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Optimally Designed PID Controller for a DC-DC Buck Converter via a Hybrid Whale Optimization Algorithm with Simulated Annealing

Baran Hekimoğlu[1], Serdar Ekinci[2]

[1]Department of Electrical and Electronics Engineering, Batman University Faculty of Engineering and Architecture, Batman, Turkey
[2]Department of Computer Engineering, Batman University Faculty of Engineering and Architecture, Batman, Turkey

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ABSTRACT

A new design approach is presented in this study for tuning of proportional-integral-derivative (PID) controller parameters in a DC–DC buck converter utilizing a hybrid whale optimization algorithm (WOA) with simulated annealing (SA), namely the WOASAT algorithm, which uses a tournament selection mechanism. The proposed algorithm's efficacy ensures that the optimum PID controller parameters are tuned quickly and that the quality of tuning is high. A time domain performance index is utilized to validate the proposed WOASAT-based PID controller's performance. In addition, from the comparative results of statistical analysis, frequency response analysis, transient response analysis, disturbance rejection analysis, and performance indices analysis, the proposed WOASAT-PID controller was found to be more efficient than the SA-PID controller and WOA-PID controller in enhancing the buck converter's transient response.

Keywords: Hybridization, whale optimization algorithm, simulated annealing, tournament selection, PID controller parameter tuning, buck converter, output voltage regulation

Introduction

Switching DC–DC converters have become the most common power electronics systems to meet the power supply needs of high-end devices such as today's battery-powered tablets, smartphones, and media players to operate well at high performance [1]. Therefore, switching power supply systems must also be well designed and perform well. However, designing of the controllers used in these systems is not an easy task due to a nonlinear and time-varying character of the switching system.

In industry, the proportional-integral-derivative (PID) controller is the most commonly utilized controller, but its effectiveness depends on fine tuning of its parameters. Although traditional methods such as the pole placement and Ziegler–Nichols have been used for this task, the use of advanced methods such as heuristic optimization algorithms have been increasing in recent years [2-4]. The heuristic optimization algorithms studied in the literature for tuning PID controller parameters in a DC–DC buck converter control are the bacterial foraging algorithm (BFA) [5], firefly algorithm (FA) [6], particle swarm optimization (PSO) [7], genetic algorithm (GA) [8], and whale optimization algorithm (WOA) [9].

The WOASA algorithm [10] is a hybridization of the WOA algorithm [11] with the simulated annealing (SA) algorithm [12]. However, in the original paper [10], two types of hybridization models and two types of solution-selection models, which enable the hybrid algorithm to explore the solution space, were proposed. The first hybridization model is called the low-level teamwork hybrid (LTH). In this hybridization model, SA works as an embedded operator in WOA, looking for a better solution around both the randomly selected solution and the best solution found until that moment. The hybrid algorithm obtained by this method was named WOASA1. In the second hybridization model, SA is used after the WOA application, that is, the best final solution WOA finds is further developed with SA. The hybrid algorithm obtained

Corresponding Author:
Baran Hekimoğlu

E-mail:
baran.hekimoglu@batman.edu.tr

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by this method was named WOASA2. In the new methods obtained by both hybridization models, a random selection mechanism was used for the solution space exploration of the algorithm. In addition, the other two new algorithms obtained by the same hybridization models using the tournament selection mechanism alternative to the random selection mechanism were referred to as WOASAT1 and WOASAT2, respectively. As a result, while the exploitation phase of the original algorithm was improved by the hybridization of WOA with SA, the exploration phase of the original algorithm was improved by the use of the tournament selection mechanism. After the conducted tests with a variety of test functions and feature selection problem as a real-world engineering problem, the aforementioned four different WOASA algorithms (WOASA1, WOASA2, WOASAT1, and WOASAT2) have been shown to effectively solve optimization problems, including the ones with unknown search spaces [10].

However, other than the aforementioned feature selection problem, the application of the WOASA algorithm to another engineering problem has not been encountered in the literature. Therefore, in this study, the WOASAT algorithm (WOASA with tournament selection [WOASAT2 in the original paper]) is proposed to optimize PID controller parameters in a DC–DC buck converter system, which is the first application of the WOASAT algorithm in electrical engineering field. The effectiveness of the proposed method was confirmed by simulation results. As for the rest of this paper, in the second section, the modeling of buck converter based on the switching signal-flow graph method is presented. In the third section, the buck converter with a PID controller is explained; in the fourth section, the WOASAT algorithm is given; in the fifth section, the application of the proposed WOASAT-based PID controller and simulation results for the buck converter are presented; and finally, the summary of important findings is presented in the conclusion.

Buck converter model

Since the buck converter is a DC–DC switching system and therefore is a time-varying and nonlinear circuit, its linearized model must first be obtained in order to design the controller. For this purpose, modeling methods such as state-space averaging or circuit averaging are usually used [13, 14]. Figure 1 shows a buck converter system without any controller.

The switching signal-flow graph method, which is also based on the state-space-averaging method, is an extension of the signal-flow graph theory [15]. The small-signal transfer functions obtained with this method, which are used in the controller design, are the same as the transfer functions obtained by the state-space-averaging method. However, it allows small-signal models for switching converters to be obtained in a more visible and rapid way [16]. Therefore, the use of the switching signal-flow graph method in modeling and controller design of high-order power electronics circuits is becoming increasingly common [16-18]. In this study, a dynamic circuit model of buck converter was obtained by the switching signal-flow graph method, but the details of the model's derivation were not given due to the number-of-pages constraint. For these, one can refer to [15] and [16]. Figure 2 shows the small-signal (dynamic) model of a buck converter circuit.

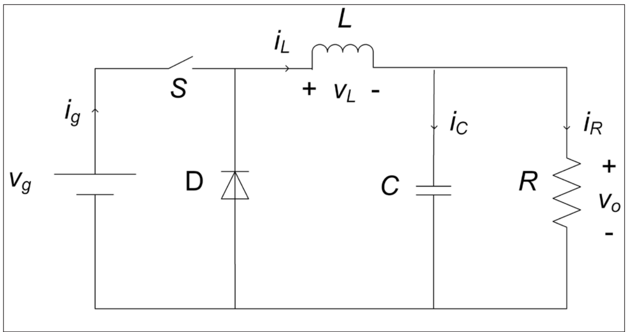

Figure 1. Buck converter system without of any controller

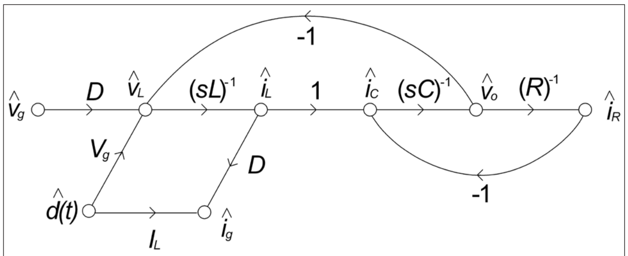

Figure 2. Buck converter small-signal (dynamic) model

From the signal-flow graph in Figure 2, the flow graph algebra and the Mason gain formula [19], small-signal (dynamic) transfer functions of a buck converter, can be obtained as follows:

$$G_{vd}(s) = \frac{\hat{v}_o}{\hat{d}} = \frac{V_g/LC}{s^2 + s/RC + 1/LC}, \tag{1}$$

$$G_{vg}(s) = \frac{\hat{v}_o}{\hat{v}_g} = \frac{D/LC}{s^2 + s/RC + 1/LC}, \tag{2}$$

$$G_{id}(s) = \frac{\hat{i}_L}{\hat{d}} = \frac{V_g/L \cdot (s + 1/RC)}{s^2 + s/RC + 1/LC}, \tag{3}$$

$$G_{ig}(s) = \frac{\hat{i}_L}{\hat{v}_g} = \frac{D/L \cdot (s + 1/RC)}{s^2 + s/RC + 1/LC}. \tag{4}$$

Equations (1) and (2) are the control-to-output and the input-to-output small-signal responses for the case where the capacitor voltage is selected as output, respectively. Similarly, Eqs. (3) and (4) are the control-to-output and the input-to-output small-signal responses for the case where the inductor current is selected as output, respectively. In Table 1, buck converter parameters [9] and, in Figure 3, its open-loop step response are given. It is obvious from the figure that in the absence of

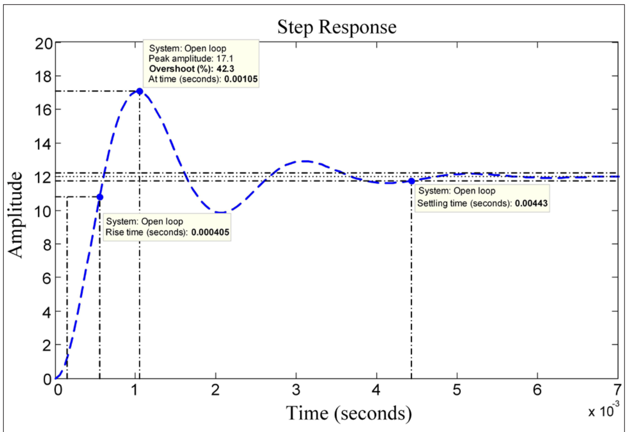

Figure 3. Buck converter open-loop step response

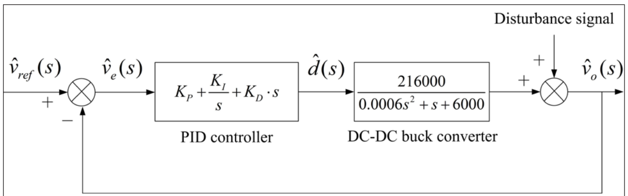

Figure 4. Buck converter system with a PID controller

the controller, the transient response of the buck converter is stable but that it needs some improvement.

Buck converter with a PID controller

Figure 4 illustrates the block diagram of the buck converter system with a PID controller.

Here, $\tilde{v}_{ref}(S)$, $\tilde{v}_e(S)$, and $\tilde{v}_O(S)$ are the reference voltage, error voltage, and output voltage, respectively. When the parameters in Table 1 are used, the unity feedback closed-loop transfer function of the buck converter is obtained as follows:

$$T_{PID}(s) = \frac{216000(K_D s^2 + K_P s + K_I)}{0.0006s^3 + s^2 + 6000s + 216000(K_D s^2 + K_P s + K_I)}. \quad (5)$$

To obtain a high-level dynamic performance from the system, it is necessary to set the K_P, K_I, and K_D parameters in the best way.

Overview of WOA, SA, and WOASAT

Whale optimization algorithm

WOA is a simulation of the bubble-net feeding behavior of humpback whales [11]. During the optimization process, whales search (explore) their prey's location and attack (exploit) it utilizing one of the two mechanisms: the shrinking encircling mechanism or spiral-position-updating mechanism. How foraging behavior of whales was modeled mathematically will be explained in the next subsections.

Table 1. Parameters of the DC–DC buck converter used in simulation

Parameters	Values
Source voltage V_g	36 V
Load resistance R	6 Ω
Filter inductor L	1 mH
Filter capacitor C	100 μF
Operating point voltage V_{ref}	12 V
Duty cycle of switch D	1/3
Switching frequency f_s	40 kHz

DC: direct current

Prey search (exploration stage)

Whales randomly search for their prey with respect to the position of each other. Therefore, forcing the search agents (all whales, except the reference whale) move away from a randomly chosen reference whale is essential to carry out a global search at this stage. This behavior can be mathematically modeled as

$$\vec{X}(t+1) = \vec{X}_{rand}(t) - \vec{A} \cdot \left|\vec{C} \cdot \vec{X}_{rand}(t) - \vec{X}(t)\right|. \quad (6)$$

Here, $\vec{A}$ and $\vec{C}$ are coefficient vectors, $\vec{X}$ is the position vector, X_{rand} is a random position vector (a random whale) chosen from the current population, · is an element-by-element multiplication, |·| is the absolute value, and t is current iteration. $\vec{A}$ and $\vec{C}$ vectors are calculated as follows:

$$\vec{A} = 2 \cdot \vec{a} \cdot \vec{r} - \vec{a}, \quad (7)$$

$$\vec{C} = 2 \cdot \vec{r}. \quad (8)$$

Here, $\vec{a}$ decreases linearly from 2 to 0 during iterations, and $\vec{r}$ is a random vector in a range of [0,1]. Since the vector $\vec{A}$ will be in a range of [$-a$,a], which is [–2,2] here, the exploration of search space by this mechanism is possible if $|\vec{A}|$ >1. This mechanism is called encircling the prey [11], and it is also used for the exploitation of the search space in a shrinking fashion when $|\vec{A}|$ ≤1, and it will be explained in the next subsection.

Bubble-net attacking of prey (exploitation stage)

As mentioned before, there are two mechanisms that can be used at the exploitation stage of WOA to mimic the bubble-net attacking behavior of humpback whales, which will be explained in the following subsections.

Shrinking encircling mechanism: Humpback whales encircle their prey when they pinpoint its location. In WOA, the target prey is the current best solution. In the search space, because the position of the optimal design is not known in advance, all other search agents will update their position toward the best search agent (target prey). This behavior is mathematically modeled as follows:

$$\vec{X}(t+1) = \vec{X}'(t) - \vec{A}\cdot\left|\vec{C}\cdot\vec{X}'(t) - \vec{X}(t)\right|\cdot \tag{9}$$

Here, $\vec{X}'$ is the position vector of the best solution (target prey) obtained so far, and $|\vec{A}| \leq 1$ with a linearly decreasing value of $\vec{a}$ as in Eq. (7) to simulate a shrinking encircling mechanism, as mentioned before. Hence, the next position of a search agent can be determined anywhere in between the original position of the agent and the position of the current best agent (target prey).

Spiral-position-updating mechanism: The first thing to do in this mechanism is to calculate the distance between a whale and its prey. Then, a spiral-position-updating equation is created between the position of a whale and its target to simulate the helical motion of whales as follows:

$$\vec{X}(t+1) = \left|\vec{X}'(t) - \vec{X}(t)\right| \cdot e^{bl} \cdot \cos(2\pi l) + \vec{X}'(t). \tag{10}$$

Here, b is a constant to define the logarithmic spiral's shape, l is a random number in a range of [−1,1], and · is an element-by-element multiplication as presented before.

The aforementioned two mechanisms of the bubble-net hunting behavior of whales happen simultaneously. Therefore, this process is modeled with an equal probability of choosing either mechanism as follows:

$$\vec{X}(t+1) = \begin{cases} \vec{X}'(t) - \vec{A}\cdot\left|\vec{C}\cdot\vec{X}'(t) - \vec{X}(t)\right| & , \ p < 0.5 \\ \left|\vec{X}'(t) - \vec{X}(t)\right| \cdot e^{bl} \cdot \cos(2\pi l) + \vec{X}'(t) & , \ p \geq 0.5 \end{cases}, \tag{11}$$

Here, p is a random number in a range of [0,1].

Simulated annealing

SA is a single-solution-based heuristic algorithm proposed by Kirkpatrick et al. [12]. In SA, a worse solution with a certain probability is accepted to overcome the local optima stagnation. It starts the optimization process with a randomly generated initial solution, and at each iteration, a neighbor solution to the best solution obtained so far is generated according to the neighborhood structure previously defined, and its fitness function is calculated. The fitter neighbor is always accepted. However, a worse neighbor can only be accepted with a certain probability. This is calculated using the Boltzmann probability as follows:

$$P_B = e^{-\varphi/T} \tag{12}$$

Here, T is the so-called temperature that is decreasing according to some cooling schedule during the search process, and φ is the difference between the best solution's fitness value ($Best_S$) and the generated neighbor's ($Trial_S$) fitness value. In this paper, the cooling schedule is defined as T=0.93·T, and the initial temperature is set to T_0 [10].

Whale optimization algorithm with simulated annealing

The original WOA algorithm yields superior results in many optimization problems. However, whatever the fitness value of the current solution and the operated one are, a blind operator is used for exploitation. To represent hybridization between the global search algorithm (WOA) and the local search algorithm (SA), this operator is replaced with a local search that takes a solution as its initial state, works on it, and replaces it with the enhanced one.

Here, the SA algorithm can be used in two hybridization models to enhance the exploitation; the LTH and the high-level relay hybrid (HRH). In the LTH model, SA searches the neighborhood of the best search agent so far to ensure that it is the local optimum, and hence, it is utilized as a component in the WOA algorithm. In the HRH, after WOA terminates the optimization process, SA is employed to improve the best solution found by WOA. Also, the diverseness of the hybrid algorithm can be preserved either by a random selection mechanism or tournament selection mechanism for selecting the search agents among the population.

In this paper, the WOASAT algorithm obtained by the HRH model, which gave the best results in the original paper [10], will be used from the two hybridization models. Accordingly, after WOA finds the best solution, SA will be used to improve and replace this final best solution. However, for selecting the random solution that lets the algorithm to explore the solution space, the tournament selection mechanism will be used as in the original paper. The flow diagram of the WOASAT algorithm is shown in Figure 5.

Simulation Results and Discussion

This section presents the PID controller design, which is tuned by the WOASAT algorithm to improve the transient response of the DC–DC buck converter system. The SA-PID and WOA-PID are the approaches selected for comparison in different analysis studies.

Design of the PID controller using WOASAT for a DC–DC buck converter system

When tuning controller parameters with heuristic and meta-heuristic optimization techniques based on artificial intelligence, some performance indices are used as the objective

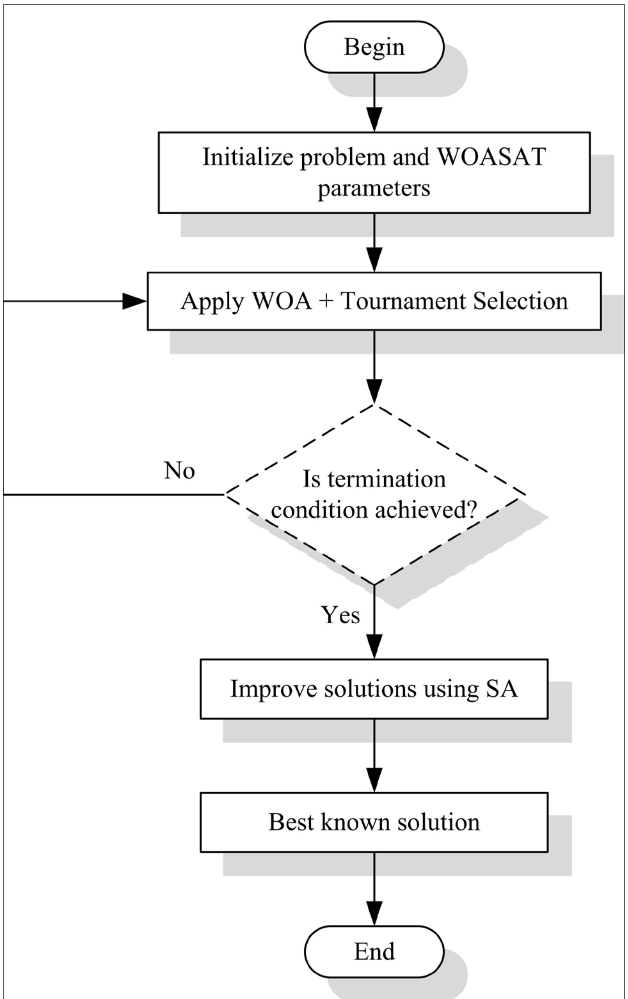

Figure 5. Flowchart of WOASAT

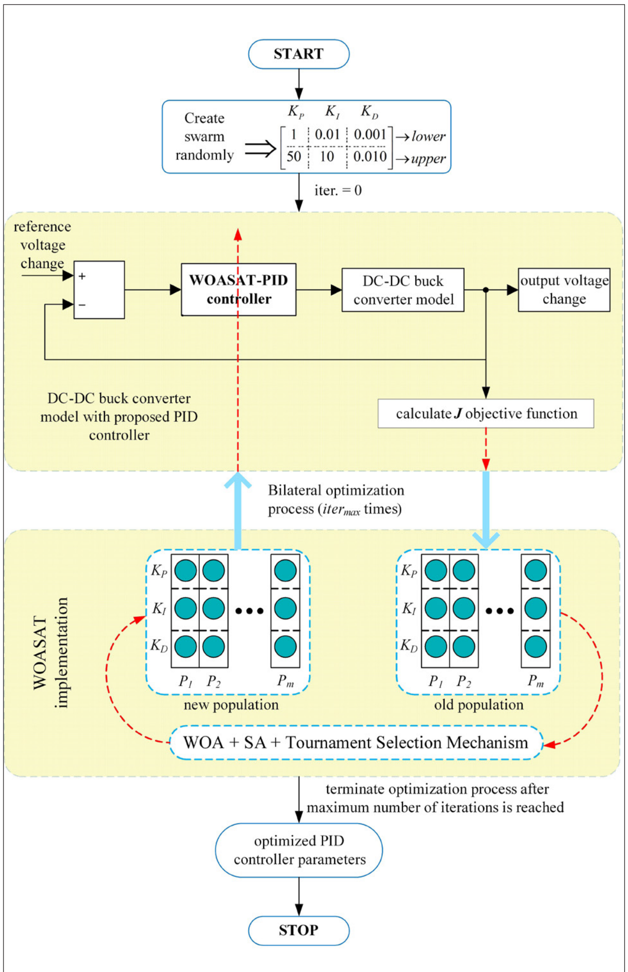

Figure 6. Block diagram of the buck converter system with a WOASAT-PID controller

function. In this study, the most common and most effective objective function [20, 21] was preferred and given as follows:

$$J = (1-e^{-\alpha})\ (E_{ss} + M_p) + e^{-\alpha}(T_s - T_r) \tag{13}$$

where E_{ss} is the steady state error, M_p is overshoot percentage, T_s is settling time for a ±2% band, and T_r is rise time. α is the weighting coefficient usually set to 1 [22, 23]. However, it is essential to specify lower and upper limits of parameters to be optimized when solving optimization problems with constraints. In this study, the limits of the PID controller parameters are given as in Eq. (14). The conceptual block diagram of the DC–DC buck converter system with a WOASAT-based PID controller using a hybrid approach is shown in detail in Figure 6.

$$\begin{aligned} 1 &\le K_P \le 50 \\ 0.01 &\le K_I \le 10 \\ 0.001 &\le K_D \le 0.01 \end{aligned} \tag{14}$$

To ensure a proper performance comparison, each algorithm (the original SA, the original WOA, and the hybrid WOASAT) was determined to have a population size of 25 and a total iteration number of 30, which is the termination criterion. In the PID controller design phase, each algorithm was run 20 times. While the PID controller parameters are optimized at each run, the average elapsed times are 73.8544 *s* for WOA, 41.9733 *s* for SA, and 86.0576 *s* for WOASAT. As can be seen in the box plot analysis shown in Figure 7, the statistical performance of the WOASAT-based approach is better than the performance of other approaches. Also, the convergence curve of each algorithm attempting to find the best parameters selected from 20 runs is illustrated in Figure 8. As seen from the figure, in comparison to SA and WOA, although the WOASAT algorithm converges after a larger number of iterations, the obtained objective function *J* has the lowest value, which indicates that the hybrid algorithm is not stagnated to the local minimum.

With the completion of the optimization process, the optimal values of PID controller gains (K_P, K_I and K_D) obtained by various algorithms are listed in Table 2. The closed-loop transfer

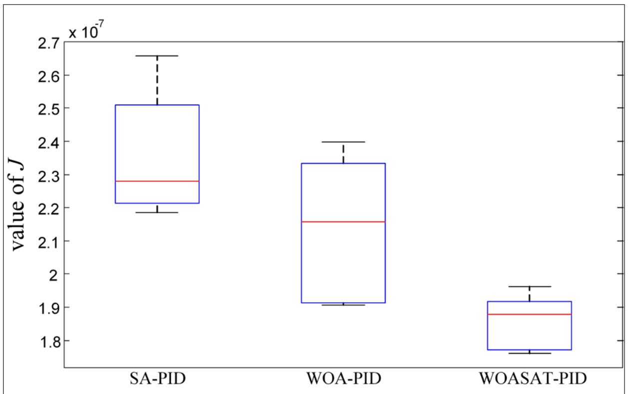

Figure 7. Box plot for SA-PID, WOA-PID, and WOASAT-PID

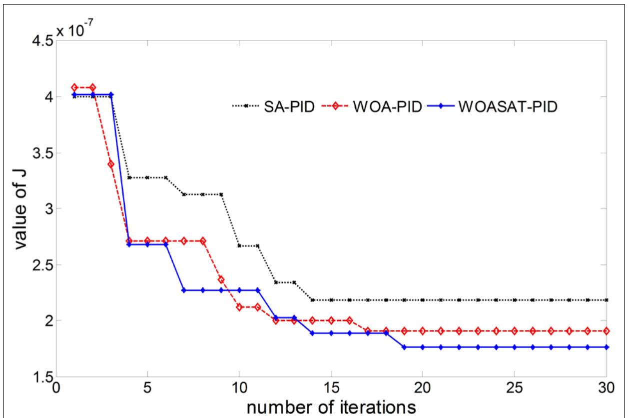

Figure 8. Convergence curves for SA-PID, WOA-PID, and WOA-SAT-PID

functions considering the parameters in the table are given in Eqs. (15-17). Numerous analyses can be easily performed and verified through these transfer functions:

$$T_{SA-PID}(s) = \frac{0.2811s^2 + 1453s + 340.4}{10^{-7}s^3 + 0.2813s^2 + 1454s + 340} \quad (15)$$

$$T_{WOA-PID}(s) = \frac{0.3238s^2 + 1569s + 283}{10^{-7}s^3 + 0.324s^2 + 1570s + 283} \quad (16)$$

$$T_{WOASAT-PID}(s) = \frac{0.3581s^2 + 608.1s + 115.6}{10^{-7}s^3 + 0.3583s^2 + 609.1s + 115.6} \quad (17)$$

Transient response analysis

The time responses of buck converter with various controllers are illustrated in Figure 9. In addition, comparative numerical results are presented in Table 3 in terms of overshoot, settling time, and rise time, which are important transient response criteria. As clearly seen from Figure 9 and Table 3, the WOA-SAT-based PID controller perfectly improves the transient response of the buck converter system.

Table 2. Optimized parameters of PID controllers

Proposed Controllers	K_P	K_I	K_D
SA-based PID	40.3741	9.45461	0.007808
WOA-based PID	43.5764	7.85992	0.008994
WOASAT-based PID	16.893	3.20991	0.009948

PID: proportional-integral-derivative; SA: simulated annealing; WOA: whale optimization algorithm; WOASAT: hybrid whale optimization algorithm and simulated annealing with tournament selection

Table 3. Transient response analysis results

Proposed Controllers	Overshoot (%)	Settling Time (±2%, s)	Rise Time (0.10→0.90, s)
SA-based PID	No overshoot	1.3726×10^{-6}	7.7874×10^{-7}
WOA-based PID	No overshoot	1.1950×10^{-6}	6.7658×10^{-7}
WOASAT-based PID	No overshoot	1.0923×10^{-6}	6.1346×10^{-7}

PID: proportional-integral-derivative; SA: simulated annealing; WOA: whale optimization algorithm; WOASAT: hybrid whale optimization algorithm and simulated annealing with tournament selection

Table 4. Comparative bode stability analysis results

Proposed Controllers	Gain Margin (dB)	Phase Margin	Bandwidth
SA-based PID	infinite	177.1461°	2.8077×10^6
WOA-based PID	infinite	177.4675°	3.2334×10^6
WOASAT-based PID	infinite	180°	3.5728×10^6

PID: proportional-integral-derivative; SA: simulated annealing; WOA: whale optimization algorithm; WOASAT: hybrid whale optimization algorithm and simulated annealing with tournament selection

Frequency response analysis

In this subsection, the frequency response analysis of a DC–DC buck converter with the proposed WOASAT-tuned PID controller is examined comparatively. In evaluation of the frequency response of the system, gain margin, phase margin, and bandwidth criteria were examined. The magnitude and phase curves of the buck converter system designed with the proposed approach are illustrated in Figure 10. In addition, comparative frequency response results are listed in Table 4. As seen from the table, compared to the other two approaches, the performance of the closed-loop controlled buck converter system using the hybrid approach based PID controller is the best because of

Table 5. Values of various performance indices

	Performance Indices			
Proposed Controllers	**IAE**	**ISE**	**ITAE**	**ITSE**
SA-based PID	4.3428×10^{-6}	2.5585×10^{-5}	2.1246×10^{-12}	4.5438×10^{-12}
WOA-based PID	3.7697×10^{-6}	2.2216×10^{-5}	1.6380×10^{-12}	3.4267×10^{-12}
WOASAT-based PID	3.3513×10^{-6}	2.0104×10^{-5}	9.4061×10^{-13}	2.8068×10^{-12}

PID: proportional-integral-derivative; SA: simulated annealing; WOA: whale optimization algorithm; WOASAT: hybrid whale optimization algorithm and simulated annealing with tournament selection

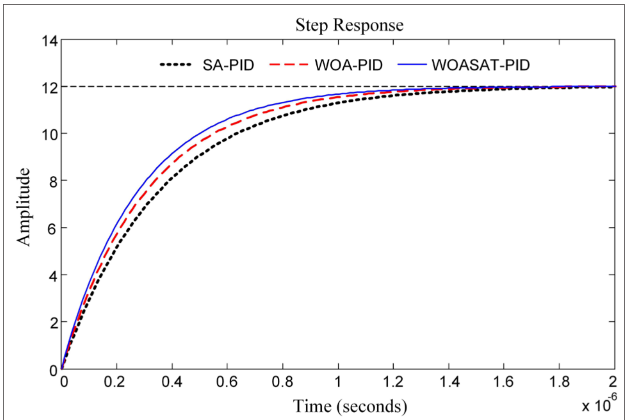

Figure 9. Step response comparisons of the buck converter system

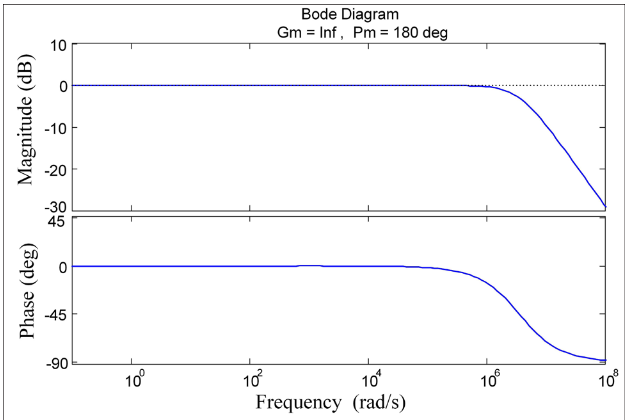

Figure 10. Bode plot of the buck converter system with a WOASAT-based PID controller

having a phase margin of 180° and the maximum bandwidth.

Comparison of time-domain integral-error-performance indices

A comparative performance analysis of the proposed WOASAT-based controller can be performed by some integral of error-based performance indices. For this purpose, four well-known indices [24, 25] were used:

$$IAE = \int_0^{T_{sim}} |e| \cdot dt = \int_0^{T_{sim}} \left|\hat{v}_{ref} - \hat{v}_o\right| \cdot dt \tag{18}$$

$$ISE = \int_0^{T_{sim}} e^2 \cdot dt = \int_0^{T_{sim}} \left(\hat{v}_{ref} - \hat{v}_o\right)^2 \cdot dt \tag{19}$$

$$ITAE = \int_0^{T_{sim}} t \cdot |e| \cdot dt = \int_0^{T_{sim}} t \cdot \left|\hat{v}_{ref} - \hat{v}_o\right| \cdot dt \tag{20}$$

$$ITSE = \int_0^{T_{sim}} t \cdot e^2 \cdot dt = \int_0^{T_{sim}} t \cdot \left(\hat{v}_{ref} - \hat{v}_o\right)^2 \cdot dt \tag{21}$$

In (18-21), $e = \tilde{v}_{ref} - \tilde{v}_O$ is an error signal, and T_{sim} is the simulation time chosen as 0.00001 s. The values of these indices for the SA-, WOA-, and WOASAT-based PID controllers are presented in Table 5, and as clearly seen, the values of the proposed WOASAT-based controller are relatively low compared to the other two approaches. This proves that the WOASAT-based controller is more effective and superior in terms of transient stability.

Disturbance rejection performance

This subsection discusses the ability of the proposed WOASAT-based controller to respond to unexpected disturbing effects. For the value of the disturbance signal, +20% of the setpoint (V_{ref}) was taken at $t = 5\times10^{-6}$ s. The sudden voltage change caused by the disturbing effect must be suppressed quickly with the proposed controller. The setpoint response due to the step input at t=0 s and response when the disturbance occurs at $t = 5\times10^{-6}$ s are shown in Figure 11. Compared to SA-PID and WOA-PID, the proposed WOASAT-PID controller is quick and better in the disturbance rejection, as observed in Figure 11.

Conclusion

In this paper, the optimum or near-optimum values of the PID controller parameters in a DC–DC buck converter system attained using a new approach based on the hybrid WOASAT algorithm are presented. During the parameter-setting process, the WOASAT algorithm was run step by step to obtain optimal

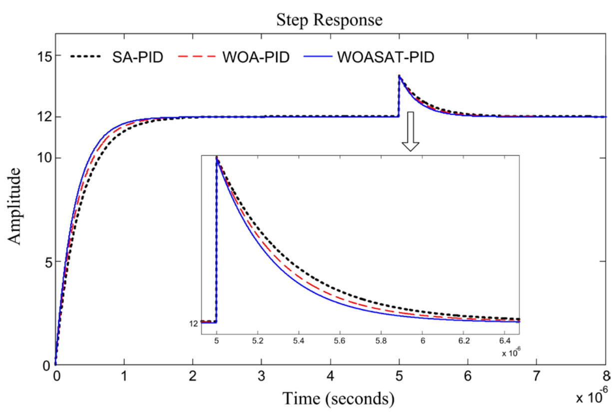

Figure 11. Set point and disturbance responses of a DC–DC buck converter

PID controller parameters according to a time domain performance criterion. From the simulation studies results, it was observed that the WOASAT-based tuning method has found the PID controller parameters quickly and effectively. Furthermore, from the statistical analysis, transient response analysis, frequency response analysis, disturbance reject analysis, and performance indices comparison results, it was confirmed that the DC–DC buck converter system with the proposed WOASAT-PID controller showed better results than the system with the SA-PID and WOA-PID controllers. These results confirmed the effectiveness of the implemented hybrid approach, the WOASAT algorithm, for the parameter tuning problem of the PID controller used in a DC–DC buck converter system.

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Baran Hekimoğlu was born in Diyarbakir, Turkey, on September 11, 1974. He received the B.Sc. degree in Electrical Engineering from Istanbul Technical University, Istanbul, Turkey in 1997, the M.Sc. degree in Mathematics Education from Florida State University, Tallahassee, USA in 2001, and the Ph.D. degree in Electrical Engineering from Kocaeli University, Kocaeli, Turkey in 2010. From 2003 to 2011, he was a Research Assistant, and from 2011 to 2013, he was an Assistant Professor with the Civil Aviation School, Kocaeli University, Kocaeli, Turkey. Since 2013, he has been an Assistant Professor with Electrical and Electronics Engineering Department, Batman University, Batman, Turkey. His research interests include power electronics and power systems control. Dr. Hekimoğlu has been a member of The Chamber of Electrical Engineers (EMO), TURKEY since 1997, and a member of The Institute of Electrical and Electronics Engineers (IEEE), since 2000.

Serdar Ekinci was born in Diyarbakir, Turkey, in 1984. He received the B.Sc. degree in Control Engineering, the M.Sc. and Ph.D degrees in Electrical Engineering all from Istanbul Technical University (ITU), in 2007, 2010 and 2015, respectively. Since 2016, he has been an Assistant Professor with Computer Engineering Department, Batman University, Batman, Turkey. His areas of interest are electrical power system, stability, control technology and the applications of heuristic optimization to power system control.