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Voltage Regulation and Power Factor Enhancement for EV Charging Station by Using Optimization Algorithm

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Abstract
A Cuk converter-based Power Factor (PF) and voltage regulation enhancement model for an electric vehicle (EV) charging circuit is created and developed, utilizing an optimization technique. Using the Cuk converter's performance measures in Continuous Conduction Mode (CCM), the charging system may produce a steady output current with better PF. This project implements an optimization algorithm-based correction approach for power factor and voltage regulation. The Jaya optimization algorithm, which is a basic metaheuristic algorithm, uses less algorithm-specific parameters. The use of an optimization algorithm aids in the dynamic adjustment of converter operation to maintain the appropriate power factor and voltage levels under non-linear situations such as load fluctuations and input changes. The algorithm evaluates the output and modifies the system's parameters to optimize performance for real-time EV applications, taking into account factors such as changing load requirements, input supply uncertainty, and desired voltage levels. The suggested method is created and tested in MATLAB/Simulink. The suggested algorithm is then confirmed experimentally as a hardware prototype.

Keywords: *Cuk converter, Power Factor Correction, Voltage Regulation, Continuous Conduction Mode, Optimal performance, Electric Vehicle, Jaya Algorithm*

1. Introduction
As the demand for EV continues to rise, the efficiency of charging stations becomes a critical aspect of their widespread adoption. One key factor influencing the efficiency of electric vehicle charging stations is the power factor. [1] The power factor is a measure of how effectively electrical power is being converted into useful work, and a higher power factor indicates a more efficient use of electrical power. In the context of EV charging stations, power factor enhancement is crucial for optimizing the energy transfer from the grid to the electric vehicle. A high-power factor ensures that the charging process is not only more energy-efficient but also minimizes power losses and contributes to a stable and reliable grid operation additionally it improves overall energy efficiency and grid performance. There are two main types of power factor correction techniques: passive power factor correction and [2] Active Power Factor Correction (APFC). Among the two techniques APFC is preferred for this application due to passive PFC systems, especially those relying on fixed capacitors, may overcorrect the power factor under light load conditions, leading to issues such as

voltage resonance. APFC systems can prevent such problems by adjusting the correction dynamically. In parallel, soft computing algorithms bring adaptability and robustness to the control strategies, addressing the intricacies and uncertainties inherent in power systems. [3] Therefore, integration of APFC and soft computing algorithms is an imperative method for enhancing the efficiency and reliability of power systems more effectively. Among various APFC's Average Current Mode Control (ACMC) is a commonly employed control in power electronics to regulate the output current in switching power supplies. In this approach, the controller modulates the average value of the inductor current, ensuring stable and efficient operation. Unlike voltage control methods, ACMC directly regulates the inductor current, offering inherent voltage loop compensation and improved transient response. [4] The key feature of ACMC is its ability to maintain a constant average current by dynamically adjusting the duty cycle of the power switch. This is achieved by continuously comparing the sensed inductor current with a reference value and if the current deviates, the duty cycle is adjusted to bring the desired output. This method is particularly beneficial in EV battery charging applications where precise current regulation is critical, as it provides better control over the energy transfer process and enhances overall system performance. To achieve the desired modification of the system a Proportional-Integral (PI) controller is often used because it combines proportional and integral control actions to provide an effective and stable response. A PI controller attempts to reduce the discrepancy between a plant's desired and measured outputs, hence improving steady-state and transient responses. [5] Optimal converter tuning is important because of its impact on EV charging systems; thus, among the various intelligent optimization techniques used in the tuning of DC-DC converters, one such intelligent method is Jaya optimization algorithm, which is inspired by population behavior in society. It is a metaheuristic method meant to solve optimization problems without using gradient information. Therefore, in this study Jaya technique is used to improve the PI controller so that the output signal of a PFC circuit closely matches the desired input voltage. By affirming the presence of fast scale instabilities through real-world experiments, this work not only consolidates the theoretical findings but also underscores the practical relevance of the proposed methodologies. The experimental validation adds a layer of authenticity to the research, affirming the robustness and applicability of the theoretical insights in real-world scenarios. This synthesis provides a holistic perspective on the efficacy of the proposed APFC methodology and the integration of soft computing algorithm. The first section of this article gives an overview of the approaches used along with their description. The second section provides the significance of the Cuk converter and its schematic representation. The third section provides an understanding of the work's fundamental design methodology. The fourth section describes how the model was simulated with feedback and without feedback with their corresponding results. The last part discusses the Jaya optimization algorithm's working model and the outcome that is produced by it. [6]

2. Overview of Cuk Converter

A Cuk converter, also known as optimum topology converter which combines the features of both the buck and boost converters, allowing it to provide step-up and step-down voltage regulation. The Buck-Boost converter is a very unique one where the output of the converter will have reversed polarity. Similarly, the Cuk converter works with the same duality principle where the output of the Cuk converter will reverse polarity similar to the buck-boost converter. The Figure 1 represents the typical circuit diagram of Cuk converter. The Cuk converter is known for its ability to invert the polarity of the output voltage compared to the input voltage, which sets it apart from other conventional converters. [7]

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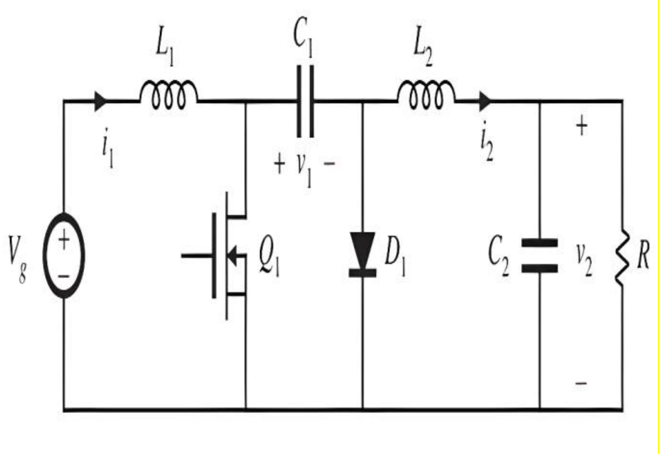

Figure 1 **Schematic Diagram of Cuk Converter**

The traditional DC-DC converter buck, boost, and buck-boost converter have one capacitor, one inductor, one diode, and one semiconductor switch. The Cuk converter consists of two inductors, two capacitors, one diode, and one semiconductor switch. The use of two inductors in the Cuk converter topology has a great advantage such that the voltage ripple is less at the input and output side. [8]

3. Block Diagram Description

The block diagram comprises two components: the Voltage Control loop and the Power factor correction loop. [9]

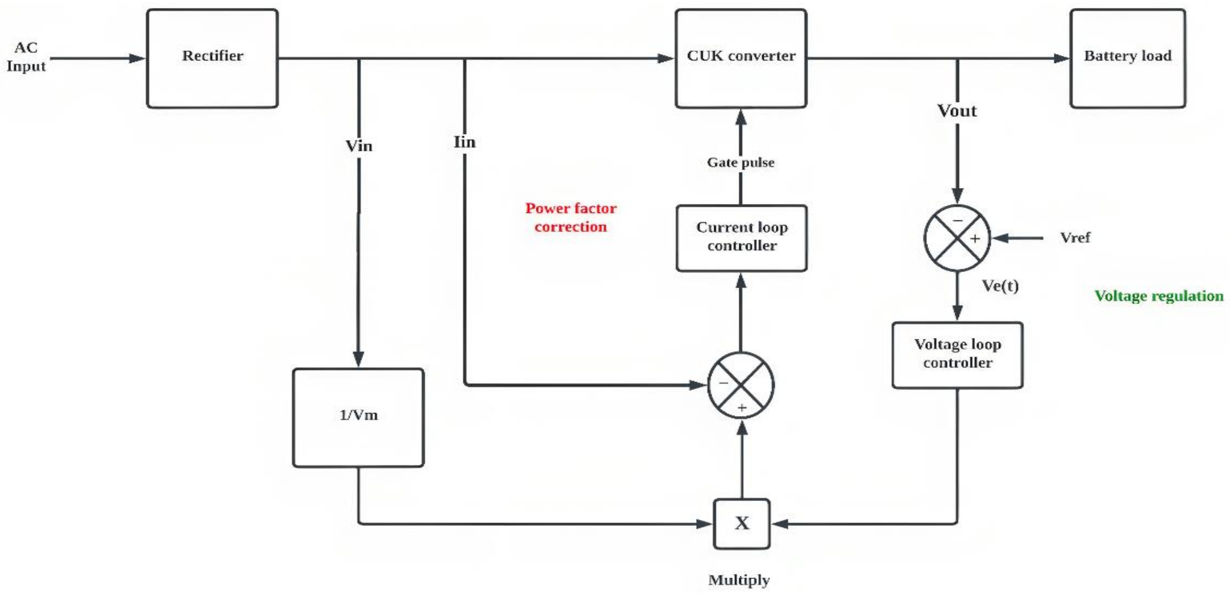

Figure 2 **Block Diagram for Power Factor Correction in EV Charging Station**

The Block diagram shown in the Figure 2 illustrates the functional blocks needed for PFC and voltage regulation in EV charging station. The initial step involves supplying an AC input of 230V to a single-phase full wave bridged rectifier, which consists of diodes to convert the AC voltage into DC voltage. And linked to the dc-to-dc converter, namely the Cuk converter. This converter modifies the voltage by altering the gate pulse to MOSFET converter, either increasing or decreasing it. This process minimizes the fluctuation in voltage and transforms the direct current (DC) converter output voltage to match the battery's requirements. A closed loop system, such as a voltage-controlled loop and power factor correction loop, is connected to the converter. This is achieved by utilizing a PI controller, which is controlled by an algorithm that regulates the gate pulse of the MOSFET. [10]

4. Simulink Model Description

4.1 Cuk Converter Simulink Model

The design of the Cuk converter incorporates a critical aspect, namely a duty cycle set at 0.5, aimed at achieving 100% efficiency in its operation. The duty cycle represents the ratio of time during which the switch is on compared to the entire switching period. [11]

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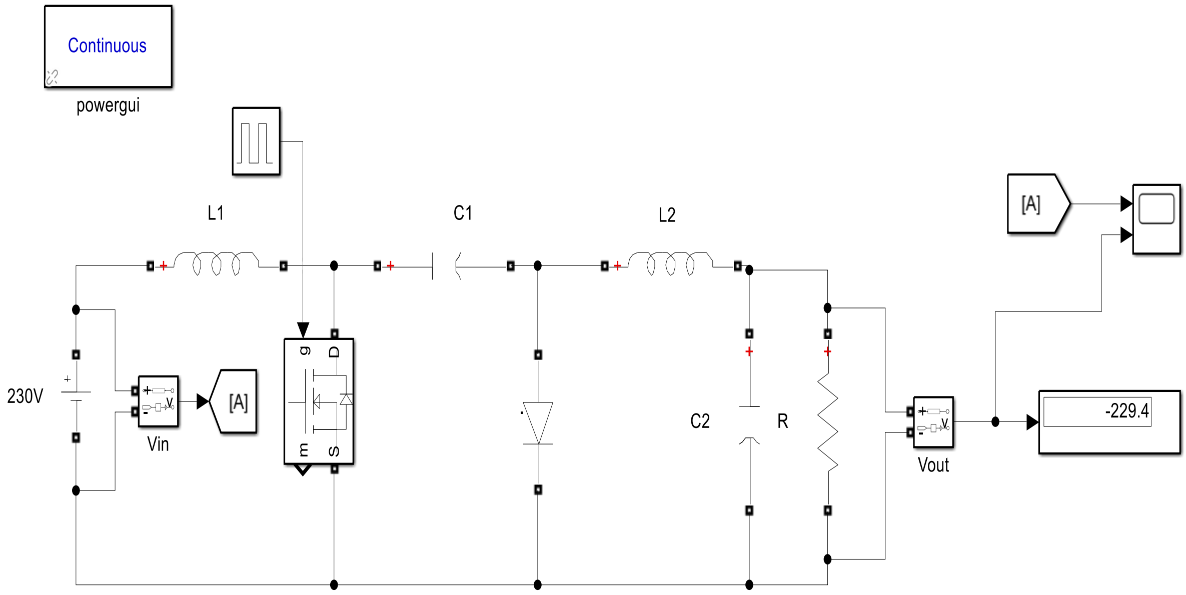

Figure 3 **Simulink Model of CUK Converter**

The simulation circuit for the Cuk converter is done by using MATLAB Simulink software as shown in the Figure 3. In this specific configuration with a duty cycle of 0.5, the switch is on for half of the total switching time. The intentional setting of the duty cycle at this value is a strategic choice to ensure that the voltages at the input and output of the converter are equal. This equilibrium is a key condition for achieving maximum efficiency in the energy transfer process. When the duty cycle is around 0.5, it leads to equal energy transfer during the on and off periods of the switching cycle, resulting in the input and output voltages being the same. This design consideration underscores the meticulous optimization required in the Cuk converter, where maintaining this balanced relationship is instrumental in achieving peak efficiency levels, making it a noteworthy solution for applications requiring precise voltage regulation and energy conservation. The input waveform depicted in Figure 4 is represented by the red line, which represents a direct current (DC) voltage of 230V. Additionally, the blue line represents the direct current (DC) voltage output generated by the Cuk converter that has been constructed. [12]

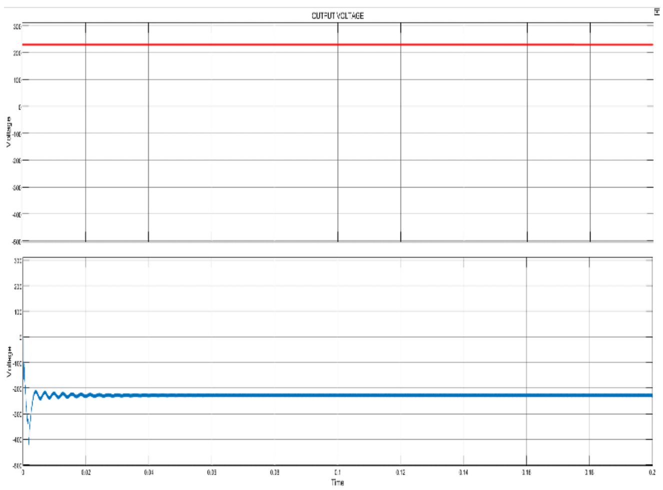

Figure 4 **Simulation Result**

4.2 Open Loop

The Figure 5 shows the Cuk converter in open loop configuration without feedback is simulated in MATLAB Simulink software. In the described simulation setup, the Cuk converter is integrated with a single-phase full-wave diode bridge rectifier. The primary function of the rectifier is to convert the variable AC voltage of 230V into a rectified DC voltage of 230V. This rectified DC voltage serves as the input for the Cuk converter.

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The Cuk converter, operating in an open-loop configuration, receives this rectified DC voltage and processes it without any feedback from the output to the input. In this context, the rectified DC voltage from the diode bridge rectifier acts as the unregulated input to the Cuk converter. The converter processes this input according to its inherent characteristics and control parameters, generating an output that is then directed to the battery load. The open-loop model provides a baseline understanding of how the Cuk converter responds to the rectified DC input without incorporating corrective feedback from the output. This simulation helps analyses the converter's performance under specific operating conditions, laying the groundwork for potential optimizations or adjustments in a controlled environment. [13]

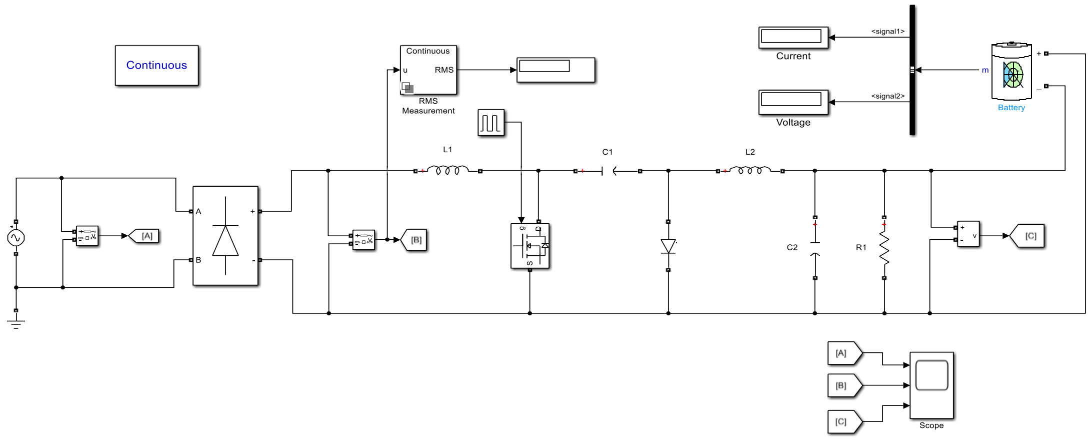

Figure 5 Simulink Model of Open Loop

4.3 Voltage Regulation

The Figure 6 shows the Cuk converter model along with the feedback loop. In the described control System, the output voltage of the Cuk converter is subjected to a closed-loop control mechanism. [14]

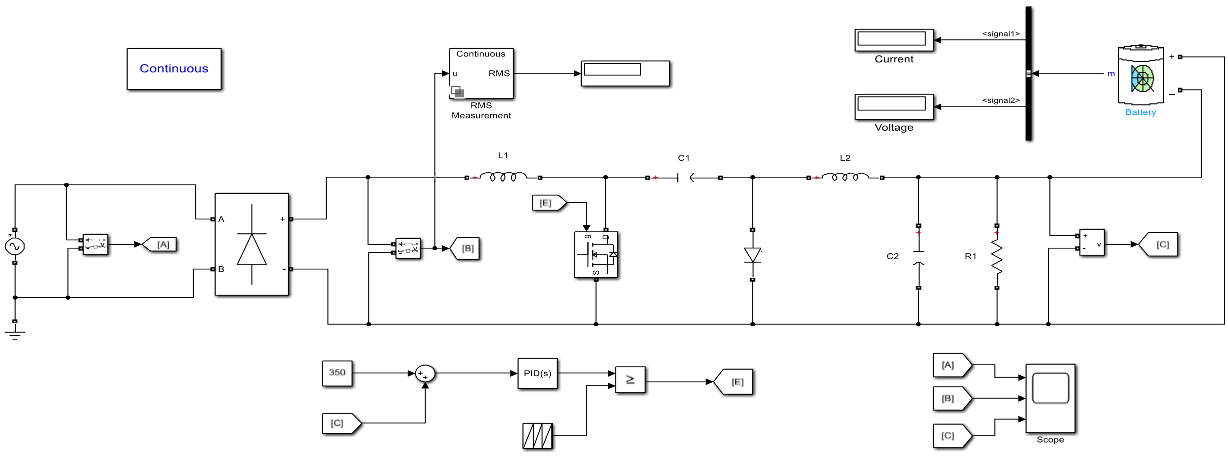

Figure 6 Simulink Model of Voltage Regulation

This involves a sequence of steps that includes a comparator, a Proportional-Integral (PI) controller, and a repeating sequence block to control the gate of the MOSFET in the converter. The intricacies of this control process are as follows: The output voltage of the Cuk converter is compared with a

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reference voltage using a comparator. This reference voltage is changed based on the battery load. The comparator outputs a signal representing the difference between the actual and reference voltages, often referred to as the error signal. The error signal from the comparator is then fed into a Proportional-Integral (PI) controller. The PI controller processes the error signal by considering both the proportional and integral components. The proportional term responds to the instantaneous error, while the integral term accumulates the error over time. The gains of the PI controller, denoted as Kp (proportional gain) and Ki (integral gain), play a crucial role in shaping the controller's response. The output from the PI controller is compared with a repeating sequence block, generating pulsating signals. These signals are then utilized to control the gate of the MOSFET in the Cuk converter, regulating the switching operation and consequently the output voltage. The various parameters of the Cuk converter Simulink model are measured and subsequently provided as input to a multiplexer (MUX) that is connected to a scope. [15]

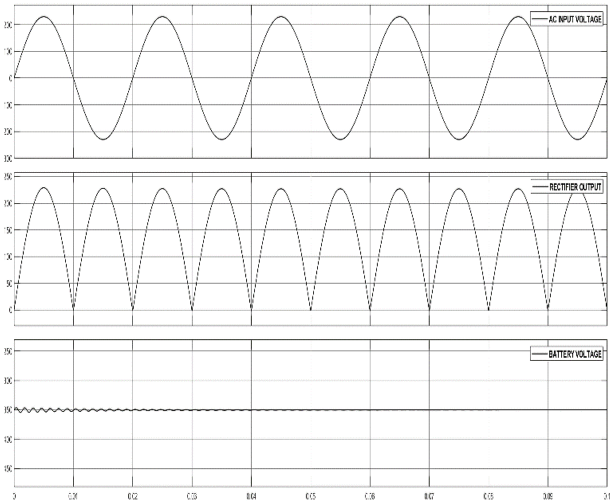

Figure 7 Simulink Result

The various parameters encompass the input alternating current (AC) voltage, rectified direct current (DC) voltage, and the voltage across the load. The findings obtained from the voltage loop controller simulation are depicted in Fig.7. The first waveform corresponds to the AC input voltage provided to the circuit. The second waveform pertains to the rectified output voltage of 230V. The final waveform represents the voltage of the battery following the process of voltage regulation. This intricate control architecture ensures that the output voltage of the Cuk converter is precisely regulated based on the battery load, enhancing the overall stability and performance of the power conversion system. [16]

4.4 Voltage Regulation and Power Factor Correction

The Figure 8 shows the controlling of both the power factor correction and voltage regulation. The characterized control system accomplishes two goals of controlling - voltage regulation and power factor correction- through the application of two PI controllers. Each PI controller is responsible for controlling a specific aspect of the system. The control signals generated by these controllers are then utilized to drive the gate of the switch, typically a Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET). The system has two primary control objectives: power factor correction and voltage regulation. Power factor correction involves adjusting the phase relationship between the current and voltage to ensure efficient power transfer, while voltage regulation ensures a stable and desired output voltage. The first PI controller is dedicated to regulating the output voltage, ensuring it remains at the desired level. The second PI controller is responsible for power factor correction, making adjustments to the system to improve the overall power factor. The gains (proportional and integral terms) of the PI controllers are determined using an optimization algorithm. This algorithm assists in finding the optimal values for the controller gains, ensuring that the control system responds effectively to changes in the output voltage and power factor. The output signals from the PI controllers represent the corrective actions needed for voltage regulation and power factor correction. These control signals are generated based on the error signals, which are the differences between the desired and actual values of voltage and power factor. [17]

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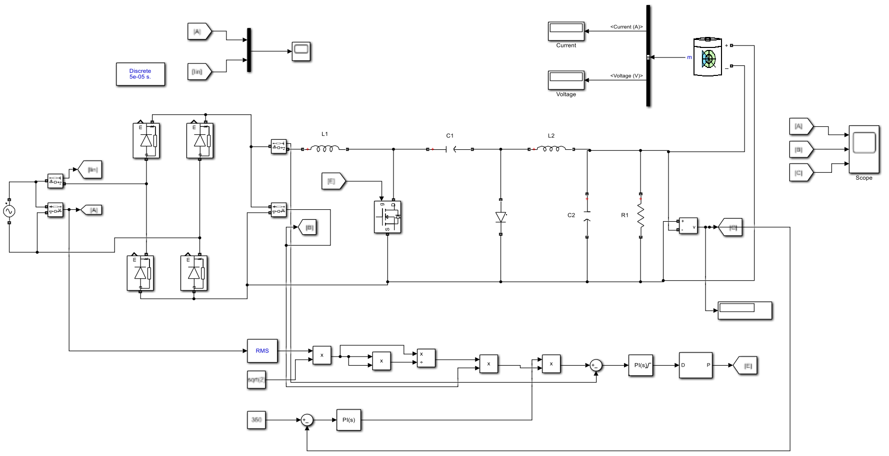

Figure 8 Simulink Model of Closed Loop

The control signals from the PI controllers are then used to generate pulses. These pulses serve as the driving signals for the gate of the switch (MOSFET). The duration and timing of these pulses control the switching operation of the MOSFET, regulating the flow of power through the system. The generated pulses are applied to the gate terminal of the MOSFET. The MOSFET acts as the switching element in the power circuit. By controlling the gate voltage, the MOSFET is turned on and off in a controlled manner, modulating the power flow through the system. The combination of two PI controllers with optimized gains, an optimization algorithm, and a pulse generation mechanism ensures precise control over both voltage regulation and power factor correction. The generated pulses are then employed to control the MOSFET switch, ultimately achieving the dual objectives of the system with improved efficiency and stability. [18]

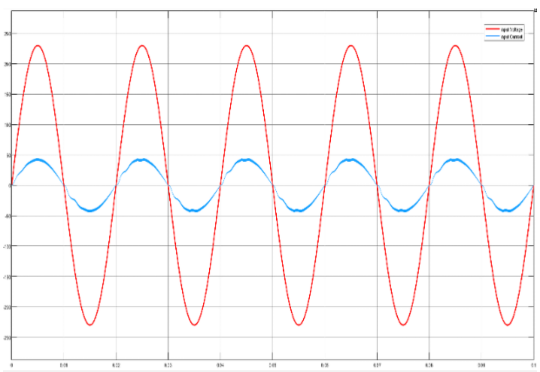

Figure 9 Simulink Result

Figure 9 illustrates the power factor adjustment of the circuit subsequent to the application of the optimized gain values derived from the optimization process within the Simulink model. The alignment of the input AC voltage and current in phase can be observed in Figure 9. By improving the power factor, the system draws less reactive power, thereby reducing the ratings required for components like capacitors and inductors. Lower current demands also enable the use of smaller conductors, transformers, and other power-carrying components. A power factor closer to unity signifies that a greater portion of the supplied power is effectively utilized for useful work. This improvement in efficiency translates to energy savings and a more economical operation of the electrical system. Improved power factor leads to a decrease in the magnitude of reactive power circulating in the system. As a consequence, the system experiences lower resistive losses, minimizing heat generation. Reduced heat dissipation is particularly crucial in power electronics systems, as excessive heat can degrade the performance of components and, in extreme cases, lead to system failures. With lower current requirements and diminished heat generation, the overall stress on electrical components is reduced. Components such as transformers, capacitors, and semiconductor devices operate under more favorable conditions, leading to an extended lifespan. This increased longevity not only

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contributes to cost savings by reducing the frequency of replacements but also enhances the overall reliability of the electrical infrastructure.

5. Optimization Algorithm for PI Controller

5.1 Jaya Algorithm

The Jaya algorithm is a nature-inspired optimization algorithm used for solving optimization problems. It is named after the Sanskrit word "Jaya," meaning victory, and is designed to mimic the process of natural selection. Developed by Dr. R. V. Rao, the Jaya algorithm draws inspiration from the behavior of individuals in a society, where the fittest individuals are more likely to succeed.

Here's a brief overview of the key features and steps involved in the Jaya algorithm:

Initialization: The algorithm starts by initializing a population of potential solutions to the optimization problem. Each solution is represented as a candidate set of parameters.

Objective Function: The optimization problem is defined by an objective function that needs to be minimized or maximized. This function quantifies the quality of a solution.

Selection of Fitter Individuals: The Jaya algorithm emphasizes the concept of "fitter" individuals, meaning solutions that yield better objective function values. In each iteration, the algorithm identifies the fittest individuals in the population.

Update Mechanism: The update mechanism is a key aspect of the Jaya algorithm. It involves adjusting the parameters of less fit individuals toward the fitter ones, simulating a collaborative improvement process.

Exploration and Exploitation: The algorithm balances exploration and exploitation by encouraging exploration of the search space to discover new solutions while exploiting existing solutions to refine the current best ones.

Termination Criteria: The algorithm continues iterations until a specified termination criterion is met. This could be a predetermined number of iterations, reaching a certain fitness threshold, or other criteria specific to the optimization problem.

Final Solution: The solution that emerges after the algorithm's completion represents the optimal or near-optimal set of parameters for the given optimization problem.

The Jaya algorithm is particularly useful in continuous optimization problems where the search space is defined by real-valued parameters. It is known for its simplicity, efficiency, and ability to handle a variety of optimization challenges. The collaborative and adaptive nature of the Jaya algorithm makes it suitable for a range of applications, including engineering design, machine learning, and other optimization tasks.

5.2 Procedural Steps for Jaya Algorithm

The flowchart shown in Figure 10 gives the general working of Jaya algorithm and its approach towards the optimal solution.

The various steps involved in the JAYA Algorithm are summarized as follows:

i. Initialization of the parameters of the JAYA Algorithm, which are population size N and iteration numbers T and the objective function f(X) parameters.
ii. Construction of the initial population.
iii. Sort the population and find the worst $f(X)_{worst}$ and best $f(X)_{best}$ solution.
iv. The solution is updated for next iteration as $X_{j,k,i}' = X_{j.k.i} + r_{1,j,i}(X_{j,best,i} - |X_{j,k,i}|) - r_{2,j,i}(X_{j,worst,i} - |X_{j,k,i}|)$ Where $X_{j.k.i}$ represents the value of the jth variable for the kth candidate during the ith iteration. $X_{j,k,i}'$ is updated to the value of $X_{j,k,i}$, $r_{1,j,i}$, $r_{2,j,i}$ are the random numbers ranges between [0,1].
v. If updated value is greater than the previous value than update the previous solution
vi. ($X_{j,k,i}' > X_{j.k.i}$). Else no update in previous solution.
vii. Repeat step IV to step v until optimal solution is reached.
viii. Print the global optimum solution.

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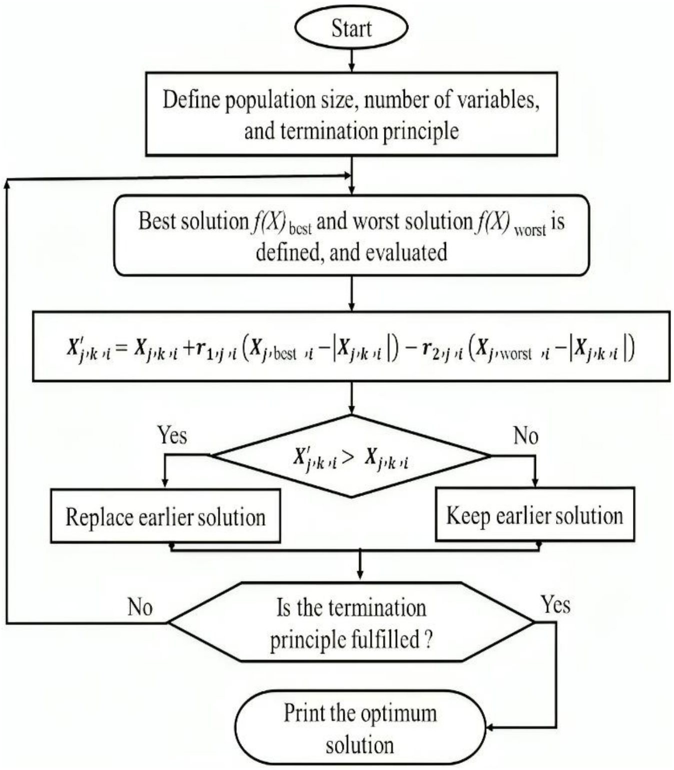

Figure 10 **Working Model of Jaya Algorithm**

5.3 Algorithm's Gain Result

The different gain values generated by different agents at each iteration by the JAYA algorithm are plotted against the number of iterations which is shown in Figure 11.s

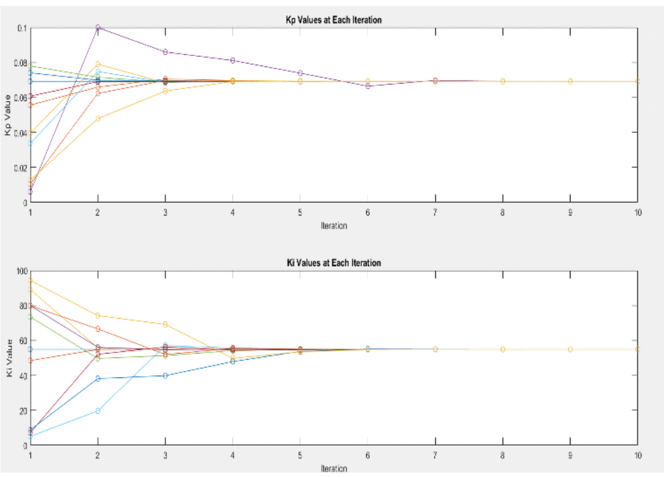

Figure 11 **Result of the Jaya Algorithm**

It is evident from Figure 11 that the convergence of the gain values occurs at a particular iteration when the JAYA algorithm is implemented. In the Simulink model, the converged K p and Ki values at the final iteration are substituted into the PI controller.

Conclusion

The Cuk dc-dc converter operating in CCM is designed and developed using the ACMC technique. The combination of voltage regulation and power factor correction along with the integration of optimization algorithm technique provides with the more improved power factor, desired voltage and minimal ripple as shown in the results. Continued research and development in this area, coupled with the implementation of smart charging infrastructure, will play a pivotal role in shaping the future of electric vehicle charging, making it more energy-efficient, economically viable, and environmentally friendly.

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