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Super-Twisting Sliding Mode Controller - based PV off-Grid Charging Station for Electric Vehicles

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***Abstract*—The rapid growth of Electric Vehicles (EVs) has increased the demand for reliable and sustainable charging infrastructure, especially in regions with limited grid connectivity. Conventional grid-based charging adds pressure to existing power networks, highlighting the need for renewable, off- grid alternatives. This study proposes a Super-Twisting Sliding Mode Controller (ST-SMC)-based Photovoltaic (PV) Off-Grid Charging Station (OGCS) to deliver stable and efficient EV charging under variable solar conditions. The system integrates a PV array, boost converter, and bidirectional converters (BDCs) for managing the charging and discharging of the Energy Storage System (ESS) and the EV battery.**

The ST-SMC provides robust and precise control of power conversion stages, minimizing chattering and enhancing voltage regulation compared to traditional controllers. The ESS ensures a continuous energy supply during low irradiance, improving overall system reliability. Simulation results in MATLAB/Simulink demonstrate enhanced voltage stability, faster dynamic response, and higher efficiency. The proposed ST-SMC-based PV OGCS offers an eco-friendly, stable, and efficient charging solution for remote and grid-independent applications.

***Index Terms*—Photovoltaic (PV), Bidirectional Converter (BDC), Energy Storage System (ESS), Electric Vehicle (EV), Off-Grid Charging, Super-Twisting Sliding Mode Controller (ST-SMC).**

I. INTRODUCTION

The rapid rise of Electric Vehicles (EVs) in India is driven by increasing environmental awareness and the depletion of fossil fuel reserves. As one of the world's largest consumers of petroleum products, India faces an urgent need to transition toward sustainable and cleaner transportation solutions. At present, most EVs rely on grid-based charging (G2V), which adds further strain to the already overloaded power infrastructure.

To overcome this issue, Kempton and Letendre (1997) introduced the Vehicle-to-Grid (V2G) concept, which allows stored energy in EV batteries to be fed back into the grid to enhance stability and balance energy flow. However, this system still depends heavily on electricity generated from fossil fuels, limiting its environmental advantages.

Renewable-powered Off-Grid Charging Stations (OGCS) offer a cleaner and more sustainable alternative. Among renewable options, photovoltaic (PV) systems are particularly suitable for India due to their affordability, easy installation, and abundant solar potential. Since solar power output fluctuates with irradiance and weather conditions, integrating an Energy Storage System (ESS) ensures stable and reliable power delivery. The combination of PV and ESS enables continuous, clean, and independent EV charging, even in remote locations without grid access. Traditional control techniques such as Proportional–Integral (PI) controllers often exhibit limitations in handling nonlinearities and rapid disturbances in system behaviour.

To overcome these challenges, this research proposes a Super-Twisting Sliding Mode Controller (ST-SMC) for a PV-based off-grid EV charging station. The ST-SMC approach provides superior robustness, faster transient response, and reduced chattering compared to conventional sliding mode control methods. In addition, the integration of an Energy Storage System (ESS) enhances the stability and energy reliability of the overall setup In summary, PV-based off-grid charging stations present an efficient, eco-friendly, and cost-effective solution to reduce grid dependency, lower carbon emissions, and advance India's transition toward sustainable and pollution-free

transportation.
Further, this paper is planned as follows. Section II presents the Literature survey. Modelling of the system framework has been discussed in Section III. The results of the simulation work have been described in Section
IV. Finally, Section V comes with the conclusion and the possible future work.

II. LITERATURE REVIEW

Recent advancements in renewable-based EV charging systems emphasize efficient energy management and robust control strategies. Bhatti and Salam [1] developed an Energy Management Scheme (EMS) for hybrid PV-grid systems that effectively balanced energy flow between PV, storage, and the grid, reducing dependency on external supply and enhancing cost efficiency. Goli and Shireen [2] proposed a smart charging station integrating grid-connected PV with bidirectional converters, ensuring flexible energy transfer between the grid, PV array, and EVs under variable conditions. Hernandez and Sutil [3] focused on Energy Storage System (ESS) optimization using voltage-sensing-based management to enhance voltage stability and reduce losses in renewable-based charging setups. Kempton and Letendre [4] investigated vehicle-to-grid (V2G) technology, proving EV batteries can act as distributed storage systems, supporting grid frequency control and peak-load management. Li et al. [5] examined hybrid renewable systems combining wind, PV, and battery storage, achieving improved power stability and SOC regulation through real-time control strategies. Nordin and Omar [6] developed an accurate PV modelling and MPPT algorithm validated through experimental data, improving power tracking efficiency. Singh et al. [7] introduced a smart bidirectional charging station, allowing EVs to store and supply energy back to the grid to stabilize power flow. Tulpule et al. [8] emphasized intelligent charging control to balance renewable integration with grid reliability and minimize economic impacts of large-scale EV adoption.
From the reviewed studies, it is evident that existing PV-based EV charging systems often face limitations in maintaining voltage stability and efficiency under fluctuating solar conditions. This work addresses these gaps by implementing a Super-Twisting Sliding Mode Controller (ST-SMC) for a PV-based off-grid EV charging system, achieving superior control robustness, dynamic performance, and system reliability.

III. MATERIALS AND METHODOLOGY

The proposed research investigates the development and control of an off-grid electric vehicle (EV) charging system powered by a photovoltaic (PV) source and enhanced through a Super Twisting Sliding Mode Controller (ST-SMC). The study emphasizes achieving stable operation, robust voltage regulation, and efficient energy utilization under varying environmental and load conditions. The complete workflow adopted for the system modelling, control design, and implementation is presented in Fig. 1 and systematically summarized in the subsequent steps.

A. System Configuration

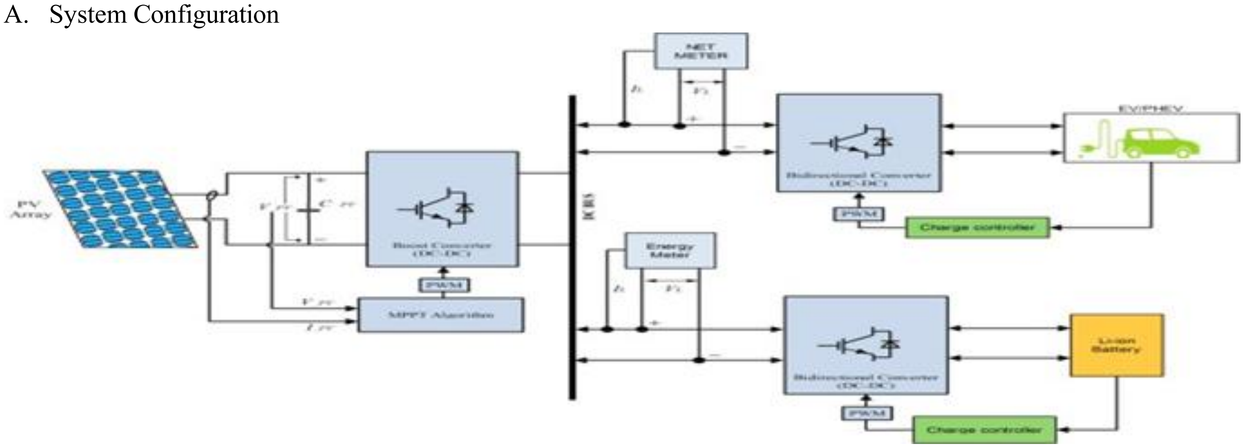

Fig 1: Proposed block diagram of the PV based Off-grid charging station with energy storage system

B. System description

The proposed off-grid EV charging station integrates three major subsystems: PV generation, EV charger, and Energy Storage System (ESS). The PV generation unit includes the PV array, MPPT module, and a DC–DC boost converter. The PV array converts incident solar irradiation into electrical energy, delivering output voltage V_{pv} and current I_{pv}. Due to variations in weather and irradiance, these outputs fluctuate; therefore, an MPPT algorithm is incorporated to continuously adjust the operating point and extract maximum power P_{pv}. The MPPT-derived control signal regulates the boost converter duty ratio, ensuring that the PV voltage is aligned with the optimal operating point.

The regulated DC-link voltage produced by the boost converter supplies both the EV charger and the ESS, as shown in Fig. 1. The EV charger includes a bidirectional DC–DC converter (BDC) interfaced with the EV battery. The BDC operates as a buck converter during charging, reducing the DC-link voltage to match battery requirements, and as a boost converter during discharging, enabling power to flow back to the DC-link. Similarly, the ESS section contains another BDC connected to the battery bank, which stores surplus solar energy and returns stored energy to the DC bus during low-generation periods. A constant current (CC) control strategy governs BDC operation by generating PWM signals to select buck or boost mode. This coordinated control ensures stable and efficient operation of the off-grid charging system. Section III provides detailed modelling and control explanations of each subsystem.

Step-1: PV Energy Generation and Monitoring:

The process begins with the extraction of solar energy using a PV array configured to achieve the required voltage and current levels. The real-time PV parameters, such as V_{pv}, I_{pv}, and irradiance variations, are continuously monitored to assess the available power.

Step-2: Maximum Power Point Tracking (MPPT) Implementation:

An MPPT algorithm evaluates the instantaneous operating point of the PV array and adjusts the control signal to maintain operation near the maximum power region. This step ensures that the PV system delivers peak energy during varying environmental conditions.

Step-3: Boost Converter Operation and DC-Link Regulation:

The MPPT output is applied to the boost converter to regulate the DC-link voltage. The converter elevates the PV voltage to the required level and stabilizes the output by generating the appropriate duty cycle.

Step-4: ST-SMC Control Integration:

The Super Twisting Sliding Mode Controller (ST-SMC) is incorporated to strengthen dynamic voltage regulation. It minimizes disturbances, reduces chattering, and maintains smooth power flow between PV, DC- link, and load components.

Step-5: Power Management for EV and ESS:

The controlled DC-link voltage feeds the bi-directional converter connected to the EV battery and Energy Storage System (ESS). Depending on the mode, the converter operates in buck(charging) or boost (discharging) configuration to manage energy flow effectively.

Step-6: System Coordination and Performance Validation:

The combined operation of PV generation, MPPT, ST-SMC, and converter modes is validated through simulation. System stability, fast response, and improved efficiency are assessed under different operating scenarios.

C. System formulation and Control

The system formulation presents the mathematical modelling, structural arrangement, and control methodology applied to the PV-based off-grid EV charging station. The control architecture ensures efficient energy extraction from the PV source, stable DC-link regulation, and coordinated charging/discharging of both EV and ESS batteries.

a. PV Array Modelling

The PV array forms the primary renewable energy unit of the system. It is configured using series–parallel interconnected modules to achieve the desired voltage Vpv and current Ipv. Series-connected modules determine the terminal voltage of the array, whereas parallel strings contribute to the total current. This combination enhances output reliability under variable solar irradiance. Electrical parameters such as short- circuit current, diode saturation current, series resistance, shunt resistance, temperature, and diode ideality factor influence the array characteristics. These voltage–current values act as inputs to the MPPT algorithm and boost converter.

b. DC-DC Boost Converter Modelling

The boost converter is responsible for elevating the PV voltage to a constant DC-link level. It operates in continuous conduction mode (CCM) and is governed by energy transfer through the inductor $Lboost$ and capacitor $Cboost$. The duty ratio Ddetermines the relationship between the PV input voltage and the output DC- link voltage. Inductor current dynamics and capacitor voltage variations are expressed through state-space equations, which are further used for control analysis. The controller modifies the duty cycle to stabilize the DC-link voltage despite changes in irradiation or load demand.

c. Maximum Power Point Tracking (MPPT)

The MPPT algorithm continuously monitors PV array parameters to track the maximum power operating point. It adjusts the converter duty cycle to align the PV operating voltage with the maximum power point. This ensures optimal utilization of solar energy and enhances system efficiency during varying irradiance. The MPPT output serves as the reference for the boost converter control loop.

d. Bidirectional Converter Modelling

The system incorporates two bidirectional DC–DC converters (BDC) one for the EV charger and one for the ESS. Each converter supports dual functionality based on the required operating mode. During charging, the BDC functions in buck mode to reduce the DC-link voltage and deliver a controlled charging current to the battery. During discharging, it operates in boost mode to transfer energy back to the DC-link when needed. Component values such as $LBDC$ and $CBDC$ are selected based on voltage ripple, current ripple, switching frequency, and power rating.

e. ESS Control Strategy

The ESS acts as an energy buffer to balance the power mismatch between PV generation and EV load demand. The BDC connected to the ESS stores excess PV energy during high irradiation and releases stored energy during low-generation periods. The constant-current (CC) control method is employed to maintain uniform charging and discharging currents, enabling stable battery operation. The control system produces switching signals to select buck or boost mode based on system requirements.

f. Super Twisting Sliding Mode Controller (ST-SMC)

The ST-SMC is implemented to enhance the converter stability and dynamic performance. This nonlinear control approach ensures robustness against disturbances, reduces chattering, and maintains tighter voltage regulation compared to conventional controllers. The controller computes an adaptive duty ratio that stabilizes the DC-link voltage and improves transient response under fluctuating environmental and loading conditions.

D. Research Methodology

The present research work aims at developing an efficient photovoltaic (PV) based off-grid charging system for electric vehicles, supported by a Super Twisting Sliding Mode Controller (ST-SMC) to enhance reliability, dynamic response, and voltage regulation. The methodological framework adopted in this study follows a structured sequence of modelling, control design, simulation, validation, and performance evaluation. The overall research approach is summarized in Fig. 1 and detailed through the following stages:

a. System Study and Requirement Analysis: The study begins with identifying the operational requirements of an off-grid EV charging station, including power demand estimation, solar irradiation profile assessment, energy storage sizing, and converter specifications.

b. PV Array Modelling: A mathematical model of the PV array is developed based on standard PV cell characteristics, temperature variations, and solar irradiance changes. The PV system is simulated to evaluate maximum power generation capability under varying environmental conditions.

c. DC–DC Converter Design: A high-gain DC–DC boost converter is designed to interface the PV module with the battery charging system. The converter parameters such as inductance, capacitance, duty cycle, and switching frequency are selected to ensure stable voltage output.

d. ST-SMC Algorithm Development: The Super Twisting Sliding Mode Controller is designed for improved robustness, reduced chattering, and fast transient response. The controller equations, sliding surface selection, and stability criteria are formulated to ensure optimal converter performance.

e. Battery Charging Control Strategy: A charging strategy is implemented to maintain safe battery charging, regulate current and voltage, and protect against overcharging or deep discharge conditions. SOC (State of Charge) estimation methods are integrated for efficient energy utilization

f. System Integration in MATLAB/Simulink: All components PV panel, converter, battery, and ST-SMC controller are integrated in a complete system-level model using MATLAB/Simulink. Thebehaviour of the system is simulated under different load and weather scenarios.

g. Performance Analysis and Validation: The system response is evaluated in terms of voltage stability, current regulation, maximum power extraction, controller robustness, and overall charging efficiency. Comparative analysis with conventional control methods is performed to validate performance improvement.

IV. SIMULATION RESULTS

4.1.SIMULATION RESULTS

The proposed super-twisting sliding mode controller PV- based off-grid charging station (OGCS) has a 15 kWh EV battery that is powered by a 24kW photovoltaic generator. Additionally, a 15 kWh ESS improves the recommended system. It has been utilized to store energy during periods of high PV generation and to provide an emergency feed to the EV batteries during periods of low PV generation. Additionally, MATLAB/Simulink was used to develop the system.

Three modes were taken into consideration when analyzing the suggested system's performance. These modes are divided into three categories: EV battery charging (i) with OGCS when ESS is not present, (ii) with OGCS when ESS and PV are present, and (iii) with ESS when PV generation is not present. Each mode is examined for 12 seconds based on the charging rate (C-rate), which simulates the EV battery's power consumption at that moment. For three seconds, the EV battery is first charged at a rate of 0.5C. and up to 12 seconds, a step of 0.5 C-rate is added every 3 seconds. In the aforementioned modes, the connected ESS and PV generation participate in accordance with changes in the C-rate power demand. Performance of each mode is analyzed in terms of battery power, SoC, terminal voltage, and current in the following subsections.

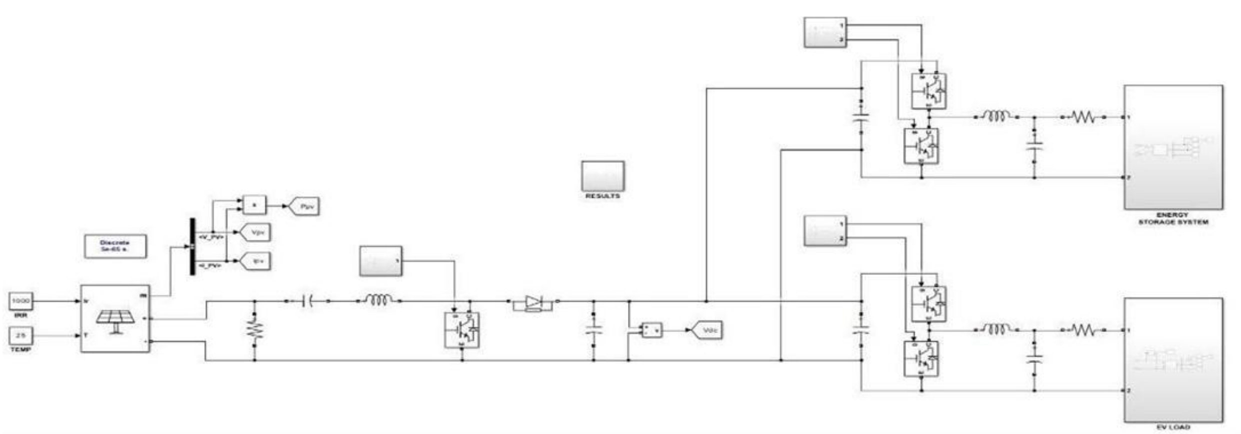

Fig 4.1: Simulink model of proposed system

CASE 1: During the absence of ESS

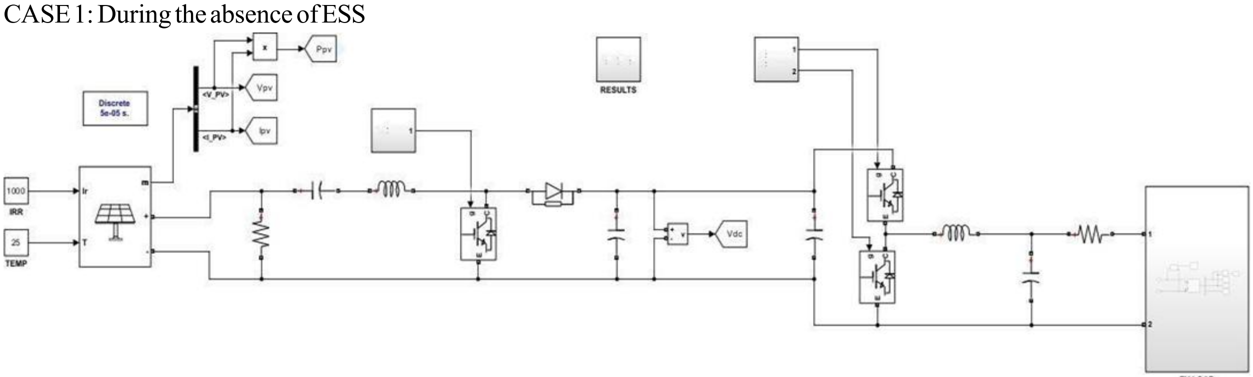

Fig 4.2: Simulink diagram of Absence of ESS

This diagram demonstrates how a renewable power system (like PV) delivers power directly to the load in the absence of an energy storage system (ESS). The DC source goes through a DC–DC converter, followed by an inverter and filter, before supplying the load. Without ESS, the system lacks backup power and cannot maintain stability during source fluctuation

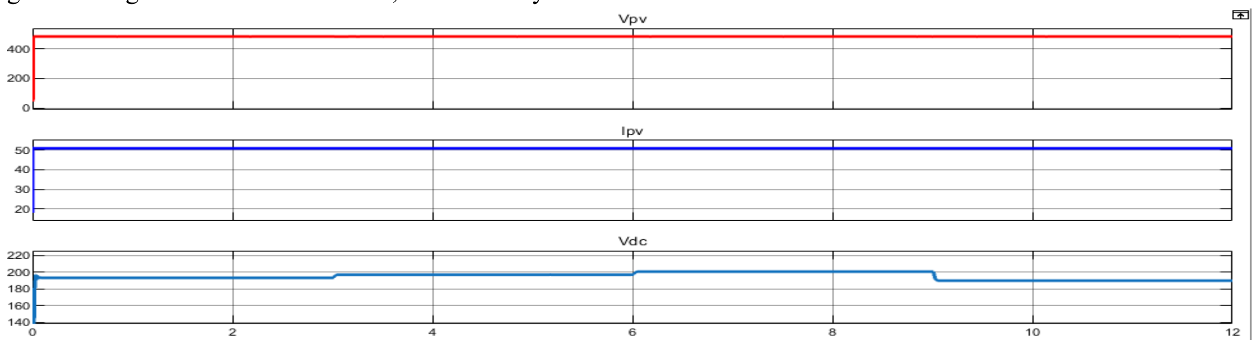

Fig 4.3: PV Voltage, Current and DC Link Voltage

The performance curves depict the behaviour of Vpv, Ipv, and Vdc. The PV voltage remains nearly constant around 400 V, while the PV current is stable at approximately 40 A, indicating consistent power generation. In comparison, the DC-link voltage exhibits a smoother and more controlled response, confirming improved regulation and enhanced overall system stability.

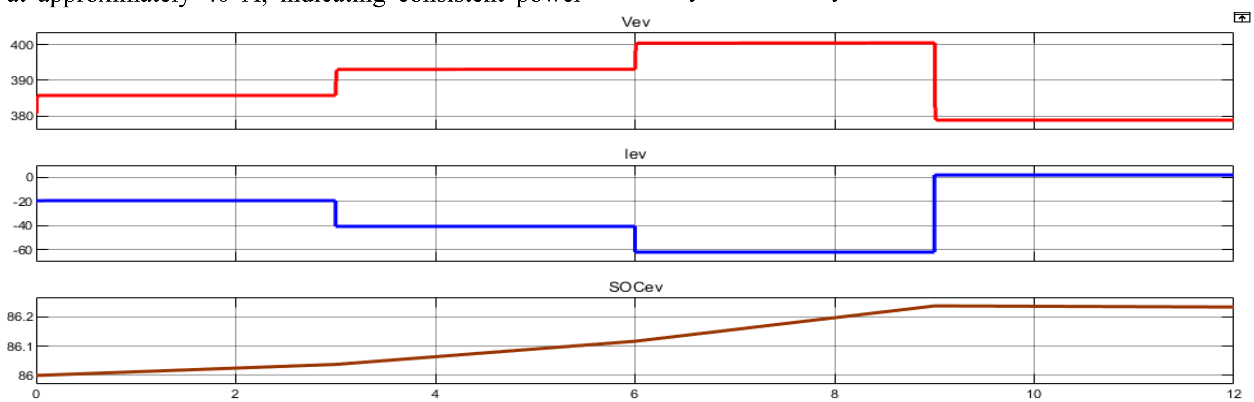

Fig 4.4: EV Load Voltage, Current and State of Charge

The PV voltage and current remain stable, while the DC-link shows the highest variation but maintains a smoother profile, ensuring better system stability. On the EV side, load voltage steps between 380–400 V, causing corresponding variations in charging current. The EV battery SOC increases steadily and becomes constant after 9 s, representing reduced solar input similar to evening hours. Overall, improved DC-link regulation leads to smoother charging and more efficient SOC progression.

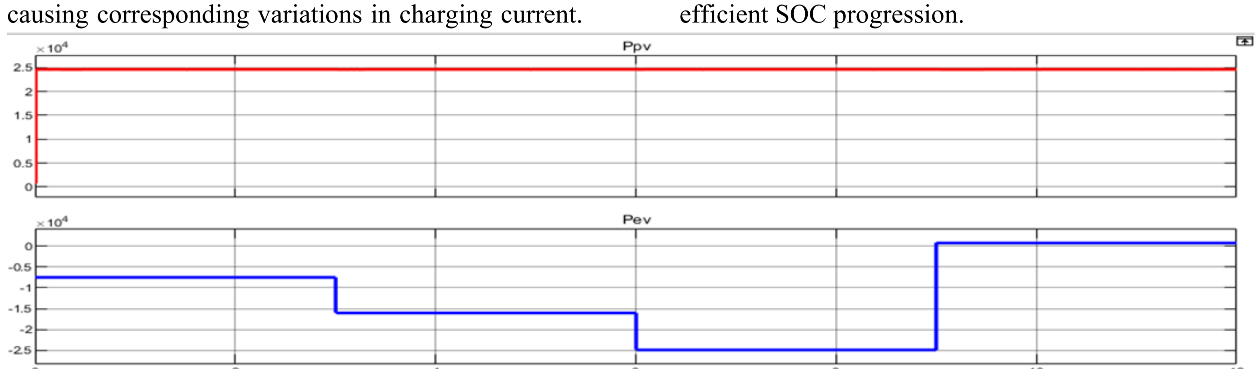

Fig 4.5: PV, EV Power

The graphs show the comparison between PV power (Ppv) and EV power (Pev) over time. Ppv stays almost constant in the graph, suggesting steady solar generation. Meanwhile, Pev fluctuates significantly between positive and negative values, reflecting charging and discharging cycles of the EV. Pev displays three separate steps, a similar step-like pattern appears, but with slightly different transitions and magnitudes. In this case suggest that EV power demand is highly dynamic, while PV power supply stays steady. The negative values of Pev indicate discharging. Overall, the graphs highlight stable PV generation against variable EV power consumption.

Here we can observe absence of ESS we can't store power in evening & night time in PV panel after 9s EV power is zero. Because of irradiance, it doesn't provide constant power. It states that PV generation is sufficient to charge the EV battery till 1.5 C-rate. Further, the increase in EV battery C-rate of EV battery C- rates indicate that PV generated is not sufficient to charge the EV battery. The increase in C-rate of EV battery leads to decrease in DC-link voltage provides during fluctuations with the proposed control strategy. The constant DC-link voltage provides desired terminal voltage for EV batteries continuously. The SoC, current and terminal voltage for EV battery response.As the energy demand increases from the EV battery (from 1.5 to 2 C-rate), only PV is unable to fulfill the demand. Therefore, an ESS is connected with PV to fulfill the requirement which as shown in next case.

CASE 2: During the presence of Energy Storage System

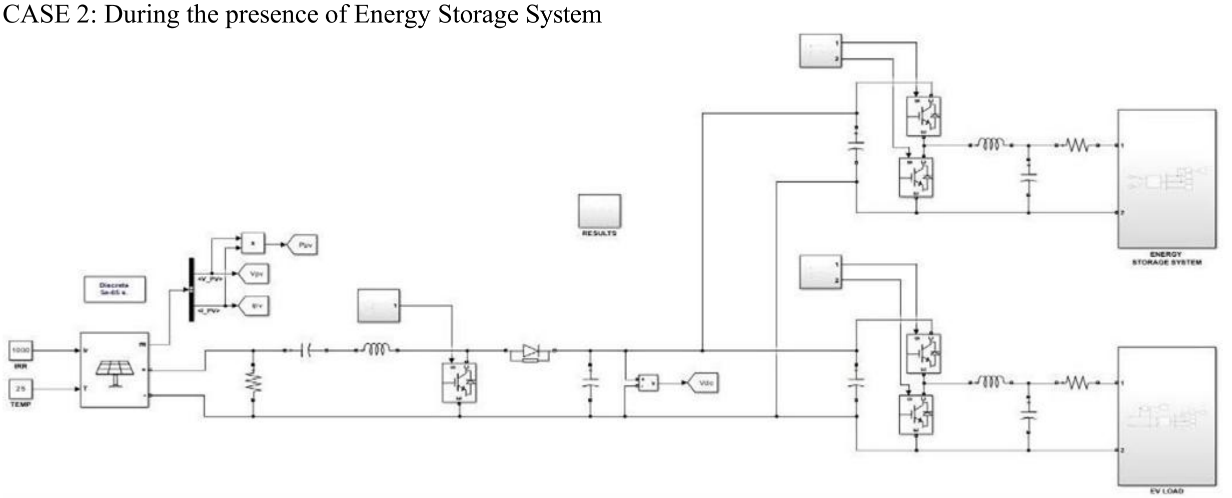

Fig 4.6: Simulink diagram of Presence of Energy Storage System

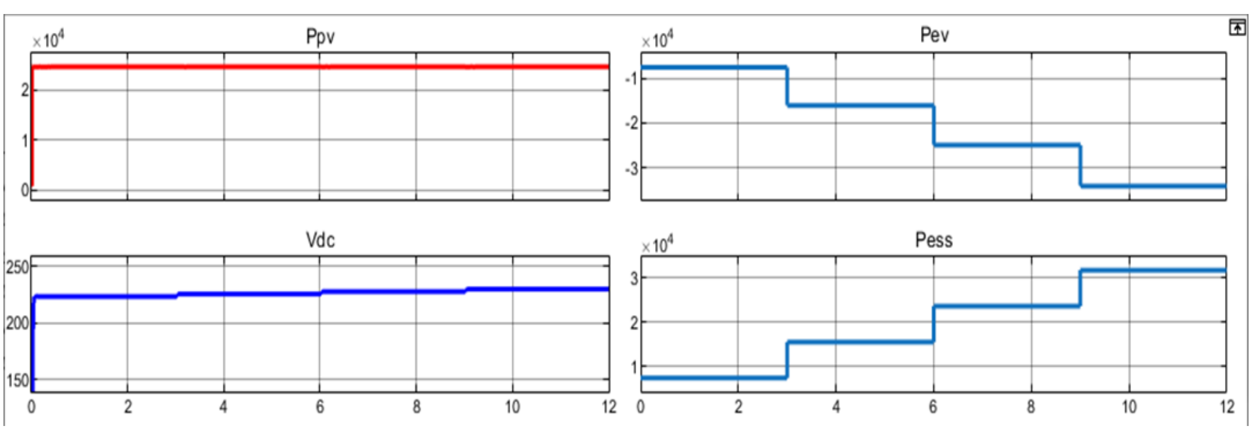

Fig 4.7: Simulink diagram of Presence of Energy Storage System

PV, EV, ESS power, and DC link voltage fluctuations are shown in the graphs in Fig. 4.7. In the plot, Ppv stays constant, suggesting steady solar generation. Pev decreases in a step-wise manner from positive to negative values, indicating dynamic charging and discharging of the EV. Vdc steadily increases over time, indicating for stable operation. that the DC link voltage is stable while operating. Pess increases in discrete steps, compensating for EV power fluctuations to balance the system. Overall, the system demonstrates coordination among PV, EV, ESS, and DC link voltage

Fig 4.8: PV Voltage and Current

PV system parameters are shown in graph: PV voltage (Vpv) and PV current (Ipv). In this case, Ipv remains constant at around 50 A throughout thesamplingtime. Similarly, Vpv stays constant at about 400 V duringtheentire simulation duration. The x-axis in both graphs represents simulation time in seconds, ranging up to 12 s. The first and second figures show identical waveforms, indicating steady PV output. No fluctuations or transient responses are observed in either voltage or current. Thus, both graphs confirm stable and constant PV operation under the given test condition.

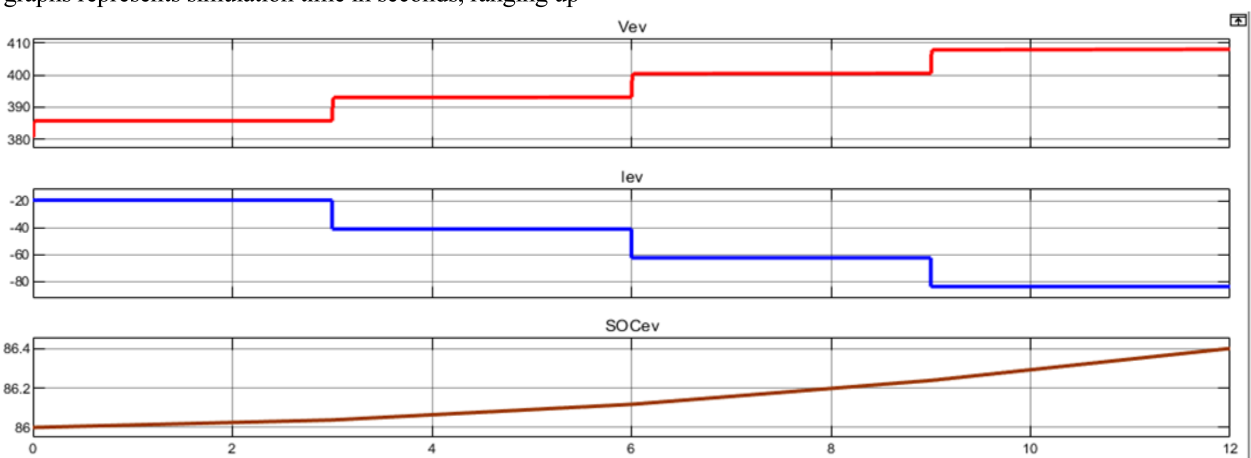

Fig 4.9: EV Voltage, Current and State of Charge

The voltage (Vev), current (Iev), and state of charge (SOCev) of EV batteries are depicted in the diagrams. voltage starts near 400 V and drops stepwise as the current demand increases. Current shows a stepped variation, moving from around –20 A to –80 A in the graph. Over time, the SOC steadily declines, beginning close to 86.4% and dipping just below 86%. Graph follow the trend of battery discharge during the 12-second simulation. Step changes in current have a high correlation with patterns of voltage drop and SOC degradation. Overall, the figures confirm steady EV battery discharge behaviour under dynamic current loading.

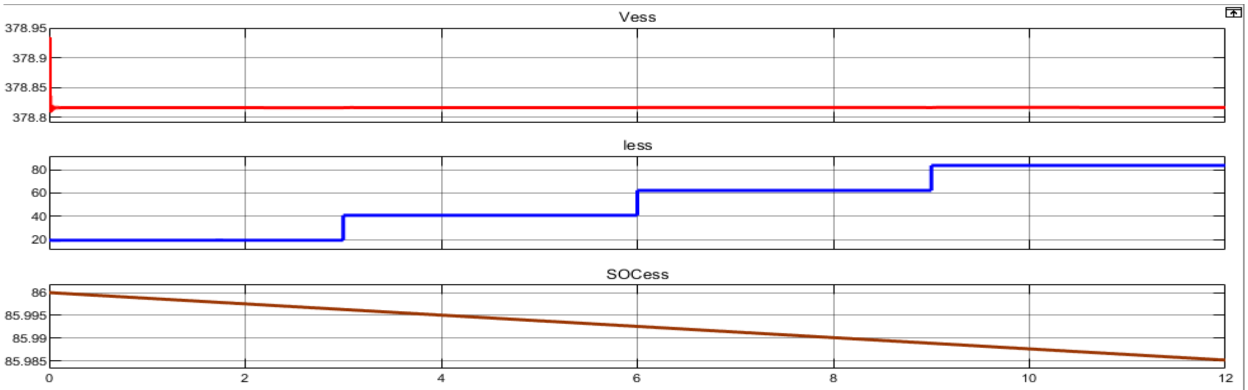

Fig 4.10: Energy Storage System Voltage, Current and State of Charge

Three parameters are displayed in the graphs: SOCess (state of charge), Vess (voltage), and Iess (current). In this case, Vess remains nearly constant around 378.9 V with very minimal variation. The Iess graphs show step changes, starting from lower values and gradually increasing in the plot but some disturbances are reduced in Iess in the graph is stable and smooth lines in the graph. The current pattern is almost identical, with discrete jumps at specific intervals. Battery discharge behaviour is shown in the graph as the SOCess decreases linearly with time. The SOCess starts slightly lower, oscillations or disturbances are observed in Iess of the plots, indicating smooth behaviour.

CASE 3: During the absence of PV

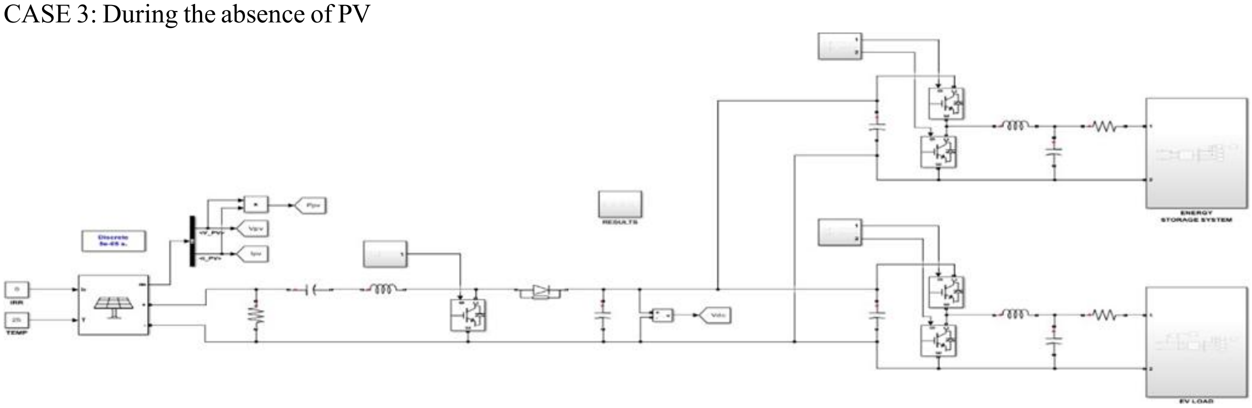

Fig 4.11: PV Absence Simulink Diagram

The above a MATLAB/Simulink circuit diagram along with simulation results. The figure is titled “Fig 4.13: Absence of PV”, indicating that the photovoltaic (PV) source is not contributing to the system.

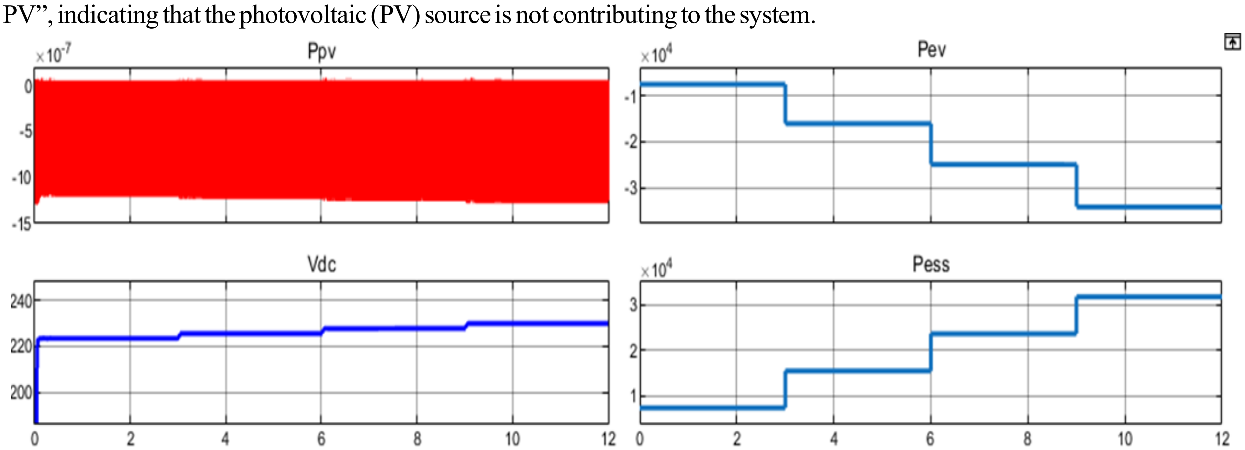

Fig 4.12: PV, EV, ESS Power and DC Link Voltage

The above image shows a MATLAB/Simulink circuit diagram along with simulation results. The figure is titled "Fig 4.13: Absence of PV", indicating that the photovoltaic (PV) source is not contributing to the system.

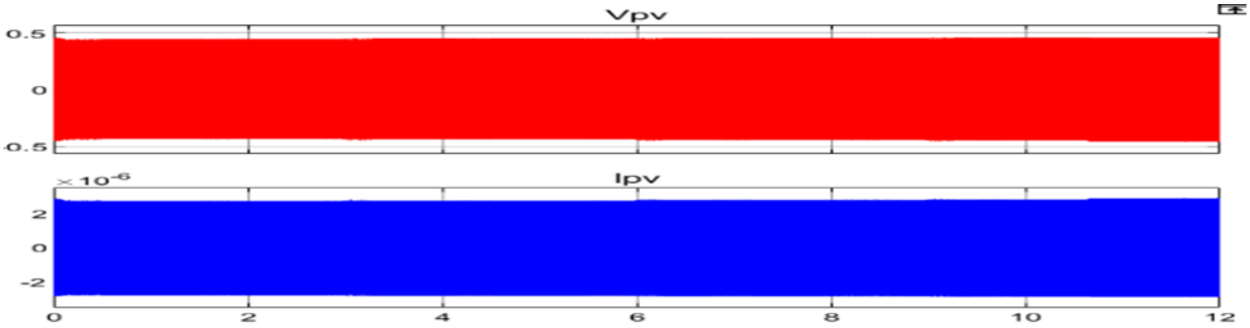

Fig 4.13: PV Voltage, PV current

Above the diagram, four plots are shown: Ppv (PV Power), the graphs (first column, top) remain at zero or very low values, confirming no power contribution from the PV system in two graphs. Pev (EV Power), this graph decreases step by step, showing the electric vehicle (EV) load is consuming power at different levels in ST-SMC Controller. Vdc (DC Link Voltage), the voltage across the DC link remains stable, around 220–240 V, with slight step increases in the graph is smooth. Pess (ESS Power), the Energy Storage System (ESS) provides power in stepped increments, compensating for the absence of PV. Overall Behavior, In the absence of PV, the ESS (battery) becomes the main source of supply while the EV continues to draw varying power. System Stability, Despite PV absence, the DC link voltage remains regulated, ensuring reliable operation. When PV generation is not available, the system efficiently switches reliance from PV to ESS.

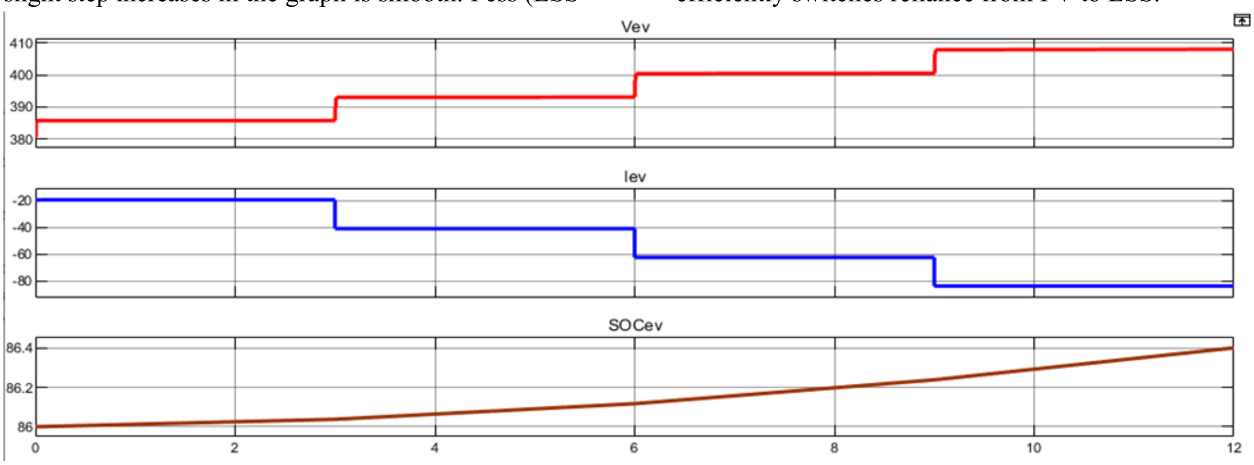

Fig 4.14: EV Voltage, Current and State of Charge

The plots in Fig. 4.14 demonstrate the behaviour of the EV's voltage (Vev), current (Iev), and state of charge (SOCev). In the plots, the EV voltage remains fairly constant with step changes, fluctuating between 380 V and 400 V, indicating regulated operation under different load conditions. The EV current shows stepped variations, moving between negative and positive values, which reflects charging and discharging phases of the EV battery. The SOCev gradually decreases with time in this case, starting around 86.6% and dropping slightly to about 86.6%, showing battery consumption during operation. Consistent simulation behaviour is confirmed by the graphs. Voltage and current maintain their respective ranges with distinct step transitions, while SOC shows a smooth declining trend. Together, the results indicate that the EV operates stably under varying current conditions. The slight drop in SOC demonstrates energy usage, while stable voltage highlights effective control. Overall, the graphs validate reliable EV performance with minor energy depletion.

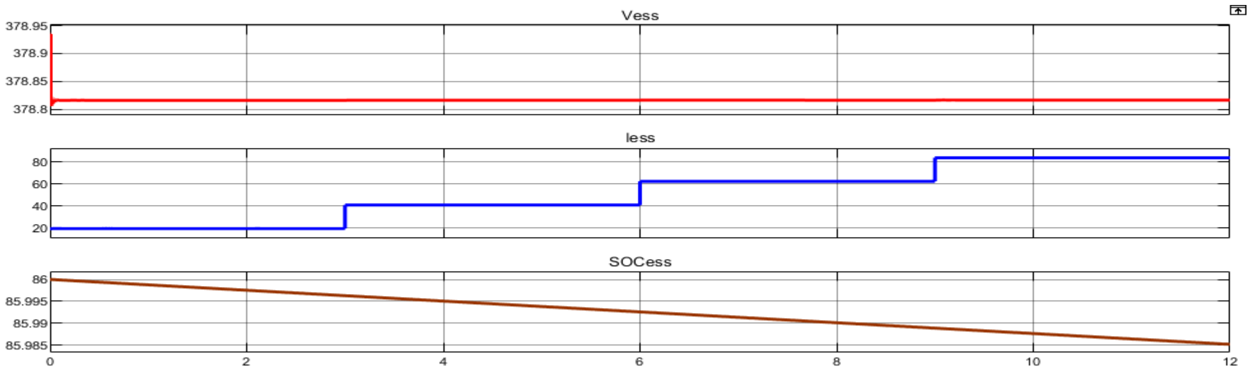

Fig 4.15: Energy Storage System Voltage, Current and State of Charge

In Fig. 4.15, the graphs show the Energy Storage System (ESS) voltage (Vess), current (Iess), and state of charge (SOCess). The ESS voltage remains almost constant around 378.8–378.9 V in the plots, indicating stable voltage regulation during operation. The ESS current exhibits stepped variations, increasing in stages from about 20 A to nearly 80 A, which reflects the dynamic charging and discharging support of the ESS. Meanwhile, the SOCess shows a gradual rising trend, starting at about 85.99% and reaching close to 86% by the end of the simulation, confirming that the battery is charging over time. The graphs present consistent behaviour, reinforcing the reliability of the system response. The stability of voltage alongside the stepped current ensures controlled power exchange. The increasing SOC clearly demonstrates energy accumulation within the storage system. Overall, the graphs confirm that the ESS maintains steady voltage while effectively charging under varying current conditions.

As a result, EV battery can charged up to 2 C-rate as shown in Fig.12,13,14,15. The corresponding SoCev, Vev, Iev, Pev, SoCess, Vess, Iess, Pess battery response are shown in Fig.14,15 respectively. The system DC-link voltage is maintained constant which is shown in Fig.4.12. This arrangement servers the system when PV generation is not sufficient. The worst condition of the PV is absent. Therefore, in this situation ESS will fulfill the requirement of the EV battery.

In this mode, the EV battery is charged only from ESS battery. In fig.12 the PV generation is almost zero and simultaneously. EV and ESS power increase and decrease with the change in C-rate respectively. The corresponding SoC, current and terminal voltage of the EV and ESS batteries are increasing and decreasing at the equal rate which as shown fig.14 and 15 respectively.

These modes reveal that the proposed Off-grid charging station (OGCS) is capable of charging the EV battery at any circumstances and it also increases utilization of renewable energy source to the maximum extent.

V. CONCLUSION

To increase EV use in remote areas and reduce grid dependency, it is advised to use PV energy to power an off-grid charging station for EV battery recharging. This paper integrates an Energy Storage System with the OGCS, ensuring reliable operation under all conditions. The ESS allows the system to provide power for charging the EV battery during periods without sunlight. Additionally, the incorporation of a Super-Twisting Sliding Mode Controller enhances the stability and performance of the charging process by improving voltage regulation and power management. Overall, this work presents a more sustainable, efficient, and resilient OGCS, fostering pollution-free transportation through the combined use of renewable energy and advanced control techniques.

VI. FUTURE SCOPE

Future developments of the proposed off-grid charging station (OGCS) include smart grid integration for Vehicle- to-Grid (V2G) and Grid-to-Vehicle (G2V) operations. Incorporating Artificial Intelligence (AI) and Internet of Things (IoT)-based management can enhance efficiency and control, while advanced storage technologies like solid- state batteries and hydrogen systems can improve reliability and sustainability.

Scalable, modular designs will support both community and large-scale EV charging. Further advancements in cybersecurity, fault-tolerant control, and energy optimization are essential for cost- effective and safe operation. Long-term studies should assess environmental and socio-economic impacts to foster sustainable electric mobility.

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