Advanced ST-SMCS Control for Efficient Power Management in Single Inductor Multi-Port Converters for EVS

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Keywords: Super Twist Mode Controller (ST-SMCS), Super Twist Algorithm, Stability, Reliability Battery State of Charge.

Abstract: A Single Inductor Multi-Port Power Converter gives Super Twist Mode Controller for Electric Vehicles (EVs) The controller uses the Super Twist Algorithm to improve power conversion efficiency, stability, and reliability in changing conditions. While navigating through thousands of simulated input-output interactions, the system traces their behavior, adapting its parameters to the variables, thereby handling the unpredictable changes to the energization and load of the battery. The STSMCS includes the number of losing energy and stability under real-time, which maximizes more stability and effectiveness as effectively as more adaptability. This technology improves efficient power transfer, contributing to sustainable transportation by strengthening EV power systems. Such a system makes EV (electric vehicle) system effective & efficient for power conversion to meet any operational requirement and is a tangible progression in both power conversion & the EV system.

1 INTRODUCTION

The increasing demand for electricity as well as the depletion of fossil fuel reserves, especially those powered by renewable sources such as those offered by solar photovoltaic (PV) systems, has led to a rise in the use of electric vehicles. Solar PV covers sunlight to electricity, and it is optimized by Maximum Power Point Tracking (MPPT).

However, its efficiency is negatively impacted by issues such as variation in irradiance and discontinuous availability. Hybrid energy storage systems (HESS) considered several secondary batteries along with the solar PV in order to stabilize the output power for improving the overall performance of electric vehicles under different conditions. By integrating the two systems, it assures energy consistency, extending the battery life, and enhancing the handling on extreme terrains. This enables HESS to optimize energy management and reduce reliance on fossil fuels by allowing for a continuous flow of power. It also overcomes some of the limitations associated with the variability of solar energy and enhances sustainability. In order to integrate different energy sources efficiently, multi input converters are necessary as employing separate DC to DC converters increases the complexity and cost of the system, similar to the one in Figure 5. In hybrid energy storage systems, multi-port converters are commonly adopted, which can be isolated or non-isolated. Whereas isolated converters use highfrequency transformers to achieve voltage matching and electrical isolation, they introduce additional losses and size. Non-isolated multiport converters, like H-bridge systems, provide small, high-performance, efficient solutions with adjustable voltage levels and high efficiency energy transfer to EVs.

Multi-port converter designs have recently been proposed to balance the energy flow regulation problem with the component count. For EV and hybrid EV applications, an economical three-port converter with integration of fuel cell, solar cell, and batteries. Energy is managed with advanced techniques to optimize power distribution and continue to reduce component size, and zero-voltage switching DCDC converters followed for greater efficiency. On the other hand, high step-up non-isolated converters can improve their performance

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under varying conditions, and multi-output converters can deliver stable voltage. The resulting design is a multiport converter that satisfies the problem with each port of the previous multiport converters, making it a great candidate for the modern EV industry.

2 LITERATURE SURVEY

Dhananjaya et al. (2022) introduced a new multi-output DC-DC converter for EV applications, dealing with cross-regulation problems in SIMO topologies. They can control the voltage independently, which improves the performance and reliability of the EV power system. Its efficiency under different conditions was validated by MATLAB simulations and experimental results. Athikkal et al. (2022) proposed a double input hybrid step-up DC-DC converter used in industrial applications with a main objective of improving the power conversion performance of step-up DC-DC converters by integrating dual power sources, voltage gain optimization and reduced switching power losses.

While the converter showed better performance in terms of reliability and efficiency over a range of loads, issues such as the complexity of controlling the operation and stability under time-varying inputs need more investigation. Alajmi et al. (2021) proposed an efficient integration of PV systems with a multi-port DC-DC converter. It provides better energy management for renewable applications by connecting both a grid and an alternative power source to the same user/load. But issues such as system complexity, thermal regulation, and stability under changing solar conditions require more optimization. Similarly, Khasim and Dhanamjayulu (2021) summarize the selection parameters and multi-input converter synthesis for electric vehicles (EVs) by new demands for efficiency, power density, and the integration of renewable energy.

They emphasized the importance of optimized switching strategies and control mechanisms to enhance system performance. Challenges like component cost, thermal management, and system complexity need more research. Faridpak et al. (2020) developed a super-lift Luo-converter in series with pop-up buck converters for EV applications to improve the voltage gain and efficiency of the converter and achieve a small construction. Their work demonstrated a stellar power conversion efficiency and voltage stability compared to conventional converters. Nevertheless, issues such as circuit complexity, thermal control and practical deployment.

3 METHODOLOGY

3.1 Modelling of PV Array

When it comes to Electric Vehicles (EVs), understanding how a Single Inductor Multiple Output (SIMO) Converter works is key to managing power efficiently. Full circuit simulation of the SIMPC integrated with battery and multiple sources, and equivalent circuit analysis of I-V; P-V characteristic as well as load profile and dynamic operating conditions.

The SIMPC efficiently manages power flow from different sources, including the battery, regenerative braking, and external power inputs, ensuring optimal energy utilization. The analogous circuit of a solar cell is shown in figure 1, incorporating the resistance when connected in a series configuration (R_s) and resistance by connected in parallel (R_p) alongside a diode to model its electrical behaviour.

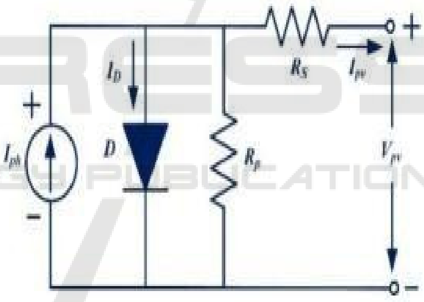

Figure 1: Solar cell analogous circuit representation.

The graphical representation highlights the inherent instability of a solar PV system's operating point, which constantly shifts between zero as well as the voltage measured under open-circuit conditions. The specific point where the solar module produces maximum power, based on its design parameters under varying temperatures and irradiance levels, is called the maximum power point (MPP).

A PV array's output voltage and current depend on factors such as temperature, irradiance, and the series parallel configuration of its strings. Selecting an appropriate solar panel requires careful evaluation. This method considers a Soltech 1STH-215-P panel with two parallel strings, each containing two series connected modules. MATLAB data is used for panel selection. Table 1 presents the characteristics and measurements of a single series module and a parallel-connected string at 1000 W/m² irradiance and 77°F. Figure 2 shows the Solar Cell I-V Characteristics.

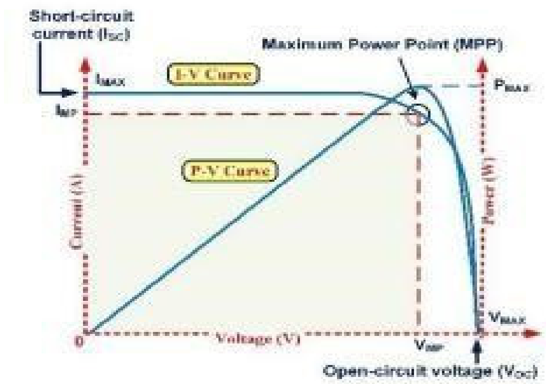

Figure 2: Solar Cell I-V characteristics.

3.2 MPPT Controller

Environmental factors, such as temperature and solar irradiance, are key in determining the power output capability of a solar module. Real time MPPT Implementation with efficient energy transformation in EV power systems since solar energy generation will depend on weather. There are three major categories of MPPT techniques, which include AI based methods, direct search algorithms, and indirect estimations. Continuously tracking the mpp, direct MPPT techniques (or real-time search-based methods) adjust the operating point of the PV array. These include Incremental Conductance (INC), Perturb and Observe (P&O), and Hill Climbing (HC) based approaches. Where P&O algorithm observes the MPP by analyzing the variations of the output voltage and the HC techniques maintain the duty cycle of the converter. These methods, while simple and widely used, are more efficient for low-power systems because of their steady-state behavior.

Table 1: Specifications of a 215W Solar Panel.

Parameter	Value
Open circuit voltage (Voc)	36.3V
The voltage at maximum power point (VMPP)	34V
The voltage at maximum power point (VMPP)	35V
Short circuit current (Isc)	7.84A
Maximum power	213.15W
Diode saturation current (I0)	2.9259 × 10^-10 A
Current at maximum power point (IMPP)	7.35A
Diode ideality factor	0.98117

The most widely used schemes is the incremental conductance method for reducing steady state oscillations at MPP. In this regard indirect methods and artificial neural networks have been around to improve the efficiency and responsiveness of the MPPT. By taking into account the non-linear dynamics of PV arrays, AI-based approaches are quick but can be expensive computationally. Indirect methods instead estimate the MPP based on the output characteristics of the system.

This work make use of ANN for MPP tracking in a Photovoltaic Solar Energy System. As shown in Figure 3 is a three-layer ANN structure for MPP identification. The ANN parameters cover temperature and irradiance as input features, and its output is the value of its MPP voltage (Vmpp). To ensure accurate training, a dataset comprising input variables and corresponding output values is collected, allowing for the optimization of neuron weights at various layers. For data acquisition and programming, MATLAB is utilized to process solar PV system data. Among the different training techniques available for ANNs, thi study implements the backpropagation algorithm to minimize errors and enhance tracking accuracy. After training the ANN, the neuron weight's must be assigned. For instance, the ANN generates V_{mpp} as an output based on the input parameters T and G. Using the modeled PV system's V-I characteristics, the corresponding MPPT current (I_{mpp}) can then be calculated.

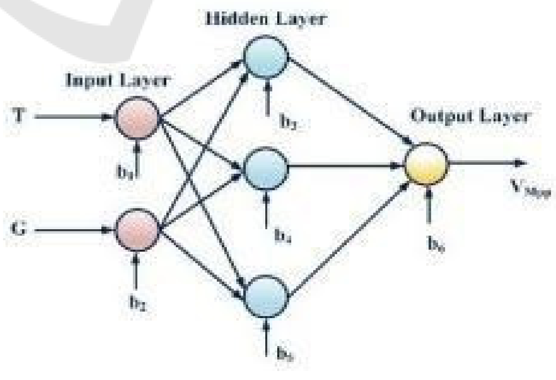

Figure 3: Neural network-based framework for maximum power point tracking (MPPT).

As a result, the maximum power (P_{max})idetermined by multiplying V_{mpp} and I_{mpp}. The PV system and MPPT tracker, illustrated in Figure 4, include an ANN-based control unit and a converter.

3.3 Proposed DC-DC Converter

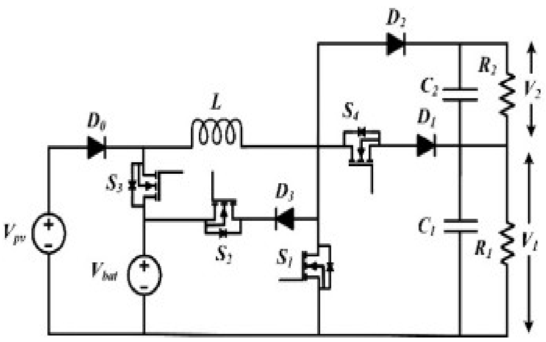

Figure 4: Novel dual-input dual-output multi-port converter architecture.

Figure 4 illustrates the two-input, two-output configuration of the converter that is proposed. The energy distribution from dual sources at the input is analyzed using load resistances R_1 and R_2. To enhance the switching efficiency of the converter, the power flow between sources and load resistances is controlled by modulating voltages at the input. Additionally, voltages at the output could be modified based on voltages at the input of the multilayer inverter, ensuring efficient power management. Because of its sturdy construction, this converter is ideal for combining a battery with a solar photovoltaic system. Using the designated circuit components, illustrates how power moves from the energy sources to the load. The load resistances (R1 and R2) can be represented in terms of the motor's equivalent resistance and the input voltages of the multilayer inverter. Moreover, the proposed controller may also be interfaced with a variety of multilevel inverters which truly makes it a versatile solution for energy management in electric car applications.

The asymmetrical voltage source requirements of multilevel inverters can all be met by the proposed controller. Four switches are considered to control energy transmission from voltages across input to those across output in the stacked inverter which increase voltage adaptability and control through the use of multilayer inverter.

In an EV power system, a new method, especially for the Super Twisting Sliding Mode Control System (ST-SMCS) is introduced to control the flow of power between battery (Vbat) and solar PV (Vpv). Vbat can't power Vpv but Vpv powers Vbat so energy is used more wisely. In EV applications, batteries are usually charged via solar PV or external sources since solar PV is not rechargeable by the battery. Battery charge-based controller the controller operates in different modes depending upon the charge Available in battery and the load Demand. When the demand is very high, only the energy sources will provide power, while S1, S3, and S4 are connected, and S2 is off. Also when demand is low Vpv charges Vbat and load is served by Vpv as S1, S2 and S4 are ON and S3 is OFF. In order to operate both stable and efficient, the system will balance the power accordingly and minimizes ripple current, allowing the entire system to work as best suited to the EV.

Historically, controllers are mainly evaluated for performance in steady-state and dynamic scenarios to ensure the best operation in continuous conduction mode (CCM). A reduction of the power consumption in fuction of the electricity demand of the load is done by the converter working in discontinuous conduction mode (DCM) at low energy demand when charging a battery needs very low current to avoid energy loss. Part IV provides a detailed examination of the various input sources by analyzing all input sources separately, allowing for single-input operation, to directly manage the flows of power. This includes Modes of operation where the converter operates primarily in battery charging and discharging modes for horizontal, well2, and well4-based EVs. Figure 5 shows the Adaptive Control Mechanism of the Proposed Converter in (a) Discharge Phase and (b) Charge Phase.

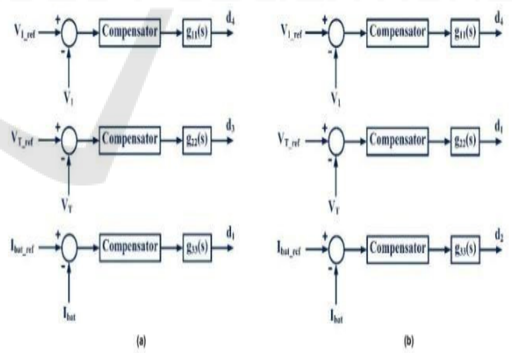

Figure 5: Adaptive control mechanism of the proposed converter in (a) Discharge Phase and (b) Charge Phase.

The Super Twist Sliding Mode Control (ST-SMC) method is one of robust control methods that establishes stability by driving the system trajectory to a specified sliding surface and then maintain it in this sliding mode in the face of uncertainties and disturbances.

Defining the Sliding Surface: In the first stage of ST-SMC algorithm, we define the sliding surface based on the desired dynamics of the system and also the tracking errors. The sliding surface for a single-input system is generally given

by: $s(x)=\dot{x}+\lambda x$ (1)

where: x is the state variable. Λ is a positive constant that determines the system's behavior and convergence rate.

3.4 ST-SMC Consists of Two Control Steps

Step 1: Twist Control:
This step applies a discontinuous control law to drive the system trajectory toward the sliding surface. It is given by:

$$u_1=-k_1\,\mathrm{sign}(s(x)) \quad (2)$$

where $k_1>0$ is a control gain. The sign function ensures rapid correction of deviations, pulling the system toward the sliding surface.

Step 2: Super Twist Control:

To further refine the control and reduce errors, a second component is added that incorporates the derivative of the sliding variable:

$$u2=-k2\dot{s}(x) \quad (3)$$

where $k_2>0$ is another positive control gain. This term smooths out control actions, reducing system oscillations and improving precision.

Combining the Control Laws:

The total control input is the sum of the two components:

$$u=u1+u2=-k1\,\mathrm{sign}(s(x))-k2\dot{s}(x) \quad (4)$$

This composite law guarantees that the system reaches the sliding surface and stays on it along the desired trajectory and is not influenced by outside disturbances.

4 STABILITY AND ROBUSTNESS

It provides for guaranteed stability and stability robustness, even for highly nonlinear or uncertain systems, reproducing the STSMC algorithm with guaranteed convergence under linear and nonlinear constraints, ensuring that the trajectory can be guaranteed to converge to the sliding surface and then sufficiently stay on it. This methodology is commonly adopted in control applications where accuracy and resilience are essential.

5 SIMULATION RESULTS

5.1 Discharging Mode

A uni directional DC to DC converter with battery to assist the virtual battery energy storage device. It governs the energy generated by the PV panel to satisfy the load and charge the battery when necessary. Critical components that help control the power flow and maintain voltage stability, include Diodes (D0–D3), capacitors (C1, C2), and switching devices (S1–S4). Current measurements are used to monitor the behaviour of a battery charge and discharge while voltage measurements (V1, V2, VT) indicates the levels of the output. This facilitates efficient power transferring, allowing this system to provide energy from the battery when the PV output is low.

The voltages at the output nodes (V1, V2, and VT) during battery discharge mode (through the inductor) are plotted for one second in Fig 8. The voltages with V1 40V, V2 80V, and VT ~120V does not change indicating good DC to DC converter regulation. The constant voltage levels imply that the battery is successfully and consistently powering the load. This attests to the system's capacity to sustain a consistent power output throughout the discharging stage.

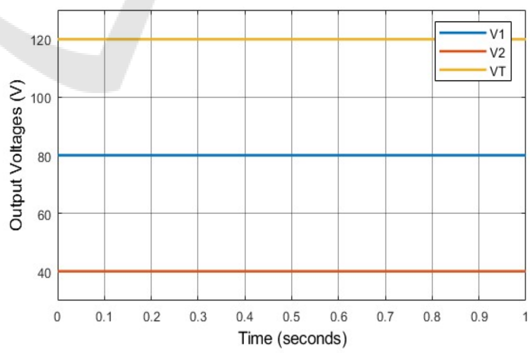

Figure 6: Voltage response during battery discharge.

The Target Current Value remains steady at approximately 3.5A, ensuring controlled power delivery to the load, while the actual battery current (I_b) fluctuates slightly due to the DC-DC converter's switching action. Figures 6, 7 and 8 depict the

Battery Current, Reference Battery Current, and I_C in Discharging Mode, respectively.

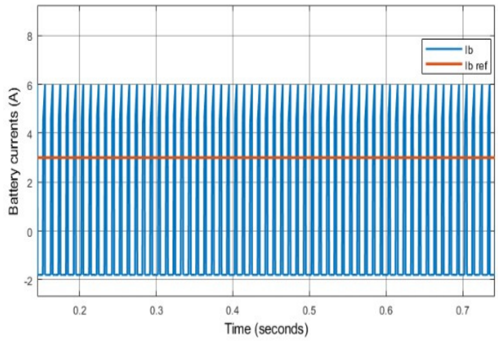

Figure 7: Comparison of battery current and control reference current during discharge mode.

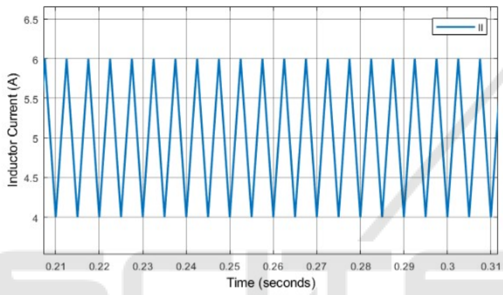

Figure 8: Inductor current in discharging mode.

The photo voltalic panel generates electricity, the battery stores extra energy and supplies it when needed, and the converter regulates voltage and current for a stable output. Figure 9 illustrates the variation in battery reference current.

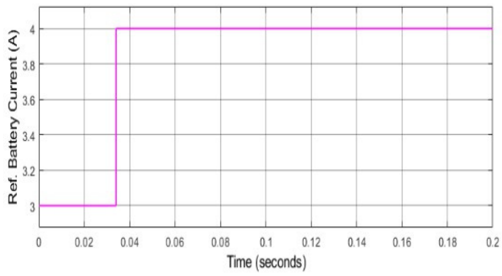

Figure 9: Change in battery reference current.

The graph represents battery current (A) over time (s) for three different control methods: RefBased4 (blue), PIBased3 (red), and STSMCBased3 (yellow). The STSMC-based control demonstrates higher fluctuations while keeping the current within a specific range, whereas the PI-based approach shows comparatively lower variations. The reference current remains steady, acting as a standard for evaluating performance. Figure 10 illustrates the Comparison of Battery Current Using Different Control Strategies.

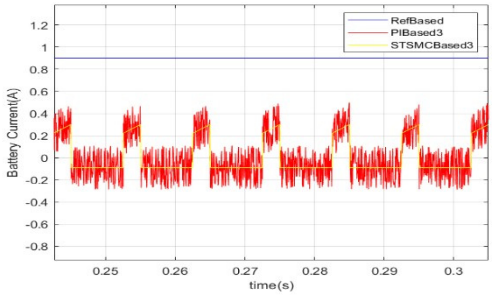

Figure 10: Comparison of Battery Current Using Different Control Strategies.

The graph represents inductor current (A) over time (s) for two control methods: PIBased5 (blue) and STSMCBased5 (red). The STSMC-based approach demonstrates smoother performance with reduced oscillations, while the PI-based method exhibits higher fluctuations around the set current value. This comparison highlights the effectiveness of STSMC in maintaining stable inductor current Figure 11 illustrates the Inductor Current Comparison for PI-Based and STSMC-Based Control.

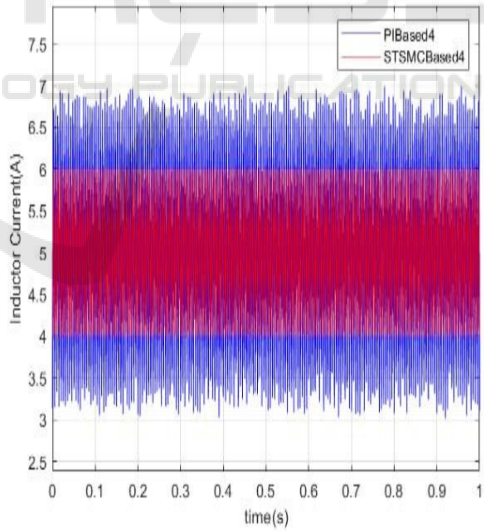

Figure 11: Inductor current comparison for PI-Based and STSMC-Based control.

5.2 Charging Mode

To maintain stable power delivery and enable real-time voltage and current monitoring, the photo voltalic panel generates electricity, the battery stores surplus power for future use, and the converter dynamically regulates voltage and current. The resultant voltage, battery power, and inductor current are depicted in Figure 12, 13, and 14, respectively

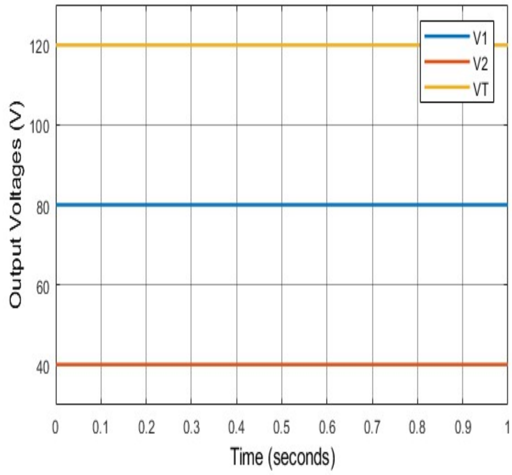

Figure 12: Output voltages in charging mode.

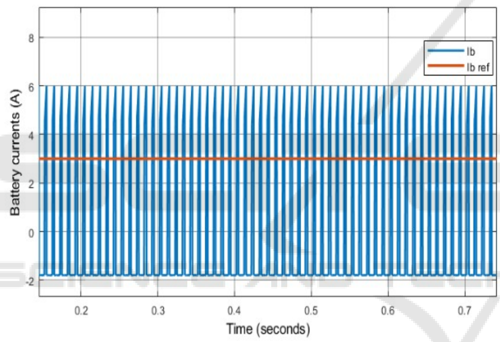

Figure 13: Battery current and reference battery current.

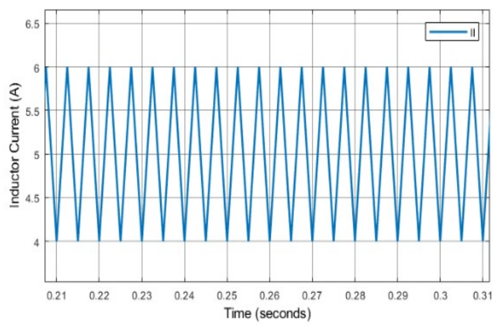

Figure 14: Inductor current in charging mode.

The converter regulates energy flow, with the PV panel supplying power while the battery charges or discharges based on changes in the reference current. This mechanism ensures stable voltage and current delivery to the load while enabling real-time system monitoring. The graph illustrating the different in battery current is presented in Figure 15.

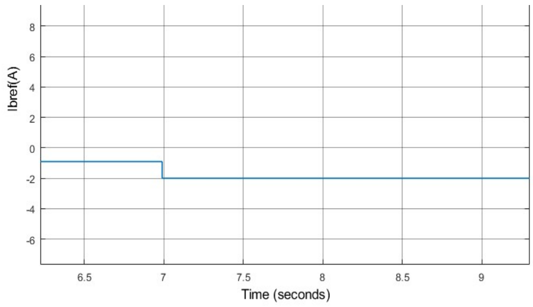

Figure 15: Change in reference battery current.

The graph illustrates battery current (A) over time (s) for three control strategies: RefBased (blue), PIBased3 (red), and STSMCBased3 (yellow). The reference current remains steady, while the PI-based and STSMC-based methods show oscillations, with STSMC exhibiting slightly higher fluctuations. This shows the performance comparison and differences between traditional PI and advanced STSMC controller techniques. Schematic representation of the Battery Current Response for Various Control Strategies is shown in Figure 16.

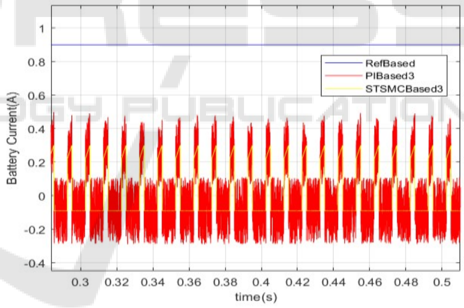

Figure 16: Battery current response for different control strategies.

The induturing current (A) over time (s) both for PIBased4 (blue) and STSMCBased4 (red) control methods is depicted. The response using STSMC method has a smoother curve and less fluctuating performance compared to that of PI achieved approach. Extending this analysis to the inductors spectrum regarding their oscillatory dynamics would provide a more sophisticated insight into how the STSMC technique outperformed previous results. Inductor Current Response Using PI-Based and STSMC-Based Control as Recorded in Figure 17.

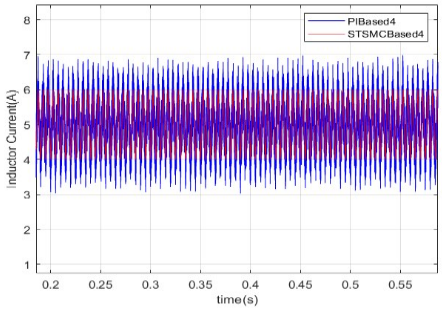

Figure 17: Inductor current response using PI-Based and STSMC-Based control.

6 CONCLUSIONS

To summarize, the design performance has a significant improvement by applying the Super-Twisting Sliding Mode Control (STSMC) for Single Inductor Multi-Port Power Controller in EV applications. By replacing the classical PI-based controller by the proposed one based on STSMC, the method succeeds in dampening chattering as well as restoring the voltage and current distortions. This leads to a smoother and more stable operation. Moreover, in comparison with STSMC, the integration of a compensator achieves better disturbance rejection response and also provides a quick dynamic response against changes in load conditions.

The findings of the Simulated and Empirical Evaluations validate the proposed advanced control strategy, showcasing a decrease in steady-state error and enhanced efficiency in the aggregation of multiple energy sources, such as battery and solar panel networks. With its data-driven power distribution and management, this approach is required for electric vehicles since the need for energy is dynamic depending on driving conditions. The proposed STSMC-based system is assessed to be suitable for use in EV applications, highlighting its advantages as a cost efficient and energy-effective solution for numerous energy splits, encourages performance improvement and diminishes distortions.

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