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Al-Qadisiyah Journal for Engineering Sciences

Journal homepage: http://qu.edu.iq/journaleng/index.php/JQES

A GWO-PID Controller with Advanced Optimization Features for DC-DC Converters

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ARTICLE INFO

Article history:
Received
Received in revised form
Accepted

Keywords:
DC-DC Converter
PID
GWO
GA
PSO
(ITAE

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 PID based on gray wolf optimization (GWO). 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 MATLAB environment where various parameters were set that can simulate various uses for the DC-DC converter within electrical systems. After conducting these tests, it was found that PID based on GWO controller had good performance when compared against other traditional controllers with regards to response time reliability efficiency higher accuracy low cost, etc. As expected GWO showed better results than conventional methods like PID or PI controllers mainly because 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. Since then, it has become a popular choice for powering hybrid energy systems, electric vehicles, aircraft, satellites, and various electronics devices [1], [2]. The essential components of a DC-DC converter are illustrated in Figure.1. DC-DC converters are an essential component of many electronic devices, providing a reliable source of power for various applications. However, despite their widespread use and importance in modern electronics, DC-DC converters also have some major disadvantages that can limit their performance or cause other issues.

Fortunately, there are several ways to overcome these drawbacks and ensure optimal operation from your DC-DC converter [3], [4], [5].

One way to address the disadvantage of DC-DC converters is by using advanced control techniques such as pulse width modulation (PWM) or digital signal processing (DSP) [6], [7]. Conventional PID controllers are designed to handle errors resulting from the work of linear systems and adjust their parameters accordingly [8], [9].

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https://doi.org/10.30772/qjes.2023.180482

Nomenclature:

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

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

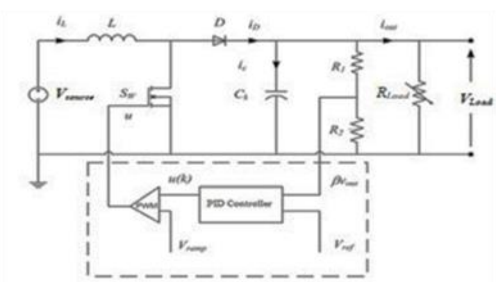

Figure 1. Main component of DC-DC converter [3]

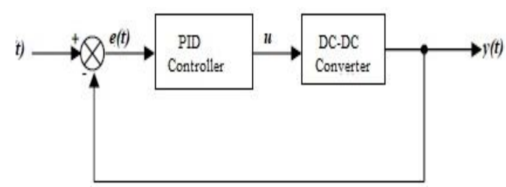

Figure 2. Typical feedback system [11]

To enhance the functioning of this linear system, a control unit is used to create an algorithm. However, traditional techniques have their limitations in terms of performance optimization, so advanced optimization solutions had to be found. These involve GA [10], PSO [11], and GWO [12]. 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 solution 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 incorporate a “leader” concept into its structure allowing them 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 all individuals.

This paper attempts to develop a PID tuning scheme using GWO algorithm that can automatically adjust the PID parameters to improve the working performance of the voltage regulation of the converter. 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 through measuring the difference between a desired output and actual output over time [13].

2- Proposed Approach

The mathematical model for the PID controller can be derived from [11]:

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

The mathematical model for the DC-DC converter is derived from [14]:

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

The ITAE model is equal:

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

Figure 3 represent the model of ITAE:

Figure 3. Proposed approach

The proposed approach of using the Grey Wolf Optimization (GWO) algorithm for tuning the coefficients of a PID controller is an effective way to improve its performance GWO is a powerful meta-heuristic optimization technique that takes its inspiration from the hunting behavior of grey wolves in real world. This allows it to quickly find optimal solutions through exploration and exploitation techniques, which are highly beneficial when used with PID controllers see Figure 4.

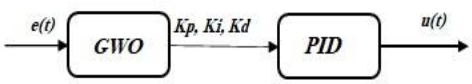

Figure 4. Proposed approach

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 Figure 5.

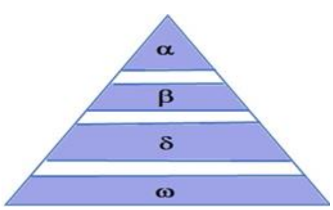

Figure 5. GWO hierarchical structure

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

1- Define the transfer function of the converter.
2- Define controllers coefficients (K_p, K_i, K_d);
3- Define GWO parameters.
4- Initialize the population.
5- Initialize the alpha, beta, and delta values.
6- Initialize the positions of the alpha, beta, and delta wolves.
7- Iterate for a fixed number of iterations.
8- Update the positions of the wolves.
9- Compute the fitness value for the current position.
10- Update the positions of the rest of the wolves.
11- Compute the new position of the wolf.
12- Update the position of the wolf.
13- Find the final solution is the position of the alpha wolf.

The mathematical representation of the GWO can be calculated utilizing the equation [15]:

$$\begin{aligned} \vec{X}_a &= \vec{X}_\alpha - \left(\left(\vec{D}_\alpha\right) \times \left(\vec{A}\right)\right); \\ \vec{X}_b &= \vec{X}_\beta - \left(\left(\vec{D}_\beta\right) \times \left(\vec{A}\right)\right); \\ \vec{X}_c &= \vec{X}_\delta - \left(\left(\vec{D}_\delta\right) \times \left(\vec{A}\right)\right); \end{aligned} \tag{4}$$

$$\begin{aligned} \vec{D}_\alpha &= \left|\left(\vec{C}\right) \times \left(\vec{X}_\alpha - \vec{X}\right)\right|; \\ \vec{D}_\beta &= \left|\left(\vec{C}\right) \times \left(\vec{X}_\beta - \vec{X}\right)\right|; \\ \vec{D}_\delta &= \left|\left(\vec{C}\right) \times \left(\vec{X}_\delta - \vec{X}\right)\right|; \end{aligned} \tag{5}$$

$$\begin{aligned} &\vec{A} = 2\vec{a} \cdot \vec{r}_1 - \vec{a}; \\ &\vec{C} = 2\vec{r}_2; \\ &\vec{a} : (2 \rightarrow 0) \\ &\vec{r}_1, \vec{r}_2 : \end{aligned} \tag{6}$$

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

The Pseudo code of the GWO:

```
function [Kp, Ki, Kd] = gwo_pid(y, u, dt);
X = rand(n, 3); % n is the population size
alpha = rand;
beta = rand;
delta = rand;
pos_alpha = X(1, :); % Position of alpha wolf
pos_beta = X(2, :); % Position of beta wolf
pos_delta = X(3, :); % Position of delta wolf
for iter = 1:max_iter
      for i = 1:n
      Kp = X(i, 1);
      Ki = X(i, 2);
      Kd = X(i, 3);
      J = pid_fitness(y, u, Kp, Ki, Kd, dt);
      if J > fitness(pos_alpha) % Update alpha wolf
         pos_alpha = X(i, :);
      elseif J > fitness(pos_beta) % Update beta wolf
         pos_beta = X(i, :);
      elseif J > fitness(pos_delta) % Update delta wolf
         pos_delta = X(i, :);
      end
   end
   for i = 1:n
      A = 2 * alpha * rand - alpha;
      C = 2 * rand;
      new_pos = pos_alpha - A * (pos_alpha - X(i, :));
      if C > 1
         new_pos = pos_beta - A * (pos_beta - X(i, :));
      end
      if C > 2
         new_pos = pos_delta - A * (pos_delta - X(i, :));
      end
      X(i, :) = new_pos;
   end
end
Kp = pos_alpha(1);
Ki = pos_alpha(2);
Kd = pos_alpha(3);
end
```

```
function J = pid_fitness(y, u, Kp, Ki, Kd, dt)
```

3- Simulation Results:

The simulation process is powered by **Table 1**, which outlines the components of converter values.

Table 1. Components value [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

This process is divided into three scenarios: the first one without a P-I-D controller Figure 6, 7, the second one with a P-I-D controller based on the Z-N method Figure 8, 9,, and the third one using a P-I-D controller and GWO Figure 10,11.

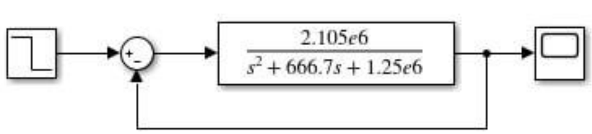

Figure 6 Model of first case.

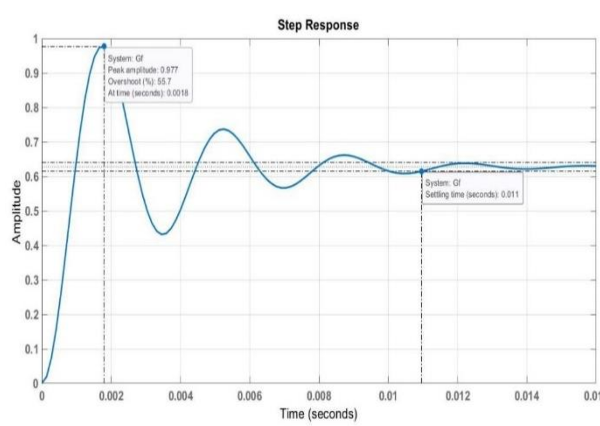

Figure 7. Simulation of first case.

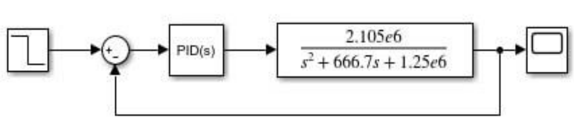

Figure 8. Model of second case.

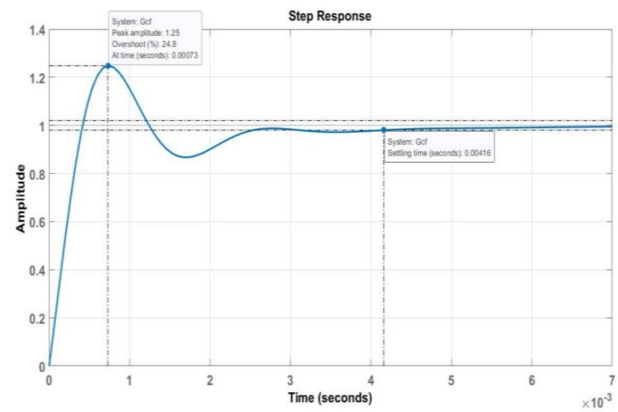

Figure 9. Simulation of second case.

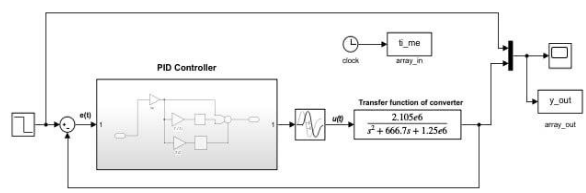

Figure 10. Simulation of third case.

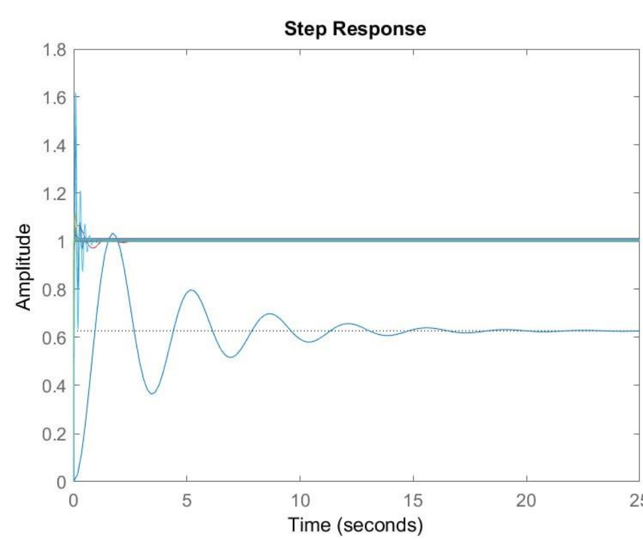

Figure 11. Simulation of proposed system

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.

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:

PID controllers are an ubiquitous control solution, widely used for their straightforward architecture, reliable control performance, and user-friendliness. They require no deep understanding of mathematics, control theory, or electrical engineering and can be applied in a broad range of applications. With proper tuning, PID controllers outperform any other control option and provide the greatest performance gains. In this paper the GWO is used as tuning method for the PID coefficients.

The designed PID controller using 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. Among the many optimization tools available, GWO is a recent and efficient choice.

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