

A Grid-Connected Photovoltaic and Battery Energy Storage Interfaced Electric Vehicle Charging Station: A Comprehensive Review

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Abstract— The rise of Electric Vehicles (EVs) is creating a demand for convenient, safe and clean access to charging stations. This paper gives a detailed review on Grid Connected EV Charging Station (CC-EVCS) for PV array and Battery energy storage system. It is proposed that architecture enables coordinated energy exchange between PV source, battery storage unit, EV and conventional energy sources to make energy charging more flexible and reduce conventional energy usage in the energy system. If there is plenty of sunlight (e.g. during daytime hours), the PV array can be used to power the EV charging stations directly, or it can go into the battery storage system or be returned to the grid. During the low solar generation period, the battery and the grid will charge together, to sustain continuous operation. Some of the energy management strategies, bidirectional power flow, synchronization mechanism and the charging control approach to maintain power quality and system stability are also summarized. Battery integration also helps to reduce peak load and optimize system efficiency. The review emphasizes the importance of RE (renewable energy) based charging stations for enabling sustainable transport and further smart grid development, in terms of better energy utilization and less environmental impact.

Keywords: Electric Vehicle (EV), Photovoltaic (PV), Battery Energy Storage System (BESS), Grid-Connected Charging Station, Energy Management, Smart Grid.

1. INTRODUCTION

The transportation industry is undergoing a major shift and electric vehicles (EVs) are quickly replacing traditional internal combustion engine cars. The ongoing transition to sustainable mobility solutions has been accelerated by rising environmental awareness, rising fuel prices, diminishing fossil fuels stocks and strict emission limits. Traditional mode of transport is a significant source of CO₂ emission and urban pollution, thus there is a need for cleaner energy technologies. Electric vehicles offer a viable solution, delivering carbon emissions benefits as well as greater energy efficiency, lower running costs and a lower reliance on petroleum-based fuels. Consequently, the governments and industries around the globe are investing heavily in EV infrastructure and are encouraging electrification on a large scale.

While EV usage is rising, the availability of sites with efficient and reliable charging stations is still regarded as one of the main hurdles for widespread adoption. The traditional charging methods that are fully dependent on utility power lead to greater peak load demand and may even contribute to stability or power quality problems in the power network. Moreover, charging time, charging availability and reliability of operation is still a challenge in user acceptance. As a result, research effort has been focused on the development of intelligent charging stations that are able to integrate renewable energy resources to assist future transportation needs without burdening existing electrical grids.

The key reason for the PV sustainable solution being one of the most promising energy options for EV charging is its ability to supply clean energy, modularity, and a declining installation price. Solar Charging Stations can be directly connected to the electricity generated locally to charge the EV battery, reducing the need to depend on the grid and reducing operating costs. However, the intermittent nature of solar energy poses challenges for having power sources available for always charging, due to its dependence on the sun's power production and the availability of solar irradiation. There is thus a need for more energy management solutions which offer stable and continuous charging performance.

One solution to the intermittent renewable energy generation concerns is with Battery Energy Storage Systems (BESS). By storing excess solar energy when generation exceeds demand and releasing energy when it is needed, BESS can help to enhance the flexibility and reliability of EV charging stations. Energy storage integration also enhances peak shaving and energy stress on the grid reduction, load balancing, and maximizing utilization of renewable energy. Further, the bidirectional power flow capability allows for the connection of the PV source, storage system, electric vehicle and the electric grid, supporting efficient energy management and optimization of overall system performance.

Advanced charging architectures are possible due to recent advances in power electronic converters, smart control algorithms and grid synchronization techniques that accommodate multiple operating conditions. The most modern charging stations employ coordinated control techniques to perform charging/discharging, power exchange control, dc link control and power quality maintenance. These smart controls can be instantaneously connected to the grid, and stand-alone when necessary, enabling uninterrupted charging of EVs. Energy management systems for smart grid and sustainable transportation systems are becoming more important in the future.

This paper presents a comprehensive overview of grid connected EV charging stations coupled with PVs and BESS. The basic concepts of EV charging infrastructure, integration of renewable energy sources, battery technologies, charging methods and energy management strategies are summarized in recent publications. Moreover, the advantages and dispatch strategies of PV-BESS integrated charging stations are described, and prospects are highlighted in the paper. The goal is to provide a systematic knowledge of new charging architectures, to facilitate sustainable mobility, efficient use of energy and reliable operation of future electric mobility systems.

II. ELECTRIC VEHICLE TECHNOLOGY AND CHARGING INFRASTRUCTURE

There are many advantages of electric vehicles (EVs), such as reduced environmental pollution, energy efficiency, and the use of less fossil fuel, and EVs play a crucial role in the modern transportation sector. It has been a problem that grows in size in the greenhouse effect, and the rapid use of traditional energy sources, which has led to an acceleration of the transition to electric mobility on a global scale. EVs use electrical energy to propel vehicles either partially or completely, as opposed to conventional vehicles relying 100% on internal combustion. The operational capability, efficiency and commercial viability of electric vehicles have been greatly enhanced due to continuing advances in power electronics, battery technologies and intelligent control systems [5], [10], [12].

There are generally two categories for electric vehicles, which is based on their propulsion and energy supply methods. A Battery Electric Vehicle (BEV) runs on electricity from a rechargeable battery pack, and produces no tailpipe emissions. The energy of electricity is transferred directly to mechanical energy by electric drive systems, and these vehicles are considered highly efficient. Hybrid Electric Vehicles (HEV) are a

more fuel efficient and less polluting version of the car that uses an electric propulsion system and an internal combustion engine. Plug-in Hybrid Electric Vehicles (PHEVs) take this one step further by providing the opportunity to charge them from the outside, and also charging them to allow for longer electric range. Fuel Cell Electric Vehicles (FCEVs) can be used to extend driving range and decrease charging dependency, as they produce electricity internally through hydrogen fuel cells. The benefits of each category of vehicle are dependent on the driving conditions, energy supply, infrastructure support and economic factors [3], [10], [12], [14].

The basic structure of an electric vehicle is comprised of a multitude of interconnected subsystems: the energy storage system, electric motor, power electronic converter, control system, and charging interface. The battery is one of the main energy resources which directly impacts on the vehicle range, charging time, and efficiency. Electric motors generate more mechanical output for a given electrical input than do conventional engines, while conventional energy transfer between the components of a vehicle is controlled by conventional engines. The evolution of motor drives and converter technology in more recent times has been assisting to make EV systems ever more power dense, lossy and dynamic. Such technological innovations have helped ensure EVs are more reliable and flexible to handle different loads [3], [10].

One of the important factors to promote EV is charging infrastructure. There are two classes of charging systems, an alternating current (AC) charging system and direct current (DC) charging system, based on the power delivery characteristics and the charging time. In the residential and workplace applications, the moderate charging requirements along with the less expensive installation costs make AC charging particularly common. It provides a charging power that is much higher than standard charging, and can greatly shorten charging time, which can be used in commercial charging stations and long-distance transportation networks. The design of the charging topology, the converter architecture, and charging control directly impacts charging efficiency, battery health and utility network interaction [2],[6].

There are several international charging standards that have been created to make sure that charging systems can be interoperable, safe and efficient in energy transfer. Charging standards are used to specify electrical connections, communication protocols, connector types and power levels associated with EV charging. Modern charging infrastructure can provide a range of charging modes from slow residential charging to high power rapid charging. Furthermore, new advancements have given rise to a bidirectional charging feature, allowing EVs to transfer energy back to the grid. This is known as vehicle-to-grid (V2G) and enables EV batteries to be used as distributed energy resources to help reduce peak demand and stabilise the grid [2], [4], [7], [11].

The number of EVs being used is steadily increasing across the world; however, multiple technical and operational challenges remain. While there are challenges of widespread adoption including limited driving range, battery degradation, charging time, charging station costs and power system impacts, some of these issues are receiving attention. The installation of high penetration of electric vehicle charging without coordination and organization can cause voltage regulation problems in the network. Additionally, temperature variations, charging rates and multiple charging cycles influence battery performance. So advanced battery management systems (ABMS) and intelligent charging algorithms have become essential to maintain the reliability of the battery, its efficiency during charging and its lifetime [4] [8] [15].

There has been recent interest in integrating EV charging stations with renewable energy sources and energy storage solutions to enhance sustainability and lessen reliance on the grid. Smart energy management measures and renewable assisted charging stations enable coordination of EVs, local energy generation and distribution sources and

networks. This is a key aspect of how such integration can help to achieve efficient energy use and in the build of future smart grid ecosystems and smart transportation. Innovation in charging technology, battery technology and in energy coordination technology will continue to play a major driving role in the development of sustainable electric mobility in the future [1] [6] [9].

III. PHOTOVOLTAIC AND BATTERY ENERGY STORAGE SYSTEM FOR EV CHARGING

With EV's rapidly increasing in popularity, there has been an increasing demand for dependable, affordable and eco-friendly energy to power EV charging stations. Charging strategies based on the traditional grid led to increase in highest demand and stress the electrical grid. To address these challenges, the coupling of renewable energy to the future charging system seems to be a viable alternative. Solar PV (PV) system has received much attention among the set of renewable technologies due to its availability, modular installation, low operational cost, and low environmental impact. Photovoltaic generation, combined with EV charging stations, helps to reduce reliance on energy from utilities and contributes to the development of low-carbon transportation [1, 5, 13].

PV systems transform the sun's rays directly into electricity using semiconductor-based solar cells. The key components of a typical PV powered EV charging system include Solar modules, Maximum power point tracking (MPPT) control, dc-link interfaces, and charging converters. The solar energy generated can directly be used for charging electric vehicles during daylight hours and excess energy can be fed into the power grid or stored for future demand. With the advancement of PV power converter technology and intelligent management of the power, the efficiency of energy extraction and charging reliability have been greatly enhanced in different environmental conditions [1], [6]. The use of PV systems in the charging process has gained increasing importance, as it facilitates decentralized energy generation and contributes to sustainable transport goals.

PV generation has significant environmental and economic advantages, but is also intermittent, which poses challenges for operations. Solar irradiation fluctuates with the intensity of the sun's radiation, temperature, seasons and weather, which means that the amount of charging power available will fluctuate continuously. Without compensation measures, these uncertainties have a negative impact on charging continuity and system reliability. Hence, these charging stations have been developed to maintain the stable charging behaviour and supporting continuous energy availability by using modern renewable charging stations with energy storage systems [1], [13].

Battery Energy Storage Systems (BESS) are now being considered one of the most important enabler technologies to enhance operational flexibility of renewable-based EV charging stations. Excess electrical energy produced when the sun shines the most can be stored in battery storage units and released when electrical energy is needed for charging or when sun generation is less than the charging demand. Along with better energy use, the deployment of BESS also helps lower reliance on the grid, aids peak load shaving and promotes system stability. Furthermore, the storage-supported charging infrastructure can offer improved power quality and facilitate coordinated energy exchange between renewables and the energy grid, as well as between charging loads [1, 7].

A number of battery technologies have been explored as potential energy storage or electric vehicle charging solutions. The first generation of energy storage solutions was based on lead-acid batteries which were relatively inexpensive and built very simply, but had limited energy density and cycle life. The main reason for the use of lithium-ion battery technology is its high energy density, fast charging capability, low self-discharge and long service life. Various other technologies have also been investigated to improve energy availability and charging performance such as ultracapacitors, hybrid energy storage systems and the fuel-cell assisted configuration. The choice of appropriate battery

technology has been shown to impact on charging efficiency, storage capacity, system costs and system reliability [3, 8, 14].

The management of batteries is becoming more and more critical because battery safety, battery life extension and charging effectiveness need to be controlled. BMS are used to monitor voltage, current, temperature and state-of-charge to ensure optimal charging and discharging operations are carried out. Advanced battery control methods to enable thermal management, fault diagnostics and energy balancing between battery storage units. In the recent years, intelligent battery charging methods and adaptive control strategies have been highlighted to mitigate degradation and enhance the performance in the long run of renewable supported EV charging systems [8] and [15].

PV systems and BES have provided the potential to design very efficient and autonomous EV charging stations. Hybrid PV-BESS architectures facilitate bi-directional energy sharing and intelligent energy management and integration between local generation, energy storage, charging loads, and utility networks. They are designed to facilitate greater renewable energy integration, lower operating expenses, and help meet the goals of the smart grid by enabling smart energy management. Current research efforts are aimed at improving converter topologies, charging coordination techniques, storage sizing and control algorithms to enhance the charging efficiency and ensure reliable operation in dynamic operating conditions [1, 4, 6, 7].

IV. GRID-CONNECTED PV-BESS INTERFACED EV CHARGING STATION

PV generation, BESS and EV charging can be a great enabler to create sustainable, reliable and energy efficient transportation systems. The traditional grid connected charging stations are very dependent of the grid and may lead to voltage fluctuations, network congestion and increased operation and maintenance costs due to peak demand. To alleviate these challenges, recent studies have turned to hybrid charging architectures, which integrate renewable energy sources, energy storage systems, and smart energy management systems. The energy exchange coordination between the PV systems, the battery storage system, and EVs and the grid with the help of the grid-connected PV-BESS interfaced charging station ensures uninterrupted energy service, as well as reduction of the dependence on traditional energy sources [1] [5] [7].

Based on the mode of Renewable integration, the manner of energy storage and charging strategy, several architectures of the charging stations are reported in the literature. Early charging systems were mostly directly grid-charged with minimal flexibility of energy control. Later, PV-assisted charging stations were added, enabling PV power to be directly used to charge EVs during times when the sun was shining brightly. These systems did lower the amount of energy the grid needed to use, but were still subject to environmental conditions for charging. In recent architectures, dedicated battery storage units are integrated and temporarily store energy or control the energy delivery during fluctuations in renewable generation, thereby increasing reliability [1, 6, 13].

One such reported architecture includes a common dc-link topology which links the PV array, the battery storage system, the EV charging interface and the grid-side converter. This option can be used to charge the demand of the PVs when the sun is available, with the surplus energy either stored in the battery system or fed to the grid. At low irradiation levels or high charging demand, the stored battery power can be used to charge vehicles and ease demands on the utility grid. The architecture will provide better energy utilization, support continuous operation and enhance the penetration of renewables when compared to traditional charging stations [1, 3, 7].

In recent years, there have also been considerable advances in converter topology and power control techniques for grid-connected charging stations. Bidirectional dc-dc converters are typically used for controlling charging/discharging operations between

the EV battery and the storage system and voltage source converters (VSCs) are used to control bidirectional power exchange with the utility grid. The structures of this advanced converter can facilitate bi-directional energy transfer, achieve high conversion efficiency and run in several modes according to various environmental and load situations. Switching loss minimization, stability of the dc-link and high-power quality during charging operation are some of the advantages intelligent converter coordination can provide for the research [2, 6, 10].

The control strategies reported in previous studies are mainly energy balancing, charging coordination, grid synchronization and power quality improvement. The conventional control techniques include proportional–integral (PI) controllers and rule-based energy management for controlling charging current and keeping constant the dc-link voltage. More recent methods make use of adaptive control, predictive algorithms, and intelligent energy scheduling methods to optimize charging performance and maximize the utilization of renewable energy. The advanced energy management systems constantly track the state of charge of the battery, PV generation, charging demand loads and grid conditions to make best use of the energy available from a variety of sources. Efficiently coordinated control frameworks help to reduce unnecessary energy exchange with the grid and increase charging efficiency [1, 4, 6].

Another area of research that is significant is the bidirectional charging and vehicle-to-grid (V2G) function. Unlike traditional charging stations that are a load on the electrical grid, a modern charging station with smart grid technology can turn EV batteries into distributed energy storage elements that supply power back to the power grid. By optimizing EV operation, V2G can allow EV fleets to offer demand response and frequency regulation, and peak shaving. Research shows that coordinated charging/discharging can enhance the stability of the power grid, and provide extra operational advantages to the charging operator. However, suitable control of battery degradation [4],[5],[7],[11] and communication infrastructure as well as suitable charging scheduling mechanisms will be required in practical implementation.

One of the key factors identified as impacting charging station performance and operational economics has been battery integration. Research indicates that charging stations powered by renewable energy are most energy dense, most efficient to charge, and have longest life cycle with lithium-ion battery technologies. Moreover, battery management systems help optimize system performance by monitoring the operating environment and controlling the charging cycles to prevent thermal stress and prolong battery life. Hybrid storage (batteries and ultracapacitors) has also been investigated to meet fast charging demands and enhance transient response [3, 8, 15].

Literature suggests that grid-connected PV–BESS interfaced EV charging stations have significant benefits when compared to traditional charging methods such as relying on fossil fuels or the grid. These benefits include renewable energy use, lower reliance on the grid, more reliable charging, and increased flexibility in energy management. With ongoing research in converter design, intelligent control, energy scheduling and optimization, charging station performance is still expected to be further enhanced, and large-scale deployment of sustainable electric transportation infrastructure is expected to be accelerated [1], [6], [9].

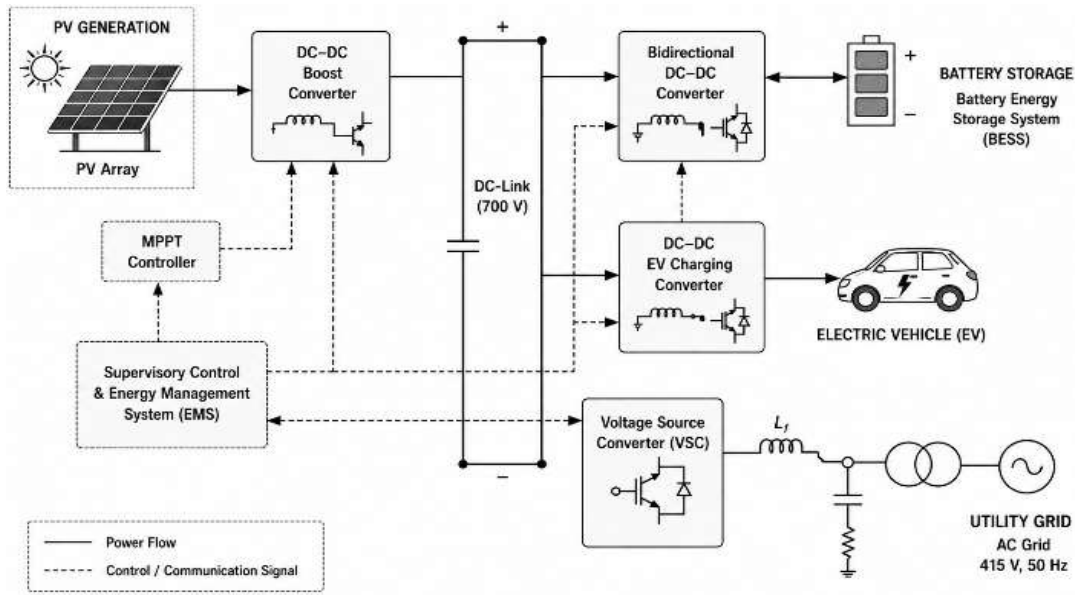
The focus of previous research is mainly on optimizing PV generation or battery storage or on optimizing charging control. Currently, there are very few studies that address in detail coordinated integration of grid connected PV–BESS system for reliable EV charging under dynamic operating conditions.

V. SIMULATION MODEL AND PERFORMANCE ANALYSIS

A simulation model is created in MATLAB/Simulink to assess the performance of the proposed Electric Vehicle (EV) charging station which is Grid Connected Photovoltaic (PV) and Battery Energy Storage System (BESS). The model seeks to emulate the interaction of the renewable sources, energy storage, energy supply from the utility grid, and EV charging demand for varying operating conditions. The simulation environment can be used for the study of practical charging continuity and energy use, converter operation and system response. Before real implementation, the behavior of charging stations can be effectively verified with the integrated model.

The developed simulation is composed of the following blocks: PV generation subsystem, battery storage, bidirectional dc-dc converter, grid-side voltage source converter (VSC), EV charging interface, and supervisory control block. The PV array is as the main renewable source and feeds a common dc-link. The BESS will store excess renewable energy and be used to charge during periods of low solar generation. VSC controls the energy flow with the grid and keeps the system stable under dynamic loading.

Fig. 1. Simulink Model of Grid-Connected PV-BESS EV Charging Station



A. Simulation Model Formulation

The electric power produced by the PV system is calculated as:

$$P_{PV} = V_{PV} \times I_{PV} \quad (1)$$

where:

P_{PV} = Photovoltaic output power (W)

V_{PV} = PV voltage (V)

I_{PV} = PV current (A)

The operating conditions are controlled to achieve maximum power extracted and efficient use of solar energy.

The model for the battery energy storage is:

$$E_{BESS} = E_{initial} + \int P_{BESS} dt \quad (2)$$

where:

E_{BESS} = Stored battery energy

P_{BESS} = Battery charging/discharging power

Battery State of Charge (SOC) is estimated by:

$$SOC = \frac{Q_{available}}{Q_{rated}} \times 100 \quad (3)$$

where:

$Q_{available}$ = Remaining battery charge

Q_{rated} = Rated battery capacity

B. Energy Flow and Charging Equations

The energy balance of the charging station is given by:

$$P_{Grid} + P_{PV} + P_{BESS} = P_{EV} + P_{Loss} \quad (4)$$

where:

P_{Grid} = Utility grid power

P_{EV} = EV charging power

P_{Loss} = System losses

The EV charging current is calculated as:

$$I_{EV} = \frac{P_{EV}}{V_{EV}} \quad (5)$$

where:

V_{EV} = EV charging voltage

Overall system efficiency is evaluated using:

$$\eta = \frac{P_{out}}{P_{in}} \times 100 \quad (6)$$

where:

η = Charging efficiency (%)

Grid active power transfer is obtained as:

$$P = \sqrt{3}VI \cos \phi \quad (7)$$

Reactive power exchange is determined by:

$$Q = \sqrt{3}VI \sin \phi \quad (8)$$

where:

V = Grid voltage

I = Grid current

ϕ = Power factor angle

C. Simulation Parameters

The simulation is carried out under typical operating conditions.

Table I: Simulation Parameters

Parameter	Value
PV Array Rating	25 kW
Battery Capacity	100 kWh
EV Charging Voltage	400 V
Grid Voltage	415 V
DC-Link Voltage	700 V
Switching Frequency	10 kHz
Solar Irradiance	600–1000 W/m ²
Simulation Duration	10 s

D. Performance Analysis

1) Performance Under Variable Solar Irradiation

The first operating scenario assesses the system's dynamics when the sun's power fluctuates. The PV array produces more power as the amount of irradiation increases, which is used to charge EVs and store them in batteries. In periods of low irradiation, the battery compensates for the lack of electric power, and allows continuous charging operation to proceed.

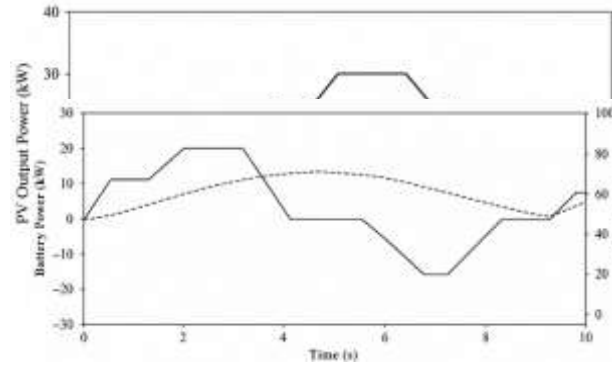


Fig. 2. PV Output Power Variation

Fig. 3. Battery Charging-Discharging Profile

The simulation results shows that a good utilization of the available solar energy is achieved with stable charging condition.

2) Grid-Connected

Charging Performance

The second scenario considers coordinated use of renewable energy generation and the network. Grid support provides peak charging demand control and helps to maintain charging continuity in the event of overloading the grid during the peak period:

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1} \times 100 \quad (9)$$

where:

V_n = Harmonic component

V_1 = Fundamental component

Fig. 4. Grid Voltage and Current Response

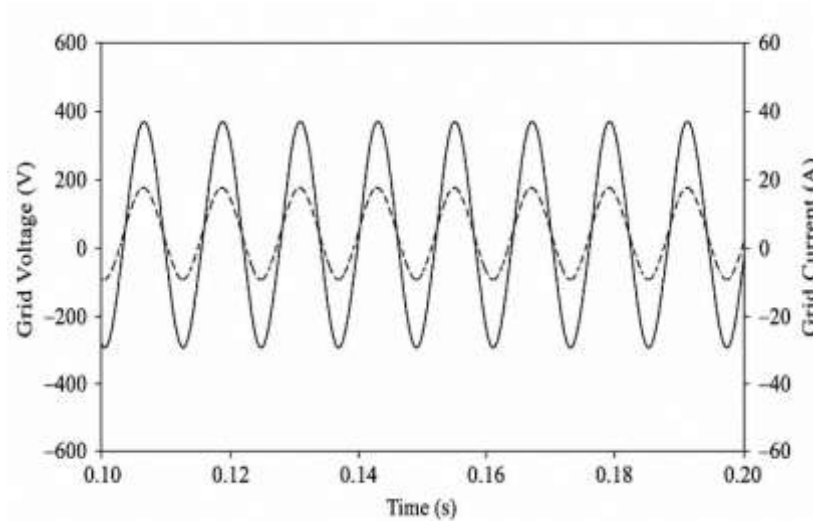
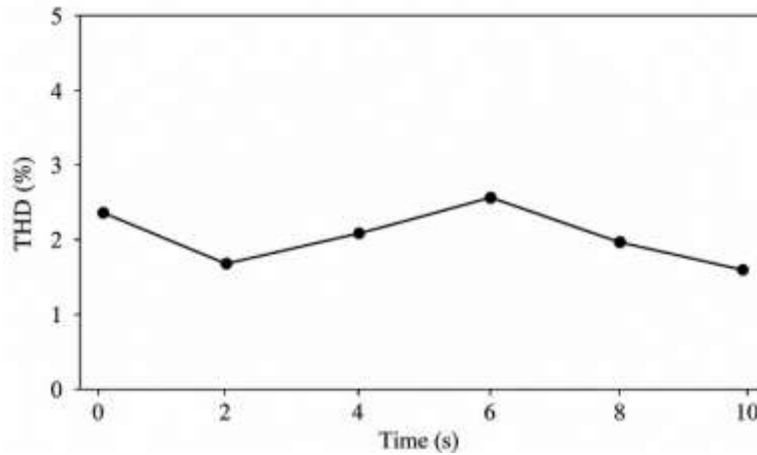


Fig. 5. Harmonic Performance Analysis.



Stable grid interaction and power quality characteristics are achieved as shown in the results.

3) Electric Vehicle Charging Characteristics

The charging profile of the EV battery is determined by the voltage, the charging current and the alteration in the state of the battery.

The energy stored when charging is found by:

$$E_{charge} = V_{EV} \times I_{EV} \times t \quad (10)$$

Charging duration is estimated as:

$$T = \frac{E_{battery}}{P_{charge}} \quad (11)$$

where:

T = Charging time

Fig. 6. EV Charging Voltage and Current

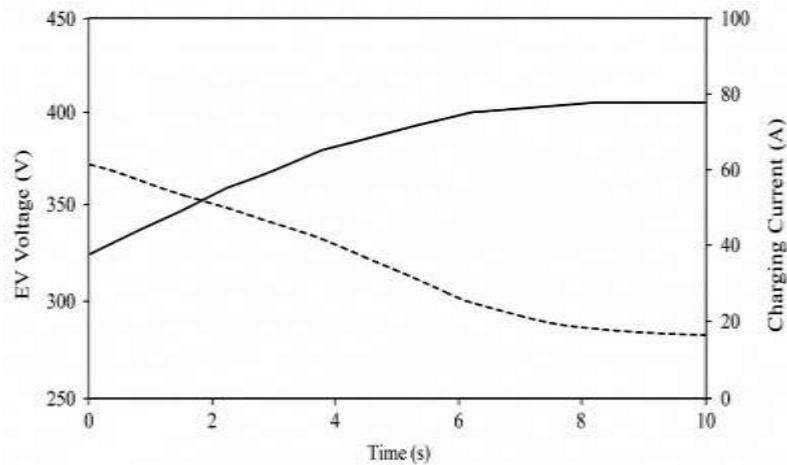


Fig. 7. State of Charge (SOC) Characteristics

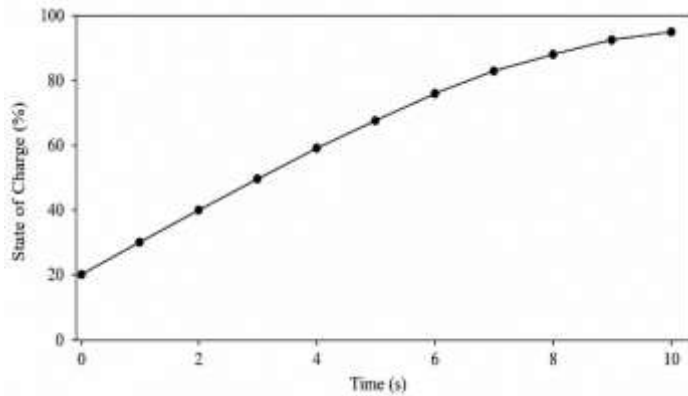


Table II: Performance Summary

Parameter	Obtained Value
Peak PV Output Power	30 kW
Maximum Battery SOC	95%
Grid Voltage	415 V
Maximum EV Charging Voltage	405 V
Minimum EV Charging Current	20 A
Maximum THD	2.6%
Estimated Charging Efficiency	96–98%

In summary, the results of the Simulation show the coordinated energy management between PV generation, battery storage and utility support to ensure stable EV charging performance and better use of renewable energy resources.

VI. FUTURE RESEARCH DIRECTIONS

The current rapid development of the electric vehicles (EV) and renewable energy sectors is driving the creation of new opportunities for the development of smart and sustainable charging infrastructure. Grid-connected photovoltaic (PV) and Battery Energy Storage System (BESS) integrated charging stations have shown great promise, but still face a number of technical, operational, and economic challenges that warrant further research. Further studies are required to increase the charge efficiency, reliability of the system, use of renewable energy resources, and integration of a large-scale system with modern power system.

A key research focus is to develop more sophisticated energy management strategies that manage energy flows between PV generation, battery storage, EVs and the grid in real time. The currently used charging method is mostly based on predetermined operating rules, which do not necessarily reflect efficiently changing generation and demand variations. Future charging systems would incorporate intelligent optimization method as well as adaptive control algorithm to optimize the usage of the device's energy, reduce the charging cost, and maximize the use of renewable energy sources without compromising the stability of the grid.

AI and machine learning will increasingly be an integral part of next generation EV charging stations. Predictive energy management techniques can predict solar generation, charging demand, battery condition and grid loading conditions to assist in proactive decision-making. An application based on data-driven approach can help with

the autonomous scheduling of charging, demand-side management and dynamic control of charging operations. For the most part, though, intelligent charging coordination can do more to improve charging availability, as well as to reduce unwarranted energy trading with the utility grid.

Another key research gap is the technology of batteries. Although lithium-ion batteries are the most popular choice for EVs and energy storage solutions now, a few challenges, including battery lifetime, charging speeds, thermal management, and battery material sustainability, continue to spur the search for alternative battery technologies. New battery technologies and hybrid storage solutions are anticipated to offer greater energy density, quicker charging time, extended service life and greater safety. More research would also be required for the more sophisticated Battery Management Systems (BMS) which would improve battery health estimation and battery storage life.

Incorporating renewable energy into charging infrastructure will become decentralized and self-sufficient energy systems. Future charging stations may be designed as a combination of renewable energy production (PV) and a wind energy resource and local storage to provide more consistent charging power and reduce reliance on utility power. In addition, studies should be carried out to identify the size of RE systems and storage units to ensure that maximum use is made of the energy provided and to reduce operating costs.

The vehicle-to-grid (V2G) and bidirectional charging (B2G) technologies are likely to be pivotal elements in the future smart energy system. EVs can be deployed to the grid as a distributed energy resource that can be used for ancillary services, peak load reduction and grid stabilization. However, areas to be further improved for deployment in practice include: communication infrastructure, charging coordination, cyber security and mitigating battery degradation. So there is a need for study of secure and reliable systems of bi-directional energy exchange in the future.

The performance of charging systems will also be affected by the power electronic converter technology. The future converter design should be aimed at achieving improvement of its parameters in terms of efficiency, switching loss, size and thermal parameters. Charging speed and system efficiency can be substantially increased, and hardware complexity decreased, by using wide-bandgap semiconductor devices and intelligent converter control methods.

Lastly, the future of EV charging infrastructure will be full of smart, connected networks, linked with digital monitoring systems, real-time analytics, and intelligent control systems. The synergy between these technologies – renewable energy, advanced energy storage, smart grids, and intelligent transportation – is expected to play a key role in transitioning to sustainable mobility and support the development of resilient energy systems. Sustainable progress in all these areas will continue to be key to the success of efficient and scalable EV charging infrastructure that is environmentally responsible.

VII. CONCLUSION

The paper was a thorough review and simulation-based analysis of an electric vehicle (EV) charging station connected to grid-connected photovoltaic (PV) and Battery Energy Storage System (BESS) for sustainable EV charging applications. The aim of this study was to explore how to integrate renewable energy sources, battery storage systems, and coordinated charging infrastructure to enhance charging reliability and decrease reliance on traditional electricity sources. Several critical issues including EV charging technologies, PV generation, battery energy storage operation, grid interaction, and energy management strategies were covered. The coordinated operation between PV system, BESS, EV charging unit and utility grid was estimated using MATLAB for

performance evaluation and good energy utilization and stable charging performance under various operating conditions were achieved.

Situated in the field of System evolution for EV charging infrastructure from renewable energy sources, the study is important in proposing a systematic design methodology for the development of integration that includes the aspects of System architecture, Mathematical modelling, Simulation analysis and Performance evaluation. The results showed that the PV generation combined with the energy storage capacity provides the flexibility of operation, continuity of charging and a better energy management capability. The presented method can serve as a guideline for the future development of smart charging stations and sustainable mobility. Further research on advanced energy management strategies, including smart charging coordination, vehicle-to-grid (V2G) integration, predictive control techniques, and the development of new battery technologies, could be considered to improve the efficiency and scalability of next-generation EV charging stations, while also fostering long-term reliability.

REFERENCES

- [1] V. Jain, B. Singh and Seema, "A Grid Connected PV Array and Battery Energy Storage Interfaced EV Charging Station," in *IEEE Transactions on Transportation Electrification*, vol. 9, no. 3, pp. 3723-3730, Sept. 2023.
- [2] Dr B Hariprasad, Goturu Sreenivasan, Sambugari Anil Kumar and Bestha Mallikarjuna (2024), "Vehicle-to-Grid Power Transfer Method for Electric Vehicles using off-board charger". *International Journal of Electrical and Electronics Research* " September 2024 12(4), 1203-1210. DOI: 10.37391/IJEER.120411.
- [3] A. Khaligh and Z. Li, "Battery, Ultracapacitor, Fuel Cell, and Hybrid Energy Storage Systems for Electric, Hybrid Electric, Fuel Cell, and Plug-In Hybrid Electric Vehicles: State of the Art," in *IEEE Transactions on Vehicular Technology*, vol. 59, no. 6, pp. 2806-2814, July 2010.
- [4] S. Habib, M. Kamran, and U. Rashid, "Impact analysis of vehicle-to-grid technology and charging strategies of electric vehicles on distribution networks – A review," *Journal of Power Sources*, vol. 277, pp. 205–214, Mar. 2015.
- [5] J. A. P. Lopes, F. J. Soares and P. M. R. Almeida, "Integration of Electric Vehicles in the Electric Power System," in *Proceedings of the IEEE*, vol. 99, no. 1, pp. 168-183, Jan. 2011.
- [6] B Hariprasad, Dr. G Sreenivasan and Dr. P Sujatha, "Islanding Detection in Distribution Generation Using Active Method", " *International Journal of Electrical and Electronics Research* ", July 2023, 11(3), pp. 662-668. DOI: 10.37391/ijeer.110304 .
- [7] S. Shao, M. Pipattanasomporn and S. Rahman, "Grid Integration of Electric Vehicles and Demand Response With Customer Choice," in *IEEE Transactions on Smart Grid*, vol. 3, no. 1, pp. 543-550, March 2012.
- [8] S. Hasan, A. A. Upam, M. Haque, P. Chowdhury, A. Rahman, and O. Farrok, "Battery management in electric vehicles: Advancements, charging standards, and associated challenges," *J. Energy Storage*, vol. 154, pt. C, Art. no. 121309, 2026.
- [9] B Hariprasad, Dr. G Sreenivasan and Dr. P Sujatha, "Review Of Islanding Detection Methods For Distribution Generation," in April 2022. DOI: 10.1109/BHARAT53139.2022.00029 , ISBN:978-1-6654-3625-0
- [10] A. Emadi, Y. J. Lee and K. Rajashekara, "Power Electronics and Motor Drives in Electric, Hybrid Electric, and Plug-In Hybrid Electric Vehicles," in *IEEE Transactions on Industrial Electronics*, vol. 55, no. 6, pp. 2237-2245, June 2008.
- [11] B Hariprasad, Dr. G Sreenivasan and Dr. P Sujatha, "A Novel Passive Islanding Detection Method for Distribution Generation", " *International Journal of Electrical and Electronics Research* " September 2023, 11(4), pp. 944-948. DOI: 10.37391/ijeer.110410

- [12] B Hariprasad, Dr.P.Bharat Kumar, Dr.P.Sujatha and Dr.G.Sreenivasan, " A Novel Adaptive Rule-Based Islanding Detection Technique for Voltage Source Inverter-Based Distribution Generation ", in Journal of Green Engineering (JGE), Online ISSN: 1904-4720 .Volume-11,Issue-1(2021),pp-511-529