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Boost Converter Control Using Proportional-Integral-Derivative Controller Optimized by Whale Optimization Algorithm

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ABSTRACT

This work offers an improved control approach for a boost converter called WOA_PID by combining a Whale Optimization Algorithm (WOA) with a Proportional-Integral-Derivative (PID) controller. The main goal is to optimize the PID controller gains for better voltage control and improved system stability and performance. Although boost converters are employed for step-up DC-DC conversion, they have nonlinear dynamics and sudden load changes that create major problems in conventional controller tuning. This work guarantees improved transient response and lower steady-state error by using the WOA employed as an optimization tool to effectively optimize the PID gains by minimizing the Integral Square Error (ISE) performance index. Simulations are used to assess the suggested WOA_PID controller, which showed better performance than traditional PID tuning techniques. The key aspects are zero overshoot, quicker rise and settling time of 0.216 and 0.654 respectively as well as improved output voltage control under changing load situations. Findings verify the efficiency of the WOA-based tuning approach in optimizing the PID controller for boost converters, providing a robust solution for practical applications in power electronics.

1. Introduction

Converters are widely employed to effectively convert DC input voltage to different level. These devices find applications in various areas such as computer hardware, power supplies, servo motor drives, and medical equipment, which has led to increasing attention in recent decades. The primary function is to provide a sustained DC output voltage in the presence of a fluctuated DC input level and variable load condition. The challenge of modulating the output level of such converters has been a topic of considerable interest over the years. Due to the switching properties inherent in their design, these converters exhibit non-linear behavior, making their control design process complex [1], [2].

Furthermore, boost converters, in particular, poses additional challenges due to their inherited nonlinearity characteristics, thus prompting significant design efforts towards the control of such application [3]. Steady-state representation is applied derive the model of the converter using the state-space averaging technique. The design of PID controllers for these converters has been the main emphasis of past research. This work intends to use the Whale Optimization Algorithm (WAO) to find the best PID controller gains to enhance the Boost converter's performance. Operation of a boost converter is typically controlled by feedback circuits, wherein the output voltage is constantly monitored and the duty cycle of the switch (most often a transistor) is varied based on the error between the reference and actual output voltage. Well-tuned controller helps in stabilizing the converter's output, reducing voltage ripples, and reducing energy losses [4].

The PID controller has been one of the most widely used feedback control techniques in power electronics due to its simplicity, ease of implementation, and well-documented performance on a very diverse group of systems [5]. While PID controllers work well for most systems, their performance is very sensitive to correct tuning of the proportional, integral, and derivative gains. Traditional tuning methods, such as trial-and-error or heuristics like the Ziegler-Nichols method, are generally used but can lead to less- -ideal performance, especially in dynamic and complex systems where operating conditions change over time [6].

Recently, optimization algorithms have been gaining more utilization for enhancing the fine-tuning of PID controllers. These mathematical concept or nature-based algorithms are applied to automatically tune the PID parameters to their optimal performance [7]. Among all the different optimization techniques, Swarm Intelligence-based algorithms, such as Particle Swarm Optimization (PSO) [8], Genetic Algorithms (GA) [9], and Ant Colony Optimization (ACO) [10], have gained significant attention since they can explore very large solution spaces and find optimal or near-optimal solutions with efficiency.

Whale Optimization Algorithm (WOA), however, is a new promising method of optimizing PID controllers. The WOA is inspired by the hunting tendency of Whales, and particularly the way that they go about finding their prey using encircling and attacking in a spiral pattern [11]. The WOA takes advantage of the idea of trade-off between exploration and exploitation while conducting search, thus being applicable in the optimization of nonlinear and complex systems. The fast convergence capability and global optimum finding of WOA place it as the best choice for optimizing PID parameters because it can effectively adapt the controller gains under different working conditions like varying input voltages and load variations [12]. Recent research has shown the efficacy of using nature-inspired optimization methods, such as WOA, to improve power converter performance such as boost converters. The methods have been effective in optimizing the parameters of the PID controller such that voltage regulation is improved and the transient responses are enhanced [13], [14].

Over the last few years, there are numerous studies that aim toward improving the efficiency of the boost converters with the consideration of employing PID optimized using various optimization algorithms. The developments have led to a massive enhancement of the dynamic response, the dynamic stability and the performance of boost converters specifically, when the loads and input voltages are varying. These optimization methods have been useful in countering the issues that occur with variations in operating conditions to provide a higher degree of control and hence energy conversion efficiency [15].

In [16], a PID controller of a boost converter was optimized via one of the Particle Swarm Optimization (PSO) algorithm. PSO was used to optimize a weighted combination of the Integral of Time-weighted Absolute Error (ITAE) and the control input and thereby the controller performance was enhanced in a large extent. This method was found to work better than regular PID controllers minimizing the transient errors and steady-state deviations. The tuned PID controller assisted boost converter to produce a quicker response, lower ripple, better stability to work in dynamic conditions.

In [17], a new topology of an GA-PID controller was suggested to control boost converter circuits. A controller design proposed in this study was PID tuned by Genetic Algorithms (GA) with the use of several performance indexes. The tuned controller had a large operating range which provided great improvement in the stability and the performance of the system. The findings revealed that the hybridization of GA and PID controller provided considerable enhancement to the converters performance and that this combination would be more favorable in systems where high degrees of precision and adjustability are necessitated.

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An approach to optimize a fuzzy PID controller of a boost converter using a combination of Moth-Flame Optimization (MFO) and Particle Swarm Optimization (PSO) was used, as in [18]. Such a hybrid optimization method was used to optimize the hybridization of both the MFO and PSO to tune the performance of the PID controller using fuzzy logic to enhance the performance of the converter. As the research indicated, the inclusion of a fractional-order control and fuzzy logic enabled substantial gains in terms of regulation of the voltage and transient response in comparison with a traditional fuzzy PID controller. The findings demonstrated the possibility of applying hybrid optimization technique in use to tackle complex behavior of boost converters and specifically in situations where both accuracy and adaptability are needed.

Flower Pollination Algorithm (FPA) and Water Cycle Algorithm (WCA) combined to optimize fractional-order PI controller of a boost converter that would have been utilized in a photovoltaic (PV) system is demonstrated in [19]. The optimization strategy addressed the issue of voltage regulation and stability of the system, which is very appropriate in the case of renewable energy, because input voltages of PV systems are constantly changing. The hybrid controller (FO-PI) achieved more efficient conversion of power, which maintained stable output voltage even when the power generation by the solar is not continuous. The optimization outcome revealed that FPA and WCA are capable of using synergy to enhance control accuracy and energy efficiency of renewable energy systems, which have the potential usage in practical systems.

In [20], Artificial Bee Colony (ABC) was applied to optimize the PID controller in buck converter, resulting into better robustness in dynamic and uncertain conditions. The ABC algorithm was useful in optimizing the parameters of the PID controller so that it can perform better in systems where the loads or input condition vary. In the study, it was established that the stability of the controller was better and the system response was quicker than the traditional PID controllers. This method worked well especially in systems where the real time performance is a critical where the converter should follow fast load or input voltage variations.

Finally, the control parameters of PID controller were further optimized in [21], [22] using a Neural Network (NN). This combination strategy gave a more stable and robust control system particularly as compared to conventional methods of tuning. NN method showed to be especially useful in improving the performance of the boost converter, providing it with greater stability and enhanced voltage regulation. The study evaluates the performance of the proposed PID-NN controller in comparison with traditional PID controllers and alternative intelligent control strategies. The findings reveal that the PID-NN controller, optimized through Particle Swarm Optimization (PSO), outperforms other methods with regard to steady-state error, settling time, and output voltage stability. This highlights the efficacy of integrating intelligent control techniques with conventional methods to overcome the inherent limitations of traditional PID controllers. The proposed PID-NN controller is designed to improve the performance of these converters by enhancing startup response and minimizing transient disturbances, thereby mitigating typical challenges encountered with conventional PID control.

All these studies demonstrate an existing trend to employ higher optimization algorithms (especially nature-inspired optimization methods) to optimize the performance of PID controllers in power converters. The algorithms such as PSO, ABC, MFO and GA have been found to work very well in enhancing the stability of the systems, responding dynamic behavior and measures the quality of control showing high applicability in realistic conditions where performance in different situations is of great importance. This work builds up on this recent body of research by employing the WOA to tune the parameters of a PID controller for a boost converter, and investigates its impact on voltage regulation, transient response and system performance. Through this optimization, we aim to achieve better system performance and control accuracy, particularly in the case of fluctuating input voltages and variable load requirements, which are generally characteristic of practical applications. The remainder of the paper will present the theoretical basis of PID control, WOA, and their utilization in the boost converter systems.

2. Boost Converter

To effectively transfer DC electrical power from one voltage level to another, DC-DC converters are widely utilized. The fact that these devices are utilized in a wide range of industries, such as computer hardware, power supply, servo motor drives, and medical equipment, has led to an increase in interest in recent decades [23]. The primary purpose of that converter is to transform an unstable current into an output current to a variable-load resistance. Over the years, the difficulty of current changing has generated much interest. DC-DC converters have non-linear behavior because of factory switching characteristics, which complicates their control design [24].

Various techniques have been proposed to achieve desired responses. Previous studies have primarily focused on the introduction PID controllers for these converters. However, this work applies the whale Optimization Algorithm (WAO) to determine the optimal PID controller gains for improving the performance of the Boost converter. There are several objective functions usually applied for this particular problem including the Integral Square Error (ISE), Integral Time Square Error (ITSE) and Mean Square Error (ITSE). The performance index employed in this particular study is the Integral Absolute Error (IAE) [25]. Circuit diagram of boost converter shown in Fig. 1.

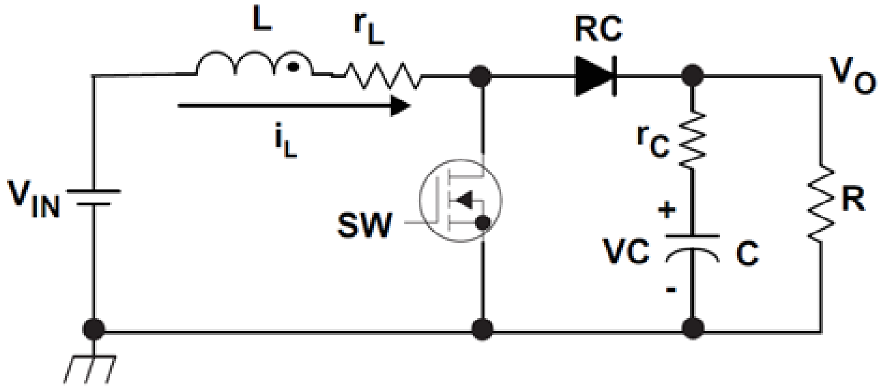

Fig. 1. Circuit diagram of boost converter

Initially, consider the diode is in reversed bias and the switch is closed (short circuit), as seen in Fig. 2. The input supply only supplies the inductor [26].

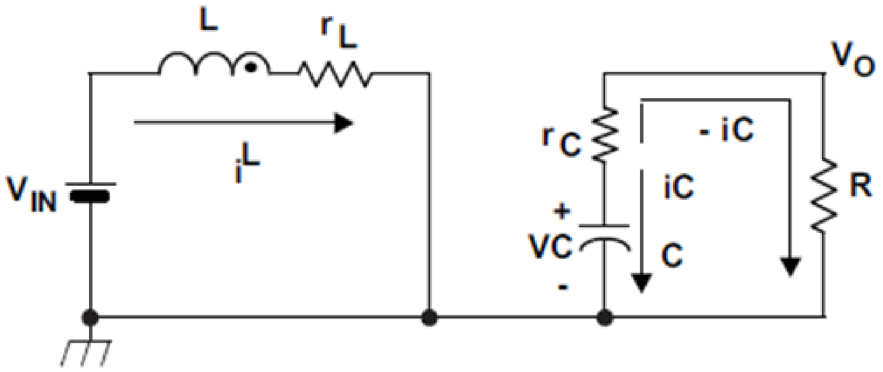

Fig. 2. Boost converter on mode

$$VL = V(IN) \tag{1}$$

$$VL = L\frac{di}{dt} \tag{2}$$

$$\frac{di}{dt} = \frac{V_{IN}}{L} \tag{3}$$

$$\frac{di}{dt} = \frac{\Delta i}{\Delta t} = \frac{\Delta i}{\Delta T} \tag{4}$$

$$\Delta i_{closed} = V_{IN} D_u \frac{T}{L} \tag{5}$$

Where Du is the duty cycle.

When the switch is opened, as seen in Fig. 3. The capacitor voltage will double as a result of the diode being in forward bias [27], [28].

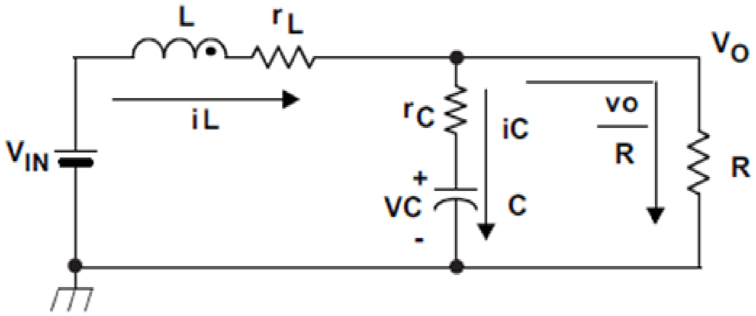

Fig. 3. Boost converter off mode

$$V_L = V_{IN} - V_o \tag{6}$$

$$L\frac{di}{dt} = \frac{di}{dt} = V_{IN} - \frac{V_o}{L} \tag{7}$$

$$\frac{di}{dt} = \frac{\Delta i}{\Delta t} \tag{8}$$

$$\frac{di}{dt} = \frac{\Delta i}{(1 - D_u)T} \tag{9}$$

$$\Delta i_{opend} = (V_{IN} - V_o)(1 - D_u)\frac{T}{L} \tag{10}$$

At steady-state operation

$$\Delta i_{closed} + \Delta i_{opend} = 0 \tag{11}$$

$$V_o = \frac{V_{IN}}{(1 - D_u)} \tag{12}$$

We can see from Equation (12) that output voltage is either higher than or equal to the input voltage.

3. PID Controller

PID involves three components, as shown in Fig. 4. The proportional term decreases error and develops a dynamic response While the integral component attempts to lower the system's steady-state inaccuracy, the derivative component optimizes the transient response [29], [30]. The application of PID is illustrated here [31].

$$G(s) = K_p + \frac{K_i}{s} + K_d s \tag{13}$$

The system is closed-loop. The Kp equals the signal u(t) output of the controller

$$u(t) = K_p e + K_i \int e\, dt + K_d \frac{de}{dt} \tag{14}$$

The plant will then receive this control signal, yielding the updated output y(t). This new output will thereafter compare with the desired input producing the error signal. Controller calculates the gain values (Kp, Ki and Kd) using that new controller action as an input signal to the converter.

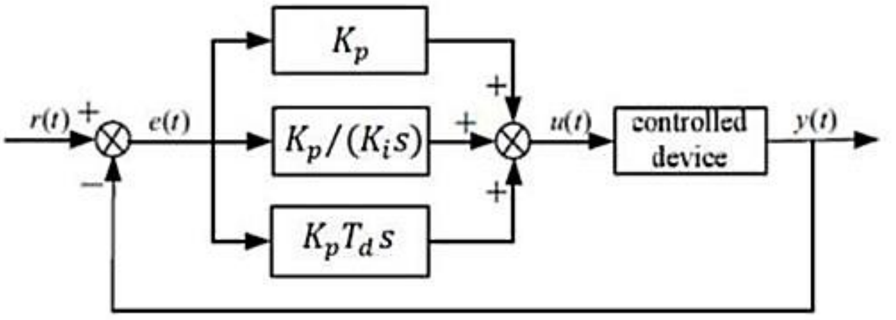

Fig. 4. Schematic diagram of PID controller

4. Whale Optimization Algorithm

Motivated by humpback whale hunting, Mirjalili et al. introduced the Whale Optimization Algorithm (WOA) as a new technique in 2016. A method that adopts the abnormal attack of whales. That method traps and encircles creatures by generating bubbles in rounded figure-eight course. Subsequent parts of the WOA's mathematical formulation detail the several phases of this hunting process. The main phases of the WOA are: [32].

- Encircling Prey
- Bubble-net Attacking Method (Exploitation)
- Search for Prey (Exploration)

4.1. Encircling Prey

Whales spot victims, usually a school of krill or small fish, and then surround it. Similarly, in the algorithm, solution position has not been recognized here. Therefore, the algorithm utilizes equations (15) and (16) to iteratively approximate the optimal solution. As the process progresses, the remaining agents adjust their positions to converge toward the best agent, with each iteration bringing the agents closer to the optimal solution [32].

$$D = |C.X^* - X_i| \tag{15}$$

$$X(t+1) = X^*(t) - A.D \tag{16}$$

X* position vector of the best solution thus far, t current iteration, X position vector, while the coefficient vectors are A and C. The equations to calculate the coefficient vectors are given by.

$$C = 2r \tag{17}$$

$$A = 2ar - a \tag{18}$$

Whereas r represents a arbitrary vector in [0,1] while a is a variable that is proportionally reduced from 2 to 0 in iteration. Different positions around the optimal solution might be explored. Vector r facilitates the exploration of positions within the search space, specifically in key points, thereby enabling a broader search for potential solutions [33].

4.2. Bubble-Net Attacking Method (Exploitation Phase)

As previously mentioned, that technique was used by humpback whales to catch victims. Below, in Fig. 5, is a detailed account of that aggressive behavior: To replicate the bubble-net behavior of these whales, two different methods were suggested: Spiral Updating Position and Retreat-Surrounding Mechanism [34].

4.2.1. Shrinking Encircling Mechanism

The value of a controls the retreat-surrounding technique. Throughout iterations, the value of an is progressively decreased from 2 to 0 in order to produce the shrinking behavior. Equation (18) illustrates that the value of A is limited to the interval [−a, a]. A simplified representation of this mechanism is provided in Fig. 5 [34].

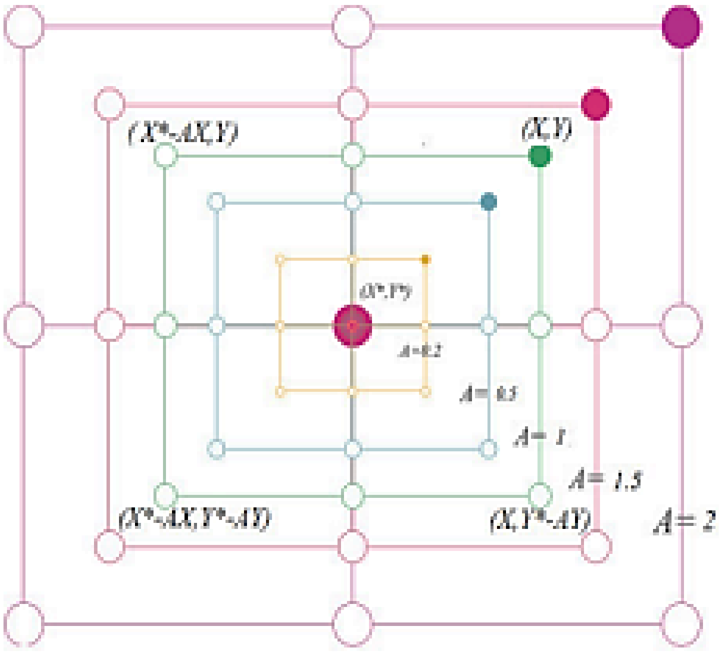

Fig. 5. Bubble-net search-shrinking mechanism

4.2.2. Spiral Updating Position

Fig. 6 illustrates the method for determining the separation between the prey at position (X*, Y*) and whale at position (X, Y). After that, a spiral equation is made to depict whales' helix-shaped movement [35].

As shown in Fig. 6, this method counts the distance between the victim, which is placed at (X∗, Y∗), and the whale, which is located at position (X, Y). The helix-shaped movement of the whale is then represented by the following spiral equation.

$$X(t+1) = D.e^{bl}.\cos(2\pi l) + X^*(t) \tag{19}$$

where D=|X* (t)-X| denotes the distance between the whale and the victim, b is a constant that determines the logarithmic spiral's shape, and l is a arbitrary value in [-1,1].

Humpback whales employ both mechanisms described above during hunting. That is, they swim around the prey within a shrinking circle while also following a spiral-shaped path simultaneously. To account for this behavior, it is assumed that there is a 50% probability of selecting either of the mechanisms. The mathematical model representing this assumption is given by [36].

$$X(t+1) = \begin{cases} X^*(t) - A.D & if\ p < 0.5 \\ D.e^{bl}.\cos(2\pi l) + X^*(t) & if\ p \geq 0.5 \end{cases} \tag{20}$$

4.3. Search for Prey (Exploration Phase)

These whales attack victims depending on the positions of other creatures. The way representing this technique has been reported in [33].

$$D = |C.X_{rand} - X| \tag{21}$$

$$X(t+1) = X_{rand} - A.D \tag{22}$$

Fig. 7 details the flow chart of the algorithm.

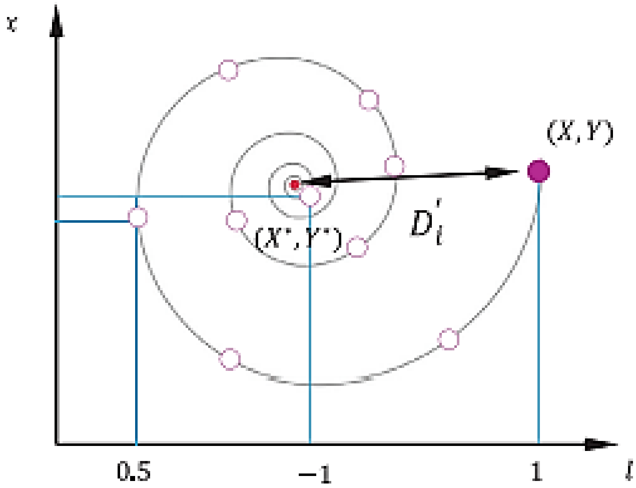

Fig. 6. Spiral updating position in WOA

5. WOA-PID Controller

The implementation of PID controller tuning using the Whale Optimization Algorithm (WOA), shown in Fig. 8, is an advanced approach to optimize the performance of systems such as DC-DC converters. Because of their simplicity and efficiency in delivering required performance, PID controllers are commonly employed to control systems particularly for systems showing non-linear behavior and changing operating conditions. Determining the optimal gains for the derivative (Kd), integral (Ki) and proportional (Kp) terms can be challenging. A modern bio-inspired optimization tool, the whale Optimization Algorithm (WOA), mimics the whales' hunting tactics. It is able to efficiently investigate and exploit the search space which has let this technique to be successfully used for several optimization problems [11]. The error criterion measures performance index is chosen as integral square error.

$$I_{ISE} = \int_0^T e(t)^2 \, dt \tag{23}$$

6. Simulation Results

The WOA algorithm uses some parameters, which significantly decrease algorithm capacity. The WOA's key input parameters are a set of search agents, iterations, and variables. These factors are quite important in deciding how well and efficiently the algorithm solves optimization issues. The algorithm's starting parameters are as follows:

N. of search agents : 100

N. of iterations : 100

N. of variables : 3

Simulations conducted for circuit of boost converter and parameters have been illustrated at Table 1.

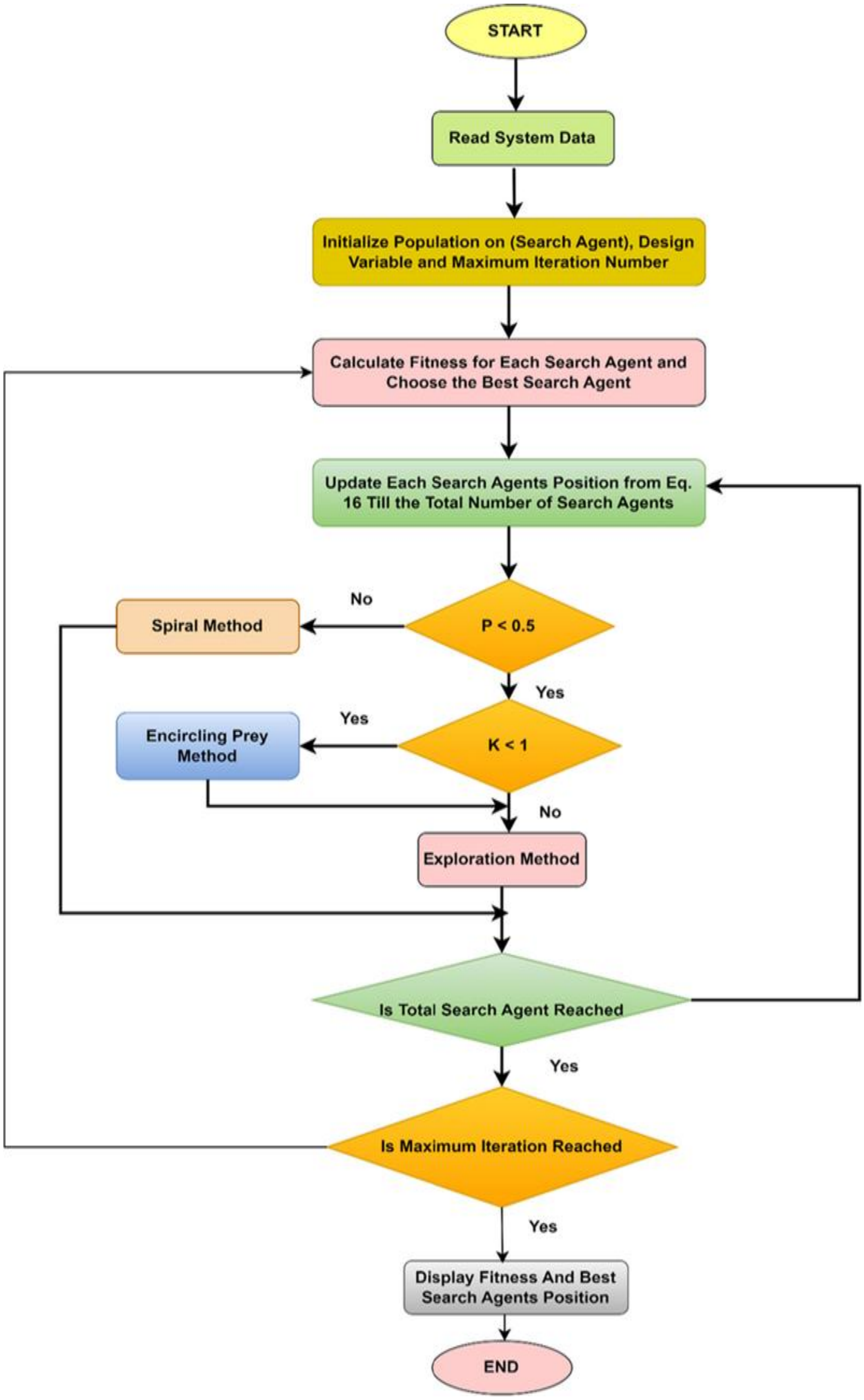

Fig. 7. Flowchart of optimization procedure of WOA

Table 1. Circuit parameters

Parameter's name	Symbol	Value
Capacitor	C	5μF
Inductor	L	16 mH
Resistance load	R	10 Ω
Voltage output	Vo	12V
Voltage input	Vin	5V

The system's response, in conjunction with the controller, is evaluated for a unit step input. System's response is illustrated in Fig. 9. Based on the figure and the corresponding tables, it is obvious that the controller, inspired by the Whale Optimization Algorithm (WOA), exhibits superior performance over standard PID, shown in Fig. 10, in time domain specification regarding settling time, rise time and peak overshoot. WOA- PID controller time domain specifications shown in Table 2.

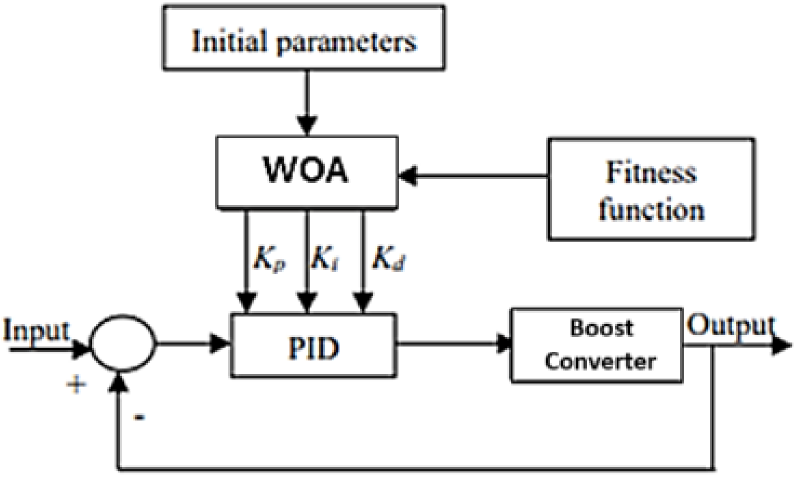

Fig. 8. Structure of WOA_PID controller

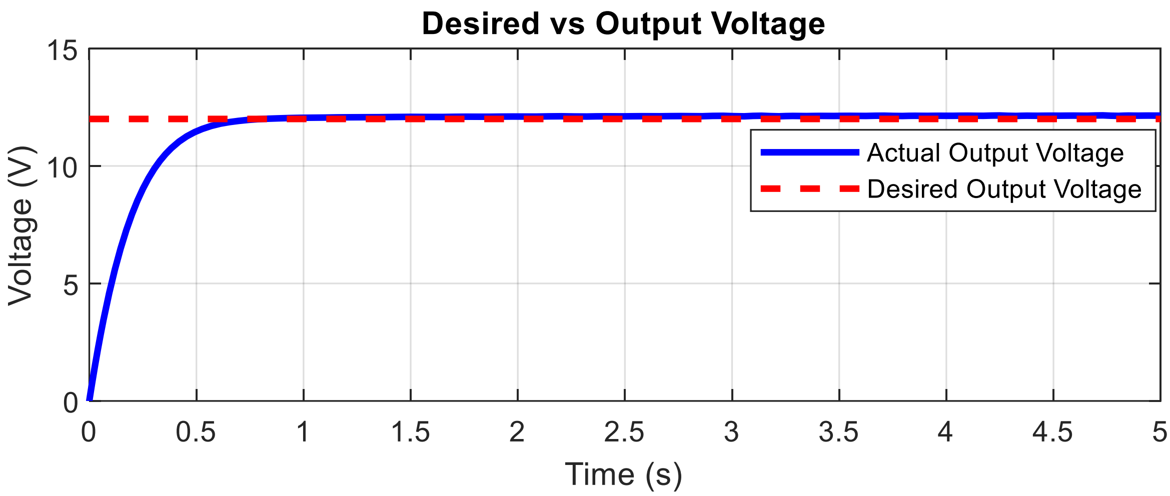

Fig. 9. WOA-PID parameter and output voltage for desired response

Table 2. WOA- PID controller time domain specifications

Time Domain Specifications	K_p	K_i	K_d	Rise time (s)	Settling time (s)	Overshoot (%)	Fitness function
WOA_PID Controller	4.9556	5.00	0.0129	0.216	0.654	0	2.5171
PID Controller	3.8357	9.7946	0.001	0.301	0.721	0	------

The responses above provides a comparative analysis of the gain parameters and time-domain performance specifications between a Whale Optimization Algorithm (WOA)-tuned Proportional-Integral-Derivative (PID) controller and a conventionally tuned PID controller. Regarding time-domain performance, the WOA-PID controller demonstrates a faster rise time of 0.216 seconds and a shorter settling time of 0.654 seconds. These values represent an improvement over the conventional PID controller's respective rise time of 0.301 seconds and settling time of 0.721 seconds. Nevertheless, both controllers achieve a zero percent overshoot. Furthermore, the WOA-PID controller's performance, in relation to the optimization objective, is quantified by a fitness function value of 2.5171, indicating its superior efficacy. The absence of a corresponding fitness value for the conventional PID controller suggests it was not evaluated within the same optimization framework. In summary, the WOA-PID controller demonstrates superior performance compared to the conventional PID design in both controllers gain optimization and transient response characteristics.

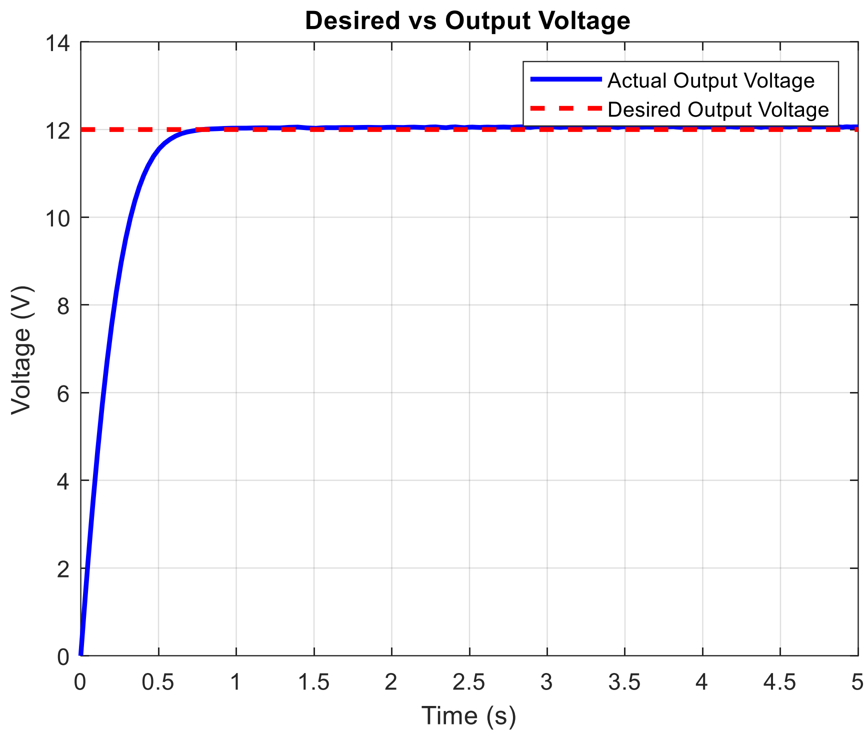

Fig. 10. Output voltage for boost PID response

Furthermore, the variation in the fitness function curve is presented in Fig. 11. The provided results illustrate the evolution of the fitness function, quantified as the error value, across 100 iterations. This fitness function serves as a metric for assessing solution quality within the optimization process, with the algorithmic objective being its minimization, thereby reducing the error associated with candidate solutions. The graph reveals a pronounced decrease in the fitness function during the initial approximately 10 iterations, signifying rapid advancements in the solution space. In Overall, the observed trend demonstrates convergence, with the ultimate fitness value stabilizing marginally above 2.5. This indicates that the optimization algorithm has likely reached a point of diminishing returns, wherein successive iterations yield minimal improvements which indicates a well-tuned algorithm.

To, test the controller validity to input voltage change and load variation, several tests were executed. Initially, the converter is subjected to significant input voltage fluctuations (40%), while maintaining a constant load as shown in Fig. 12 a. The result unequivocally demonstrates highly effective output voltage regulation. The control system successfully compensates for large step changes in input voltage, maintaining the desired 12V output with minimal transient deviation and ripple. Then, the input voltage is kept constant while the load resistance is by 20 %. The unperturbed output voltage, shown in Fig. 12 b, remaining tightly regulated at the desired value, indicates excellent rejection of disturbances caused by load resistance fluctuations. This performance highlights the robustness of the employed control strategy in rejecting substantial disturbances and managing the converter's inherent nonlinearities. Such stable regulation is critical for supplying sensitive electronic loads from variable power sources.

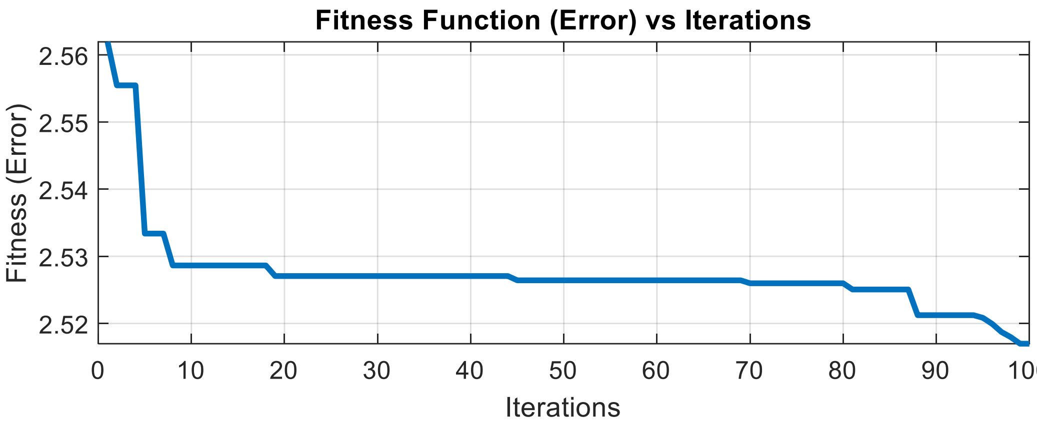

Fig. 11. Fitness function curve

While Fig. 13 illustrates the exceptional performance of the boost converter control system in maintaining a stable 12V output despite simultaneous input voltage fluctuations and implied load resistance variations. The tight regulation and minimal transient excursions in the output voltage demonstrate the control strategy's high robustness against combined, significant disturbances. This signifies a highly effective design capable of reliably supplying critical loads under complex operating conditions. The time domain specification of these tests under different conditions are summarized in Table 3.

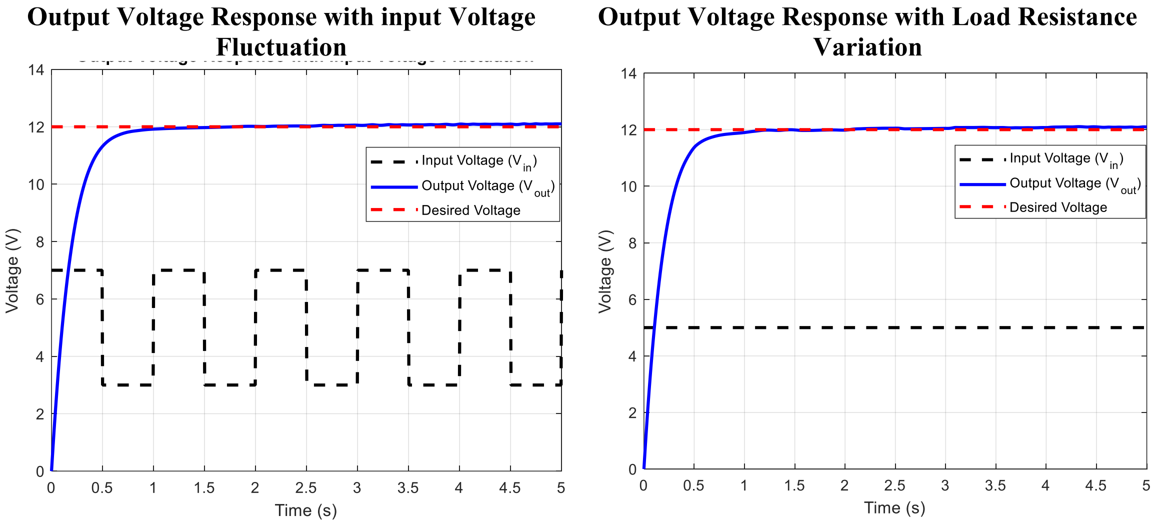

Fig. 12. Output voltage response with input voltage fluctuation and load resistance variation separately

Table 3. Controller time domain specifications under different conditions

Time Domain Specifications	Rise time (s)	Settling time (s)	Mp (%)	Steady state error
WOA_PID controller with input voltage fluctuation	0.3843	0.6934	0.87	0.1011
WOA_PID controller response with R load variation	0.3804	0.7018	0.88	0.0952
WOA_PID controller response with input voltage fluctuation and R load variation	0.3815	0.7211	0.86	0.0951

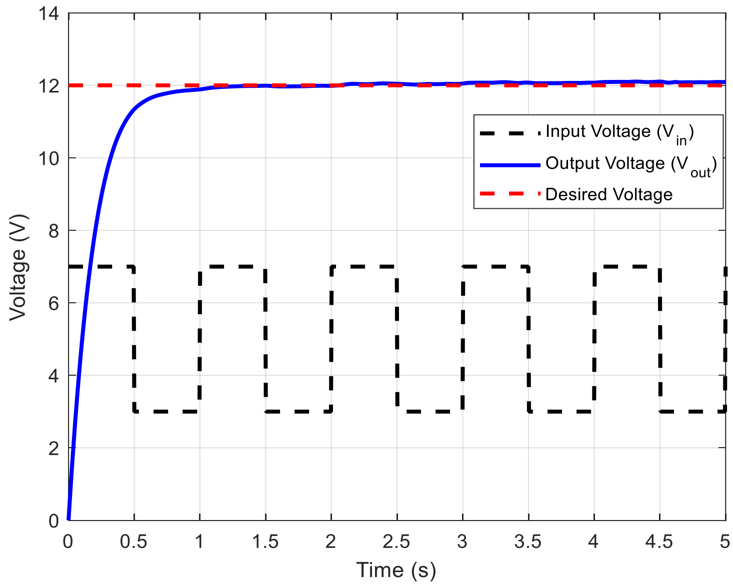

Fig. 13. Output voltage response subjected to input voltage fluctuation and load resistance variation

7. Conclusion

In this paper, a PID controller is tuned for a high-performance boost using a unique Whale optimization approach. Both analytical and graphical results indicate significant improvements, including reduced rising time, improved settling time, and decreased peak time. Additionally, these results indicate that optimization curve, derived for integral square error criteria for PID controller tuned through the Whale Optimization Algorithm (WOA). In terms of time-domain performance, the WOA-PID controller exhibits superior dynamic characteristics, achieving a faster rise time of 0.216 seconds and a reduced settling time of 0.654 seconds. These results indicated an enhancement compared to the conventional PID controller, which records a rise time of 0.301 seconds and a settling time of 0.721 seconds. However, it is noteworthy that both controllers maintain a zero percent overshoot. Future research will focus on tuning a Fractional Order PID (FOPID) controller and comparing its performance to the standard PID controller employed to a range of systems with different conditions.

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