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A GWO-PID controller with advanced optimization features for DC-DC converters

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ABSTRACT

This work seeks to use both traditional control algorithms and advanced optimization algorithms to enhance the performance of a DC-DC converter. The chosen algorithm was Proportional-Integral-Derivative (PID) based on gray wolf optimization (GWO). The PID controller is known for its ease of control and wide range of industrial applications. This type of controller has been used successfully in many types of systems, such as power electronics, automation systems, robotics, etc., due to its ability to effectively optimize the system's parameters with minimal effort from the user. To test this new technique on a DC-DC converter, different simulations were conducted using a MATLAB environment where various parameters that can simulate various uses for the DC-DC converter within electrical systems were set. After conducting these tests, it was found that PID based on GWO controller had good performance (rise time 0.0004 sec, settling time 0.0001sec) when compared with other traditional controllers (increase time 0.00416 sec, settling time 0.000323sec), reliability, efficiency, higher accuracy, low cost, etc. As expected, GWO showed better results than conventional methods like PID or PI controllers due to the fact that it's an evolutionary approach that allows more flexibility during the configuration process.

1. Introduction

The DC-DC converter has been around for many years and is an important part of power electronics. It was first developed in the 1950s as a way to convert direct current (DC) electricity from one voltage level to another, allowing for better control of the device's power and performance. According to previous, these devices can work effectively with electric vehicles, sustainable energy systems, airborne electronics, and many modern appliances [1-7]. Such a DC-DC converter can be illustrated in Fig.1. Which mainly acts as a reliable DC power source. Nevertheless, despite their robustness and dynamic operation range, these converters still reflect effective disadvantages in the real world which could affect the converter's performance and try to reduce its efficiency.

Considering depending on the above, different methods and approaches can be adopted to reduce the impact of these defects [8-10]. Digital control techniques are considered one of the most effective methods to improve transformer performance such as pulse width modulation (PWM) or digital signal processing (DSP) [11-13].

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Nomenclature:

a	Coefficient value over the period of iteration.	$\vec{X}_c$	Posit. of the 3rd wolf.
C_s	Capacitor.	$Y(s)$	Output.
$E_{rror}(t)$	error signal.	$\vec{r}_1, \vec{r}_2$	Random values
$K_{der.}$	Derivative gain.		
$K_{int.}$	Integral gain,	*Greek symbols*	
K_{prop}	Proportional gain.	α	First wolf.
L	Inductor.	β	Second wolf.
R_{Load}	Load resistance.	δ	Third wolf.
$u(t)$	Controller output.	α_c	Sensor gain.
$U(x)$	Input.	*Subscripts*	
V_{load}	Output voltage.	c	Controller
V_{source}	Input voltage.	d	Derivative
$\vec{X}_a$	Position of the first wolf.	i	integral
$\vec{X}_b$	Position of 2nd wolf.	p	Proportional

However, one of the most common controllers that can handle errors, which is the result of the linear operating procedure of the system, is the conventional PID controller [14-16].

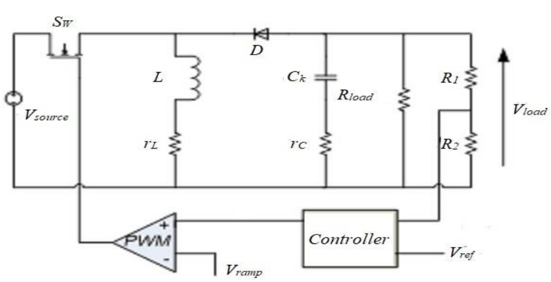

Figure 1. The main component of the DC-DC converter [8]

A control unit is used to create an algorithm to enhance the functioning of this linear system. However, traditional techniques such as the Ziegler-Nichols method, which is a well-known tuning technique, are used to optimize controller performance. This method involves gradually increasing the proportional gain until the system reaches instability. The value of K_P at the point of instability is known as K_{max}, while the oscillation frequency is referred to as f_0. Although this method has been widely used, it has certain limitations in performance optimization, so advanced optimization solutions had to be found. These involve genetic algorithms (GA) [17], particle swarm optimization (PSO) [18], and GWO [19]. All these approaches simulate hunter-prey dynamics as well as iterative processes based on similar cases or experiences accumulated over time.

The main advantage that comes with using advanced optimization solutions such as GWO is that it can provide better results than conventional methods in terms of accuracy and speed when it comes to solving complex problems involving multiple variables. The GWO incorporates a "leader" concept into its structure, allowing it to achieve faster convergence rates compared with other evolutionary algorithms due mainly because it eliminates redundant computations during iterations by following only one leader at each step instead of all individuals.

This paper attempts to develop a PID tuning scheme using a GWO algorithm that can automatically adjust the PID parameters to improve the working performance of the voltage regulation.

An integral time absolute value (ITAS) is chosen as a target function, which is an important metric used to measure the performance of a system by calculating the difference between a desired output and actual output over time [18].

2. Proposed approach

A PID controller combines Proportional, Integral, and Derivative gains to provide precise control over a system. As shown in **Fig. 2**, a feedback control system is created by linking input *(r(t))*, error signal*(e(t))*, controller output *(y(t))*, and controlled variable *(u(t))* respectively.

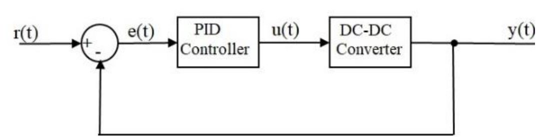

Figure 2. Typical feedback system [16]

The mathematical model for the PID controller can be derived from [16]:

$$u_c(t) = K_{prop.} * E_{rror}(t) + K_{int.} * \int_0^t E_{rror}(t)dt + K_{der.} * \frac{d}{dt} E_{rror} \quad (1)$$

The mathematical model for the DC-DC converter is derived from [19]:

$$G\_(s) = \frac{Y\_(s)}{U\_(s)} = \frac{\frac{\alpha(V_{source} - V_{load})}{L*C}}{s^2 + \left(\frac{1}{R_{load}*C}\right)s}; \quad \alpha_c = 0.2083 \quad (2)$$

Where: V_{source}- source voltage, V_{load}-load voltage, L- inductance, C-capacitance, R_{load}- load resistance. The ITAE model is equal [20]:

$$ITAE\_ = \int_0^\infty t * |e(t)| dt \quad (3)$$

Fig. 3 represents the model of ITAE:

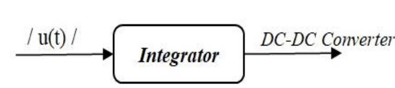

Figure 3. Proposed approach (ITAE)

The Gray Wolf Optimization (GWO) algorithm is an optimization technique based on the hunting mechanism of Gray Wolves in the real world. It is an iterative method**,** which means that after some iterations, the fitness function tries to reach a planned value. The GWO algorithm consists of four types of Gray Wolf: alpha, beta, delta, and omega - each representing a different level within their hierarchical structure, as shown in Fig. 4. The proposed approach of implementing the Gray Wolf Optimization (GWO) algorithm to fine-tune the coefficients ($K_{Prop.}$, $K_{Int.}$, $K_{Der.}$) of a PID controller is a highly effective method of enhancing its performance. GWO is a sophisticated meta-heuristic optimization technique that draws inspiration from the hunting behavior of gray wolves in the wild. This allows for the speedy identification and implementation of optimal solutions through exploration and exploitation techniques, which are highly beneficial when used with PID controllers see Fig. 5.

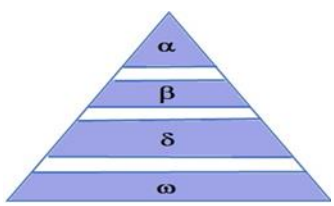

Figure 4 Suggested approach

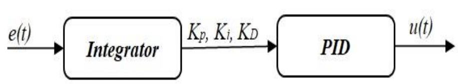

Figure 5. GWO hierarchical structure

The GWO method for tuning coefficients of PID controller can be summed up as:

- Define the transfer function of the converter.
- Define controller coefficients (K_p, K_i, K_d)which represent objective function;
- Define GWO parameters (α, β, γ).
- Initialize the population (n).
- Initialize the alpha, beta, and delta values.
- Initialize the positions of the alpha, beta, and delta wolves.
- Iterate for a fixed number of iterations (n-iterations).
- Update the positions of the wolves.
- Compute the fitness value for the current position.
- Update the positions of the rest of the wolves.
- Compute the new position of the wolf.
- Update the position of the wolf.
- The final solution is the position of the alpha wolf.

The mathematical representation of the GWO can be calculated utilizing the equations in [20]:

$$\vec{X}_a = \vec{X}_\alpha - \left(\left(\vec{D}_\alpha\right) \text{x} \left(\vec{A}\right)\right); \quad \vec{X}_b = \vec{X}_\beta - \left(\left(\vec{D}_\beta\right) \text{x} \left(\vec{A}\right)\right); \quad \vec{X}_c = \vec{X}_\delta - \left(\left(\vec{D}_\delta\right) \text{x} \left(\vec{A}\right)\right); \qquad (4)$$

$$\vec{D}_\alpha = \left|\left(\vec{C}\right) \text{x} \left(\vec{X}_\alpha - \vec{X}\right)\right|; \quad \vec{D}_\beta = \left|\left(\vec{C}\right) \text{x} \left(\vec{X}_\beta - \vec{X}\right)\right|; \quad \vec{D}_\delta = \left|\left(\vec{C}\right) \text{x} \left(\vec{X}_\delta - \vec{X}\right)\right|; \qquad (5)$$

$$\vec{A} = 2\vec{a} \cdot \vec{r}_1 - \vec{a}; \quad \vec{C} = 2\vec{r}_2; \quad \vec{a} : (2 \rightarrow 0) \quad \vec{r}_1, \vec{r}_2 : \qquad (6)$$

$$\vec{X}_{-new}(t+1) = \frac{1}{3}\left(\vec{X}_a + \vec{X}_b + \vec{X}_c\right); \qquad (7)$$

The flow chart diagram of GWO is shown in Fig. 6.

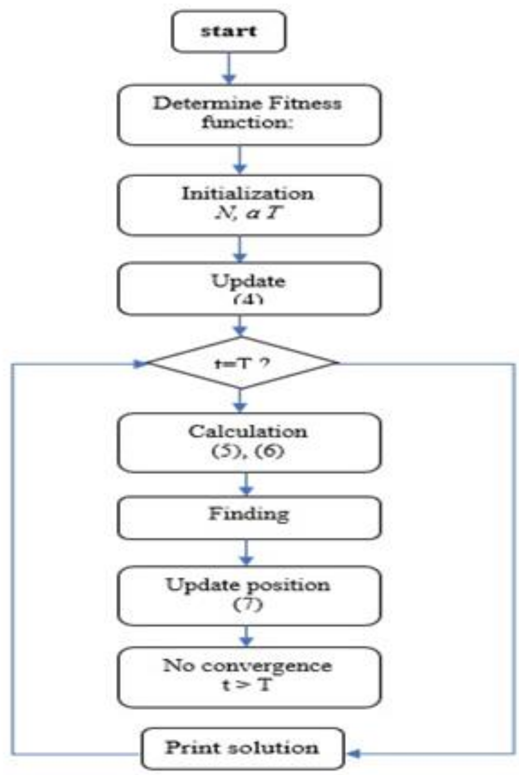

Figure 6. Flow chart of GWO

Table 1. Components value (Fig. 1)

Component	Description	Value
V_{source}	Input voltage	12V
V_{Load}	Output voltage	24V
C_k	Capacitor	1470μF
L	Inductor	330μH
R_{load}	Output resistance	3Ω
f_{PWM}	Pulse width modulation frequency	7.874kHz

3. Simulation results

The simulation process is supplied in Table 1, which states the converter parameter values.

This process is divided into three scenarios: the first one without a P-I-D controller Figs. 7 and 8, the second one with a P-I-D controller based on the Ziegler-Nichols method Figs. 9 and 10, and the third one using a P-I-D controller and GWO Figs. 11 and 12.

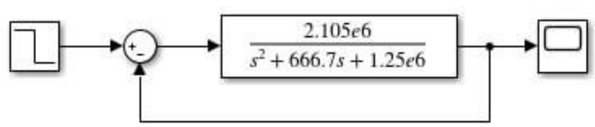

Figure 7 Model without PID controller

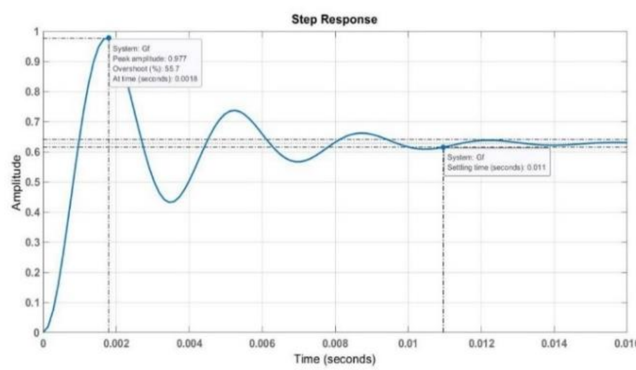

Figure 8. Simulation result without PID controller

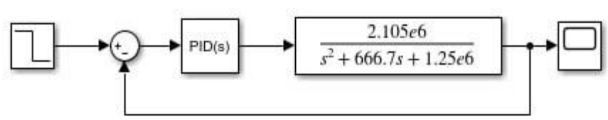

Figure 9. Model with PID controller.

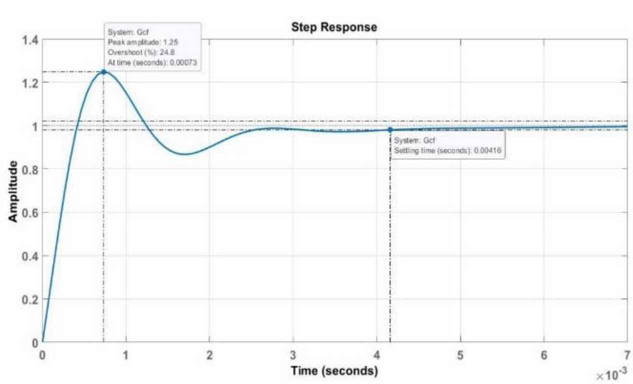

Figure 10. Simulation with PID controller

Examining the results of the three scenarios reveals that the third one (with GWO) demonstrates an especially formidable dynamic response, and achieves superior outcomes in system overshoot, settling time, and rise time see Table 2**.**

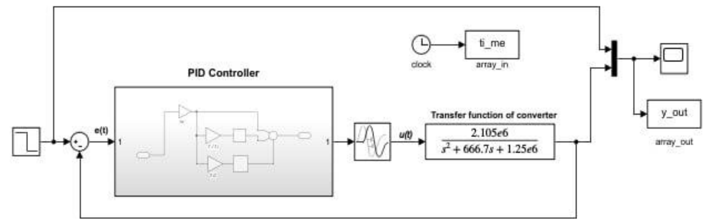

Figure 11. Model of PID controller using GWO

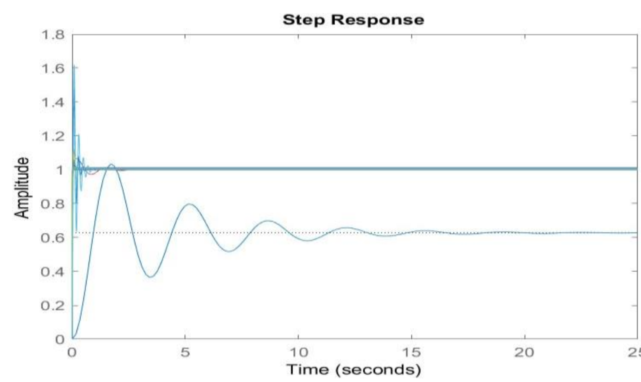

Figure 12. Simulation of PID controller using GWO

Table 2. Results of scenarios

Approach	Overshoot %	Rise time(S)	Settling time(s)
Converter without controller	55.7	0.011	0.0018
Convertor with PID Using Z-N	24.8	0.00416	0.000323
Converter using PID with GWO	-	0.0004	0.0001

4. Conclusion

This paper adopts a proper tuning (KP, KI, KD) of PID controllers using the GWO optimization method. A comparison of responses of the PID controller using the Ziegler-Nichols method and a PID controller using the GWO algorithm has been considered regarding the system overshoot, settling time, and rise time. Ziegler Nichols method in terms of the system overshoot, settling time, and rise time.

The designed PID controller using the GWO algorithm gives a powerful performance benefit over the traditional Ziegler-Nichols method, exhibiting lower system overshoot, settling time, and rise time. Utilizing modern AI optimization to complement the PID controller designed by the conventional method provides an optimal tuning solution. GWO is a recent and efficient choice among the many optimization tools available, as it was proved in the simulation part.

Authors' contribution

All authors contributed equally to the preparation of this article.

Declaration of competing interest

The authors declare no conflicts of interest.

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