A COMPARATIVE STUDY FOR OPTIMUM COMPUTATION OF PID PARAMETERS USING METAHEURISTIC ALGORITHMS IN A DC-DC BUCK CONVERTER APPLICATION

Bulut AKAY[1*], Yahya DANAYİYEN[2]

[1,2]Department of Electrical and Electronics Engineering, Engineering Faculty, Karadeniz Technical University, Trabzon, Turkey

Bulut AKAY - ORCID Code: 0009-0006-5552-4399

Yahya DANAYİYEN - ORCID Code: 0000-0002-8679-4088

ABSTRACT

In this paper, optimal computation of PID (Proportional-Integral-Derivative) parameters is carried out for a DC-DC Buck Converter by using GWO (Grey Wolf Optimizer) Algorithm. Moreover, the results obtained using GWO are compared with HHOA (Harris Hawks Optimization Algorithm), WOA (Whale Optimization Algorithm) and GA (Genetic Algorithm). In addition, the study selects the ITSE (Integral of Time multiplied Squared Error) as the performance measure for PID controllers, which is widely used in literature. The comparison of the results indicates that the GWO algorithm outperforms HHOA, WOA, and GA in terms of transient responses such as settling time, rise time, and overshoot, leading to superior PID parameters.

Keywords: GWO (Grey Wolf Optimizer) Algorithm, DC - DC Buck Converter, PID Controller, Metaheuristic Algorithms

INTRODUCTION

DC - DC converters are becoming a necessity in the wide area of engineering applications such as battery management systems (Affam et al., 2021), DC power supplies (Danayiyen et al., 2017), railway tracking applications (Piraino et al., 2023; Zandabad & Fazel, 2023) and electrical vehicle applications(Campaña & Inga, 2023; Rajabi et al., 2023; Savrun et al., 2022). The main requirement is to obtain a stable output voltage in varying environmental conditions and circuit requirements in the DC-DC converters. Among these converters, buck, boost and buck-boost structures are the most used three types of converters in the industry. In order to obtain a safe, stable, and high quality output voltage, the output voltage is controlled in such converters. A suitable controller is designed for the systems to obtain these requirements. In practice, besides the classical control methods (Savrun et al., 2022), there are many advanced control methods have been investigated (Bai et al., 2022; Bi et al., 2022; Danayiyen et al., 2017; Restrepo et al., 2022; Rostami et al., 2022). In recent years, PID control methods based on

metaheuristic algorithms have become more popular since the controller parameters can be computed in an optimal manner (Azizuddin et al., 2019; ÇAVDAR et al., 2022; Deboucha et al., 2021; Hamouda et al., 2022; Jamaludin et al., 2021; Khairi et al., 2023; Panduranga Vittal et al., 2021; Yurdusever & Danayiyen, 2023). A maximum power point tracking (MPPT) technique for a converter system in a photovoltaic (PV) application using Particle Swarm Optimization (PSO) to maximize power generation is porposed (Khairi et al., 2023). The system uses a DC-DC buck converter to control the solar PV power, operating in both MPPT and voltage control modes. The PSO method is used to track the maximum power point of the PV system in the proposed study. Hamouda et al., (2022) present an intelligent optimization method for designing a fractional-order proportional, integral and derivative (FO-PID) controller for an active power factor corrector (PFC) circuit in an arc welding power supply (AWPS). The particle swarm optimization (PSO) algorithm is used to determine the unknown parameters of the FO-PID controller, and the proposed controller is used to regulate the welding voltage and current. Another control scheme using a FOPID controller manages the DC-link capacitor voltage of a bridgeless PFC converter. The optimally designed controllers offer many exceptional features, such as rapid response to welding load and grid voltage variations, and improved welding performance and weld bead quality. The performance of the developed controllers is validated through MATLAB simulations under different working conditions. Simulation results show that the proposed controllers provide very good control of the welding voltage and a good smoothing of the PFC's output voltage under different operating mode conditions, even under fluctuating welding loads. Panduranga Vittal et al., (2021) proposed a study on the performance of PI and PID controllers for a Buck-Boost converter with closed-loop control using bio-inspired optimization techniques such as GWO, GA, PSO, ALO, and WOA. The optimal values of PI and PID parameters obtained by these techniques were compared to investigate their performance when the system is subjected to load disturbance. The study found that the PID controller is more suitable for the Buck-Boost converter as it can damp out the oscillations caused by load disturbance faster than the PI controller by 87.56%. Additionally, GA was found to be the best optimization technique for tuning PID in a Buck-Boost converter based on the evaluated error performance indices and dynamic behavior. Deboucha et al., (2021) propose a Collaborative Swarm Algorithm (CSA) scheme to tackle the Partial Shading Condition (PSC) issue faced by photovoltaic (PV) modules. The CSA method allows the share of the best solution (Gbest) found between each algorithm dynamically, diversifying the exploration phase and helps to determine the accurate global maximum power point (GMPP). The proposed method is deterministic and only requires tuning of two parameters. Experimental results show that the average tracking time is significantly improved compared to other optimization algorithms and that the collaborative approach is superior to the utilization of individual types of metaheuristic algorithms in terms of tracking speed and efficiency. Jamaludin et al., (2021) investigate a duty cycle-based direct search method that utilizes the salp swarm algorithm (SSA) to improve the tracking capability of the maximum power point (MPP) controller in photovoltaic (PV) systems under dynamic environmental conditions. The performance of SSA is compared with conventional and other metaheuristic methods in simulations and hardware experiments using a DC-DC buck-boost converter. The results show that the proposed SSA method outperforms the conventional and other metaheuristic methods in terms of fast-tracking, convergence speed, and accuracy under partial shading conditions and dynamic conditions. The SSA method also reduces steady-state oscillations and improves energy yield. Azizuddin et al., (2019) discuss the need for a control strategy for future smart grids, which have multiple converters linked in parallel to supply electrical demand. Communication networks can be used to distribute control signals, but time delays can lead to poor system performance and instability. The authors propose the use of the grey wolf optimizer (GWO) to optimize the performance of a parallel DC-DC converter system with communication delay in the control signals. The GWO was found to be more effective than particle swarm optimization in this context.

In contrast to previous literature, this study compares the performance of the GWO (Grey Wolf Optimizer) Algorithm, HHOA (Harris Hawks Optimization Algorithm), WOA (Whale Optimization Algorithm), and GA (Genetic Algorithm) in a DC-DC buck converter application. The optimal gains of the PID controller are determined with these algorithms and the performance of the methods are validated based on the output voltage performance of the converter system.

MATERIALS AND METHODS

DC DC Buck Converter Circuit

A buck converter shown in Figure 1 is a type of DC-DC power converter that steps down the voltage from a higher level to a lower level. It is also known as a step-down converter. Buck converters are widely used in electronic devices and power supplies since they are efficient, compact, and cost-effective. The basic operation of a buck converter involves the use of a switch, an inductor (L), a diode (D), and a capacitor (C out). The switch is typically a MOSFET (Q) or a transistor that is controlled by a pulse-width modulation (PWM) signal. When the switch is on, the inductor stores energy from the input voltage. When the switch is turned off, the inductor releases its stored energy to the output capacitor and load. The diode prevents the energy from flowing back to the input voltage source. The output voltage of a buck converter is determined by the duty cycle (d) of the PWM signal, which is the ratio of the time the switch is on to the total switching period. By adjusting the duty cycle, the output voltage can be regulated to a desired level. Buck converters have several advantages over other types of DC-DC converters. They are more efficient than linear regulators because they use the inductor to store and release energy, which reduces power dissipation. They also provide a stable output voltage even when the input voltage varies. Buck converters are used in a wide range of applications, including power supplies for computers, consumer electronics, automotive systems, and renewable energy systems. They are also commonly used in battery-powered devices, such as smartphones and laptops, to regulate the voltage and extend battery life.

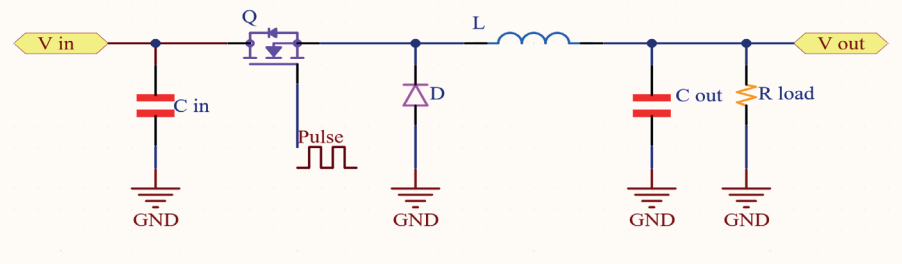


Figure 1. Main circuit of DC-DC buck converter

To design a controller to control the output voltage of a buck converter, a proper transfer function should be derived. The transfer function of a buck converter $G(s)$ describes the relationship between the input voltage and the output voltage. It is a mathematical expression that shows how the converter operates and can be used to design and analyze the system. The transfer function of a buck converter can be derived by analyzing the circuit's behavior during the on and off states of the switching element. During the on state, the switch is closed, and the input voltage is applied to the inductor. The inductor stores energy, and the output capacitor is charged. During the off state, the switch is open, and the inductor releases its stored energy to the output capacitor and load. The voltage across the inductor and the output voltage decrease. The transfer function can be expressed as in Eq. (1):

$$G(s) = \frac{v_{out}}{d} = \frac{\frac{v_{in}}{LC}}{s^2 + \frac{s}{RC} + \frac{1}{LC}} \quad (1)$$

where v_{out} is the controlled output voltage, v_{in} is the input voltage, d is the duty cycle (control variable) of PWM signal. The nominal parameters given in Table 1 are used in the simulation studies in this paper.

Table 1. Nominal parameters

Parameter	Value	Unit
Input Voltage	36	V
Reference Voltage	12	V
Load	6	Ω
Filter Capacite	100	µF
Filter Inductance	1	mH
Duty Cycle	1/3	-
Switching Frequency	40	KHz

Controller Design

A classical PID controller given in Eq. (2) is designed to control the output votlage of the buck converter. A PID controller is a feedback control system that uses three terms: proportional K_p, integral K_i, and derivative K_d to regulate a process or a system. The proportional term of the PID controller is proportional to the error between the setpoint and the measured variable. The error is the difference between the desired setpoint and the actual value of the controlled process variable. The proportional term produces an output that is proportional to the error, so the larger the error, the larger the output. The integral term of the PID controller is proportional to the integral of the error over time. It accumulates the error over time and produces an output that is proportional to the total accumulated error. The integral term is used to eliminate steady-state errors and reduce the settling time. The derivative term of the PID controller is proportional to the rate of change of the error. It anticipates the future trend of the error and produces an output that is proportional to the rate of change of the error. The derivative term is used to reduce overshoot and improve stability. The output of the PID controller is the sum of the proportional, integral, and derivative terms. The PID controller continuously measures the error and adjusts the output to the system to minimize the error and achieve the desired setpoint. PID controllers are widely used in industrial control systems, robotics, and process control applications. They are popular because they are simple, reliable, and easy to tune. However, they may not be suitable for some complex systems with non-linear dynamics or changing parameters.

$$C_{PID} = K_p + \frac{K_i}{s} + K_d s \quad (2)$$

Performance Criteria

In order to use a metaheuristic algorithm to determine the optimal PID parameters (K_p, K_i, K_d) a performance criteria should be chosen. In this study integral time square error (ITSE) given in Eq. (3) is selected as a performance criteria. The ITSE performance criterion is calculated by taking the

integral of the squared error over time. The squared error is the difference between the setpoint and the measured variable, squared to eliminate negative errors. The integral of the squared error over time is then multiplied by the time, resulting in a measure of the system response to a step change in the setpoint. The ITSE performance criterion is often used in the design and evaluation of control systems, especially in the tuning of PID controllers. The ITSE value can be used to compare different control system designs and evaluate their performance. In the tuning of PID controllers, the ITSE value can be used to find the optimal values for the proportional, integral, and derivative gains that minimize the ITSE value.

$$ITSE=\int_0^{tsim} t.e^2(t).dt \quad (3)$$

The combination of metaheuristic algorithms and PID controller can be used in the tuning of the PID controller parameters (K_p, K_i, K_d). Tuning the parameters of a PID controller is an important task in control system design to achieve good control performance. However, the manual tuning of the parameters can be time-consuming and challenging, especially for complex systems. Metaheuristic algorithms can be used to automate the tuning of the PID controller parameters by searching for the optimal values that minimize the error between the desired setpoint and the measured variable. The metaheuristic algorithm can explore the parameter space and find the best set of PID controller parameters that provide the desired control performance. The combination of metaheuristic algorithms and PID controller can provide a robust and efficient control system design that can adapt to changes in the system's dynamics and parameters. In this study, GWO (Grey Wolf Optimizer) Algorithm (Mirjalili et al., 2014), HHOA (Harris Hawks Optimization Algorithm) (Heidari et al., 2019), WOA (Whale Optimization Algorithm) (Mirjalili and Lewis, 2016), GA (Genetic Algorithm) (Katoch et al., 2021) are used to design the PID controller to control the output voltage of the buck converter. More details about these algorithms can be found in the given references.

RESULTS

The results given in Table 2 that is obtanied by GWO algorithms are compared with HHOA, WOA and GA. The comparative results given in Table 3 considering rise time (Tr), settling time (Ts) and overshoot (Mp) show that the optimal parameter computed using GWO are beter than that of the HHOA, WOA and GA. Faster rise time and settling time are obtained with GWO.

Table 2. Parameters of PID Controller according to the methods

Controller	Kp	Ki	Kd
Proposed GWO PID	47.0566	6.50948	0.01
HHO PID	17.1269	3.7594	0.00999
WOA PID	36.1219	5.7947	0.00947
GA PID	24.1506	7.5391	0.00778

Table 3. Transient response of output voltage of DC-DC buck converter according to the methods

Controller	Ts	Tr	Mp(%)
Without controller	4.4300*10^(-3)	4.0500*10^(-4)	42.3069
Proposed GWO PID	1.0763*10^(-6)	6.0876*10^(-7)	0
HHO PID	1.0876*10^(-6)	6.1087*10^(-7)	0
WOA PID	1.1391*10^(-6)	6.4306*10^(-7)	0
GA PID	1.3883*10^(-6)	7.8296*10^(-7)	0

The performance of the controller can be also evaluated in Figure 3. It is clear that there is no overshoot for all algortihms. Hovewer, the peformance of GWO algorithm is beter then the other three methods.

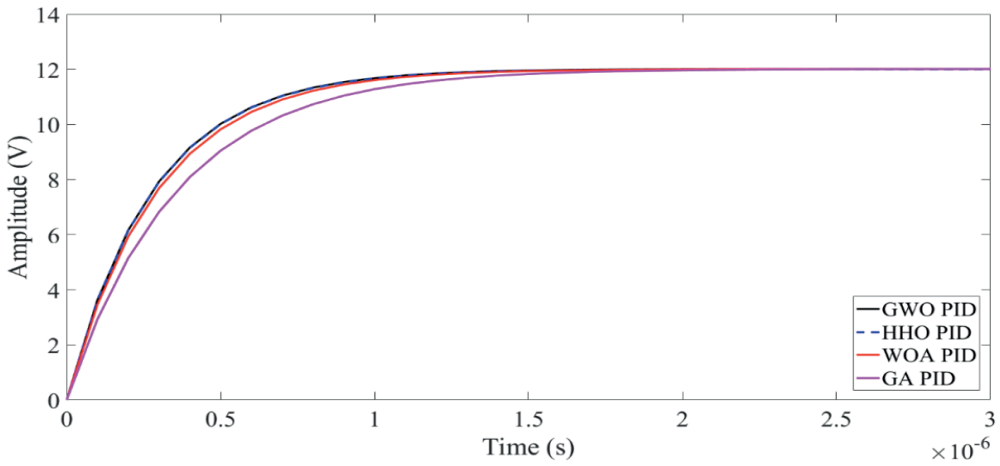


Fig. 5. Step response of output voltage of DC-DC buck converter

Figure 3. The step response of output voltage of DC-DC buck converter

CONCLUSION

This paper proposes an optimal computation method for the PID parameters of a DC-DC Buck Converter using the Grey Wolf Optimizer (GWO) algorithm. The study compares the results obtained using GWO with those obtained using other optimization algorithms, including Harris Hawks Optimization Algorithm (HHOA), Whale Optimization Algorithm (WOA), and Genetic Algorithm (GA). The comparison shows that the GWO algorithm produces superior results in terms of transient responses, such as settling time, rise time, and overshoot, leading to better PID parameters compared to HHOA, WOA, and GA. It is shown that faster rise time and settling time can be obtained using GWO in a PID controller to control the output voltage of a DC-DC buck converter. This study can be extended using different types of DC-DC converter such as boost, buck-boost, dual active bridge etc.

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