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Grey Wolf Optimization of Fractional PID controller in Gas Metal Arc Welding process.

Sami Kahla[1, 2], Amar Boutaghane[1], Lemita Abdallah[2], Said Dehimi[1], Noureddine Hamouda[1], Badreddine Babes[1], Rachid Amraoui[1] .

[1]Research Center in Industrial Technologies, CRTI, P.O. Box 64, 16014 Cheraga, Algiers, Algeria.
[2] Department of Electronics, Faculty of Engineering, University of Setif, 19000 Setif, Algeria.
s.kahla@crti.dz, a.boutaghane@crti.dz, abdallahlemita@yahoo.fr, s.dehimi@crti.dz, n.hamouda@crti.dz , b.babes@crti.dz, r.amraoui@crti.dz

Abstract— **Gas metal arc welding (GMAW) plays the great importance in the welding industry. This paper presents a grey wolf optimization (GWO) of fractional PID controller in order to optimize arc length and arc current in the GMAW process. Firstly, fractional PID control of gas metal arc welding system is proposed, wherein the arc length and current of welding process are controlled, then the Grey Wolf Optimization is introduced to solve multi-objectives functions of GMAW in order to find the optimal parameters of fractional PID controller. The obtained results are compared with those given by fractional PID controller in which our proposed method can ensure a better dynamic behavior of the GMAW process.**

Keywords— **GMAW, MIMO system, GWO, Fractional PID controller**

I. Introduction

Welding is an assembly technique used in the most industrial sectors. It is a multidisciplinary technique mobilizing a large number of phenomena [1]. Several welding processes can be classified in the industrial manufacturing. The GMAW process proved to be faster, especially on thicker materials. Today this welding process is indispensable in the production industry in series of components in particular robotized [2]. There are many advantages in the welding by gas metal arc welding process, such as the high productivity, high welding speed, wide range of thickness and both manual and automatic process[3].

In order to evaluate and ensure the weld quality in the GMAW process, arc length and current are important controlled variables. These two variables of welding is determined by several characteristics such as the transfer mode of melting droplets and the weld geometry [4], in this reason the control of the GMAW process can be separated into weld pool control and arc control [5]. Previous studies for the GMAW process have been implemented to control the arc length and current; in [6, 7, and 8] a controller design has already been combined with feedback linearisation technique using an additional feedback signal where non linearities are cancelled and the linearised strategy is managed by (PI) controller. A similar strategy with sliding mode control has been applied to ensure robustness in [9]. Thomsen proposed a control system for manual pulsed gas metal arc welding. The particular arc length controller is dependent on a non-linear SISO model of the arc length process and uses feedback linearization approach [10].

Khatamianfar et al are proposed a novel application of sliding control in the manual gas metal arc welding process; Arc length is controlled successfully by the robust control system with combined the feedback linearization technique and sliding mode control [11].Golob. M [12] combined a full-bridge inverter circuit together with the GMAW model.

Recently, a fractional order controller $PI^{\lambda}D^{\mu}$ which is a generalization of the classical PID controller have received great attention technique of robust controllers for complex nonlinear dynamic systems operating under uncertain conditions [13, 14].

In the past decade there has been an increasing research to developing tuning methods for $PI^{\lambda}/PI^{\lambda}D^{\mu}$ controllers [15, 16 and 17].

In order to control the GMAW process, the control objective can be formulated as an optimization problem, and there is a certain difficulty about the tuning methods for $PI^{\lambda}D^{\mu}$ controllers, concerning the definition of the controller parameters.

The optimization problems can be solved using meta-heuristic optimization methods. Some of these approaches include genetic algorithm (GA) [18], bacterial foraging (BF) [19], gravitational search algorithm (GSA) [20], and particle swarm optimization (PSO) [21].

Grey Wolf Optimization (GWO) is recently developed meta-heuristics algorithm simulates hunting mechanism of gray wolves in nature proposed by Mirjalili et al. [22].GWO has been successfully applied for solving the engineering optimization problems [23,24].

This paper studies the GMAW arc self-regulating process utilizing a nonlinear mathematical state space model of the process. In addition, a fractional order controller $PI^{\lambda}D^{\mu}$ is designed to control the wire feed speed and open circuit voltage.

This paper is organized as follows: First in section 1, the mathematical modeling of a GMAW process is presented and, then in section 2, the control objective is discussed. Subsequently, a fractional order controller $PI^{\lambda}D^{\mu}$ is designed. Applications of the fractional order control to the GMAW process and simulation results are given in the section 3.Finaly, the conclusions are drawn.

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II. Modeling of the GMAW process

The schematic diagram of the GMAW system is illustrated in the Figure 1. The power source consists of a constant voltage source connected to the electrode and the work piece. The wire speed, S, travel speed of the torch, R, open circuit voltage Voc, and contact tip to work piece distance, CT, are adjusted to get the desired weld. The model used in this work is the fourth-generation of the derivative equation that originated at the Idaho National Engineering and Environmental Laboratory (INEEL) [25, 26].

The main parts of the model will be presented as follows. Basically, the important aspects with respect to control are the electrical circuit, the drop dynamics, the drop detachment criteria and the melting rate.

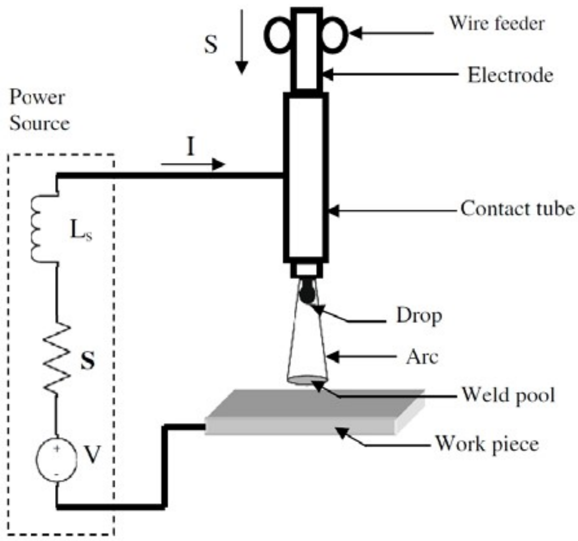

Figure 1.Schematic diagram of GMAW system.

The current is obtained from a simple electrical circuit as [27]:

$$\dot{I} = \frac{V_{oc} - R_L I - V_{arc} - R_s I}{L_s} \quad (1)$$

$$V_{arc} = V_o + R_a I + E_a (CT - l_s) \quad (2)$$

$$R_L = \rho\left[l_s + \frac{1}{2}(r_d + x_d)\right] \quad (3)$$

The pendant drop attached to the tip of the electrode can be modelled as a mass-spring-damper system as described by [28] and Wu et al given by the following equation:

$$m_d \ddot{x}_d = F_T - b_d \dot{x}_d - k_d x_d \quad (4)$$

Where F_T is the total external force affecting the droplets is as follows:

$$F_T = F_g + F_{em} + F_d + F_m \ (5)$$

Where F_g, F_{em}, F_d and F_m are the gravity force, electromagnetic force, plasma drag force, and momentum flux force, respectively. The gravity force F_g is defined as

$$F_g = m_d \quad (6)$$

Whereg is the gravity and m_d is the mass of the droplet, which can be computed in terms of the droplet radius r_d (Fig. 2). It is assumed that the droplets have a spherical shape.

$$m_d = \frac{4}{3}\pi \rho_e r_d^3 \quad (7)$$

ρ_e describes the density of the liquid electrode material. Considering uniform distributed current and a spherical droplet with a radius larger than the solid electrode, the electromagnetic force F_{em} can be written as

$$F_{em} = \frac{\mu_0 I^2}{4\pi}\left[\ln\left(\frac{r_d \sin\theta}{r_e}\right) - \frac{1}{4} - \frac{1}{1-\cos\theta} + \frac{2}{(1-\cos\theta)^2}\ln\left(\frac{2}{1+\cos\theta}\right)\right] \quad (8)$$

Where μ_0 is the permeability of free space, I is the welding current, θ is the angle of the arc-covered area, and r_e is the radius of the electrode (Fig. 2). The plasma drag force F_d is determined as follows.

$$F_d = 0.5\left(c_d A_d \rho_p v_p^2\right) \quad (9)$$

Where c_d is the drag coefficient, ρ_p is the density of the plasma, v_p is the shielding gas velocity, and A_d is the area of droplet hit by the shielding gas

$$A_d = \pi(r_d^2 - r_e^2) \quad (10)$$

The momentum flux F_m is determined as follows [29].

$$F_m = \frac{\mu_0}{4\pi}\left(\left(\frac{I}{\sigma}\right)^2 - I_2\right) \quad (11)$$

Whereσ is defined as r_d/r_e and I_2 is determined as

$$I_2 = \int J_0 dA_d \quad (12)$$

$J_0$is the uniform current density on the arc covered area of the drop surface (Fig. 2).

The melting rate M_R is expressed by the following equation:

$$M_R = C_2 I_a^2 \rho l_s + C_1 \quad (13)$$

The stick-out evolution is controlled by

$$\frac{dl_s}{dt} = S - \frac{M_R}{\pi r_e^2} \quad (14)$$

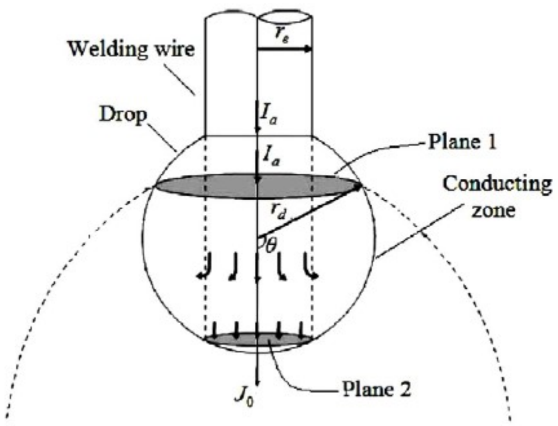

Figure 2.Schematic diagram of droplet and electrode.

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The state-space representations of the resulting equation are given in the following equations. Firstly, the state variables are defined as:

$x_1 = x_d$ Droplet displacement (m).
$x_2 = \dot{x}_d$ Droplet velocity (m/sec).
$x_3 = m_d$ Droplet mass (kg).
$x_4 = l_s$ Stick-out (m).
$x_5 = I$ Current (A).

Where x_d is the distance of the center of the mass of the droplet above the work piece.

Then the nonlinear state equations can be written as follows:

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= \frac{-kx_1 - Bx_2 + F_T}{x_3} \\ \dot{x}_3 &= M_R \rho_e \\ \dot{x}_4 &= u_1 - \frac{M_R}{\pi r_e^2} \\ \dot{x}_5 &= \frac{u_2 - (R_a + R_s + R_L)x_5 + V_0 - E_a(CT - x_4)}{L_s} \end{aligned} \quad (15)$$

Where k and B are the spring constant and damping coefficient of the droplet. R_a and R_s are the arc resistance and source resistance, respectively. ρ_e is the electrode density, V_0 is the arc voltage constant, E_a is the arc length factor and L_s is the source inductance.

The output equations are given by the following equations:

$$\begin{aligned} y_1 &= x_4 \\ y_2 &= x_5 \end{aligned} \quad (16)$$

And the control variables are

$u_1 = S$ Wire feed speed (m/sec),
$u_2 = V_{oc}$ Open-circuit voltage (V).

States of the system must be reset after each detachment of a drop, which means:

$$F_T > F_s \quad (17)$$

Or

$$r_d > \frac{\pi(r_d + r_e)}{1.25\left(\frac{x + r_d}{r_d}\right)\left(1 + \frac{\mu_0 I^2}{2\pi^2\gamma(r_d + r_e)}\right)^{\frac{1}{2}}} \quad (18)$$

Where:

$$r_d = \left(\frac{3x_5}{4\pi\rho_w}\right)^{\frac{1}{3}} \quad (19)$$

And F_s is the surface tension of the droplet given as:

$$F_s = 2\pi\gamma r_e \quad (20)$$

Where γ is the surface tension of liquid steel [23].

The GMAW dynamics model, given by Equations (1), is highly nonlinear. Based on some approximations the simplified model of GMAW is [25]:

$$\begin{aligned} \dot{x}_4 &= u_1 - \left(\frac{C_2\rho}{\pi r_e^2} x_4 x_5^2 + \frac{C_1}{\pi r_e^2} x_5\right) \\ \dot{x}_5 &= \frac{u_2 - (R_a + R_s + \rho x_4)x_5 + V_0 - E_a(CT - x_4)}{L_s} \end{aligned} \quad (21)$$

Tab. 1 gives the numerical data for the nonlinear model parameters.

Table 1.Parameters and variables of the GMAW process

Nomenclature	Symbol	Value (unit)
Source resistance	R_s	6.8×10^{-3} (Ω)
Source inductance	L_s	306×10^{-6} (H)
Arc resistance	R_a	0.0237 (Ω)
Arc length factor	E_a	400 ($V\,m^{-1}$)
Contact tip to work piece distance	l_c	0.025 (m)
Arc voltage constant	V_0	15.5 (V)
Permeability of free space	μ_0	$4\pi \times 10^{-7}$ ($H\,m^{-1}$)
Gravity	g	9.8 ($m\,s^{-2}$)
Spring constant of drop	k_d	3.5 ($kg\,s^{-2}$)
Damper constant of drop	b_d	0.8×10^{-3} ($kg\,s^{-1}$)
Density of the liquid electrode material	ρ_e	7860 ($kg\,m^{-3}$)
Electrode radius	r_e	0.006 (m)
Shielding gas velocity	v_p	10 ($m\,s^{-1}$)
Density of the plasma	ρ_p	1.784 ($kg\,m^{-3}$)
Drag coefficient	c_d	0.44
Melting rate constant 1	c_1	3.3×10^{-10} ($m^3\,s^{-1}\,A^{-1}$)
Melting rate constant 2	c_2	0.78×10^{-10} ($m^3\,s^{-1}\,\Omega^{-1}\,A^{-2}$)
Surface tension of liquid steel	γ	1.3 ($N\,m^{-1}$)

III. Grey wolf optimization of fractional order PID controller of MIMO GMAW process

A. *Basic definitions of fractional calculus*

The generalized derivative operator or the continuous integro-differential operator is defined as follows [30]:

$$D_t^m = \begin{cases} \frac{d^m}{dt^m} & \Re(m) > 0 \\ 1 & \Re(m) = 0 \\ \int (d\tau)^{-m} & \Re(m) < 0 \end{cases} \quad (22)$$

The commonly used definitions in literatures are Grunwald-Letnikov, Riemann-Liouville, and Caputo definitions. In the literature we find different definitions of fractional differ-integral, but the commonly used are:

The Riemann– Liouville definition of order $\alpha \in \mathbb{R}^+$ has the following form:

$$D_t^\alpha f(t) = \frac{1}{\Gamma(m-\alpha)}\left(\frac{d}{dt}\right)^m \int_0^t \frac{f(\tau)}{(t-\tau)^{1-(m-\alpha)}} d\tau \quad (23)$$

Γ (.) represents the Euler's Gamma function expressed by the following equation:

$$\Gamma(x) = \int_0^\infty e^{-t} t^{(x-1)} dt, \quad x > 0 \quad (24)$$

The definition of the fractional order derivative introduced by Caputo is given by

$$D_t^\alpha f(t) = \frac{1}{\Gamma(m-\alpha)} \int_0^t \frac{f^m(\tau)}{(t-\tau)^{1-(m-\alpha)}} d\tau \quad (25)$$

Where α is the fractional order, and m is an integer satisfying $m - 1 < \alpha < m$ and

Due to its importance in applications, we will consider here the Grunwald– Letnikov's definition, based on the generalization of the backward difference. This definition has the form:

$$D_t^\alpha f(t) = \lim_{h\to0} \frac{1}{h^\alpha} \sum_{k=0}^{(t-\alpha)/h} (-1)^k \binom{\alpha}{k} f(t - kh) \quad (26)$$

B. *Fractional PID controller*

The fractional $PI^\lambda D^\mu$ corrector is a generalization of the classical PID corrector. Her Transfer function is given by :

$$G_c(s) = K_p + T_i s^{-\lambda} + T_d s^\mu \quad (27)$$

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With $\lambda > 0$ and $\mu > 0$ are respectively the integration and derivation orders. In the plane (λ, μ), the classical PID is represented by a single point corresponding to $\lambda = 1$ and $\mu = 1$; On the other hand, the fractional corrector $PI^{\lambda}D^{\mu}$ is represented by an infinity of points of the first dial of the plane (λ, μ) as shown in Figure 3.

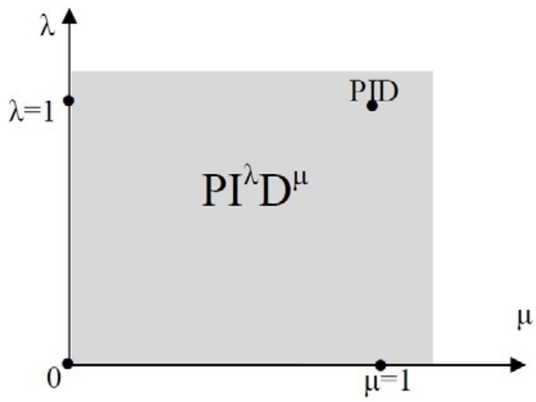

Figure 3.Closed loop control process with fractional $PI^{\lambda}D^{\mu}$ controller.

C. *Grey wolf optimization Fractional PID controller*

The two parameters λ and μ make it possible to have an infinity of possibility of the corrector for the improvement of the closed-loop system. To see the effects of the five parameters (K_p, T_i, T_d, λ and μ) of the corrector $PI^{\lambda}D^{\mu}$ on its temporally response, Grey wolf optimization is proposed methods for solving optimization problems. The GWO algorithm simulates the natural behavior of a group of wolves to hunt their prey [22]. Within the different wolves categories like alpha, beta, delta and omega are distinguished for the simulation. The mechanism that follows is simple. The first group of alpha wolves are the leaders of the pack and, therefore, influence in a more forceful way in the search space. At the end of the execution, the best individual is going to be the one associated with the alpha wolf. The Fundamental stages of grey wolf hunting are tracking, chasing, pursuing, encircling, and attacking the prey.

Firstly, the following equations are proposed for the modeling of encircling the prey [22]:

$$\vec{D} = \left|\vec{C}.\vec{X}_p^t - \vec{A}.\vec{X}^t\right| \quad (28)$$

$$\vec{X}^{t+1} = \vec{X}_p^t - \vec{A}.\vec{D} \quad (29)$$

Where t is the current iteration, $\vec{X}_p$ is the position vector of the prey, and $\vec{X}$ indicates the position vector of a grey wolf. $\vec{A}$ and $\vec{C}$ are vectors that have three different random numbers and that help the candidate solutions by moving them into the search spacecalculated as follows:

$$\vec{A} = 2\vec{a}.\vec{r}_1 - \vec{a} \quad (30)$$

$$\vec{C} = 2.\vec{r}_2 \quad (31)$$

The parameter $\vec{a}$ is the exploration factor that starts with a value of 2 and decreases over the course of iterations until it reaches 0 and r_1, r_2 are random vectors in [0, 1].

The position of the best search agents can be calculated by the following equations:

$$\begin{cases} \vec{D}_\alpha = \left|\vec{C}_1.\vec{X}_\alpha - \vec{X}\right| \\ \vec{D}_\kappa = \left|\vec{C}_2.\vec{X}_\kappa - \vec{X}\right| \\ \vec{D}_\delta = \left|\vec{C}_3.\vec{X}_\delta - \vec{X}\right| \end{cases} \quad (32)$$

$$\begin{cases} \vec{X}_1 = \vec{X}_\alpha - \vec{A}_1.\vec{D}_\alpha \\ \vec{X}_2 = \vec{X}_\kappa - \vec{A}_2.\vec{D}_\kappa \\ \vec{X}_3 = \vec{X}_\delta - \vec{A}_3.\vec{D}_\delta \end{cases} \quad (33)$$

$$\vec{X}(t+1) = \frac{\vec{X}_1 + \vec{X}_2 + \vec{X}_3}{3} \quad (34)$$

When $|A| < 1$, the wolves attack towards the prey, which represents an exploitation process.

The overall optimization of the control structure is illustrated by Fig.4 while the optimization model for $PI^{\lambda}D^{\mu}$ parameters is developed as follows:

$$\text{Minimize} \begin{cases} \text{Fit1} = \frac{1}{n_1 T_s}\sum_{l=1}^{n_1}(l_{s\_ref}(k_1) - l_s(k_1)) \\ \text{Fit2} = \frac{1}{n_2 T_s}\sum_{l=1}^{n_2}(I_{ref}(k_2) - I(k_2)) \end{cases} \quad (35)$$

Where: T_s is the sampling time.

Numerical values for the parameters of the Grey wolf optimization are given in Tab.2.

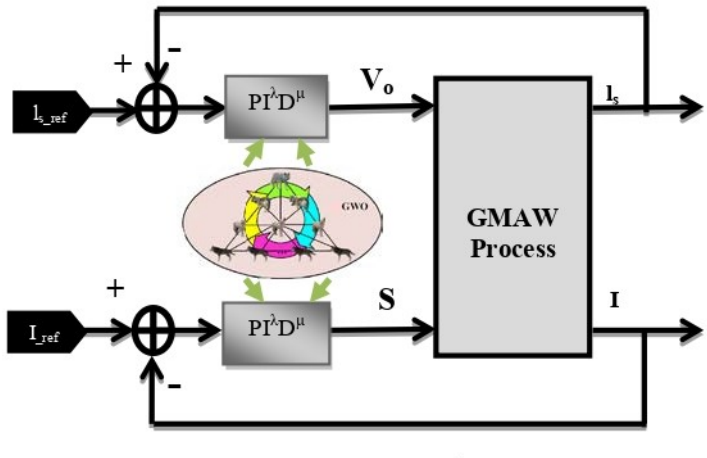

Figure 4.GWO based fractional order $PI^{\lambda}D^{\mu}$ controller of MIMO GMAW process.

Table 2.GWO parameters.

Parameters	Values
Number of search agents	25
Maximum number of iterations	100

IV. Process Simulation and Results

The simulation results are carried-out using the *Matlab/ Simulink* software.

Fig.5 compares the curves of arc current given by the fractional PID controller and the GWO based fractional PID controller of the welding current variation range (180–250 A).

According to Fig.5, it is easy to observe that the response given by optimized fractional PID controller and the

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reference arc current are matched as close as possible in each time point.

Under the same conditions as in the previous simulation, Fig. 6 shows the results when the stick -out was controlled with the different controller in the welding stick -out range (1mm-11mm). The effectiveness of the fractional PID controller is clearly illustrated and the system tracks the desired response quickly.

To confirm this above result, Fig.7 compares the open circuit voltage curves of previous controllers. However, Fig.8 compares both obtained melting rate by the standard and optimized fractional PID controllers.

According to Fig.7 and Fig.8, the proposed controller ensures the better minimization of the discrepancy and shows satisfactory robustness of the system under the mechanical parameters uncertainty.

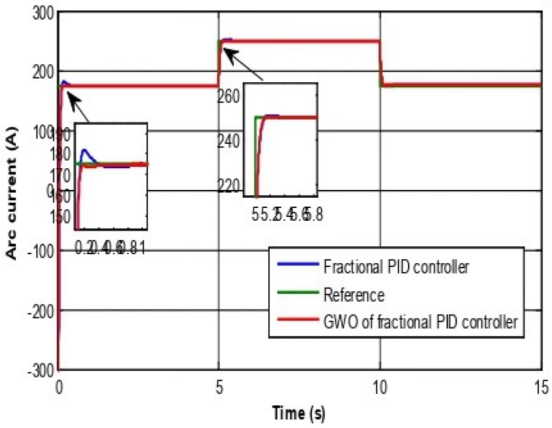

Figure 5.Current response with different controller

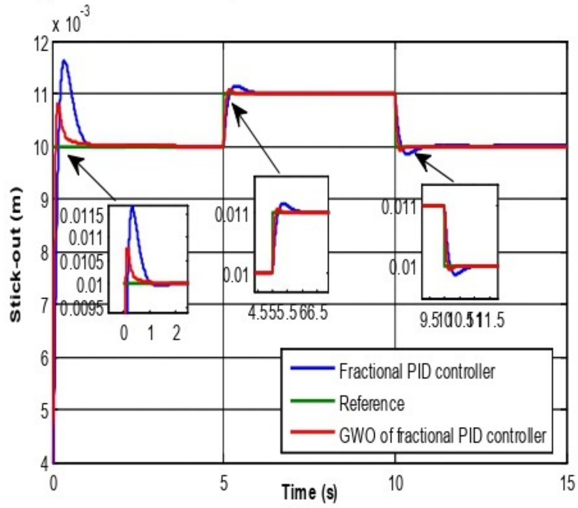

Figure 6.Stick-out response with different controller

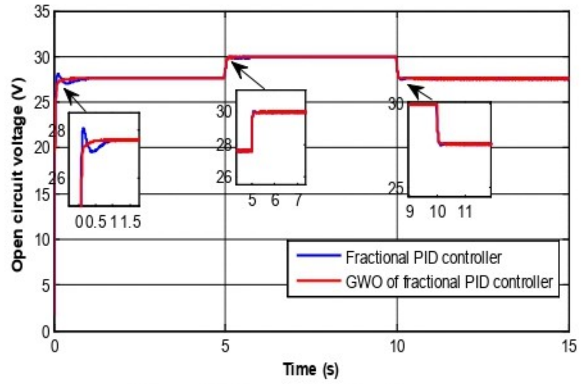

Figure 7.Open circuit voltage

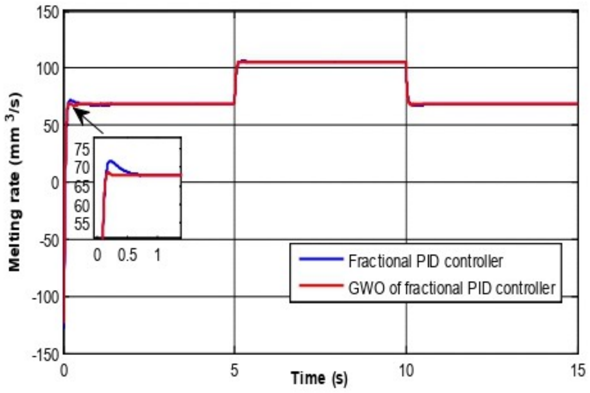

Figure 8.Melting rate response with different controller

V. Conclusions

In this paper, a method to optimize arc length and arc current in a GMAW process was proposed. This method called Grey wolf optimization to find the optimal parameters of the fractional PID controller. Firstly, the different parts of the proposed GMAW have been modeled separately and the fractional PID controller aims at controlling arc length and arc current of a nonlinear gas metal arc welding. Based on two objectives criteria in order to optimized the arc length and arc current, GWO is employed to selection the controller parameters .The obtained results of the proposed method compared with fractional PID controller was really encouraging in the application of GMAW process in order to ensure the robustness of the process.

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