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Sliding Mode Controller-Based Single-Stage Bridgeless Power Factor Correction Charger for Solar-Assisted Light Electric Vehicles with Enhanced Battery State-of-Charge

Dr. P. Sangeetha[1], Vookanti Deepak Reddy[2]
[1]Associate Professor, [2]PG, M.Tech (Electrical Power Systems), Department of Electrical and Electronics Engineering, JNTUH, University College of Engineering Jagtial (Autonomous), TS, India

Abstract: The rapid growth of light electric vehicles (LEVs) has increased the demand for efficient battery charging systems capable of achieving faster charging while maintaining high power quality and converter efficiency. Conventional proportional–integral (PI) controller-based bridgeless power factor correction (PFC) chargers exhibit limited dynamic performance under varying photovoltaic (PV) generation, grid disturbances, and battery operating conditions, resulting in reduced charging efficiency and lower battery State-of-Charge (SOC). To overcome these limitations, this paper proposes a Sliding Mode Controller (SMC) for a single-stage bridgeless PFC charger integrated with a solar PV source and utility grid. The nonlinear SMC provides superior robustness against parameter uncertainties, rapid disturbance rejection, and accurate regulation of battery charging current, output voltage, and DC-link voltage. Furthermore, an Incremental Conductance maximum power point tracking algorithm continuously extracts the maximum available PV power under changing irradiance conditions. The complete charging system is developed in the MATLAB/Simulink environment and evaluated under identical operating conditions. Simulation results demonstrate that the proposed SMC significantly improves converter stability, minimizes charging current ripple, enhances renewable energy utilization, and achieves a substantially higher battery State-of-Charge within the same charging duration compared with the conventional PI controller. The proposed charging strategy therefore offers an efficient, reliable, and practical solution for next-generation renewable-energy-assisted light electric vehicle charging applications.
Keywords: Fast Battery Charging, State-of-Charge (SOC), Light Electric Vehicle (LEV), Bridgeless PFC Charger, Solar Photovoltaic, Intelligent Control, MATLAB/Simulink.

I. INTRODUCTION

The rapid advancement of electric mobility has accelerated the global adoption of Light Electric Vehicles (LEVs) as an environmentally sustainable alternative to conventional internal combustion engine vehicles. Increasing concerns regarding greenhouse gas emissions, depletion of fossil fuel resources, and stringent environmental regulations have encouraged governments and industries to promote battery-powered transportation systems that offer high energy efficiency and reduced carbon emissions [1], [2]. Among the various components of an LEV, the battery charging system plays a crucial role in determining vehicle reliability, charging duration, battery lifespan, and overall energy utilization. Lithium-ion batteries have become the preferred energy storage technology due to their high energy density, long cycle life, and superior charging capability. However, the charging efficiency of lithium-ion batteries is significantly influenced by the topology of the power converter and the employed control strategy. Conventional charging systems generally utilize two-stage AC–DC and DC–DC conversion architectures controlled by Proportional–Integral (PI) controllers. Although these systems provide acceptable steady-state performance, they suffer from increased component count, higher switching losses, slower dynamic response, and reduced charging efficiency under nonlinear operating conditions [3], [4]. To overcome these limitations, single-stage bridgeless Power Factor Correction (PFC) converters have emerged as an attractive solution due to their reduced conduction losses, compact structure, improved power density, and near-unity power factor. Furthermore, integrating solar photovoltaic (PV) energy with the charging system enhances sustainability by reducing dependency on the utility grid and improving renewable energy utilization.

Nevertheless, fluctuations in solar irradiance, grid disturbances, and continuously varying battery characteristics introduce significant nonlinearities that require intelligent and robust control techniques for maintaining stable charging performance [5]–[7].

The overall performance of a solar-assisted bridgeless PFC charger is predominantly governed by its control strategy, which directly influences converter stability, charging current regulation, power quality, and battery State-of-Charge (SOC). Conventional PI controllers are widely adopted because of their simple implementation; however, they exhibit degraded performance when subjected to parameter uncertainties, load variations, fluctuating photovoltaic generation, and utility voltage disturbances. These limitations result in increased charging current ripple, slower transient response, larger steady-state error, and inefficient energy transfer to the battery, ultimately reducing the achievable SOC within a given charging duration [8], [9]. Consequently, nonlinear control techniques have gained significant research attention for improving converter robustness and charging efficiency. Among these approaches, the Sliding Mode Controller (SMC) has emerged as one of the most effective control techniques because of its inherent robustness against parameter variations, rapid disturbance rejection capability, fast dynamic response, and excellent tracking accuracy. Unlike conventional linear controllers, the SMC continuously forces the converter operating point towards a predefined sliding surface, thereby maintaining accurate regulation of battery charging current, output voltage, and DC-link voltage even under severe operating disturbances. In addition, the incorporation of an Incremental Conductance Maximum Power Point Tracking (MPPT) algorithm enables continuous extraction of the maximum available photovoltaic power, ensuring efficient utilization of renewable energy under varying environmental conditions. The coordinated operation of MPPT and SMC significantly enhances converter efficiency, minimizes switching losses, improves power quality, and delivers smoother battery charging characteristics compared with conventional PI-controlled systems [10]–[12].

Motivated by these research challenges, this work proposes a Sliding Mode Controller-based single-stage bridgeless Power Factor Correction charger integrated with a solar photovoltaic source for Light Electric Vehicle battery charging applications. The proposed system retains the existing converter topology while replacing the conventional PI controller with an advanced nonlinear Sliding Mode Controller to improve battery charging performance without increasing hardware complexity. The complete charging system, comprising the photovoltaic source, bridgeless PFC converter, Incremental Conductance MPPT algorithm, utility grid, and lithium-ion battery, is developed and analysed in the MATLAB/Simulink environment. The effectiveness of the proposed controller is evaluated under identical operating conditions and compared with the conventional PI-controlled charging system. Simulation results demonstrate that the proposed Sliding Mode Controller substantially improves charging current regulation, converter stability, disturbance rejection capability, and renewable energy utilization while achieving a significantly higher battery State-of-Charge (SOC) within the same charging interval. Moreover, the proposed controller reduces charging current ripple, improves DC-link voltage regulation, enhances charging efficiency, and maintains superior power quality, making it a reliable and efficient solution for next-generation renewable-energy-assisted electric vehicle charging infrastructure. These contributions demonstrate the potential of Sliding Mode Control in developing intelligent fast-charging systems capable of improving battery performance, extending driving range, and supporting the future expansion of sustainable electric transportation [13]–[15].

II. LITERATURE SURVEY

The rapid advancement of electric vehicle (EV) technology has significantly increased research efforts toward developing compact, efficient, and intelligent battery charging systems capable of meeting the growing demand for sustainable transportation. Conventional onboard chargers generally employ two-stage AC–DC and DC–DC conversion architectures that utilize Proportional–Integral (PI) controllers for battery charging. Although these systems provide acceptable steady-state performance, they suffer from increased component count, higher switching losses, bulky structures, and reduced overall efficiency. To overcome these limitations, researchers have focused on single-stage bridgeless Power Factor Correction (PFC) converters, which integrate multiple power conversion functions into a single conversion stage while eliminating the conventional diode bridge. Chen et al. [16] introduced a low-stress buck–boost PFC converter for universal-input applications that significantly reduced semiconductor stress and improved efficiency. Huber et al. [17] demonstrated that bridgeless PFC rectifiers considerably reduce conduction losses and improve thermal performance compared with conventional bridge rectifiers. Fardoun et al. [18] proposed efficient bridgeless Cuk rectifiers capable of achieving continuous input current with improved power quality characteristics. Oh et al. [19] further developed a high-efficiency non-isolated single-stage onboard charger for electric vehicles, demonstrating improved converter compactness and reduced switching losses. Gupta and Singh [20] proposed a transformerless bridgeless charger specifically designed for Light Electric Vehicles (LEVs), achieving significant reductions in Total Harmonic Distortion (THD) while maintaining near-unity power factor. More recently, Kumar and Singh [21] developed a dual-input bridgeless PFC charger integrating photovoltaic (PV) power with the utility grid, highlighting the advantages of renewable energy-assisted charging.

Although these studies substantially improved converter efficiency and power quality, most relied on conventional linear controllers, limiting their dynamic performance under rapidly changing operating conditions.

The increasing integration of renewable energy sources into electric vehicle charging infrastructure has further intensified the need for intelligent control strategies capable of managing multiple energy sources while maintaining stable converter operation. Solar photovoltaic (PV) systems have emerged as one of the most promising renewable energy sources because of their clean, abundant, and environmentally friendly characteristics. However, fluctuations in solar irradiance, varying battery conditions, and utility disturbances introduce strong nonlinearities that challenge the performance of conventional PI controllers. Saxena et al. [22] presented a grid-integrated PV–battery charging system capable of coordinating renewable energy and grid power for residential and EV applications. Verma et al. [23] proposed a multifunctional solar PV-based EV charger supporting grid interaction and ancillary services. Zhang et al. [24] investigated power decoupling control techniques for PV–battery hybrid systems to improve DC-link stability and reduce voltage ripple. Kim et al. [25] introduced a single-stage electrolytic capacitor-less EV charger with improved reliability and converter lifespan, whereas Mishra and Kim [26] proposed an economical onboard charging system for light electric vehicles emphasizing reduced hardware complexity. Despite these advancements, most PV-assisted charging systems primarily focused on converter topology optimization rather than improving charging performance through advanced nonlinear control algorithms. Furthermore, limited attention has been devoted to enhancing battery State-of-Charge (SOC) within the same charging duration, which is one of the most important performance indicators for practical electric vehicle charging applications.

To address these limitations, recent research has increasingly focused on robust nonlinear control techniques capable of improving converter stability, charging efficiency, and battery performance under uncertain operating conditions. Sliding Mode Control (SMC) has attracted considerable attention owing to its superior disturbance rejection capability, fast transient response, and robustness against parameter uncertainties. Praneeth and Williamson [27] emphasized the importance of advanced control strategies for improving onboard battery charger performance through detailed converter modelling and control analysis. Nazi et al. [28] developed an isolated single-stage charger with improved control performance for electric vehicle applications. Shameli et al. [29] introduced soft-switching bridgeless Cuk converters to improve converter efficiency under wide operating ranges, while Zhou et al. [30] identified intelligent nonlinear controllers and renewable energy integration as important future research directions for next-generation EV charging systems. Although significant progress has been achieved in converter design and renewable energy integration, there remains a noticeable research gap in developing Sliding Mode Controller-based bridgeless PFC chargers specifically aimed at improving battery State-of-Charge (SOC) within the same charging interval while simultaneously enhancing converter stability, charging current regulation, renewable energy utilization, and power quality. Motivated by this gap, the present work proposes a Sliding Mode Controller-based single-stage bridgeless PFC charger integrated with a solar photovoltaic source for Light Electric Vehicle battery charging. The proposed controller replaces the conventional PI controller to achieve faster charging dynamics, reduced charging current ripple, enhanced converter robustness, and significantly higher battery SOC under identical operating conditions, thereby providing an efficient and reliable charging solution for future renewable-energy-assisted electric mobility systems.

III. METHODOLOGY

The proposed charging methodology is based on a Sliding Mode Controller (SMC)-assisted single-stage bridgeless Power Factor Correction (PFC) charger integrated with a solar photovoltaic (PV) source and the utility grid for charging a lithium-ion battery used in a Light Electric Vehicle (LEV). The overall system comprises a PV array, an Incremental Conductance Maximum Power Point Tracking (IC-MPPT) algorithm, a single-stage bridgeless PFC converter, a utility grid interface, the Sliding Mode Controller, and the lithium-ion battery. Initially, the IC-MPPT continuously extracts the maximum available power from the PV array despite variations in solar irradiance and temperature, ensuring efficient utilization of renewable energy. The extracted PV power is combined with the utility grid whenever the solar generation becomes insufficient to satisfy the battery charging demand. Unlike the conventional PI-controlled charger, which produces slower corrective action under dynamic operating conditions, the proposed Sliding Mode Controller continuously monitors the battery charging current, battery terminal voltage, and DC-link voltage to generate high-speed switching pulses for the bridgeless converter. Since the SMC is a nonlinear control technique, it effectively compensates for disturbances arising from fluctuating PV power, grid voltage variations, converter parameter uncertainties, and battery impedance changes. Consequently, the charging current closely follows its reference value with minimal overshoot and negligible steady-state error, enabling faster and more efficient charging. Stable regulation of the converter operating point also minimizes charging current ripple, reduces converter losses, and improves overall charging efficiency.

Therefore, a greater proportion of the supplied electrical energy is effectively stored in the battery, resulting in a higher State-of-Charge (SOC) within the same charging duration when compared with the conventional PI controller.

The mathematical operation of the proposed Sliding Mode Controller begins by defining the charging current error as the difference between the reference charging current and the measured battery charging current. This error is expressed as

$$e(t) = I_{ref} - I_{bat} \qquad \ldots(1)$$

where I_{ref} is the desired charging current and I_{bat} is the measured battery charging current. The controller then constructs the sliding surface, which combines the instantaneous error and its rate of change to achieve rapid convergence toward the desired operating point. The sliding surface is defined as

$$S(t) = \lambda e(t) + \frac{de(t)}{dt} \qquad \ldots(2)$$

where is a positive design constant that determines the convergence speed of the controller. The switching control law forces the converter trajectory toward the sliding surface by satisfying the reaching condition

$$S(t)\,\dot{S}(t) < 0 \qquad \ldots(3)$$

which guarantees asymptotic stability of the charging system. Whenever the operating point deviates because of solar irradiance fluctuations, battery parameter variations, or sudden load disturbances, the Sliding Mode Controller immediately changes the converter switching state to restore the charging current to its reference value. In contrast, the conventional PI controller depends only on proportional and integral gains, requiring additional settling time before correcting the error. As a result, the PI controller exhibits slower transient response and larger charging current oscillations. The rapid corrective action provided by the Sliding Mode Controller significantly reduces current ripple, improves DC-link voltage regulation, suppresses converter oscillations, and maintains stable battery charging throughout the charging process. Consequently, the converter operates with higher efficiency and improved power quality under both steady-state and transient operating conditions.

The enhancement in battery State-of-Charge (SOC) is primarily attributed to the superior dynamic characteristics of the proposed Sliding Mode Controller. The battery SOC represents the ratio of stored charge to the rated battery capacity and is mathematically expressed as

$$SOC(t) = SOC(0) + \frac{1}{C_{bat}} \int_0^t \quad I_{bat}(\tau)\, d\tau \qquad \ldots(4)$$

where C_{bat} denotes the battery capacity (Ah), I_{bat} is the battery charging current, and $SOC(0)$ is the initial state of charge. From this relationship, it is evident that maintaining a stable charging current close to its reference value directly increases the accumulated charge stored inside the battery during a fixed charging interval. Since the proposed Sliding Mode Controller minimizes charging current ripple, rapidly rejects disturbances, and accurately regulates the converter output, the battery continuously receives the optimum charging current with minimal interruptions. This results in greater energy transfer from the PV-grid charging system into the battery compared with the PI-controlled charger, where transient oscillations and slower error correction reduce the effective charging current. Furthermore, improved DC-link voltage regulation decreases converter switching losses and enhances renewable energy utilization, enabling a larger fraction of the harvested photovoltaic power to contribute directly to battery charging. The coordinated operation of the IC-MPPT algorithm and the Sliding Mode Controller therefore increases charging efficiency, shortens the battery charging time, and achieves a significantly higher battery State-of-Charge under identical operating conditions. The MATLAB/Simulink simulation results confirm that the proposed SMC-based charging methodology outperforms the conventional PI controller by providing faster dynamic response, enhanced converter stability, lower charging current ripple, improved power quality, and superior SOC performance, making it a promising control strategy for next-generation solar-assisted electric vehicle charging stations.

IV. RESULTS AND DISCUSSION

The performance of the proposed Sliding Mode Controller (SMC)-based single-stage bridgeless Power Factor Correction (PFC) charger was evaluated using the MATLAB/Simulink platform under various operating conditions. The simulation model integrates a solar photovoltaic (PV) source, Incremental Conductance Maximum Power Point Tracking (IC-MPPT), a bridgeless PFC converter, utility grid, lithium-ion battery, and the proposed Sliding Mode Controller to investigate the charging characteristics of the battery. The objective of the simulation study is to analyse the dynamic behaviour of the charging system, validate the effectiveness of the proposed controller, and compare its performance with the conventional PI-controlled charger. Particular emphasis is given to converter stability, PV power extraction, disturbance rejection capability, charging performance, and battery State-of-Charge (SOC).

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The obtained simulation results demonstrate that the nonlinear Sliding Mode Controller provides superior regulation of the charging current and DC-link voltage, thereby improving energy transfer efficiency and enabling a faster increase in battery SOC compared with the conventional PI controller.

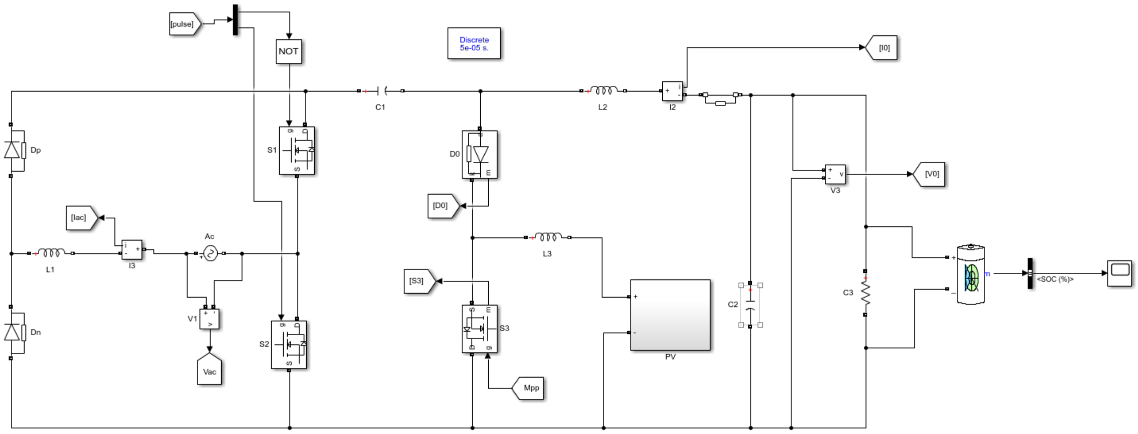

Fig. 1. System Simulation Configuration

Figure 1 illustrates the complete MATLAB/Simulink model of the proposed solar-assisted battery charging system. The simulation integrates the utility grid, photovoltaic source, bridgeless PFC converter, Sliding Mode Controller, lithium-ion battery, and measurement blocks into a single charging platform. The developed model accurately represents the power flow from both the grid and PV source to the battery while allowing evaluation of converter performance under different operating conditions. This configuration serves as the foundation for validating the effectiveness of the proposed control strategy.

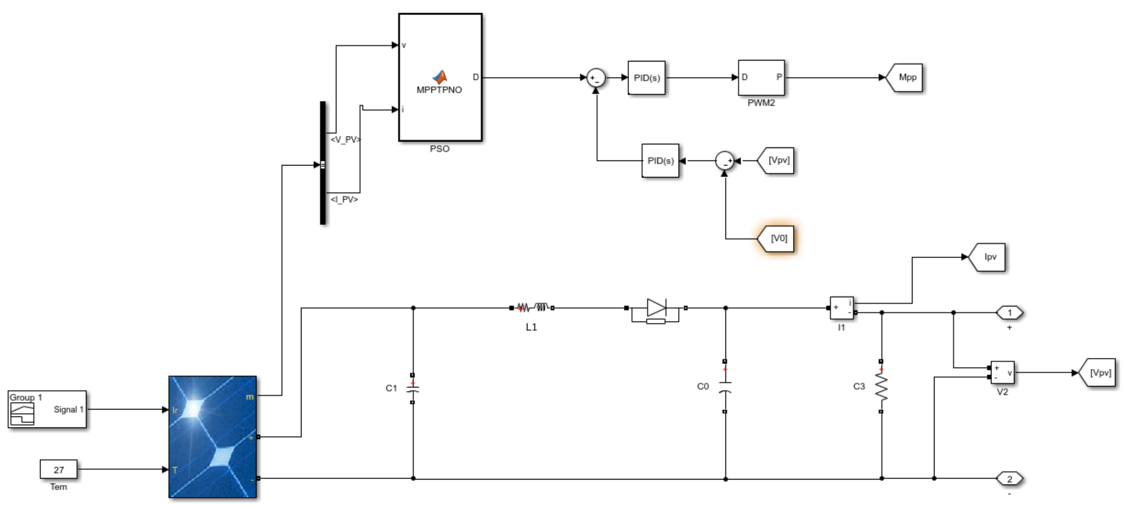

Fig. 2. PV System with MPPT Algorithm

Figure 2 presents the photovoltaic subsystem equipped with the Incremental Conductance Maximum Power Point Tracking (IC-MPPT) algorithm. The MPPT controller continuously monitors PV voltage and current to determine the operating point corresponding to maximum power generation despite variations in solar irradiance and temperature. Consequently, the available solar energy is efficiently extracted and supplied to the charging converter, reducing dependence on the utility grid and improving renewable energy utilization. The effective coordination between the MPPT algorithm and the proposed Sliding Mode Controller contributes to improved charging efficiency.

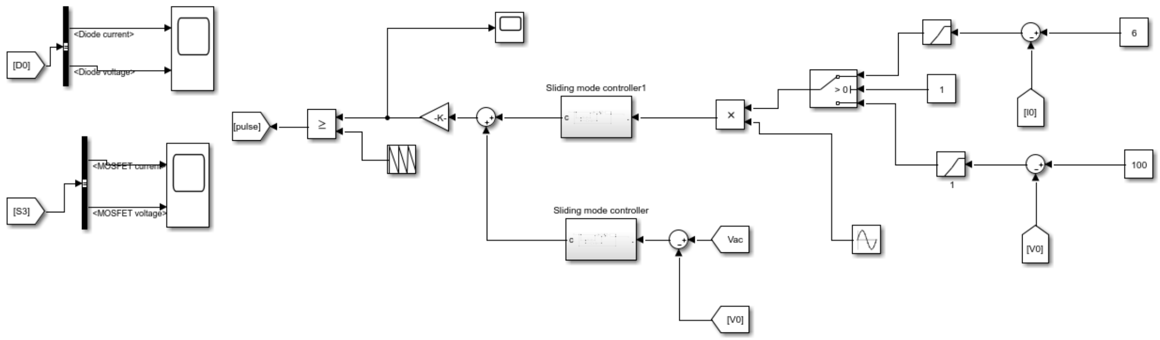

Fig. 3. Sliding Mode Controller

Figure 3 illustrates the implementation of the proposed Sliding Mode Controller within the charging system. The controller continuously monitors the charging current and voltage, generating high-speed switching signals for the bridgeless converter. Unlike the conventional PI controller, the SMC rapidly responds to system disturbances and parameter variations, ensuring accurate current regulation and stable converter operation. Its robust nonlinear control action minimizes charging current ripple and maintains stable DC-link voltage, leading to improved converter efficiency and enhanced battery charging performance.

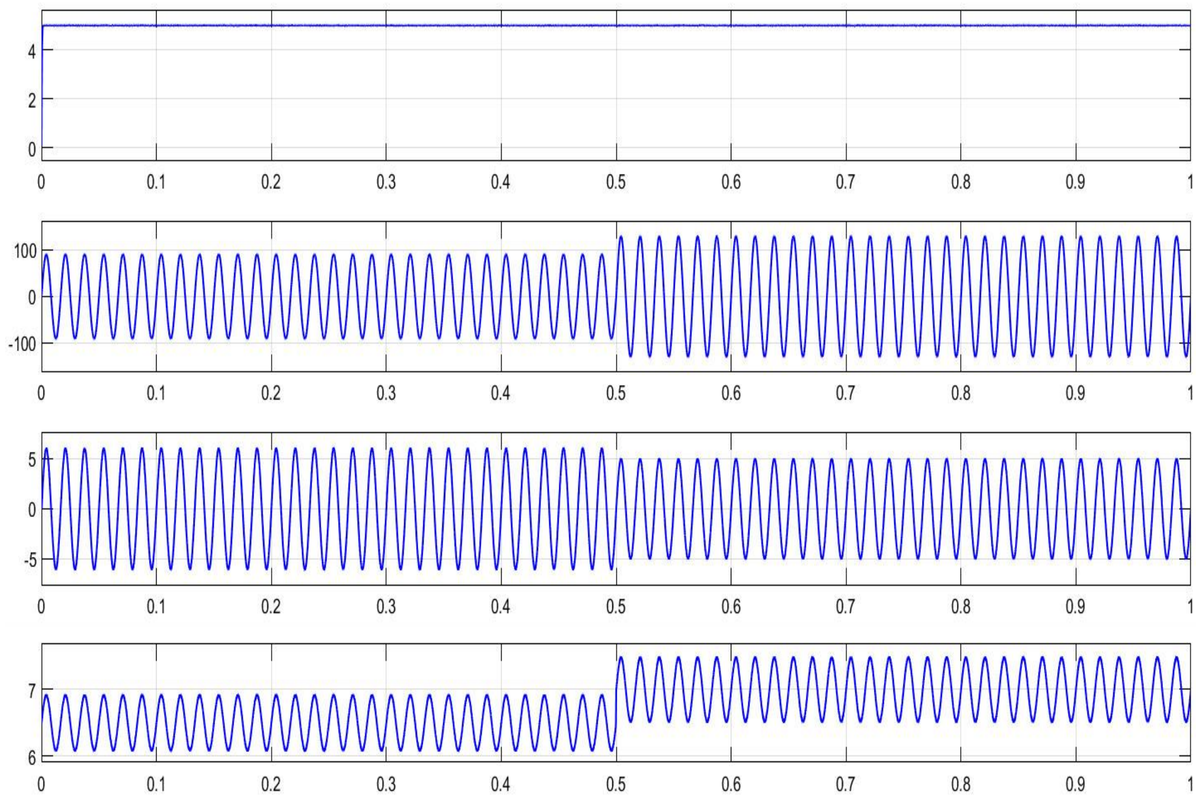

Fig. 4. Voltage Swell of Vac (90–130 V)

Figure 4 illustrates the performance of the proposed charging system under an input voltage swell condition, where the AC supply increases from 90 V to 130 V. The Sliding Mode Controller (SMC) rapidly compensates for the increase in input voltage by maintaining stable converter operation and regulating the battery charging voltage and current. The output waveform exhibits minimal overshoot and fast settling characteristics, demonstrating the superior disturbance rejection capability and robustness of the proposed controller during sudden grid voltage variations.

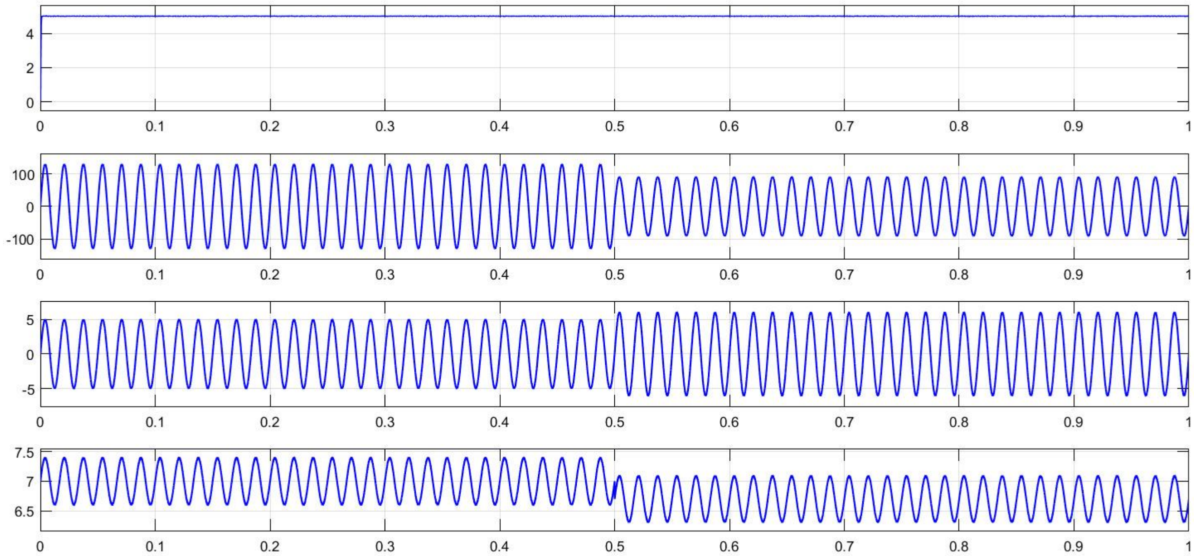

Fig. 5. Voltage Sag of Vac (130–90 V)

Figure 5 presents the response of the proposed charger when the input voltage decreases from 130 V to 90 V. Despite the sudden reduction in supply voltage, the Sliding Mode Controller effectively maintains stable charging operation by quickly adjusting the converter switching action. The charging current and output voltage remain well regulated with negligible oscillations, confirming that the proposed controller provides reliable battery charging even during severe voltage sag conditions.

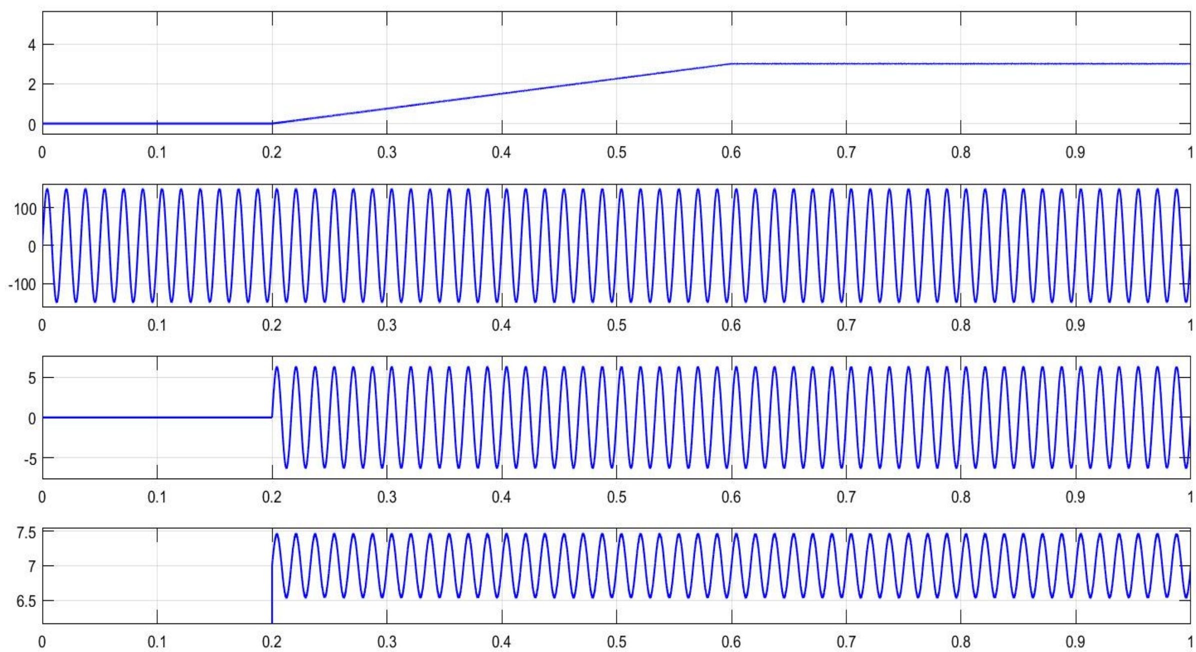

Fig. 6. Step Increase in Load Current (0%–100%)

Figure 6 demonstrates the dynamic performance of the charging system when the load current is suddenly increased from 0% to 100%. The proposed Sliding Mode Controller responds immediately to the increased power demand by stabilizing the converter output and maintaining the desired charging current. The transient period is very short, and the system quickly reaches steady-state operation with limited current ripple, indicating excellent dynamic response and high control accuracy.

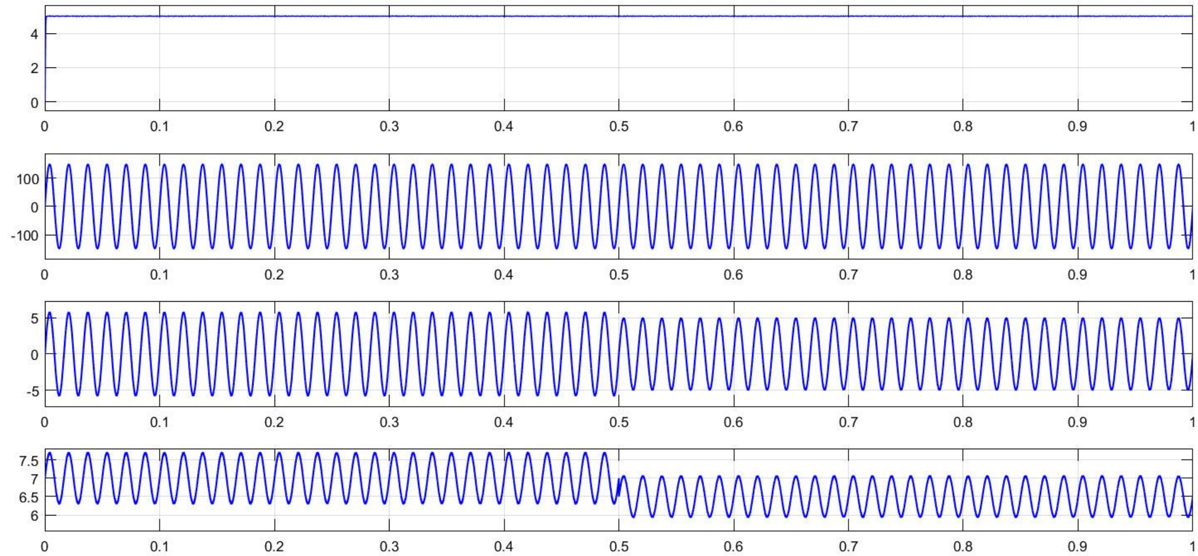

Fig. 7. Step Decrease in Load Current (100%–50%)

Figure 7 shows the transient response of the proposed charger during a sudden reduction in load current from 100% to 50%. The Sliding Mode Controller rapidly adapts to the reduced load without introducing significant voltage fluctuations or current oscillations. The converter quickly settles to the new operating condition while maintaining stable battery charging, demonstrating the controller's ability to handle abrupt load variations efficiently.

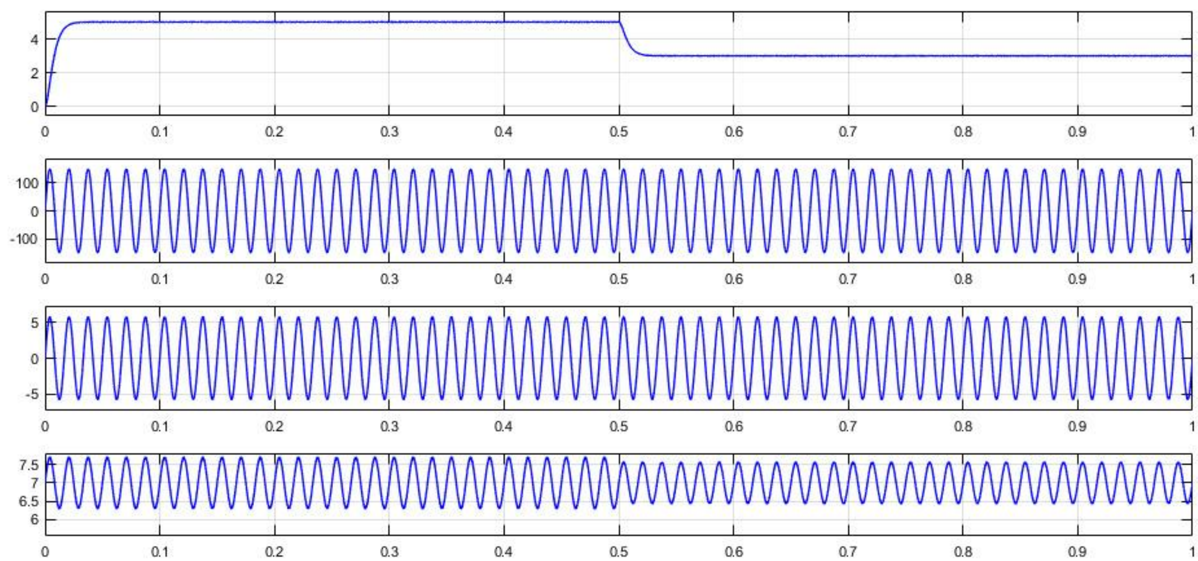

Fig. 8. Effect of Sudden Outage of PV Panel Input in Dual-Input Charging

Figure 8 illustrates the operation of the proposed charging system when the photovoltaic (PV) source is suddenly disconnected during dual-input charging. At the instant of PV outage, the utility grid immediately compensates for the loss of solar power, ensuring uninterrupted battery charging. The Sliding Mode Controller maintains stable output voltage and charging current with negligible transient disturbances, highlighting its excellent robustness and seamless power management capability during renewable energy interruptions. This result confirms the reliability of the proposed charging system under practical operating conditions where solar power availability is intermittent.

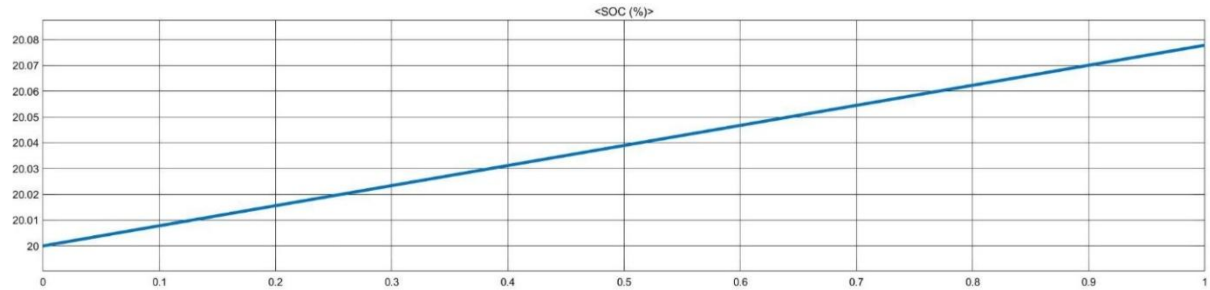

Fig. 9. Battery State of Charge with PI Controller

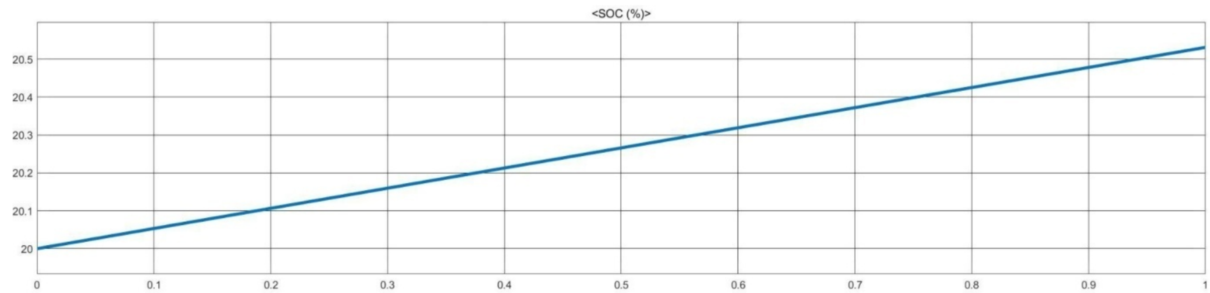

Fig. 10. Battery State of Charge with Sliding Mode Controller

Figure 9 shows the variation of battery State-of-Charge (SOC) using the conventional PI controller. Although the battery SOC increases steadily during charging, the charging rate is comparatively lower because the PI controller exhibits slower dynamic response and reduced adaptability under changing operating conditions. Consequently, the charging current requires a longer settling time, leading to comparatively lower energy transfer efficiency and reduced SOC within the same charging interval.

Figure 10 illustrates the battery State-of-Charge obtained using the proposed Sliding Mode Controller. Compared with the PI-controlled charger, the SMC achieves a noticeably faster increase in SOC owing to its rapid transient response, robust disturbance rejection capability, and accurate charging current regulation. The improved converter stability allows more electrical energy to be delivered to the battery with minimal current ripple and reduced converter losses. Consequently, the proposed controller achieves higher battery SOC within the same charging duration, confirming the effectiveness of the proposed charging strategy for renewable-energy-assisted electric vehicle applications.

Table I. Performance Comparison Between PI Controller and Proposed Sliding Mode Controller

Performance Parameter	PI Controller	Proposed Sliding Mode Controller
Dynamic Response	Moderate with longer settling time	Fast response with rapid convergence
Disturbance Rejection	Limited under voltage variations	Excellent robustness against disturbances
Charging Current Ripple	Comparatively higher	Significantly reduced
Battery State of Charge (SOC)	Lower SOC within the same charging duration	Higher SOC within the same charging duration
Overall Charging Efficiency	Moderate	Higher due to improved current regulation and lower converter losses

The comparative analysis confirms that replacing the conventional PI controller with the proposed Sliding Mode Controller significantly improves the charging performance of the solar-assisted bridgeless PFC charger. The SMC provides faster transient response, stronger robustness against grid voltage variations, lower charging current ripple, and improved converter stability. These improvements enable more effective utilization of the available photovoltaic and grid power, resulting in increased charging efficiency and a higher battery State-of-Charge within the same charging period.

Therefore, the proposed SMC-based charging strategy is a more suitable solution for intelligent, fast, and reliable charging of light electric vehicle batteries than the conventional PI-controlled approach.

V. CONCLUSION

This paper presented a Sliding Mode Controller (SMC)-based single-stage bridgeless Power Factor Correction (PFC) charger integrated with a solar photovoltaic (PV) source for efficient charging of lithium-ion batteries in Light Electric Vehicles (LEVs). The proposed charging architecture combines an Incremental Conductance Maximum Power Point Tracking (IC-MPPT) algorithm with a robust nonlinear SMC to maximize photovoltaic power extraction while ensuring accurate regulation of battery charging current and DC-link voltage. Compared with the conventional PI-controlled charger, the proposed SMC demonstrated superior dynamic performance, rapid disturbance rejection capability, and improved converter stability under varying operating conditions. Simulation studies carried out in the MATLAB/Simulink environment verified that the proposed controller effectively reduced charging current ripple, improved voltage regulation, and enhanced renewable energy utilization. Most importantly, the improved control strategy enabled the battery to achieve a higher State-of-Charge (SOC) within the same charging duration, indicating faster and more efficient charging. The bridgeless converter topology also contributed to reduced conduction losses and improved overall conversion efficiency while maintaining satisfactory power quality. Therefore, the proposed SMC-based charging system provides a reliable and intelligent solution for next-generation renewable-energy-assisted electric vehicle charging infrastructure. Future work will focus on real-time hardware implementation, experimental validation, adaptive sliding mode control techniques, battery ageing analysis, and integration with smart grid and vehicle-to-grid (V2G) technologies to further enhance charging performance and system reliability.

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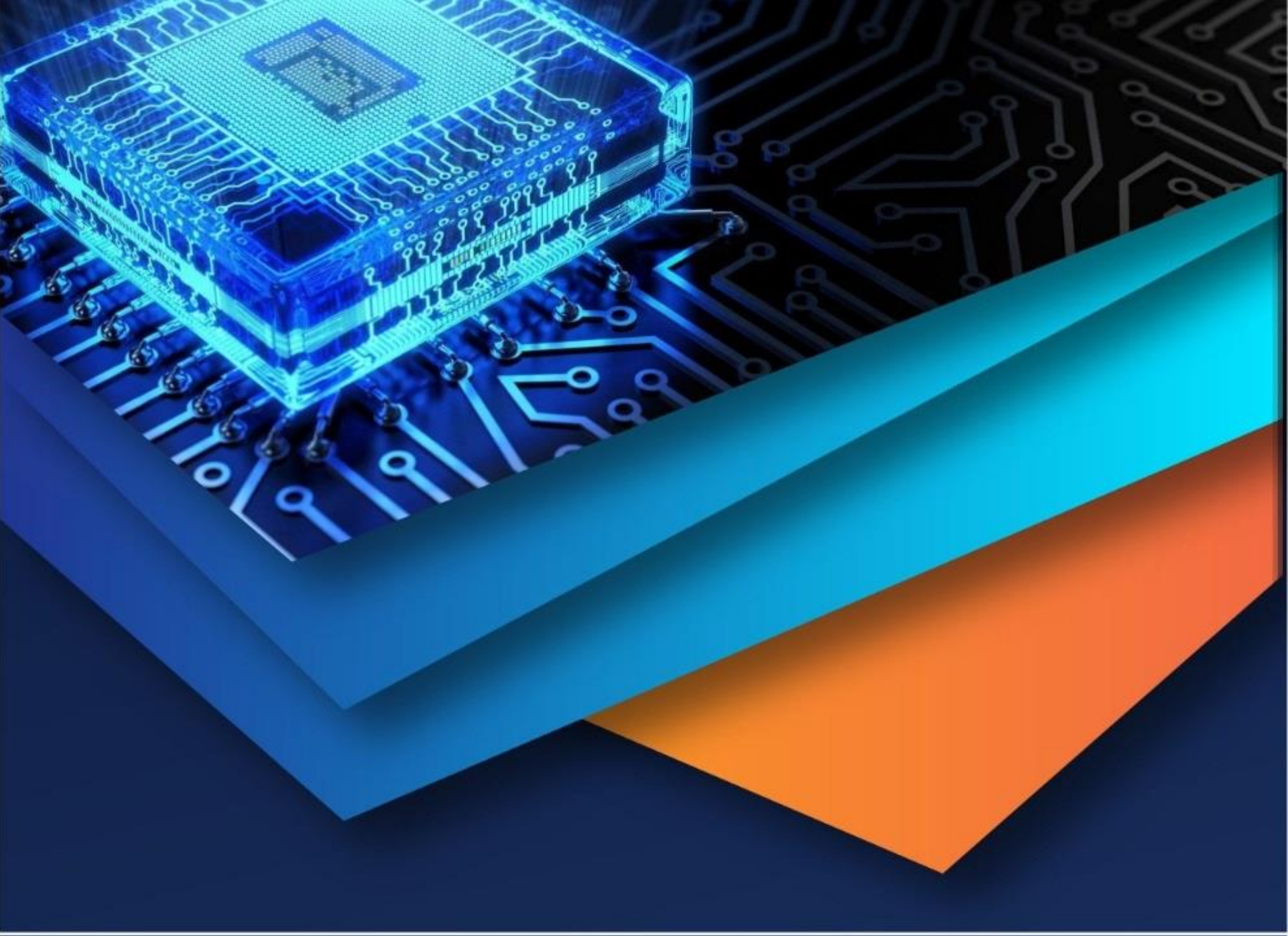

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