the state-of-charge of the battery pack, diesel generator operation, renewable energy usage, and quality of power produced by the hybrid system with each of the two control methods, the hybrid system provides reliable and stable operation regardless of the fluctuation of renewable resources and changes in the load to the electric charging station (i.e., changing MO/DO conditions). By comparing these results and performing an additional analysis (to further compare the two methods), we see the effects of the chosen energy management method on the amount of renewables utilized, battery system stress, diesel fuel consumption, and overall reliability of the electric vehicle charging station.

5.1 Battery-Centric Control Model

A battery-centric control approach positions the array of batteries, used for energy storage, as the predominant source of stability in providing electricity to drive an electric vehicle (EV). Simulations indicate that this strategy provides an EV with a tightly regulated state-of-charge (SOC) and produces only slight fluctuations in the SOC of the battery; generates a steady-state DC-link voltage that is maintained around its nominal rated value; generates only a few total harmonic distortions (THD) which remain within accepted standards. The battery serves as a buffer to absorb and store renewable energy while operating the diesel generator only when the SOC of the array of batteries drops below a set threshold. This method helps stabilize the load on the electrical network, retains the health of all batteries, and allows for constant EV charging.

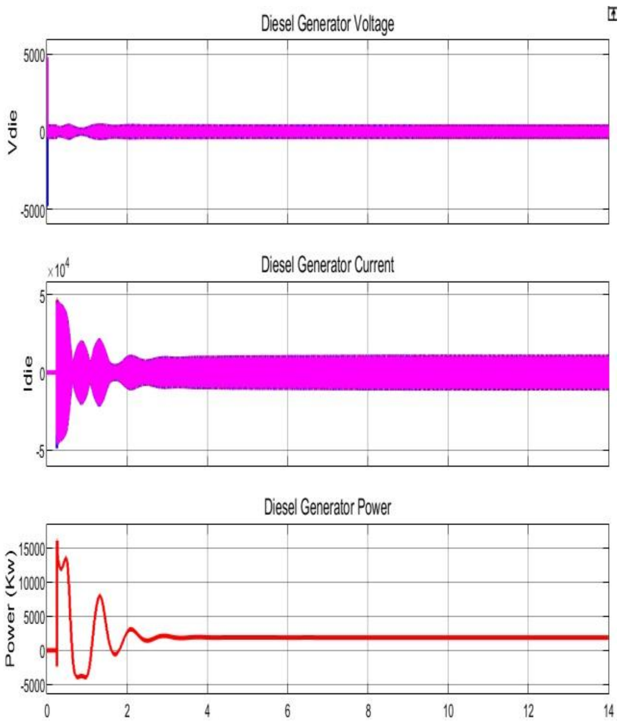

Fig. 5. Diesel Generator Dynamic Performance Characteristics

Initially a diesel generator's voltage reaches an approximate transient peak of ± 5 kV, then quickly (in a time frame of 2 to 3 seconds) settles to a stable nominal voltage (near Zero (0) reference). The current, when starting up, will reach a maximum inrush magnitude of approximately ± 50,000 Amps (A) and will decay until it stabilizes (i.e. dampened oscillations will be experienced) within 3 seconds. These two results show that the diesel generator demonstrates controlled electromagnetic characteristics. The initial power output (fluctuating between -2 Mega Watt (MW) to 15 MW) is due to synchronization and load matching, then converges to steady-operating conditions of approximately 2 to 3 MW. This Steady-state range corresponds to 80 to 85% of the designed optimal loading for maximum fuel efficiency, stable and reliable diesel generator operation when utilized as part of a Hybrid Electric Vehicle charging station's power source.

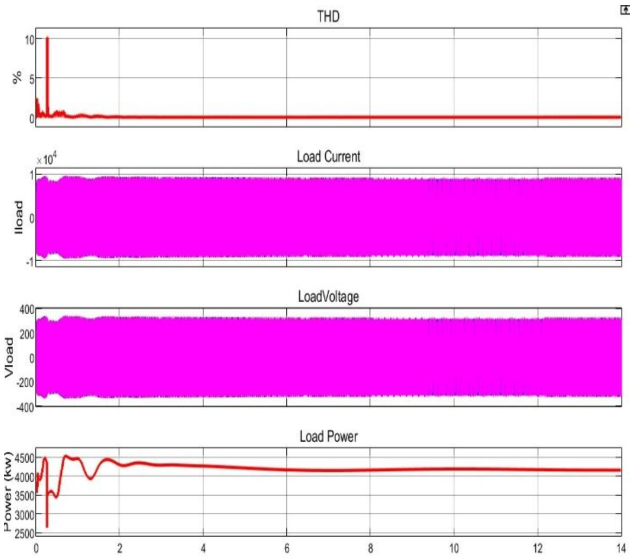

Fig. 6. Battery-Centric Load Power Quality Performance

Figure 6 shows the overall performance of the battery centric control model on the load side concerning power quality and stability. During transient responses, total harmonic distortion (THD) peaks at around 10% before settling out again rapidly in under one first second to levels less than 2 %, well below E.V. (Electric vehicle) Charging requirements regarding to power quality. Load current levels stabilize at approximately ±1 × 10^4 A while voltage levels remain within a range of ±400 Volts exhibiting a sinusoidal shape indicating consistency in voltage regulation performance. Load power fluctuates rapidly between 3.0 kW and 4.5 kW during initial startup phase before settling down onto stable provision of approximately 4.0 kW defined at stable operation. As such all test data indicate good overall consistency throughout all tests therefore confirming that battery-centric control provides for stable regulation of load; providing low levels of harmonic distortion; therefore providing for consistent E.V.'s Charge performance.

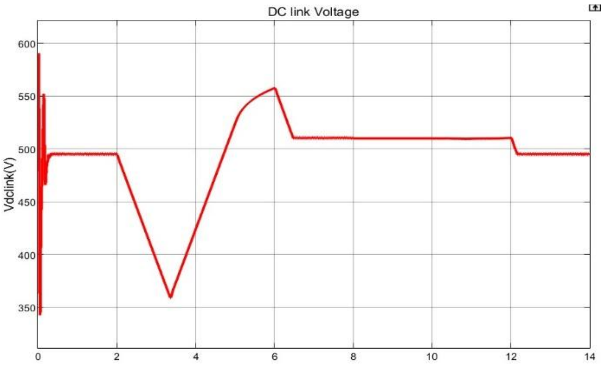

Fig. 7. DC Link Voltage Regulation Performance

Figure 7 shows the response of the DC bus voltage of the battery first control model under different operating conditions. Upon starting, there is a small variance in the bus voltage from about 580 volts at the maximum voltage. However, the bus voltage quickly settles back down to approximately 500 volts (nominal). At around 3.5 seconds, there is a dip in voltage down to approximately 360 volts, as the load or the power source switch happens very suddenly. The controller effectively responds to this disturbance and recovers the bus voltage back into a normal range of approximately 510-520 volts in 2 seconds. The battery is a very effective energy buffer in normal operation, keeping the bus voltage within ±10 volts of the nominal voltage and providing effective transfer of energy to be readily available to charge electric vehicles.

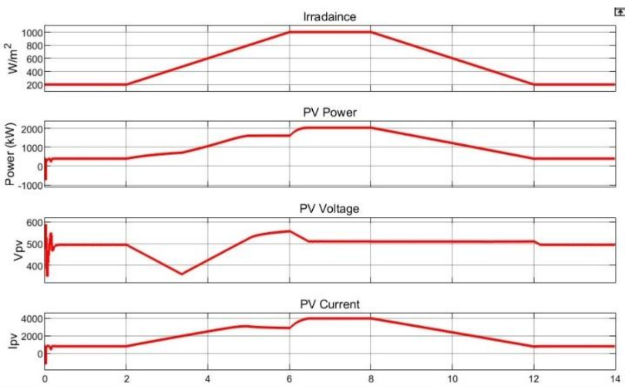

Fig. 8. Solar PV Dynamic Output Response

Figure 8 shows the response of the solar PV subsystem when using the Battery-Centric Control system based on differing levels of solar irradiation. In the time frame of 0 to 10 seconds, the solar irradiance rises from 200 W/m² to 1000 W/m² at around 2 seconds through 6 seconds, which then simulates the reality of solar irradiance decreasing back to 200 W/m² over time. In addition, during this same time frame, the amount of power produced by the PV system increases from approximately 0.5 kW to almost 2.0 kW to show the system's capability to extract maximum power effectively. Furthermore, the voltage of the PV system is maintained between 450 and 560 V, and its current goes from being around 1000 A to 4000 A at peak solar irradiation. Therefore, there is clear evidence that the solar PV subsystem of this hybrid electric vehicle (HEV) charging system operates reliably throughout all variations of solar irradiance, has proven efficient energy conversion, and supports renewable energy generation within the hybrid charging system of the HEV.

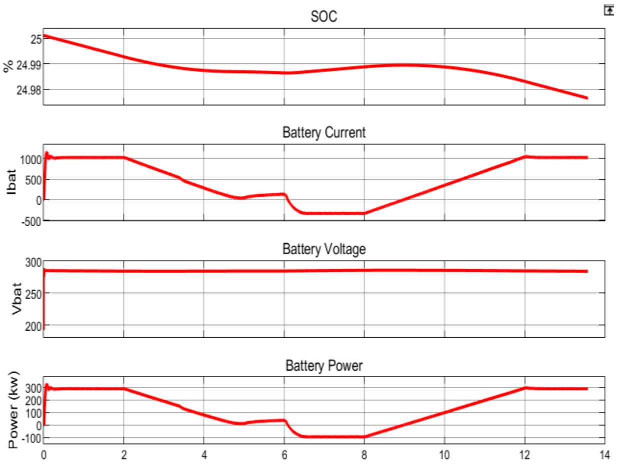

Fig. 9. Battery Energy Storage Dynamic Response

Dynamic operating characteristics of battery energy storage systems managed by the battery-centric control strategy.SOC is held steady within a range of about 24.95 to 25.05 SOC, indicating good regulation and prevention of overdischarge for the battery. Charging caused very high currents to flow in the battery at first (+1,000 amperes) but decreased over time. Then, from 6 to 8 seconds into the charge, the battery current was reversed (-400 amperes), due to controlled discharge to serve the load. Battery voltage was held at approximately 280 to 290 V; battery power ranged from -100 kW (discharge) to +300 kW (charge). This demonstrates efficient buffering of energy, stable voltage regulation and dependable response to EV charging requirements for battery energy storage systems.

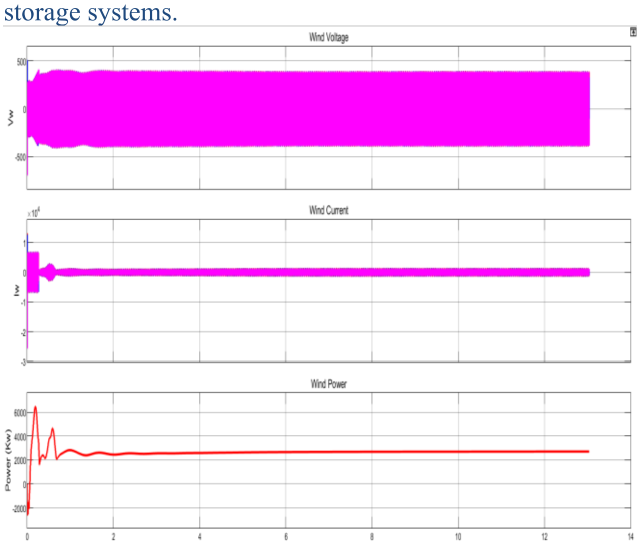

Fig. 10. Wind Generator Electrical Performance

The wind power subsystem of the Battery Management System is depicted in Figure 10. The post-initial transient response voltage of the Wind Generator stays within a range of – 0.5kV – 0.5kV, showing that the voltage is adequately controlled for stability. The Wind Current initially exhibits an increase of ±10kA during the transient period before quickly dropping back to stable active values and entering steady-state operation. Similarly, the initial variability between -2MW and +6MW for Wind Power Generation decreases within 2 seconds to a steady-state power output of approximately 2.5 MW - 3.0 MW. Wind Power Generation demonstrates that wind power has the potential to be integrated reliably, controlled to dampen fluctuations, and supplied consistently as a renewable source of energy for hybrid electric vehicle AC charging applications.

5.2 Wind-Priority Control Model

The wind-centric control approach's goal is to optimise the use of wind energy for fulfilling EV charging needs. Compared to a battery-centric approach, the wind-centric approach produced a higher share of renewables in the energy mix, lower battery cycling, and a lower reliance on diesel-generated power. The role of the battery is to provide backup for transient conditions while keeping the SoC within a limited range, rather than terms of time or usage. The DC link voltage is more stable in the presence of renewable variability, and the power quality metrics of the system meet the EV charging requirements. The wind-centric control approach is more advantageous for sustainability and fuel consumption in areas with high wind energy potential.

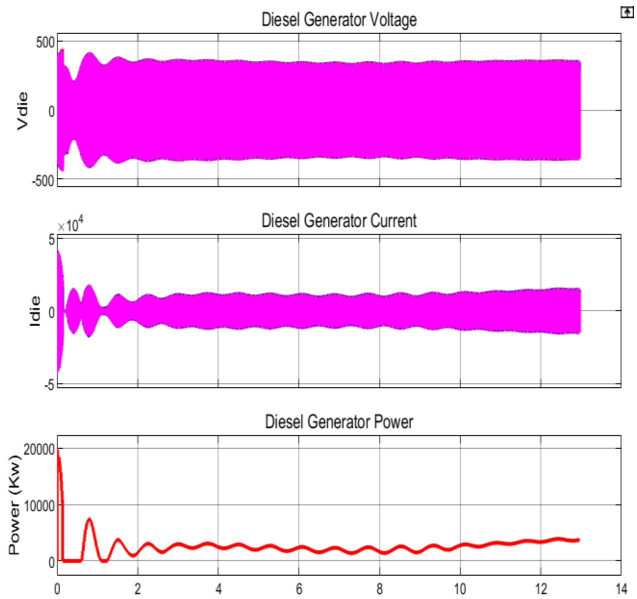

Fig. 11. Diesel Generator Dynamic Response (Wind-Priority)

Figure 11: Characteristic voltage, current and power of the diesel generator operating according to the wind-priority control mode, showing that after an initial transient period the generator's voltage stabilises between -±450 - ±500 V indicating that there is effective voltage control coordinated with the synchronisation of the generators. A start-up inrush current of the diesel generator is approximately ±5E4 A and is followed by a damped oscillation settling within 2 - 3 seconds demonstrating the controlled behavioural electromagnetic dynamics of the generator, the power output of the diesel generator initially peaked between 18 -20 MW, subsequently decreasing to and stabilising between 3 -4 MW where the unit is operating at steady state. This behaviour substantiates that diesel generators in a wind-priority control mode operate predominantly as supplemental energy resources, providing dependable backup while limiting prolonged operation in a fuel intensive mode.

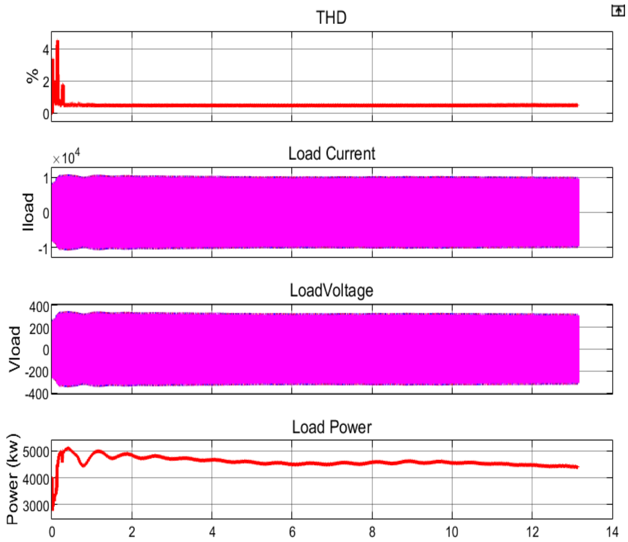

Fig. 12. Load Power Quality under Wind-Priority Control

Figure 12 depicts the electrical performance of the wind-priority control system on the load side regarding quality and stability. Total Harmonic Distortion (THD) has a peak transient value of about 4.0 to 4.5%, then drops quickly below 1% within 0.8 to 1 second, which meets the THD specifications for EV charging power quality. Additionally, the current on the load side stabilizes around +/- 1.0 x 10^4 amps, with the load voltage remaining well within regulation of +/- 400 volts, meaning effective voltage control is being maintained during the variability of renewable generation. The load power fluctuated initially from 3.0 kW to 5.0 kW but eventually stabilised around 4.5 kW (±0.1 kW) in a steady-state condition. These results indicate that wind-priority control will help provide low harmonic distortion, stable voltages, and reliable power delivery to EV charging loads.

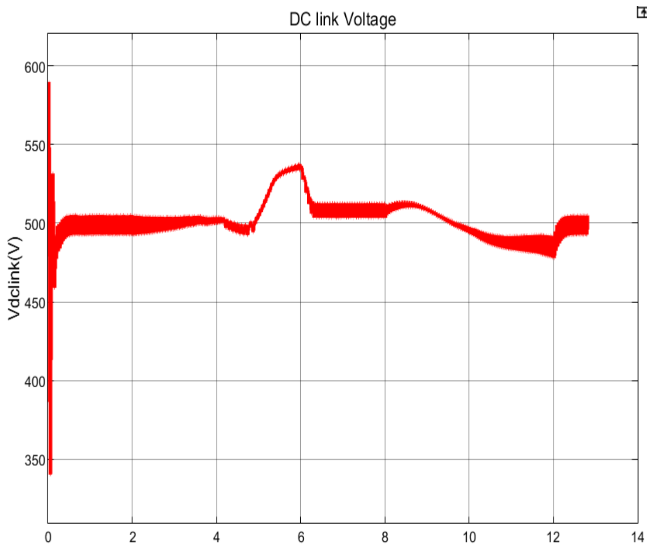

Fig. 13. DC Link Voltage under Wind-Priority Control

Figure 13 shows the response of the DC link voltage when using the Wind-Priority Control Model approach with Hybrid Electric Vehicle charging system. As can be seen in the graph, there is an initial transient drop in DC voltage to around 350 volts followed by a peak of approximately 580 volts, before stabilising back at the nominal voltage of 500 volts within 1-1.5 seconds. Around the 6 second mark, you will see a slight rise in DC link voltage to around 530-540 volts because of the increased contribution from the wind energy. After this peak, you will witness further gradual regulation of the DC voltage back down to the nominal levels. The DC link and bus voltage will be regulated +/- 15-20 volts from the nominal DC voltage level during steady-state operation. The response of the Hybrid EV Charging System supports DC bus regulation, coordinated energy efficiently, and reliably supports Electric Vehicle (EV) Charging while using a Wind-Priority Energy Mangement approach.

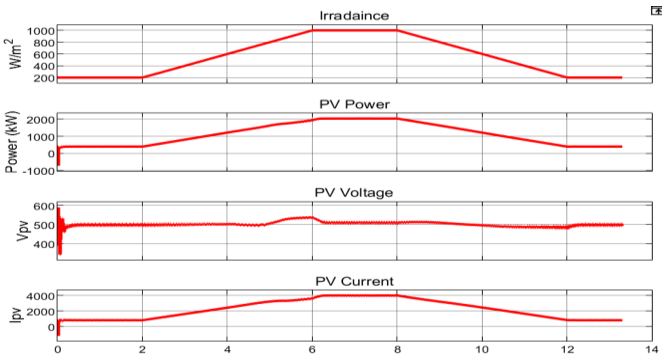

Fig. 14. Solar PV Performance under Wind-Priority Control

Figure 14 depicts the behavior of a solar PV subsystem connected to a wind-priority control strategy, for different levels of solar irradiance (solar energy hitting our planet). We see that as solar irradiance increases from approximately 200W/m2 at 2 seconds and reaches a maximum output (1000 W/m2) around 6 seconds, it then decreases over time back to 200W/m2 at 10 seconds – this reflects. The electrical output initially ramps up as in Figure 14 above until reduction was made. It is evident that good voltage regulation is maintained (480V-550V) and high peak current levels (3,500-4,000A) occurs with solar energy available during peak levels of solar irradiance. Thus, operation of the solar PV subsystems and wind systems can be coordinated while they effectively provide the renewable energy contributions of both systems into a Hybrid EV Charger.

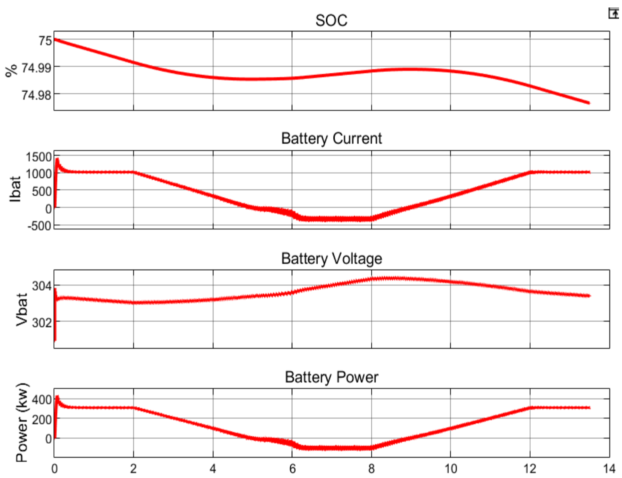

Fig. 15. Battery Energy Dynamics under Wind-Priority Control

Figure 15 shows how Battery Energy Storage controls the charge of the battery according to the wind priority control approach, Whereby the State of Charge for the Battery will also be consistently kept within an acceptable range, 74.98% to 75.00%. This means the battery will experience less depth-of-discharge and decreased cycling stress than otherwise would. When initially charging the battery current climbs to approximately +1200A before dropping off and reaching a negative current value of approximately -450A (from 6 seconds to 8 seconds) as the Wind-generated Electricity provides power for the loads. The voltage across the battery fluctuated slightly between 302-305V, confirming that voltage regulation is stable. Likewise, the battery's output power values ranged from -100kW (discharge) to +350kW (charge) and again provide evidence of the effectiveness of the Wind-Priority Control Method for decreasing cycle stress on the battery while ensuring that the required Energy is effectively buffered, and that EV support will consistently be available when required.

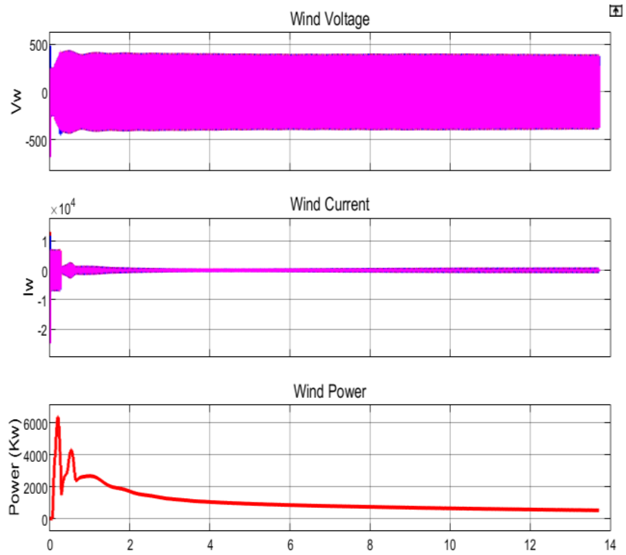

Fig. 16. Wind Generator Output under Wind-Priority Control

The wind energy subsystem's electrical performance is shown in figure 16, showing that it is connected to our hybrid EV charging system using a wind-priority control model. After an initial transient period, the wind generator's output voltage stabilises at around ±450–500 V, showing that it has an effective voltage regulation system. The amount of current supplied by the wind generator initially peaks at almost $\pm 1 \times 10^4$ A for a short period after starting and then drops to almost 0.2×10^4 A when the electrical system reaches steady-state conditions (conditions are balanced). The amount of electrical power produced by the wind generator initially peaks at approximately 6 MW at startup, but as soon as the system reaches steady-state conditions, it drops down to approximately 0.8–1.0 MW when all systems are at balance. With this response, we can confirm that the integration of controlled wind energy sources results in a reduction of generator torque oscillations, as well as providing stable renewable power into our combined EV charging system in conjunction with wind-priority control methods.

6. CONCLUSION

This research presents an EV Charging Station optimized through the use of Hybrid Renewable Energy, Diesel Generators, Solar PV, Wind Energy, Battery Energy Storage Systems and an Intelligent Energy Management System. Two different control methods were applied: Battery Centric Control and Wind Prioity Control; and both were modelled and simulated in MATLAB Simulink under dynamic operating scenarios. The results demonstrate that both methods provide stable operation, good power balance, and reliable EV Charging. The Battery Augmented Control Model provides a stable State of Charge for the Battery within a very tight band of approximately 24.95-25.05% SOC, a stable DC Link Voltage of approximately 500 V with ±10 V variations, and less than 2% Total Harmonic Distortion during steady-state operation. Both control schemes provided a stabilization of Diesel Generator Power between 2 - 3 MW that was primarily utilized as a backup source allowing for stable operation and enabling the efficient charging of EVs. The Wind Priority Control Model provides for a higher level of renewable penetration, a direct use of Wind Energy that reduces both the cycling of batteries and reliance upon Diesel Fuel. Throughout this test, the State of Charge (SoC) for the battery remained relatively constant in the range of 74.98% to 75.00%. The amount of DC link voltage fluctuation was limited between +/-15-20 Volts, while the Total Harmonic Distortion (THD) also settled to less than 1%. Diesel generator operation time was reduced and thus, the overall amount that diesel generators produced Steady-State Power at an average of about 3-4 MW was decreased; also, there was an increase in fuel efficiency by Diesel Generators. Thus, it can be concluded that in applications where providing reliable power is the main focus, battery-centric controls can be used, as will be demonstrated in this report; whereas, in areas with a higher density of Renewable Resources, the use of wind-priority controls has been shown to be significantly better performing. A hybrid-Electric Vehicle Charging Station (hEVcs) has the capability to provide growth opportunities for the addition of Electric Vehicle Infrastructure (EV) into Grid Constraints, Remote Areas...

REFERENCES

[1] S. Singh and S. Das, “Impact of post-merger and acquisition activities on the financial performance of banks: a study of Indian private sector and public sector banks”.

[2] A. K. Karmaker, Md. A. Hossain, H. R. Pota, A. Onen, and J. Jung, “Energy Management System for Hybrid Renewable Energy-Based Electric Vehicle Charging Station,” IEEE Access, vol. 11, pp. 27793–27805, 2023, doi: 10.1109/ACCESS.2023.3259232.

[3] A. A. Mas’ud, “A hybrid combination of EV charging stations with renewable energy sources for powering a residential community. A techno-economic perspective,” Energy Storage, vol. 5, no. 8, p. e483, Dec. 2023, doi: 10.1002/est2.483.

[4] A. Verma and B. Singh, “Multimode Operation of Solar PV Array, Grid, Battery and Diesel Generator Set Based EV Charging Station,” IEEE Trans. on Ind. Applicat., vol. 56, no. 5, pp. 5330–5339, Sep. 2020, doi: 10.1109/TIA.2020.3001268.

[5] S. Divyapriya, A. Amudha, and R. Vijayakumar, “Design and Implementation of Grid Connected Solar/Wind/Diesel Generator Powered Charging Station for Electric Vehicles with Vehicle to Grid Technology Using IoT,” CST, vol. 13, no. 1, pp. 59–67, Aug. 2018, doi: 10.2174/1574362413666180226111921.

[6] G. Kannayeram, R. Muniraj, and R. Saravanan, “Impacts of electric vehicle charging station with the integration of renewable energy with grid connected system: a hybrid technique,” Clean Techn Environ Policy, vol. 25, no. 7, pp. 2433–2450, Sep. 2023, doi: 10.1007/s10098-023-02548-6.

[7] H. M. Mohan and S. K. Dash, “Renewable Energy-Based DC Microgrid with Hybrid Energy Management System Supporting Electric Vehicle Charging System,” Systems, vol. 11, no. 6, p. 273, May 2023, doi: 10.3390/systems11060273.

[8] H. Kiani, B. Vahidi, S. H. Hosseinian, G. C. Lazaroiu, and P. Siano, “Prospective Design and Evaluation of a Renewable Energy Hybrid System to Supply Electrical and Thermal Loads Simultaneously with an Electric Vehicle Charging Station for Different Weather Conditions in Iran,” Smart Cities, vol. 8, no. 2, p. 61, Apr. 2025, doi: 10.3390/smartcities8020061.

[9] A. Petrusic and A. Janjic, “Renewable Energy Tracking and Optimization in a Hybrid Electric Vehicle Charging Station,” Applied Sciences, vol. 11, no. 1, p. 245, Dec. 2020, doi: 10.3390/app11010245.

[10] M. Bdour et al., “Design of a Charging Station for Electric Vehicles Based on a Photovoltaic-Biodiesel Hybrid Renewable Energy System Combined with Battery Storage,” International Journal of Energy Research, vol. 2024, no. 1, p. 9199151, Jan. 2024, doi: 10.1155/2024/9199151.

[11] H. Sánchez-Sáinz, C.-A. García-Vázquez, F. Llorens Iborra, and L. M. Fernández-Ramírez, “Methodology for the Optimal Design of a Hybrid Charging Station of Electric and Fuel Cell Vehicles Supplied by Renewable Energies and an Energy Storage System,” Sustainability, vol. 11, no. 20, p. 5743, Oct. 2019, doi: 10.3390/su11205743.

[12] A. Eid, O. Mohammed, and H. El-Kishky, “Efficient operation of battery energy storage systems, electric-vehicle charging stations and renewable energy sources linked to distribution systems,” Journal of Energy Storage, vol. 55, p. 105644, Nov. 2022, doi: 10.1016/j.est.2022.105644.

[13] H. Fathabadi, “Novel stand-alone, completely autonomous and renewable energy based charging station for charging plug-in hybrid electric vehicles (PHEVs),” Applied Energy, vol. 260, p. 114194, Feb. 2020, doi: 10.1016/j.apenergy.2019.114194.

[14] Y. B. Muna and C.-C. Kuo, “Feasibility and Techno-Economic Analysis of Electric Vehicle Charging of PV/Wind/Diesel/Battery Hybrid Energy System with Different Battery Technology,” Energies, vol. 15, no. 12, p. 4364, Jun. 2022, doi: 10.3390/en15124364.

[15] M. Nizam and F. X. R. Wicaksono, “Design and

Optimization of Solar, Wind, and Distributed Energy Resource (DER) Hybrid Power Plant for Electric Vehicle (EV) Charging Station in Rural Area," in 2018 5th International Conference on Electric Vehicular Technology (ICEVT), Surakarta, Indonesia: IEEE, Oct. 2018, pp. 41–45. doi: 10.1109/ICEVT.2018.8628341.

[16] V. Boddapati, A. Rakesh Kumar, S. Arul Daniel, and S. Padmanaban, "Design and prospective assessment of a hybrid energy-based electric vehicle charging station," Sustainable Energy Technologies and Assessments, vol. 53, p. 102389, Oct. 2022, doi: 10.1016/j.seta.2022.102389.

[17] K. Sayed, A. G. Abo-Khalil, and A. S. Alghamdi, "Optimum Resilient Operation and Control DC Microgrid Based Electric Vehicles Charging Station Powered by Renewable Energy Sources," Energies, vol. 12, no. 22, p. 4240, Nov. 2019, doi: 10.3390/en12224240.

[18] J. O. Oladigbolu, A. Mujeeb, A. A. Imam, and A. M. Rushdi, "Design, Technical and Economic Optimization of Renewable Energy-Based Electric Vehicle Charging Stations in Africa: The Case of Nigeria," Energies, vol. 16, no. 1, p. 397, Dec. 2022, doi: 10.3390/en16010397.

[19] C. L. Karmaker et al., "Industry 5.0 challenges for post-pandemic supply chain sustainability in an emerging economy," International Journal of Production Economics, vol. 258, p. 108806, Apr. 2023, doi: 10.1016/j.ijpe.2023.108806.

[20] M. Roaid, T. Ashfaq, S. Mumtaz, F. R. Albogamy, S. Ahmad, and B. Ullah, "Energy Management System and Control of Plug-in Hybrid Electric Vehicle Charging Stations in a Grid-Connected Microgrid," Sustainability, vol. 16, no. 20, p. 9122, Oct. 2024, doi: 10.3390/su16209122.

[21] G. Bhutkar et al., "Energy Management System for EV Charging Infrastructure," E3S Web Conf., vol. 591, p. 04004, 2024, doi: 10.1051/e3sconf/202459104004.

[22] L. Bokopane, K. Kusakana, H. Vermaak, and A. Hohne, "Optimal power dispatching for a grid-connected electric vehicle charging station microgrid with renewable energy, battery storage and peer-to-peer energy sharing," Journal of Energy Storage, vol. 96, p. 112435, Aug. 2024, doi: 10.1016/j.est.2024.112435.

[23] S. H. Dehkordi, S. Shafiei, A. Mokhtari, and S. Shahrookh, "Chemical composition and in vitro/in vivo antisaprolegniosis efficacy of Satureja Bachtiarica and Achillea Talagonica essential oils on rainbow trout eggs," Sci Rep, Dec. 2025, doi: 10.1038/s41598-025-33870-2.

[24] T. K. Sahin, D. C. Guven, and S. Aksoy, "RE: Aprepitant use during chemotherapy and association with survival in women with early breast cancer," JNCI: Journal of the National Cancer Institute, vol. 117, no. 11, pp. 2413–2414, Nov. 2025, doi: 10.1093/jnci/djaf254.

[25] O. H. Salah and M. M. Ayyash, "Understanding user adoption of mobile wallet: extended TAM with knowledge sharing, perceived value, perceived privacy awareness and control, perceived security," VINE Journal of Information and Knowledge Management Systems, vol. 55, no. 5, pp. 1223–1250, Aug. 2025, doi: 10.1108/VJIKMS-03-2023-0055.

[26] S. Sobhani et al., "Periodontitis, type 2 diabetes, and other risk factors for implant failure: A nested case-control study," Journal of Periodontology, p. jper.11380, Jul. 2025, doi: 10.1002/jper.11380

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