Integration of Hybrid Energy Storage Systems in Solar-Powered Electric Vehicle Charging Stations

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Abstract: Electric vehicles (EVs) have emerged as pivotal solutions to mitigate greenhouse gas emissions in the transportation sector. This paper explores the integration of hybrid energy storage systems in solar-powered EV charging stations to enhance sustainability and efficiency. Hybrid systems combine multiple storage technologies like batteries and supercapacitors to manage energy fluctuations from renewable sources effectively. The study employs MATLAB Simulink for modeling and simulation, evaluating various charging scenarios under different weather conditions and demand patterns. Key objectives include optimizing bidirectional converters using AI-based algorithms and enhancing power flow control through Bat Optimization for Power Flow Control (BA_PFC). Results demonstrate the viability of hybrid storage systems in stabilizing grid interaction and maximizing renewable energy utilization in EV charging infrastructure.

Keywords: Electric Vehicles, Solar Energy, Hybrid Energy Storage Systems, Supercapacitors, DC-DC Converters, Renewable Energy Integration, MATLAB Simulink.

I. INTRODUCTION

Electric vehicles (EVs) have revolutionized electricity and transportation. In recent years, electric vehicles have emerged as an alternative to the transportation sector for 23% of the world's energy-related greenhouse gas (GHG) emissions. The proportion of renewable energy used in transportation is currently very low but is changing significantly, especially in the vehicle category, which includes electric vehicles [1]. According to the IEA report, global electric vehicle sales will reach 10 million units in 2020. Among them, the country with the most electric vehicles is Europe, with 4.5 million electric vehicles, and Europe will have the highest annual increase in 2020. 3.2 million. If most cars produced after 2040 are electric, more than 1 billion people could drive electric cars by 2050 [2]. Electricity is an ideal low-cost means of transportation due to the low cost of generating electricity from renewable energy sources. The development of electric vehicles offers a large growth opportunity for the electric industry because these vehicles can reduce emissions and save energy. EVCS has the ability to provide large amounts of energy. The lack of control of electric vehicles on the grid will lead to excessive physical activity, requiring improvements in distribution and transmission, as well as building capacity [3-4]. Private investment is required to generate payoffs in real estate, but few business models make sense for them anymore. The government can provide incentives for the installation of EVCS in residential and public spaces. Additionally, an important and ongoing challenge is to improve the payment, aggregation, and overall management of electric vehicles on the grid. Therefore, when creating the payment infrastructure, important decisions must be made about the location of payment points, which technology is used, how slow payment is started and how fast payment is optimized for the customer [5].

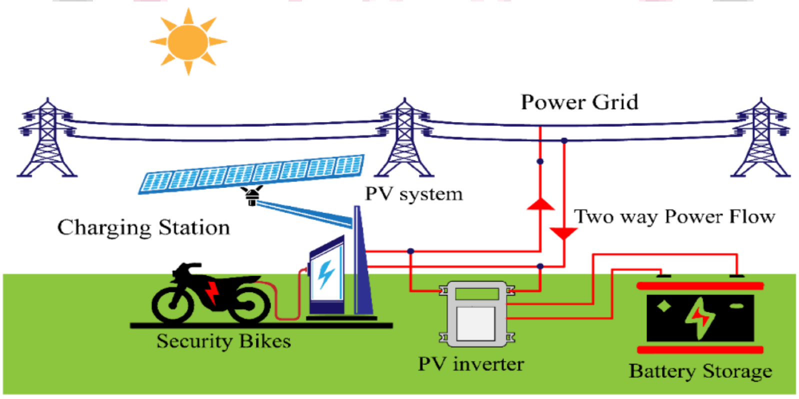

Figure 1 Grid-Connected Solar Charging Station [6]

Importance of Hybrid Energy Storage Systems in Renewable Energy Applications

Hybrid energy storage systems are increasingly recognized as indispensable components in advancing the reliability and efficiency of renewable energy applications. Their significance lies in their ability to address the inherent variability and intermittency of renewable sources such as solar and wind power. By integrating multiple storage technologies—such as batteries, pumped hydro, or thermal storage—hybrid systems can effectively smooth out fluctuations in energy output. This capability not only stabilizes the grid but also enhances its resilience against sudden changes in renewable generation or energy demand. Moreover, these systems optimize the use of renewable energy by storing surplus electricity during periods of high generation and releasing it during peak demand, thereby maximizing the overall efficiency of renewable resources. In off-grid applications, hybrid storage systems provide a reliable and sustainable power supply, reducing dependence on fossil fuels and enhancing energy independence. Economically, they contribute to cost savings by reducing the need for additional grid infrastructure and optimizing the use of renewable energy assets. Environmentally, hybrid storage systems help mitigate greenhouse gas emissions and other pollutants associated with conventional energy sources, supporting global efforts towards sustainability. In conclusion, hybrid energy storage systems play a pivotal role in integrating renewable energy into mainstream energy infrastructure, ensuring stability, reliability, and sustainability in our energy systems. Their continued development and deployment are essential for achieving a cleaner and more resilient energy future.

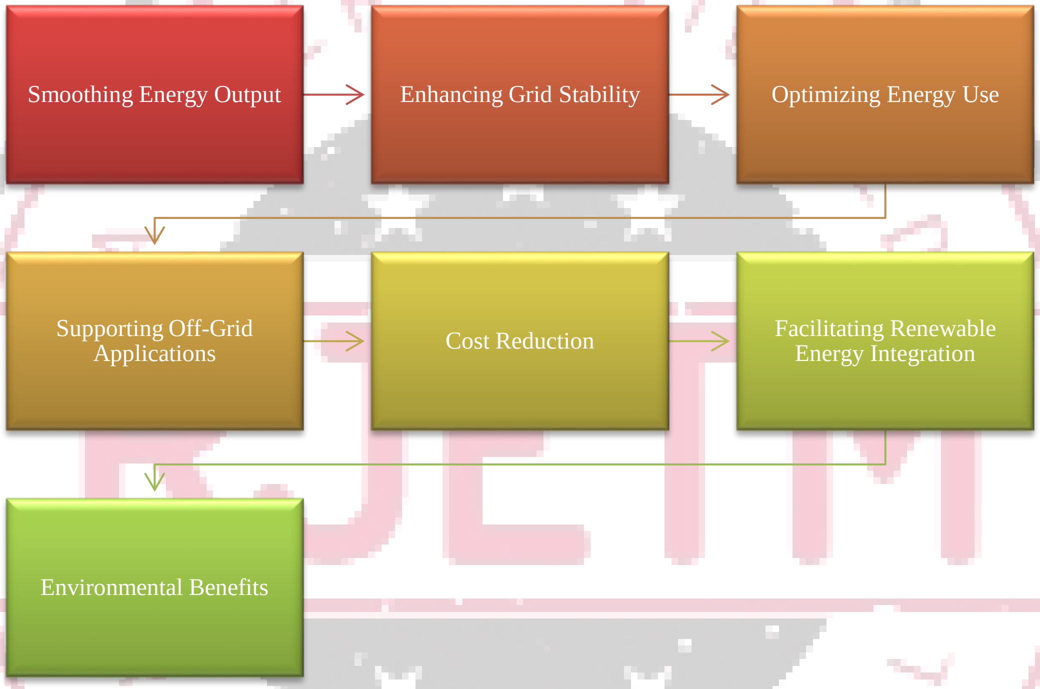

Figure 2 Applications of Renewable Energy

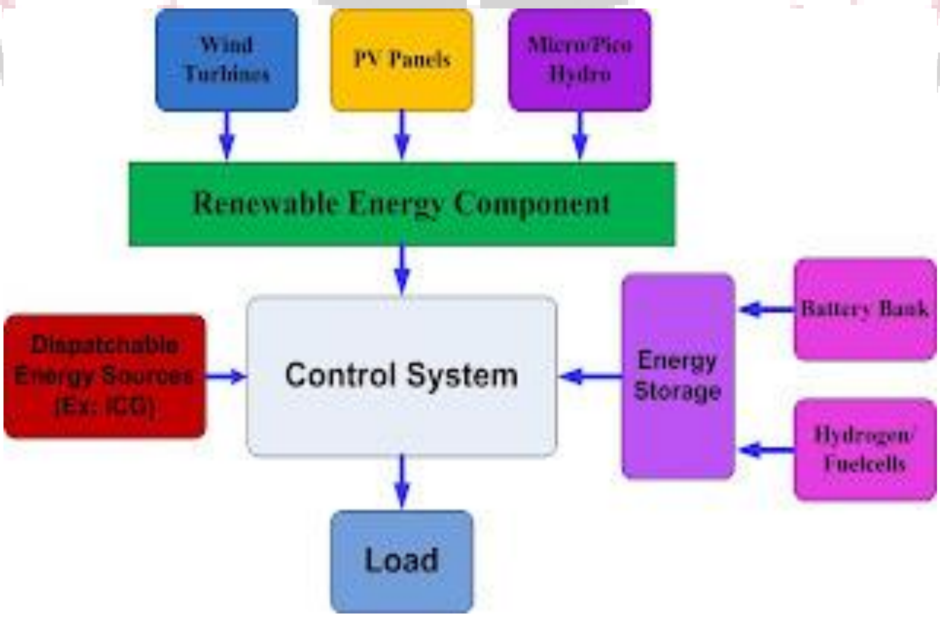

Figure 3 Schematic diagram of a stand-alone hybrid energy system [7]

II. LITERATURE REVIEW

Suresh et al. (2024): This study introduces a ground-breaking wireless EV charging technology powered by solar energy, enabling convenient, cordless charging while reducing environmental impact. By leveraging solar power, the system aims to enhance affordability and sustainability in EV ownership, marking a significant advancement over traditional plug-in chargers.

Amir et al. (2024): Investigates the integration of solar-powered Distributed Generation (DG) charging stations for EVs, focusing on managing grid challenges with intelligent energy management systems. The study proposes coordinated control strategies to optimize power flow between PV generation, the grid, and EV batteries, enhancing system efficiency and reliability under varying solar conditions.

Kumar et al. (2024): Proposes the Fire Hawk Optimizer (FHO), a solar-fed wireless EV charging system designed to optimize charging efficiency and reduce energy consumption. The system utilizes adaptive control and communication enhancements to mitigate range anxiety and improve overall EV performance through solar integration.

Nazari et al. (2024): Explores the design and optimization of EV charging stations powered by standalone or hybrid renewable energy systems. The research evaluates performance factors influenced by technology choices, environmental conditions, and control strategies, highlighting potential and challenges in deploying renewable energy for sustainable EV charging infrastructure.

Nirmala et al. (2024): Introduces the Dung Beetle Optimizer (DBO) combined with Binarized Spiking Neural Networks (BS4NN) to optimize EV charging operations. The study focuses on reducing harmonic distortions and improving charging efficiency through intelligent control algorithms, demonstrating superior performance compared to traditional optimization methods.

Balal et al. (2024): Addresses the impact of solar irradiance variations on PV system performance and proposes distributed maximum power point tracking (MPPT) for efficient EV charging. The study discusses strategies to overcome challenges like shading and mismatched arrays, emphasizing the role of distributed MPPT in enhancing charging station efficiency and grid integration.

Khan et al. (2024): Highlights the urgency of transitioning to sustainable transportation powered by solar PV-based EV charging systems. The study reviews global trends in PV-EV infrastructure deployment, discussing advancements in energy storage and charging technologies to support widespread adoption of electric vehicles while reducing carbon emissions.

Nafeh et al. (2024): Presents a case study on a Fast Charging Station for Electric Vehicles (FCSEV) in Cairo, Egypt, utilizing PV power integration and economic optimization techniques. The research evaluates the feasibility of PV-powered charging stations, incorporating novel algorithms like Modified Snake Optimization (MSO) for efficient energy management and cost-effectiveness.

Kancherla et al. (2024): Focuses on grid-connected solar-powered EV charging stations tailored for agricultural regions, proposing the Modified Zeta Integrated Low Converter (MZILC) and control strategies to optimize charging efficiency. The study emphasizes the role of PV systems in decarbonizing transportation and improving energy sustainability in rural areas.

IV. OBJECTIVES

The work aims to achieve the following key objectives:

1. Designing of stand-alone solar based Charging station feeding variable loads with partial shading conditions.
2. Storage system designing making use of battery and super capacitor for managing the power requirement across the system
3. Analyzing the bidirectional converters utilized and designing an effective control for the same employing artificial intelligence-based algorithms.

IV. METHODOLOGY

Electric vehicle (EV) charging stations using renewable energy-based systems have gained increasing popularity as a way to reduce greenhouse gas emissions and improve sustainability. These charging stations typically rely on solar, wind, or other renewable energy sources to power the charging equipment, reducing their reliance on fossil fuels and lowering their carbon footprint.

In recent years, the demand for electric vehicles has grown rapidly, and the need for charging infrastructure has become increasingly important. Renewable energy-based charging stations offer a sustainable and cost-effective solution to meet this demand. They can be installed in various locations such as parking lots, highways, or residential areas, providing convenient and accessible charging options for EV drivers.

Renewable energy-based charging stations require careful planning and design to ensure their efficiency, reliability, and safety. This involves selecting appropriate renewable energy sources, sizing the solar panel array or wind turbine, selecting the appropriate battery storage system, and choosing the appropriate charging equipment.

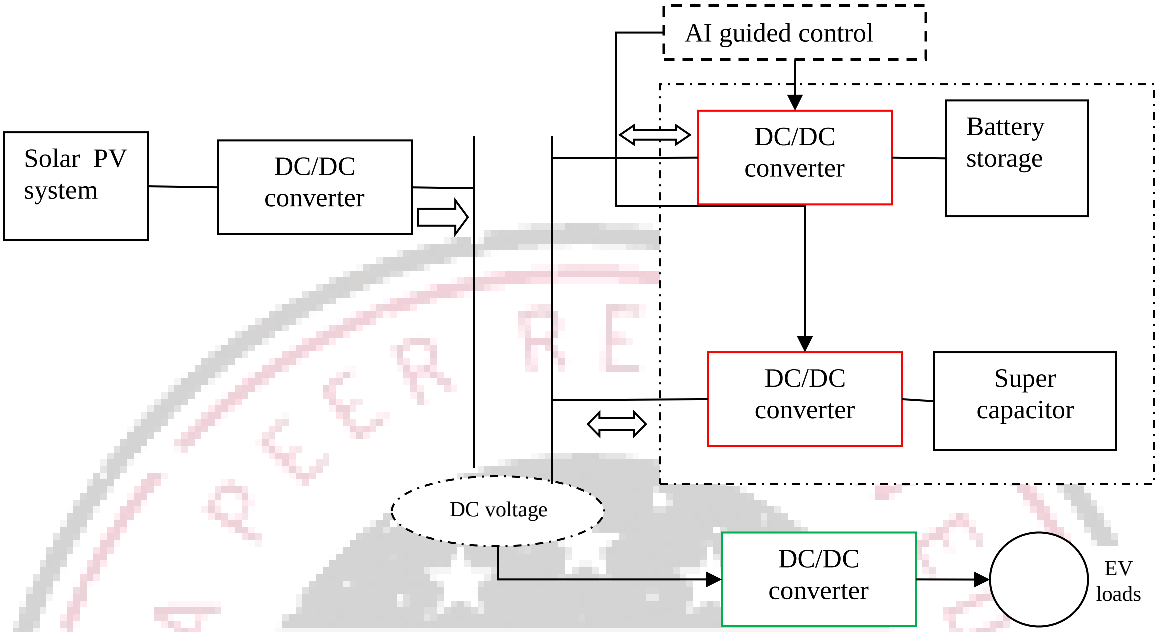

Figure 4 Proposed controller architecture at the bi-directional DC-DC converter topology

Modelling and simulation of solar energy systems for Charging Station

MATLAB Simulink is a powerful tool that is used to model and simulate a solar energy system used as a charging station for electric vehicles. The Simulink platform provides an easy-to-use graphical interface for modelling and simulating complex systems, allowing users to simulate the behavior of the system under different scenarios and conditions.

In the context of a solar energy-based charging station, the Simulink model include a solar panel array, battery storage system, charging equipment etc. The model is simulated to the behavior of the system under different scenarios, such as varying weather conditions or different levels of EV demand.

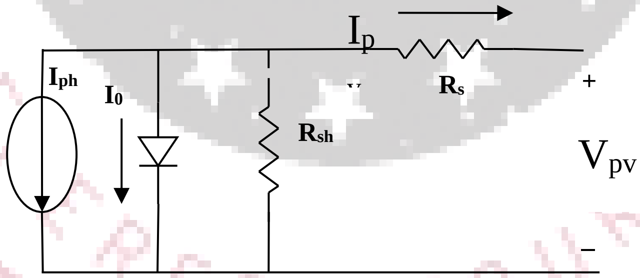

Figure 5 Solar cell circuit

Table 1 Input parameters for PV modeling

Parameters	Symbols	Values
Short circuit current	Isc	8.83
Irradiation	R	variable
Open circuit voltage	Voc	36.8
Maximum current	Imp	8.3
Temperature	K	25
Maximum Power	Pmax	249
Maximum voltage	Vmp	30

Charging Station Energy Storage Devices

Super Capacitor Storage units with bi-directional flow controller

A supercapacitor is an electrochemical energy storage device that can store and release energy much faster than a traditional battery. It is also known as an ultracapacitor or a double-layer capacitor.

The basic construction of a supercapacitor consists of two electrodes separated by an electrolyte. The electrodes are usually made of activated carbon, which provides a large surface area for storing charge. The electrolyte is typically an organic solvent containing ions that can move between the electrodes.

When a voltage is applied to a supercapacitor, ions from the electrolyte are attracted to the electrodes, forming an electrical double layer. This double layer stores energy in the form of an electrostatic field. Unlike a battery, a supercapacitor does not undergo chemical reactions to store energy, so it can be charged and discharged rapidly without degrading.

Supercapacitors have many advantages over batteries, such as high-power density, long cycle life, and excellent performance at low temperatures. They are particularly useful for applications that require high power output, such as hybrid vehicles, renewable energy systems, and mobile electronics.

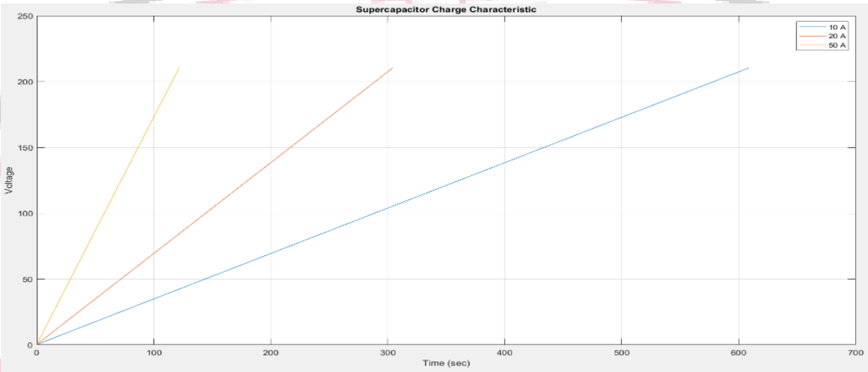

Figure 6 Voltage current charge characteristics of super capacitor (SC)

Battery Storage systems with bi-directional flow controller

Battery storage systems with bi-directional flow controllers are energy storage systems that can both store and release electrical energy. The bi-directional flow controller ensures that the energy flow is balanced and efficient. It monitors the state of charge of the battery, the power demand of the load, and the availability of power from the renewable sources. It then adjusts the flow of energy to optimize the performance and longevity of the battery storage system and ensure reliable operation.

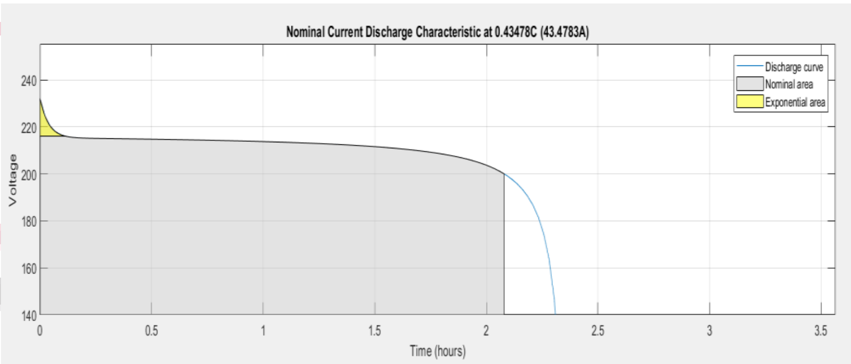

Figure 7 Discharge Characteristic of Battery

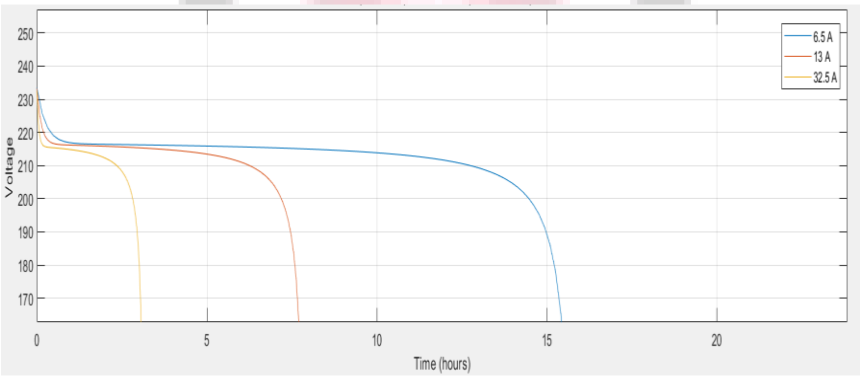

Figure 8 Voltage and current relation graph of the battery

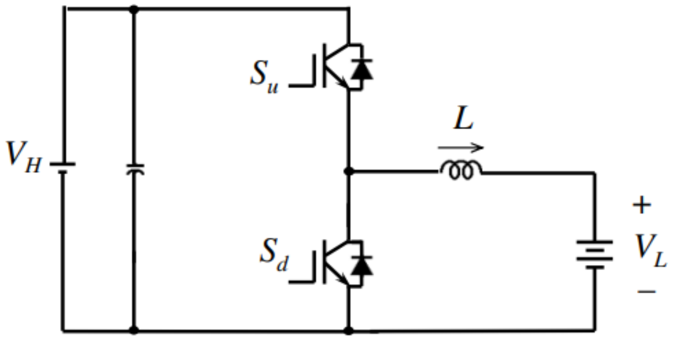

Figure 9 Bidirectional buck-boost Converter Circuit

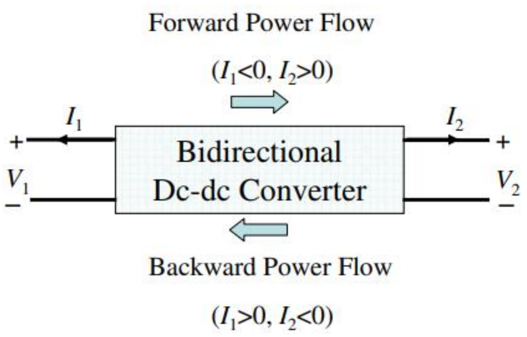

Figure 10 Flow Controls logic across the DC-DC Converter

DC-DC converter Control designing with Bat Optimization for Power flow Control (BA_PFC)

In wide area of modern power electronics, the design and optimization of DC-DC converters play a pivotal role in efficiently managing power flow in various applications, including renewable energy systems, electric vehicles, and portable electronic devices. A DC-DC converter is essential for converting the unregulated DC input voltage to a regulated DC output voltage, ensuring stable and efficient power delivery. The control of these converters significantly impacts their performance, efficiency, and reliability.

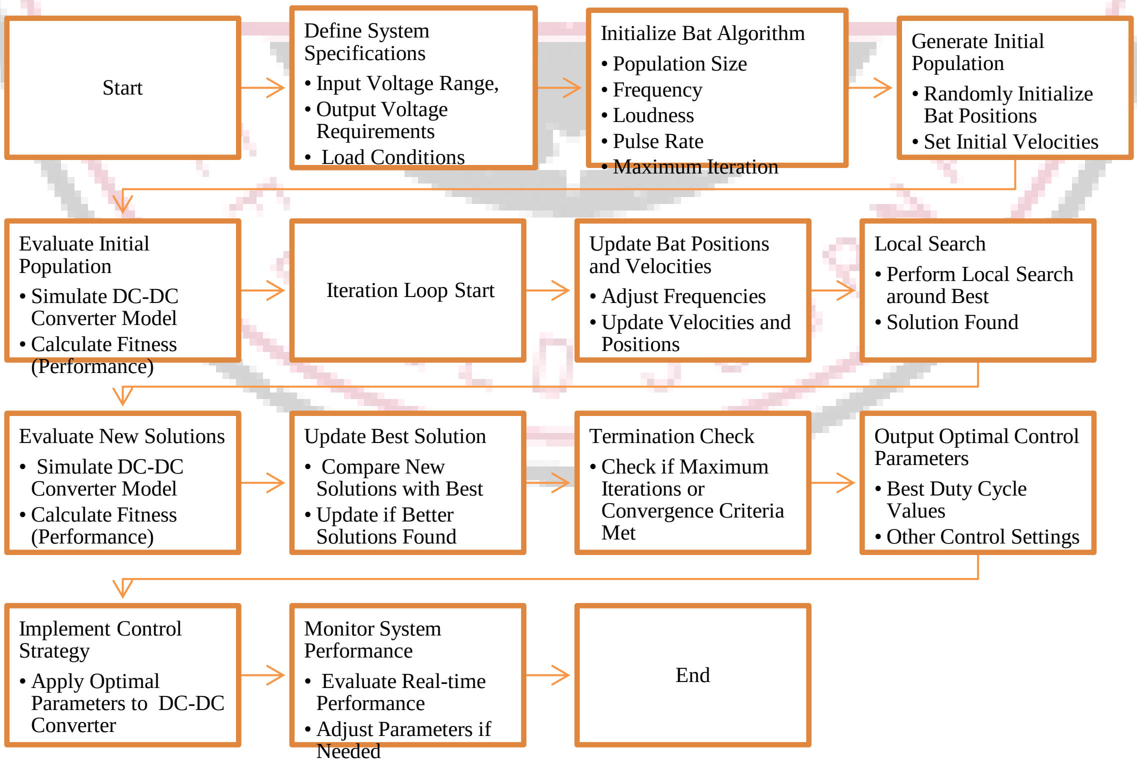

Figure 11 Flow chart for BA_PFC method in charging station

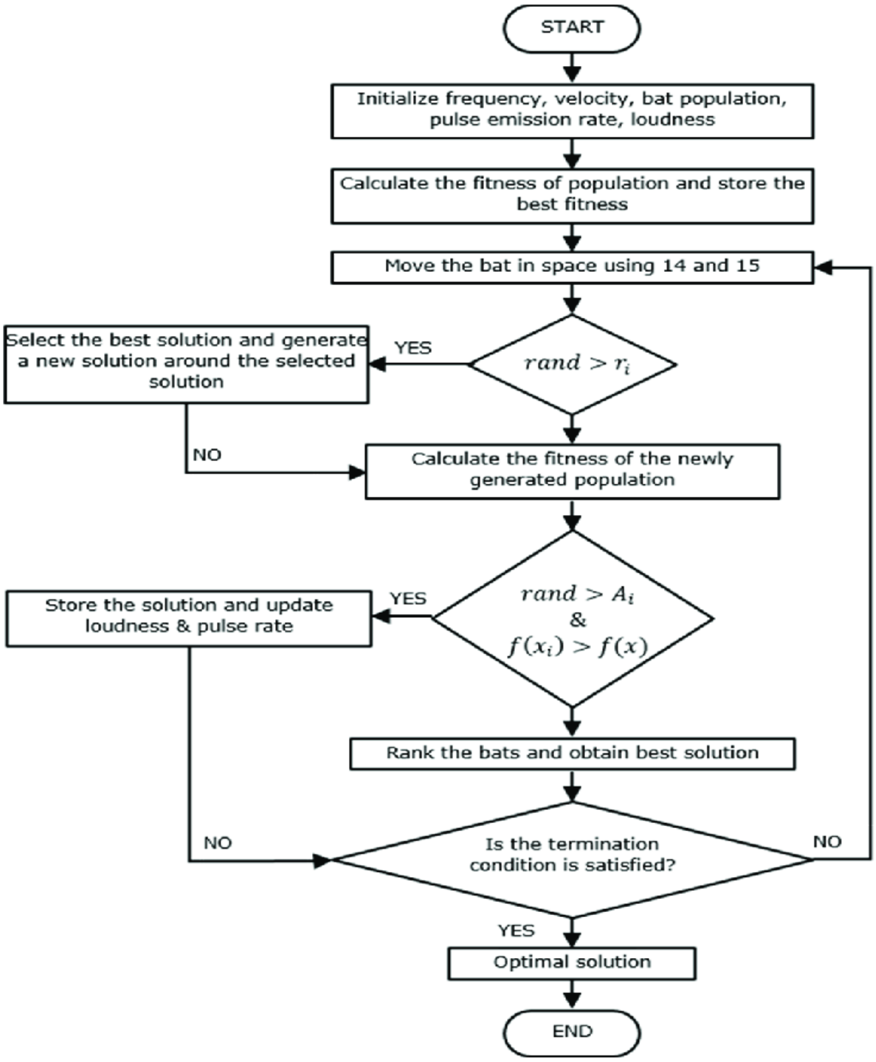

Figure 12 Bat Algorithm Working Flow

V. RESULT AND DISCUSSION

MATLAB is a powerful tool for simulating and designing control systems, including DC-DC converter control systems. These systems regulate the output voltage of a converter by employing a feedback loop. This loop measures the output voltage and adjusts the converter's duty cycle to maintain a constant voltage level. Typically, a PI (Proportional-Integral) controller is used within the feedback loop. This controller compares the desired output voltage with the measured output voltage, adjusting the duty cycle accordingly. MATLAB facilitates the creation of mathematical models for these systems, simulation of their responses to different inputs, and analysis of their performance under varying load conditions.
A DC-DC converter control system is used to regulate the output voltage of a DC-DC converter. The control system consists of a feedback loop, which measures the output voltage and adjusts the duty cycle of the converter to maintain a constant output voltage. The feedback loop typically uses a PI controller to adjust the duty cycle based on the difference between the desired output voltage and the measured output voltage.
Case 1: Designing of the Charging Station based on Solar energy resource having low DC link voltage
Case 2: Designing of the Charging Station based on Solar energy resource having high DC link voltage driving constant loads with Constant Input irradiation
Case 3: Analysis of Charging Station Architecture with variable loading pattern and partial shading conditions as inputs to the solar system

5.1 Case 1: Designing of the Charging Station based on Solar energy resource having low DC link voltage

The system in this case is designed with solar energy resource with a DC link voltage of 40V. The storage units comprised of battery and a super capacitor model which together are driving a resistive load.

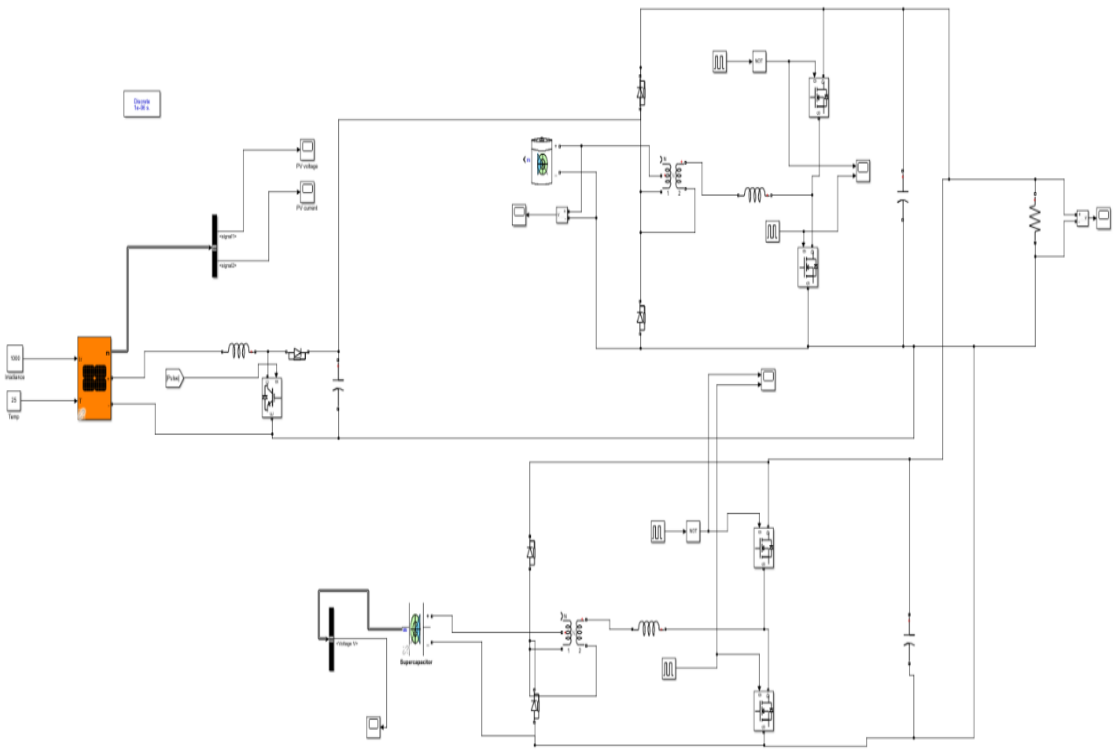

Figure 13 MATLAB/SIMULINK Representation of designed charging system as in case 1

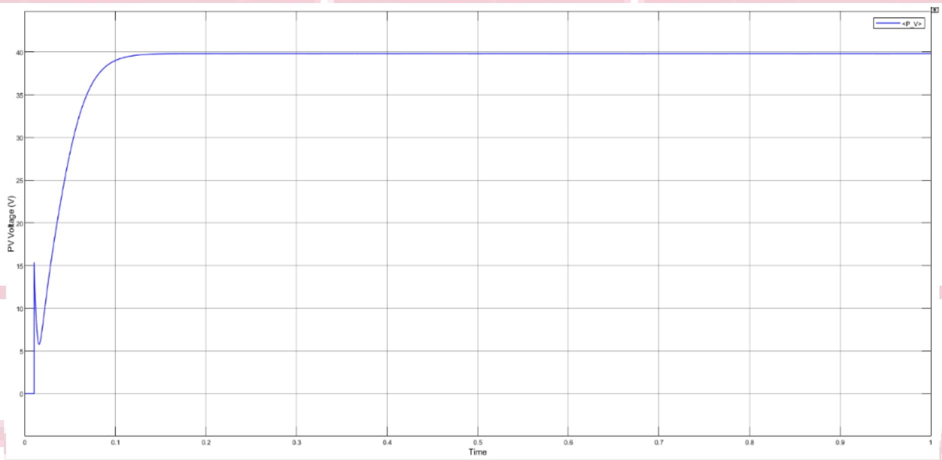

Figure 14 Output voltage from the solar system in case 1

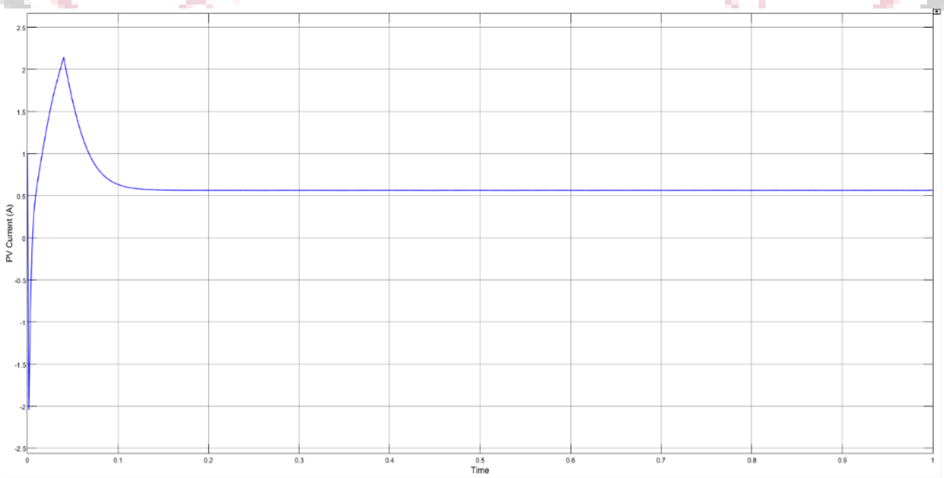

Figure 15 Output current from the solar system in case 1

The figure shows the output current from the PV system as in case 1 which is found to be approximately 0.57 A which is fed to the loads.

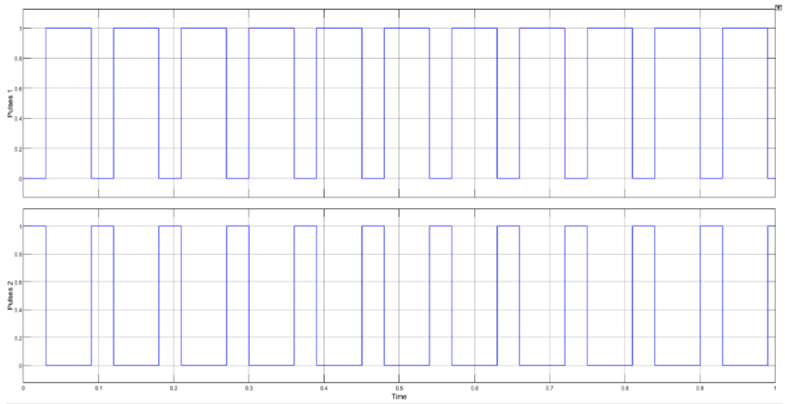

Figure 16 Pulses Provided to the battery side controller

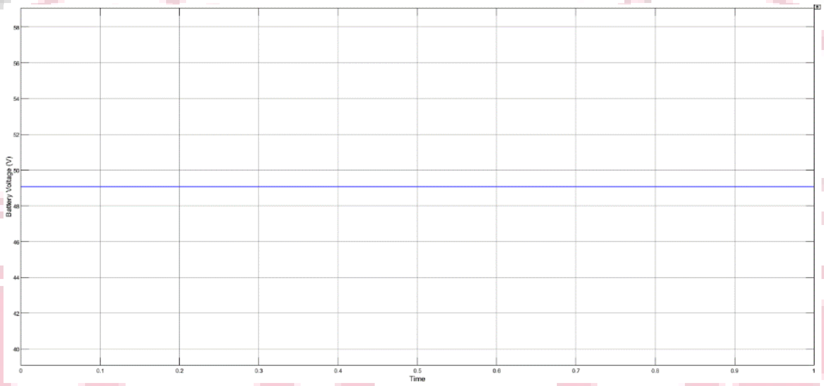

Figure 17 Voltage input to the battery for its charging

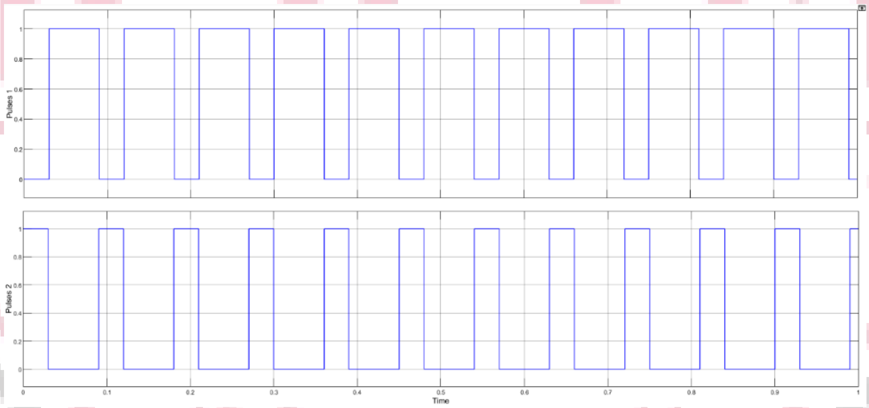

Figure 18 Pulses Provided to the Super Capacitor side controller

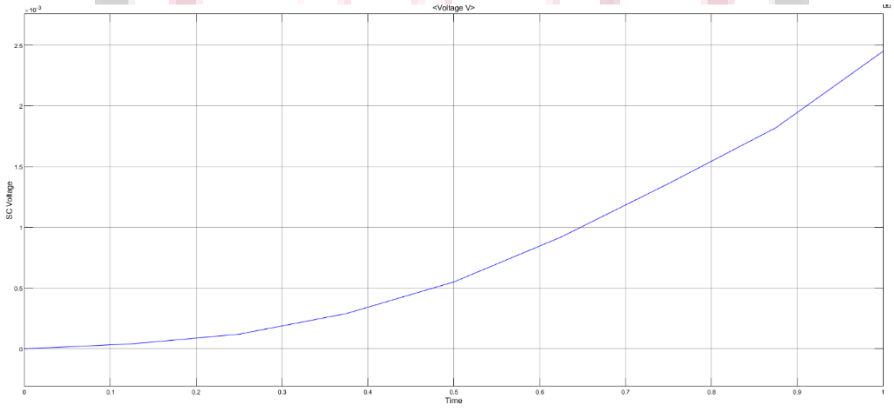

Figure 19 Charging Profile of super Capacitor Voltage in the charging station of case 1

Case 2: Designing of the Charging Station based on Solar energy resource having high DC link voltage driving constant loads with Constant Input irradiation

The development of charging system with DC link voltage of approximately 210V has been achieved in this case. A 10KW solar system is connected to the charging station as energy source with two storage units connected in hybridization of 4 KW each. The load in this case is kept low at 5KW only and the input irradiation provided to the solar system units is being presented in figure which is 1000 W/m^2.

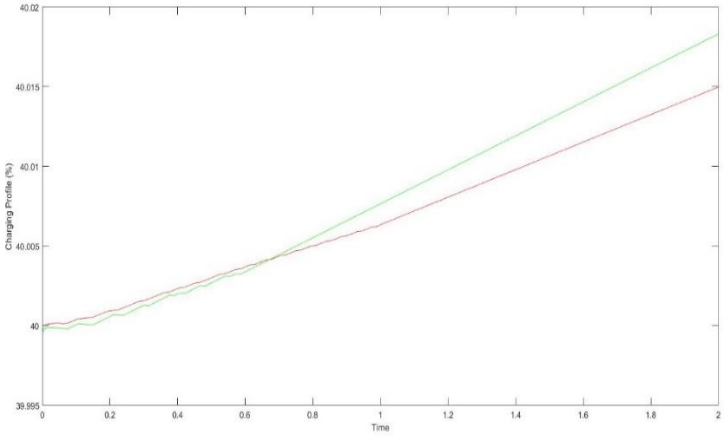

Figure 20 Comparative analysis of charging profiles in the charging station in case 2 using two algorithms

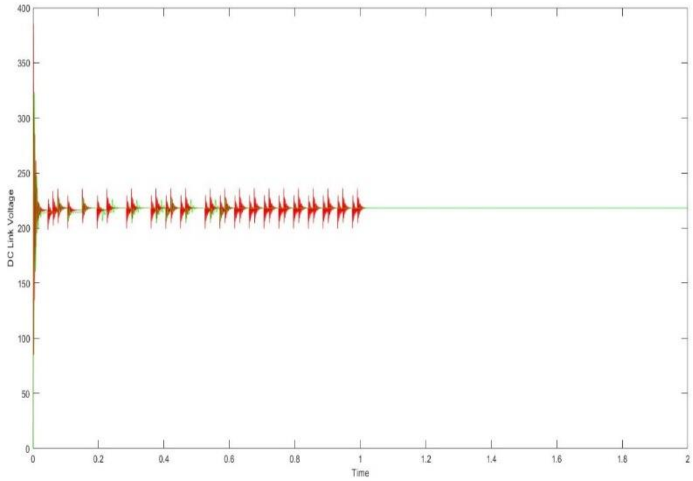

Figure 21 Comparative analysis of Link Voltage in the charging station in case 2 using two algorithms

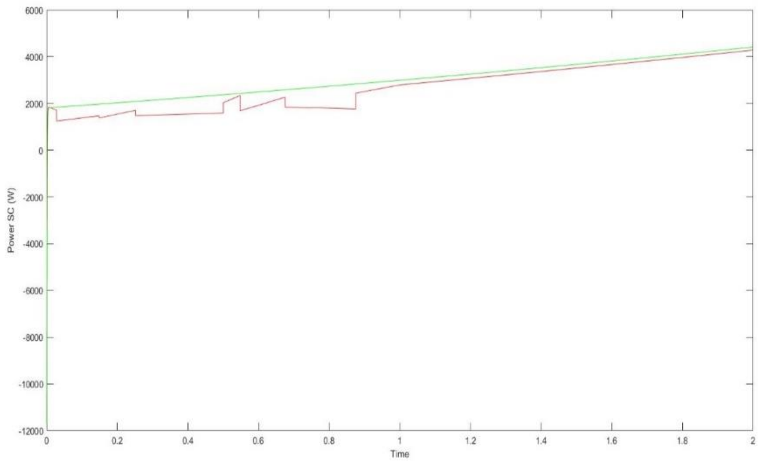

Figure 22 Comparative analysis of SC Power in the charging station in case 2 using two algorithms

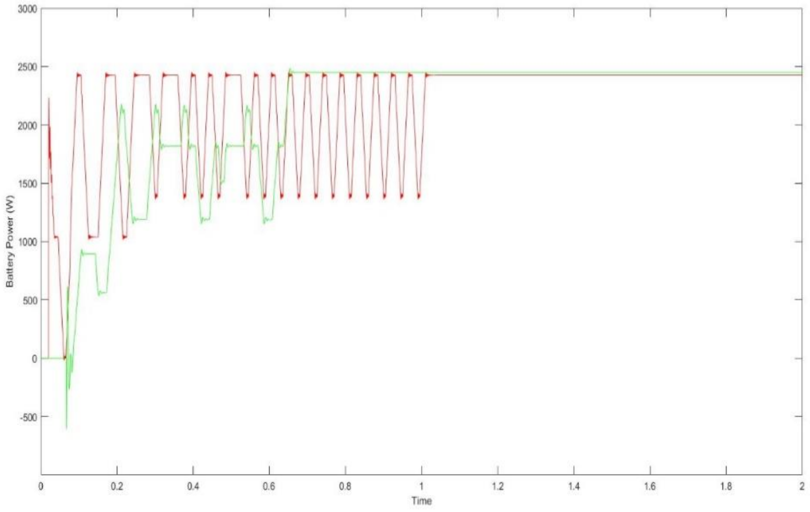

Figure 23 Comparative analysis of Battery Power in the charging station in case 2 using two algorithms

Case 3: Analysis of Charging Station Architecture with variable loading pattern and partial shading conditions as inputs to the solar system

The charging station designed in this case is supplied by solar energy system whose input irradiations are also kept variable at different solar panels. The Limited input conditions at the panels reduces the power available from the renewable energy resource which increases the dependency on the storage units namely battery and super capacitor (SC).

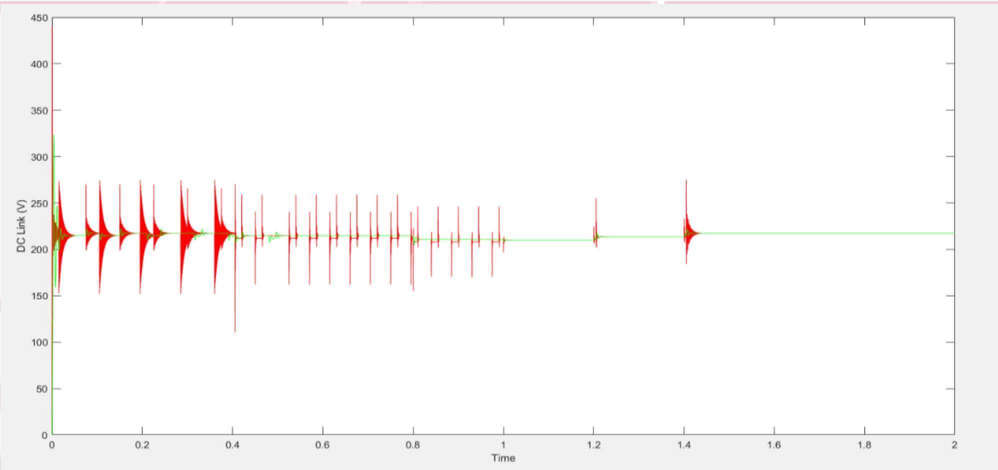

Figure 24 Comparative DC Link voltage of system 1 and system 2 for case 3

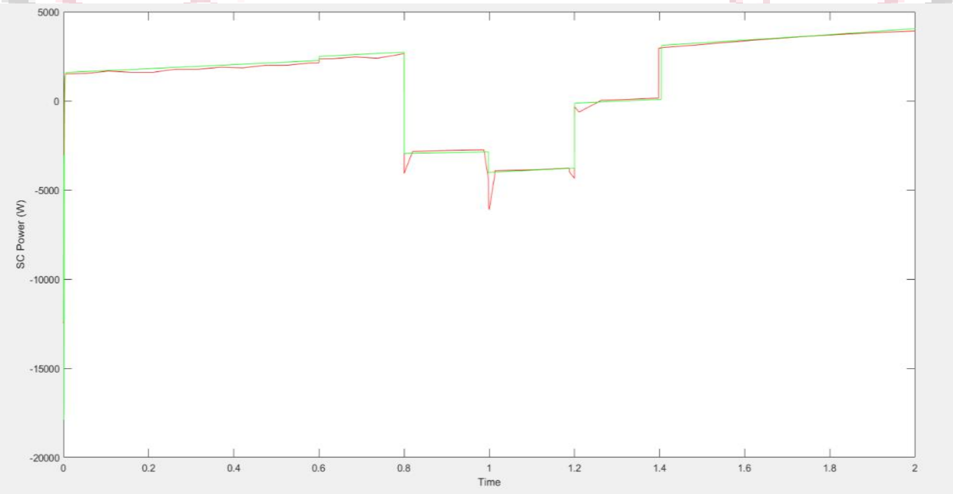

Figure 25 SC Power comparison from the system 1 and system 2 in CS subjected to variable loads and non-uniform irradiation inputs

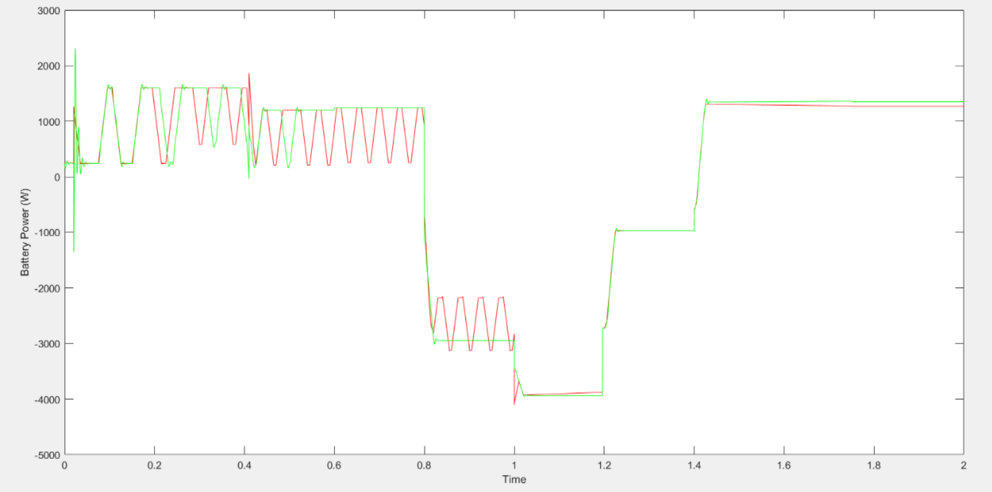

Figure 26 Battery Power comparison from the system 1 and system 2 in CS subjected to variable loads and non-uniform irradiation inputs

Table 2 Summary and Comparative Analysis of the algorithms proposed under different working scenarios

Cases	**Parameters**	**System 1**	**System 2**
Case 1 (Low DC link voltage implementation)	DC link Voltage	40V	
Case 2 (Link voltage 210, Constant Loading)	Battery SOC profile	Comparatively slow	Stable and fast
	DC link voltage	More spikes and stabilizing time are 1 sec	Reduced Spikes and smooth output after 0.6 sec
	Battery Power	Stabilizing at 1 sec	Stable at 0.6 seconds
Case 3 (Partial Shading and variable loading, reduced available power from solar)	SC Power	Unstable variation in power	Stable power variation with loading
	DC link voltage	Unstable with high spikes at the loading instant	Voltage balanced and stable
	Battery Power	unsteady	More steady and stable

VI. CONCLUSION

Hybrid energy storage systems play a crucial role in advancing the reliability and efficiency of solar-powered EV charging stations. By integrating diverse storage technologies, these systems effectively manage energy variability, optimize grid interaction, and enhance overall sustainability. MATLAB Simulink simulations have validated the performance and robustness of these systems under varying operational conditions. Future research should focus on refining control algorithms and expanding hybrid storage capabilities to meet the evolving demands of renewable energy integration in transportation infrastructure.

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