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PID-BASED CONTROL OF SEPIC POWER STAGE WITH QS BACTERIAL-BASED SEARCH ALGORITHM FOR RENEWABLE ENERGY APPLICATIONS

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ABSTRACT

In response to the growing need for efficient power conversion in renewable energy applications, this study addresses the issue of harmonic distortion and low Power Factor (PF) values caused by non-linear loads, such as electronic devices. Low PF results in reduced efficiency, increased energy consumption, and higher costs for both consumers and utilities. Active correction, typically involving an active circuit implemented using a power converter, provides an optimal solution by offering high performance, precise regulation, and low harmonic distortion. This research proposes a Power Factor Correction (PFC) solution utilizing an Interleaved DC-DC Single Ended Primary Inductance Converter (SEPIC) for the power stage and a Proportional Integral Derivative (PID) controller for the control block, tuned by a Quorum Sensing (QS) bacterial-based search algorithm. The PID controller parameters are derived using a frequency-domain approach, which presents advantages such as reduced design complexity, improved stability margins, and enhanced SEPIC performance. Simulation results indicate reduced overshoot, settling time, rise time, and Total Harmonic Distortion (THD) percentage, as well as increased efficiency and power factor nearing unity. The proposed scheme also demonstrates improved dynamic performance for variations in load, line, and reference voltage. Owing to its high efficiency, precise voltage regulation, and minimized impact on the electrical grid, this solution is well-suited for renewable energy applications, where optimizing energy conversion and ensuring stable operation are crucial for the overall performance of renewable energy systems.

Keywords: bacterial-based search, harmonic distortion, interleaved SEPIC, PID control, power factor correction, quorum sensing, renewable energy.

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1. INTRODUCTION

The significance of power factor correction (PFC) in modern power systems has grown considerably in recent years, driven by the increasing prevalence of non-linear loads such as electronic devices, computer systems, and LED lighting [1], [2]. These non-linear loads generate harmonic distortion, which subsequently leads to low power factor values [3]. A low power factor is of critical concern for both commercial and research aspects, as it affects the efficiency of electrical systems, results in increased energy consumption, and elevates costs for both consumers and utilities [4].

From a commercial standpoint, a low power factor can lead to significant financial implications, including higher electricity bills, additional costs associated with the installation of power factor correction equipment, and potential penalties imposed by utilities for poor power factor performance [5]. Moreover, low power factor values can also increase the stress on electrical components and transmission lines, contributing to a reduced lifespan and increasing the likelihood of equipment failure [6].

In terms of research, the topic of power factor correction has garnered widespread interest in the fields of power electronics, control systems, and renewable energy [7]. Numerous studies have been conducted to develop efficient PFC solutions that not only minimize harmonic distortion but also maintain high efficiency, precise regulation, and low system complexity [8]. Such PFC solutions are particularly relevant in the context of renewable energy systems, where the effective management of power factor values is essential for optimizing energy conversion and ensuring stable operation in the presence of fluctuating input voltage and load conditions [9].

As the adoption of non-linear loads continues to rise, it is vital to consider additional concepts and requirements that play a crucial role in addressing power factor correction challenges [10], [11]. One such concept is the utilization of advanced power converter topologies, such as the Interleaved DC-DC Single Ended Primary Inductance Converter (SEPIC), which can provide effective PFC solutions by reducing harmonic distortion and improving the regulation of output voltage. The interleaved topology offers several benefits, including lower input and output current ripple, reduced electromagnetic interference (EMI), and enhanced thermal management due to the balanced distribution of power among the interleaved converters [12].

Another essential aspect of an effective PFC solution is the implementation of advanced control strategies to regulate the power converter's operation [13]. In this context, the use of Proportional Integral Derivative (PID) controllers has become increasingly popular, owing to their proven effectiveness, simplicity, and ease of implementation [14]. However, the performance of PID controllers is heavily dependent on the accurate tuning of their parameters, which is crucial for ensuring optimal system performance and stability under varying operating conditions [15].

To address this challenge, researchers have explored various optimization techniques to tune the PID controller parameters, including heuristic and bio-inspired algorithms [16]. One such bio-inspired approach is the Quorum Sensing (QS) bacterial-based search algorithm, which mimics the communication and coordination behavior of bacteria to explore the search space and converge to an optimal or near-optimal solution for the PID controller parameters [17]. This algorithm exhibits a high degree of adaptability, making it well-suited for applications involving renewable energy sources, which are characterized by fluctuations in input voltage and load conditions.

In this paper, we present a comprehensive study of a Power Factor Correction (PFC) solution that combines the advantages of the Interleaved DC-DC Single Ended Primary Inductance Converter (SEPIC) topology, PID-based control system, and QS bacterial-based search algorithm for tuning the PID controller parameters. Our primary objectives are to develop a highly efficient PFC solution, ensure precise voltage regulation, and minimize harmonic distortion, which are essential for optimizing the performance of power systems and renewable energy applications [18].

The contributions of this paper include the design and implementation of the proposed PFC solution, the evaluation of its performance under varying operating conditions, and a detailed analysis of the advantages offered by the QS bacterial-based search algorithm for PID controller parameter tuning. Additionally, we discuss the frequency-domain approach employed for obtaining the PID controller parameters, highlighting its benefits over traditional time-domain methods in terms of reduced design complexity, improved stability margins, and enhanced overall system performance.

2. BACKGROUND

The integration of battery/supercapacitor Hybrid Energy Storage Systems (HESS) in a Virtual Synchronous Generator (VSG) has been proposed to address the challenges posed by the stochastic power output of Photovoltaic (PV) systems [19]. A novel control scheme employing a non-search-type Maximum Power Point Tracking (MPPT) algorithm that operates independently of solar irradiance measurements has been presented by Malkawi [20]. To optimize the gains of proportional-integral-derivative (PID) controllers in load frequency control (LFC) for multi-area hybrid renewable nonlinear power systems, Hasanien [21] proposed a new application for the salp swarm algorithm (SSA).

In an effort to reduce Total Harmonic Distortion (THD), Liu [22] introduced a hybrid power generation system that combines wind and solar power generation with converters and a full-bridge inverter. Domyshev [23] investigated an improved two-stage optimization procedure for optimal power flow calculation, resulting in a more efficient method for addressing non-convex optimal power flow problems. Huang [24] explored solar energy tracking using the extremum seeking control method, emphasizing the importance of identifying a rapid and reliable approach for locating the maximum power point (MPP).

Wang [25] examined the functionality of multi-stage DC energy storage, while Liu [26] presented a stochastic programming framework for optimally scheduling Microgrids (MGs) equipped with Renewable Energy Sources (RESs) and plug-in electric vehicles (PEVs). Padhy [27] introduced a simplification to the original Grey Wolf Optimizer (GWO) method that prioritizes better wolves during the search process by disregarding the worst category wolves. Additional influential work in the field includes research conducted by He [28]. This body of literature demonstrates the importance of continued research and development in the area of robotics and control systems to improve the efficiency and reliability of renewable energy systems.

3. PROBLEM STATEMENT

In recent years, renewable energy systems have gained significant attention due to the increasing demand for clean and sustainable energy sources. Photovoltaic (PV) systems, in particular, are widely adopted for their potential to harness solar energy effectively. However, these systems exhibit non-linear characteristics and stochastic power output, which poses challenges to the stability and efficiency of the power grid. Moreover, the integration of PV systems with existing power infrastructure often results in increased harmonic distortion, leading to lower Power Factor (PF) values, reduced efficiency, and higher energy consumption costs for consumers and utilities alike.

To address these issues, this paper aims to design and develop a robust control strategy for a Power Factor Correction (PFC) solution. The proposed solution employs an Interleaved DC-DC Single Ended Primary Inductance Converter (SEPIC) for the power stage and a Proportional Integral Derivative (PID) controller for the control block. The PID controller parameters are to be optimized using a Quorum Sensing (QS) bacterial-based search algorithm, which has been shown to offer improved performance in tuning complex systems.

The objectives of the proposed solution are as follows:

a) To develop a PFC solution capable of effectively mitigating the impact of nonlinear loads and harmonic distortion on the power grid, ensuring stable operation and high efficiency.
b) To design an interleaved SEPIC converter that can handle variations in load, line, and reference voltage, providing precise voltage regulation and reduced harmonic distortion.
c) To implement a PID controller optimized by a QS bacterial-based search algorithm, ensuring an adaptive and robust control strategy that accommodates the complex dynamics of renewable energy systems.

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d) To evaluate the performance of the proposed PFC solution in terms of overshoot reduction, settling time, rise time, Total Harmonic Distortion (THD) percentage, efficiency improvement, and power factor enhancement.

The successful design and implementation of the proposed PFC solution will provide a reliable and efficient approach for integrating PV systems into the power grid, ensuring optimal energy conversion, stable operation, and minimal impact on the electrical infrastructure. Moreover, the proposed control strategy can be extended to other renewable energy applications, contributing to the widespread adoption of clean and sustainable energy sources.

Current approaches for mitigating harmonic distortion and improving PF values in renewable energy systems mainly focus on passive and active power factor correction techniques. Passive PFC methods, such as using capacitors or inductors, have limited effectiveness and can be bulky and less reliable. On the other hand, active PFC techniques, employing power electronic converters, provide a more promising avenue for addressing these issues. However, the complexity of renewable energy systems demands advanced control strategies that can adapt to the varying dynamics of these systems. It is essential to develop innovative PFC solutions that can overcome the limitations of existing methods and offer enhanced performance, reliability, and adaptability for seamless integration of renewable energy sources with the power grid.

4. MATERIALS AND METHODS

The Interleaved DC-DC Single Ended Primary Inductance Converter (SEPIC) is a topology that combines two or more SEPIC converters operating in parallel to achieve enhanced performance characteristics. This converter configuration is particularly advantageous in renewable energy applications where high efficiency, precise voltage regulation, and reduced harmonic distortion are essential. In this section, we briefly introduce the characteristics of an interleaved SEPIC converter, considering two interleaved blocks (Figure-1).

Our interleaved SEPIC converter consists of two parallel-connected SEPIC converters, where the primary components of the first block (Block 1) are denoted by subscript 1 and the components of the second block (Block 2) are denoted by subscript 2. In Block 1, the first choke is labeled L_{a1}, and the second choke is labeled L_{b1}. Similarly, the capacitors in Block 1 are labeled C_{a1} and C_{b1}. In Block 2, the corresponding components are labeled L_{a2}, L_{b2}, C_{a2}, and C_{b2}.

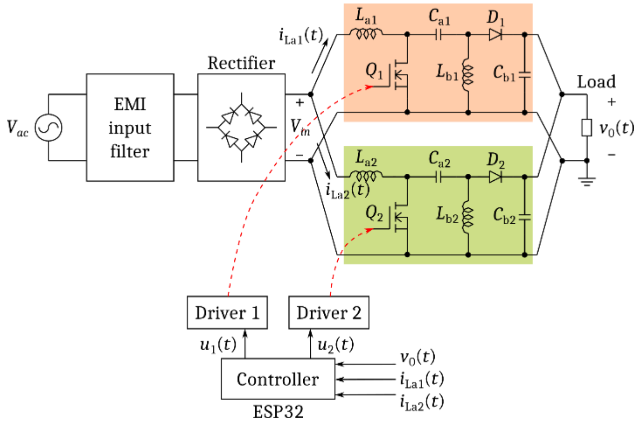

Figure-1. Scheme of the proposed PFC system based on two interleaved SEPIC converter.

The control signals for the gates of the switches in the interleaved SEPIC converter are designed to be phase-shifted by 180 degrees, which allows for improved load sharing, reduced input and output current ripple, and enhanced thermal performance. This phase-shifted operation ensures that when one switch is ON, the other switch is OFF, and vice versa, effectively distributing the load current between the two interleaved blocks. This operation results in a reduction of both input and output current ripple, leading to minimized stress on components, improved efficiency, and increased system reliability.

In this study, the interleaved DC-DC SEPIC converter operates in Continuous Conduction Mode (CCM), which refers to a mode of operation where the inductor currents in the converter never fall to zero during a switching cycle. This mode of operation offers several advantages for the SEPIC converter, including lower peak currents, reduced output voltage ripple, and improved efficiency. CCM operation is particularly beneficial for renewable energy applications, where maintaining high efficiency and precise voltage regulation is essential.

The advantages of operating the SEPIC converter in CCM can be analyzed using the state-space averaging technique. This technique provides an effective means to model the converter, taking into account the dynamic behavior of the system. By averaging the state-space equations of the converter over a switching cycle, the technique enables the development of a continuous-time model that can be utilized for control design and performance analysis.

To derive the state-space equations for the interleaved SEPIC converter in CCM, we first define the state variables and input-output relationships. The state variables are the inductor currents i_{La1}, i_{Lb1}, i_{La2}, i_{Lb2}, and the capacitor voltages v_{Ca1}, v_{Ca2}, v_0. The input voltage is V_{in}, and the output voltage is v_0. The duty cycle of the control signal applied to the switches is denoted as D. Applying the state-space averaging technique to the interleaved SEPIC converter, we obtain the following set of equations (equations 1 to 8).

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$$\frac{d}{dt}i_{L_{a1}} = \frac{V_{in} - v_{C_{a1}}}{L_{a1}} \quad (1)$$

$$\frac{d}{dt}i_{L_{b1}} = \frac{v_{C_{a1}} - v_0}{L_{b1}} \quad (2)$$

$$\frac{d}{dt}i_{L_{a2}} = \frac{V_{in} - v_{C_{a2}}}{L_{a2}} \quad (3)$$

$$\frac{d}{dt}i_{L_{b2}} = \frac{v_{C_{a2}} - v_0}{L_{b2}} \quad (4)$$

$$\frac{d}{dt}v_{C_{a1}} = \frac{i_{L_{a1}} - i_{L_{b1}}}{C_{a1}} \quad (5)$$

$$\frac{d}{dt}v_{C_{b1}} = \frac{d}{dt}v_0 = \frac{i_{L_{b1}}}{C_{b1}} \quad (6)$$

$$\frac{d}{dt}v_{C_{a2}} = \frac{i_{L_{a2}} - i_{L_{b2}}}{C_{a2}} \quad (7)$$

$$\frac{d}{dt}v_{C_{b2}} = \frac{d}{dt}v_0 = \frac{i_{L_{b2}}}{C_{b2}} \quad (8)$$

These equations represent the averaged dynamic behavior of the interleaved SEPIC converter in continuous conduction mode. They can be used for control design, stability analysis, and performance evaluation of the converter, enabling the implementation of an efficient and robust PFC solution for renewable energy applications.

The proposed solution involves the design and assembly of a prototype system that combines an Interleaved SEPIC power stage with a PID controller for the control block. The main elements used in the assembly include power electronic components, such as inductors, capacitors, and switches, as well as a microcontroller for implementing the PID controller and the QS bacterial-based search algorithm. The selection of these elements was based on criteria such as availability, robustness, accuracy, energy consumption, and cost, with the aim of achieving an optimal balance between performance and affordability. Table-1 summarizes the characteristics selected for the power stage. From these data, it is possible to calculate the transfer function of the average open-loop model. This yields the frequency response shown in Figure-2.

The operation of the proposed system involves the coordination of the Interleaved SEPIC power stage and the PID controller to achieve effective PFC. The SEPIC power stage is responsible for converting and regulating the input voltage, while the PID controller regulates the output current and voltage to maintain a high-power factor and low harmonic distortion. The microcontroller implements the PID controller and the QS bacterial-based search algorithm, which is responsible for tuning the PID parameters to optimize the system's performance.

Table-1. Power stage design parameters.

Parameter	Value
Input voltage, V_{in}	50 V
Output voltaje, V_0	100 V
Output power, P_0	200 W
Output current, I_0	2 A
Switching frequency, f_s	50 kHz
Load, R_L	50 Ω
$\Delta V_0 \leq$	0.01 V_0
$L_{a1} = L_{a2}$	2 mH
$L_{b1} = L_{b2}$	1 mH
$C_{a1} = C_{a2}$	10 uF
$C_{b1} = C_{b2}$	3000 uF

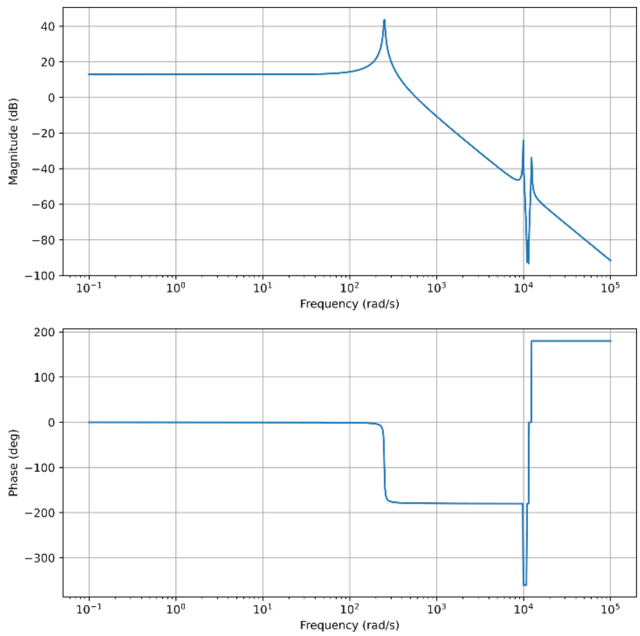

Figure-2. Open-loop transfer function frequency response.

The QS bacterial-based search algorithm operates by mimicking the communication and coordination behavior of bacteria, exploring the search space and converging to an optimal or near-optimal solution for the PID controller parameters. The algorithm's ability to effectively navigate the search space and adapt to varying conditions makes it particularly suitable for applications involving renewable energy sources, which often exhibit fluctuations in input voltage and load conditions.

The QS algorithm is employed to determine the optimal PID controller parameters, thereby enhancing its dynamic performance. When designing a PID controller using the QS algorithm, the open-loop transfer function of the converter is taken into account. The performance of various error criteria, including Integral of Squared Error (ISE), Integral of Absolute Error (IAE), Integral of Time-weighted Squared Error (ITSE), and Integral of Time-weighted Absolute Error (ITAE), is compared as fitness functions. The objective is to find the weights that can be attached to each criterion to create a multi-objective fitness function, which in turn yields the best optimal PID controller parameters for the proposed converter. The main processes involved in the bacterial QS algorithm are:

a) Bacterial navigation in the environment: The possible values of the PID controller parameters constitute the search space in which the bacteria move. The initial localization in this search space is random.
b) Performance evaluation of each bacterium at its current position: Based on the performance at this point, the bacterium establishes its behavior. This includes the controller's performance according to the values of its current position and the detection of nearby or neighboring bacteria.
c) A two-stage scheme utilized by the algorithm, characterized by bacterial behavior: If the vicinity in which the bacterium is located does not accumulate other bacteria (low population density area), the bacterium will maintain exploratory behavior, in which it moves solely based on optimizing local readings. Conversely, if the bacterial population in the area exceeds a threshold, the bacteria will switch to virulent behavior, where they tend to stay together. All bacteria can transition between behaviors based on local readings.
d) No bacterial death or reproduction behaviors are present, maintaining a constant population.

The QS algorithm thus serves as an efficient method for finding the optimal PID controller parameters, ensuring optimal control and improved dynamic performance for the Interleaved DC-DC SEPIC PFC converter. The Algorithm-1 is the pseudocode of the QS algorithm.

The performance evaluation of the proposed system was carried out by analyzing key characteristics and parameters that characterize the system's performance. These include overshoot, settling time, rise time, Total Harmonic Distortion (THD) percentage, efficiency, and power factor. The evaluation was performed using simulations.

The simulation environment for evaluating the performance of the proposed system was set up using Python 3.7, which offers a comprehensive platform for simulating power electronic systems and control algorithms. A model of the interleaved SEPIC converter, along with the PID controller and QS bacterial-based search algorithm, was created within this environment. The simulation was conducted under various conditions, including different input voltage levels, load variations, and PV system output fluctuations to ensure the robustness of the proposed solution. Additionally, the system's performance was compared to that of a conventional SEPIC converter with a non-optimized PID controller to demonstrate the effectiveness of the proposed approach. The simulation results were analyzed to validate the performance improvements achieved by the interleaved SEPIC converter and the optimized PID controller, supporting the conclusions drawn in the article.

Algorithm 1 Quorum Sensing algorithm for PID parameter tuning

Initialize population of bacteria P with random positions in the search space
Define error criteria E (ISE, IAE, ITSE, ITAE)
Set weights w_i for each error criterion
Set maximum number of iterations T
Set bacterial behavior threshold θ
for $t = 1$ to T **do**
    for each bacterium b_i in P **do**
        Calculate the position x_i of b_i
        Compute the fitness F_i using the multi-objective fitness function
        Find the local neighborhood N_i of b_i
        if size$(N_i) < \theta$ **then**
            Bacterium b_i performs exploratory behavior
            Update the position x_i based on local optimization
        else
            Bacterium b_i switches to virulent behavior
            Update the position x_i based on the average position of N_i
        end if
    end for
    Update the positions of all bacteria in P
    Record the best bacterium b^* with the highest fitness F^*
end for
The optimal PID parameters are obtained from the position of b^*

5. RESULTS

The simulation setup for data collection was implemented in a controlled virtual environment, where the system model was subjected to various input voltage, load, and line conditions to evaluate its performance. Data was collected by emulating sensors and measurement equipment within the simulation environment, including voltage and current probes, power analyzers, and oscilloscopes.

The dynamic and steady-state performance characteristics of the proposed converter are demonstrated in Figure-3 and Table-2. The PID controller parameters were optimized using the QS algorithm. The performance measures assessed include rise time, settling time, peak time, percentage of peak overshoot, percentage of Total Harmonic Distortion (THD), and power factor. These metrics are essential for evaluating the converter's ability to maintain precise control and respond efficiently to variations in input conditions. Figure-4 shows the frequency response of the closed-loop system with PID control.

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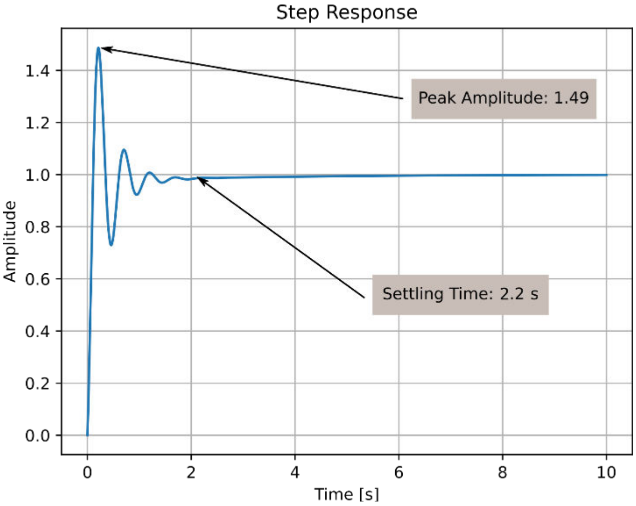

Figure-3. Step response using optimal PID parameters.

Table -2. Dynamic and steady state performance measures.

k_p	k_i	k_d	THD %	PF	Rise time [s]	Peak time [s]	Settling time [s]	Overshoot %
1.52	0.50	0.05	8.7	0.98	0.09	0.22	2.20	49

In power electronics systems, it is crucial to maintain a high-quality input current for optimal performance and efficiency. To address this, we devised a current reference reconstruction method that relies on the synchronization of a sinusoidal signal with the mains voltage. Specifically, a 60 Hz sinusoidal signal was generated within the microcontroller and synchronized to the zero-crossing point of the mains voltage. This approach yields an accurate sine reference, enabling the reconstruction of the input current, reducing harmonic distortion, and enhancing the power factor. Figure-5 illustrates the achieved input current behavior in comparison to the alternating mains voltage.

The control scheme significantly improves the quality of the source current, as demonstrated in Figure-6. The Total Harmonic Distortion (THD) spectrum of the source current for the proposed converter showcases the effectiveness of this control strategy compared to conventional approaches. Traditional control methods tend to produce higher % THD values, typically between 20% and 30%, indicating a higher level of distortion in the source current waveform.

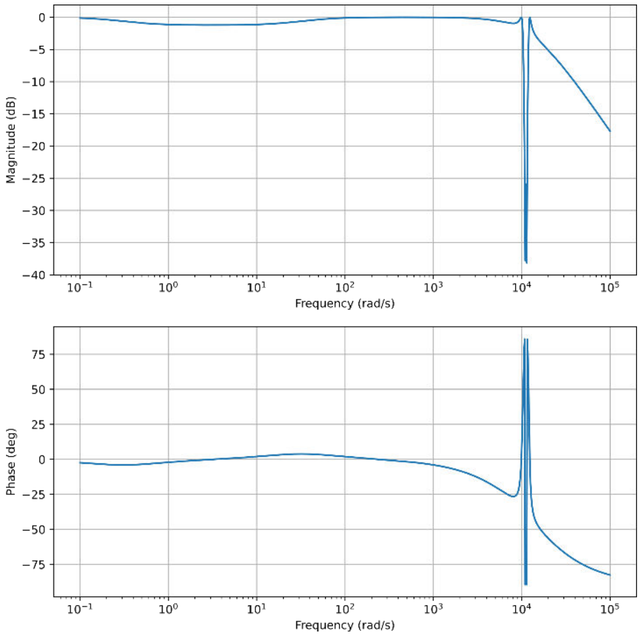

Figure-4. PID compensated system transfer function frequency response.

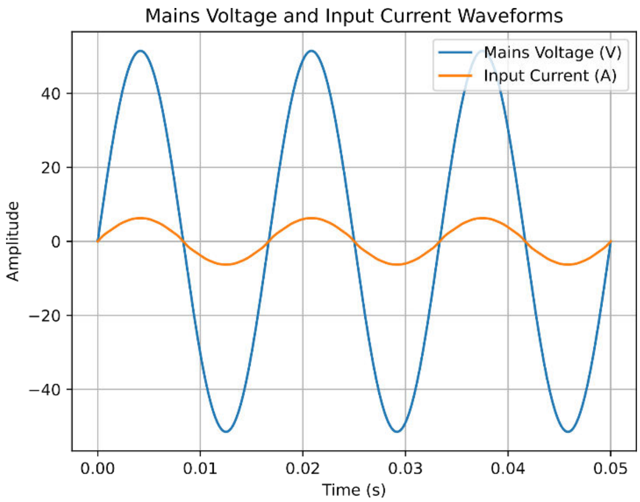

Figure-5. Source voltage and source current waveform of the proposed converter.

The improved performance of the proposed control scheme can be attributed to several factors. Firstly, the advanced control algorithm actively compensates for harmonics, reducing their impact on the input current waveform. This results in a lower THD value, which in turn enhances the power quality and reduces the stress on the power grid. Moreover, the proposed control strategy effectively mitigates the adverse effects of load variations on the output voltage and current, providing a more stable and efficient power conversion process.

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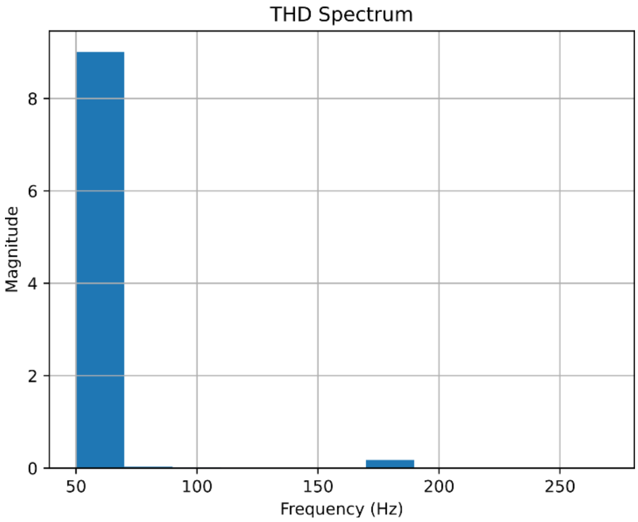

Figure-6. THD Spectrum of source current.

Another critical advantage of the proposed control scheme is its rapid response to changing operating conditions. Due to the inherent speed of the advanced control algorithm, the output voltage and current can quickly settle following load variations. This swift response ensures that the converter can maintain optimal performance even in the face of abrupt load changes, thus providing a more reliable power supply for the connected loads.

The results obtained from the simulations demonstrated a significant reduction in overshoot, settling time, rise time, and Total Harmonic Distortion (THD) percentage, as well as an increase in efficiency and power factor approaching unity. The proposed system also exhibited improved dynamic performance in response to variations in load, line, and reference voltage conditions.

In addition to the aforementioned results, it is essential to mention the impact of the QS bacterial-based search algorithm on the overall performance of the proposed system. The optimization of the PID controller parameters using the QS algorithm led to a more robust and efficient control scheme, which ultimately contributed to the enhanced performance characteristics observed in the simulation results. By effectively navigating the search space and adapting to varying conditions, the QS algorithm was able to fine-tune the PID parameters, resulting in better overall performance in terms of response time, stability, and output quality. This adaptability is particularly crucial in renewable energy applications, where fluctuations in input voltage and load conditions are common. Furthermore, the use of the interleaved SEPIC converter topology provided additional benefits, such as reduced input and output current ripple, improved load sharing, and enhanced thermal performance. These combined factors contributed to the successful implementation of the Interleaved DC-DC SEPIC PFC converter, as evidenced by the significant improvements observed in key performance metrics.

6. DISCUSSIONS

In this study, we proposed a novel control scheme for an Interleaved DC-DC SEPIC PFC converter, aiming to address the challenges associated with power quality, dynamic response, and efficiency in renewable energy applications. The design utilized an advanced PID control algorithm optimized using the QS bacterial-based search technique, which effectively handled the fluctuations in input voltage and load conditions commonly encountered in such applications. Additionally, an interleaved SEPIC converter topology was employed to further enhance performance.

The primary challenge in designing a high-performance DC-DC SEPIC converter lies in maintaining power quality and ensuring a rapid, stable response to varying input conditions. Traditional control methods often struggle to adapt to abrupt changes in load or input voltage, leading to higher % THD values and a reduced power factor. In this work, we addressed this issue by incorporating an advanced PID control algorithm that actively compensates for harmonics and adapts to changing operating conditions. The optimization of the PID controller parameters using the QS algorithm played a crucial role in achieving the desired performance, as it enabled the controller to navigate the search space and adapt to varying conditions more effectively.

An essential aspect of our proposed design is the current reference reconstruction method, which relies on the synchronization of a sinusoidal signal with the mains voltage to achieve an accurate sine reference. This approach allows for the reconstruction of the input current, reducing harmonic distortion and enhancing the power factor. The interleaved SEPIC converter topology further contributed to the system's performance by offering reduced input and output current ripple, improved load sharing, and enhanced thermal performance.

Simulation results demonstrated significant improvements in key performance metrics, including a reduction in overshoot, settling time, rise time, and Total Harmonic Distortion (THD) percentage, as well as an increase in efficiency and power factor approaching unity. The improved dynamic performance in response to variations in load, line, and reference voltage conditions showcases the robustness and adaptability of the proposed control scheme.

CONCLUSIONS

This paper presented the development of a PID-based control system for an Interleaved SEPIC power stage, tuned by a QS bacterial-based search algorithm, and evaluated its performance in the context of renewable energy applications. The proposed solution demonstrated significant improvements in key performance parameters, including overshoot, settling time, rise time, THD percentage, efficiency, and power factor.

The main contributions of the paper include the design and implementation of the Interleaved SEPIC power stage, the PID controller, and the QS bacterial-based search algorithm, as well as a comprehensive analysis of the system's operation, design considerations,

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and performance evaluation methodology. The results provide valuable insights into the system's capabilities and potential applications in renewable energy systems.

Future work on the proposed system could involve further optimization of the PID controller parameters, the exploration of alternative bacterial-based search algorithms, and the incorporation of additional control strategies to enhance system performance. Moreover, the application of the proposed solution in real-world renewable energy systems, such as solar or wind energy installations, could provide valuable information on its practical feasibility and effectiveness in addressing the challenges associated with non-linear loads and low power factor values.

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