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Stability analysis and internal dynamics of MIMO GMAW process

Mohammad Eghtesad*,Yousef Bazargan-Lari, Babak Assadsangabi*****

**Mechanical Engineering Department, Shiraz University, Shiraz, Iran (e-mail:eghtesad@shirazu.ac.ir)*
*** Mechanical Engineering Department, Islamic Azad University of Shiraz,Shiraz,Iran(e-mail:iman_bl@yahoo.com)*
****Mechanical Engineering Department, Shiraz University, Shiraz, Iran,*
(e-mail: babakbowo@yahoo.com)

Abstract: In this paper, stability and internal dynamics for a gas metal arc welding (GMAW) process will be studied. GMAW process is considered as a nonlinear MIMO system and input-output feedback linearization method will be applied for control purposes. Internal dynamics is the unobservable part of the system dynamics; its stability analysis is a vital step in the investigation of the system stability as a whole. Also, drop detachment dynamics, will be considered here by tracking a saw-toothed arc length voltage Simulations results are presented to illustrate the system performance.

1. INTRODUCTION

There exists a wide variety of welding processes. Each one represents some advantages and is usually best suited for a particular type of operation. The GMAW process is the most wide spread one because of its low initial cost and high productivity. The process can be performed either automatically or manually. Due to the nature of the process which needs many parameters to be adjusted to give a good quality weld, even an experienced welder can fail to produce a weld with the desired level of accuracy in a short period of time. Also, presence of toxic fumes and gasses produced during the welding process can be hazardous to the welder. Considering these issues and with the growing request for faster, safer and more accurate production procedures, control and automation of the GMAW process seems to be inevitable. The control area itself can be directed into many subjects such as control of the weld pool, arc length and the electrode. This paper concentrates on the control and stabilization of the arc length which can be related to the quality of the weld; to achieve this goal the electrode melting rate must be controlled. Because of the nonlinear nature of the melting process, the controller must be able to handle nonlinearities.

Arc length control can be performed by a PI control strategy as reported in (Naidu *et al.*, 1998), another linear control strategy is reported in (Zhang *et al.*, 2002), in which robustness is also considered. Basically using linear control strategies has the difficulty of tuning the controllers over a range of operating points and also some kind of gain scheduling must be implemented; but, this is not the case for the controller proposed in this paper .In (Thomsen, 2005), the GMAW process was considered as a nonlinear SISO system and a feedback linearization controller was proposed. In (AbdelRahman., 1998), (Naidu *et al.*, 1999), (Moore *et al.*, 2003), the GMAW process is considered as a nonlinear MIMO system and nonlinearities are canceled using an additional feedback signal for each control input but these works neglected the internal dynamics associated with the MIMO system and only set point regulation problem was considered that did not include drop detachment dynamics. To achieve robustness sliding mode control also been suggested in (Ebrahimirad *et al.*, 2003). In this paper an input-output feedback linearization controller will be designed by carefully investigating the stability of the whole system dynamics and particularly its internal dynamics which will be justified by considering mass rate of vaporizing electrode. Also to include the drop detachment dynamics and improve the performance of the arc length controller, a saw-toothed arc length voltage reference will be tracked.

2. THE GMAW PROCESS

Gas metal arc welding (GMAW), by definition, is an arc welding process which produces the coalescences of metals by heating them with an arc between a continuously fed filler metal electrode and the work. The process uses shielding from an externally supplied gas to protect the molten weld pool. The application of GMAW generally requires DC + (reverse) polarity to the electrode.

The reasons for accepting GMAW for almost all industrial applications are due to its versatility and advantages:

- GMAW process is easily adapted for high-speed robotic, hard automation and semiautomatic welding applications.
- Lower heat input when compared to other welding processes.
- Generally, lower cost per length of weld metal deposited when compared to other open arc welding processes.

3. MATHEMATICAL MODEL OF GMAW PROCESS

Detailed discussion for deriving the state-space equations of the GMAW process is given in (AbdelRahman., 1998) and the result is adopted here. The GMAW process can be

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approximated by the following model:

$$\dot{x}_1 = x_2 \tag{1}$$

$$\dot{x}_2 = \frac{-Kx_1 + Bx_2 + F_{tot}}{x_3} \tag{2}$$

$$\dot{x}_3 = M_R\rho_w + M_{ve} \tag{3}$$

$$\dot{x}_4 = u_1 - \frac{M_R}{\pi r_w^2} \tag{4}$$

$$\dot{x}_5 = \frac{u_2 - (R_a + R_s + R_L)x_5 - V_o - E_a(CT - x_4)}{L_s} \tag{5}$$

where state variables are :

$x_1 = x : droplet\ displacement - m$
$x_2 = \dot{x} : droplet\ velocity - \frac{m}{sec}$
$x_3 = m_d : droplet\ mass - Kg$
$x_4 = l_s : stick-out - m$
$x_5 = I : current - A$
and,

$$M_R = C_2\rho_w x_5^2 + C_1 x_5 \tag{6}$$

$$M_{ve} = a\ constant\ mass\ rate\ of\ vaporizing\ electrode \tag{7}$$

$$R_L = \rho\left[M_R + 0.5\left(\left(\frac{3x_3}{4\pi\rho_w}\right)^3 + x_1\right)\right] : electrode\ resistance \tag{8}$$

The output equations are:

$$y_1 = V_{arc} = V_o + R_a x_5 + E_a(CT - x_4) \tag{9}$$

$$y_2 = I = x_5 \tag{10}$$

where, the output variables are:

$y_1 = V_{arc}: arc\ voltage - volts$
$y_2 = I : current - A$

and the control variables are:

$u_1 = S: wire\ feed\ speed - m/sec$
$u_2 = V_{oc}: open-circuit\ voltage - volts$

The above model of the GMAW process can be written in the affine form:

$$\dot{x} = f(x) + g(x)u \tag{11}$$

$$y = h(x) + i(u) \tag{12}$$

Until here we only considered dynamics of the process before detachment; to find out when drop detachments occur the following criteria is used(Agarwala, 2000):

$$r_d > \frac{\pi(r_d + r_w)}{1.25\left(1 + \frac{x}{r_d}\right)\left(1 + \frac{\mu I^2}{2\pi^2\gamma(r_d + r_w)}\right)^{0.5}} \tag{13}$$

where,
$r_d : droplet\ radius - m$
$r_w : electrode\ radius - m$
$\gamma : surface\ tension\ of\ liquid\ steel - 2\ \frac{N}{m^2}$

Cycles of detachment are shown in simulation results Fig. 10. Variables used in the equations are illustrated in Fig. 1.

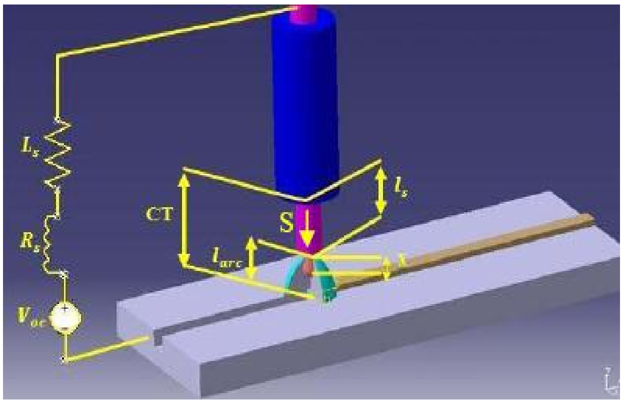

Fig. 1. Variables used in the GMAW modeling.

4. INPUT-OUTPUT FEEDBACK LINEARIZATION

By input-output linearization it is meant the generation of a linear differential relation between the output y and a new input v (Slotine *et al*., 1991). Given the nonlinear system in (11) and (12), input-output linearization of the system is obtained by first differentiating the output y_i until all the inputs appears. Assume that r_i is the smallest integer such that at least one of the inputs appears in $y_i^{r_i}$, then,

$$y_i^{r_i} = L_f^{r_i} h_i + \sum_{j=1}^{m} L_{g_j} L_f^{r_i - 1} h_i u_j \tag{14}$$

with $L_{g_j} L_f^{r_i-1} h_i(x) \neq 0$ for at least one output . Performing the above procedure for each output , y_i ,yields:

$$\begin{bmatrix} y_1^{r_1} \\ \cdots \\ \cdots \\ y_m^{r_m} \end{bmatrix} = \begin{bmatrix} L_f^{r_1} h_1 \\ \cdots \\ \cdots \\ L_f^{r_m} h_m \end{bmatrix} + E(x)u \tag{15}$$

where,
$L_f h = \nabla h . f$
$h: \mathbb{R}^n \to \mathbb{R}$ be a smooth scalar function
$f: \mathbb{R}^n \to \mathbb{R}^n$ be a smooth vector field on $\mathbb{R}^n$
and the $m \times m$ matrix $E(x)$ is systematically obtained during taking the derivatives of the outputs.

If, as assumed above, the partial relative degrees (relative degree of a nonlinear system is equal to required number of differentiation of the output of a system to generate an explicit relationship between the output y and input u) r_i are all well defined, then Ω is a finite neighborhood of x_0. Furthermore, if $E(x)$ is invertible over the region Ω, then, input transformation is:

$$u = E^{-1} \begin{bmatrix} v_1 - L_f^{r_1} h_1 \\ \cdots \\ \cdots \\ v_m - L_f^{r_m} h_m \end{bmatrix} \tag{16}$$

which yields m equations of the simple form

$$y_i^{r_i} = \nu_i \tag{17}$$

Since the input ν_i only affects the output y_i as in (17), it is called a *decoupling control* law, and the invertible matrix $E(x)$ is called the *decoupling matrix* of the system.
The system (11), (12) is then said to have relative degrees $(r_1, r_2, \dots r_m)$ at x_0, and the scalar $r = (r_1 + r_2 + \cdots r_m)$ is called the total relative degree of the system at x_0.

4.1 Internal dynamics

When input-output linearization method is performed, the dynamics of nonlinear system is decomposed into an external (input-output) part and an internal (unobservable) part. Since the external part consists of a linear relation between y and ν (or equivalently the controllability canonical form between y and u) , it is easy to design input ν so that the output y behaves as desired. Then the question is whether the internal dynamics will also behave well, i.e. whether the internal dynamics will remain bounded. Since the control design must account for the whole dynamics, the internal behavior is to be addressed carefully.

4.2 Controller design

To apply the input - output feedback linearization procedure the output is differentiated until the inputs are all appeared in the outputs or its derivatives:

$$\dot{y}_1 = -E_a u_1 + \frac{R_a u_2}{L_s} + \frac{R_a(-V_0 - E_a(CT - x_4) + (-R_a - R_s - \rho x_4)x_5)}{L_s} - \frac{E_a(-C_1 x_5 - \rho C_2 x_4 x_5^2)}{\pi r_w^2} \tag{18}$$

$$\dot{y}_2 = \frac{u_2}{L_s} + \frac{-V_0 - E_a(CT - x_4) + (-R_a - R_s - \rho x_4)x_5}{L_s} \tag{19}$$

$$E = \begin{bmatrix} -E_a & \dfrac{R_a}{L_s} \\ 0 & \dfrac{1}{L_s} \end{bmatrix} (which\ is\ invertible) \tag{20}$$

As it can be seen from the above equations, the total relative degree of the system is equal to 2. So the system has 2 external dynamic state variables (x_4, x_5) and 3 internal dynamic state variables (x_1, x_2, x_3). Then the inputs can be calculated according to (16) to be:

$$u_1 = \frac{R_a(-V_0 - E_a(CT - x_4) + (-R_a - R_s - \rho x_4)x_5)}{L_s E_a} - \frac{E_a(-C_1 x_5 - \rho C_2 x_4 x_5^2) + \nu_1}{\pi r_w^2 E_a} + R_a\left(\frac{-V_0 - E_a(CT - x_4) + (-R_a - R_s - \rho x_4)x_5}{L_s E_a} + \frac{\nu_2}{E_a}\right) \tag{21}$$

$$u_2 = L_s\left(\frac{-V_0 - E_a(CT - x_4) + (-R_a - R_s - \rho x_4)x_5}{L_s} + \nu_2\right) \tag{22}$$

The above inputs transform the output equations to the simple form of (17) and external dynamics can be easily controlled by linear techniques.

4.3 Zero-Dynamics Stability Investigation

To investigate the stability of the internal dynamics an intrinsic property of the nonlinear system is defined by considering the system's internal dynamics when the control inputs are such that the outputs y_i are maintained at zero. Since for linear systems the stability of the internal dynamics is simply determined by the location of the zeros, this relation can be used for nonlinear systems by extending the concept of zero to nonlinear systems. A way to extend this concept is to define a so-called *zero–dynamics* for a nonlinear system. The zero-dynamics is defined to be the internal dynamics of the system when the system outputs are kept at zero by the inputs. So stability of the internal dynamics can be deduced from the stability of the zero-dynamics. To derive the zero dynamics the zero inputs (inputs that cause the output to be zero at all times) should be calculated. To calculate the zero inputs the following variables should be set to the following values in the inputs (u_1, u_2):

$$x_5 = 0$$
$$x_4 = CT + \frac{V_0}{E_a}$$
$$\nu_1 = 0$$
$$\nu_2 = 0$$

So the zero inputs are equal to zero vector:

$$u_0 = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \tag{23}$$

As it was mentioned before, internal dynamics variables are (x_1, x_2, x_3) which have the following dynamics :

$$\dot{x}_1 = x_2 \tag{24}$$

$$\dot{x}_2 = -\frac{kx_1}{x_3} - \frac{Bx_2}{x_3} + \left(\frac{a\mu x_5^2}{4\pi x_3\left(1 + Exp\left(\frac{b - \frac{r_d}{r_w}}{c}\right)\right)}\right) + \left(C_d\frac{(r_d^2 - r_w^2)\pi\rho_p U_b^2}{2x_3}\right) + \left(\frac{(C_2 x_5^2 \rho x_4 + C_1 x_5)\rho_w u_1}{x_3}\right) + g \tag{25}$$

$$\dot{x}_3 = (\rho C_2 x_5^2 x_4 + C_1 x_5)\rho_w + M_{ve} \tag{26}$$

M_{ve} includes mass rate of vaporizing electrode during melting which has a negative value because it reduces the mass rate that is transferred to the droplet; as it was noticed before this term was neglected in previous works, Fig. 2.

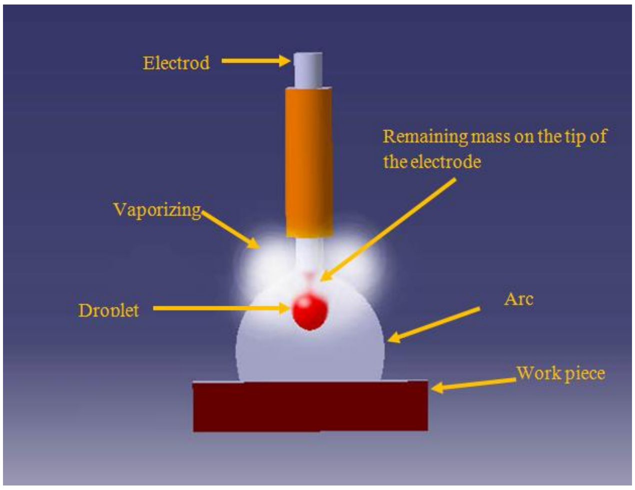

Fig. 2. Vaporizing electrode

By applying the zero input, (24), (25), and (26) become:

$$\dot{x}_1 = x_2 \tag{27}$$

$$\dot{x}_2 = \frac{-kx_1 - Bx_2 + C_d \frac{\left((\frac{3x_3}{4\pi\rho_w})^{0.333} - r_w^2\right)\pi\rho_p U_b^2}{2} + gx_3}{x_3} \tag{28}$$

$$\dot{x}_3 = M_{ve} \tag{29}$$

where r_d is replaced by $(\frac{3x_3}{4\pi\rho_w})^{0.333}$ in (28), (Agarwala, 2000). The last equation, (29), by knowing that M_{ve} is negative and x_3 cannot be negative, represents a stable equation. The first two equations, (27)-(28), represent a second order equation which its homogeneous part is stable and its particular part, by knowing that x_3 has a stable behavior, will remain stable. The above system of equations is solved numerically; results are presented in Figs. 3-5.The results in the figures numerically support the above conclusions of the stability and boundedness of the system internal dynamics and therefore the whole system is stable; in consequence, we can use the control structure illustrated in Fig. 6.

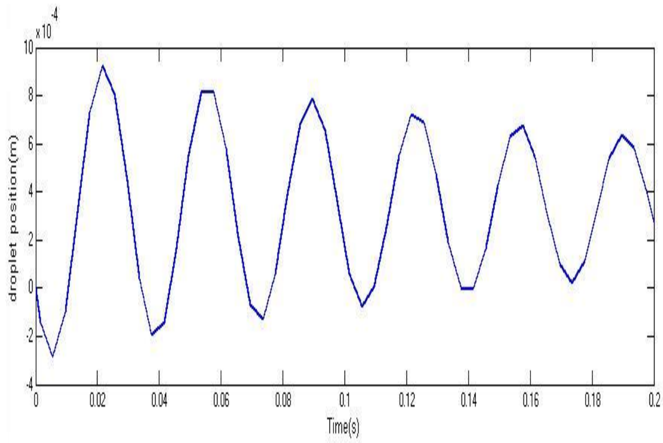

Fig. 3.Droplet position (x_1)

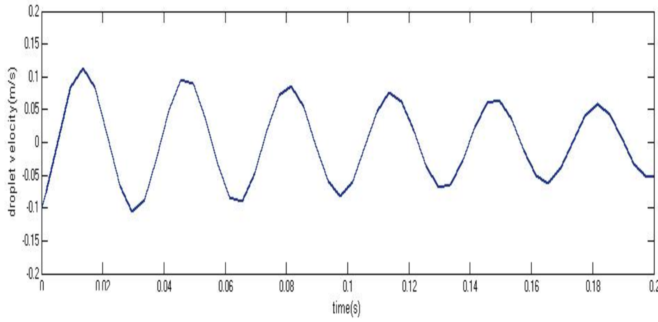

Fig. 4.Droplet velocity (x_2)

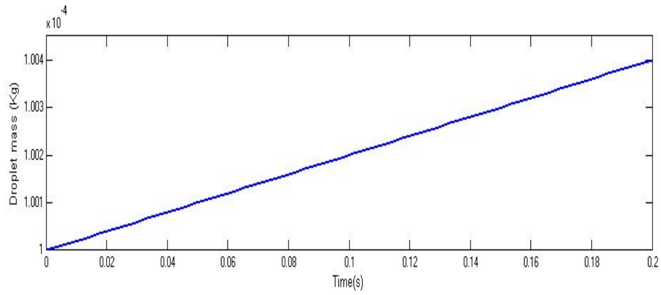

Fig. 5.Droplet mass (x_3)

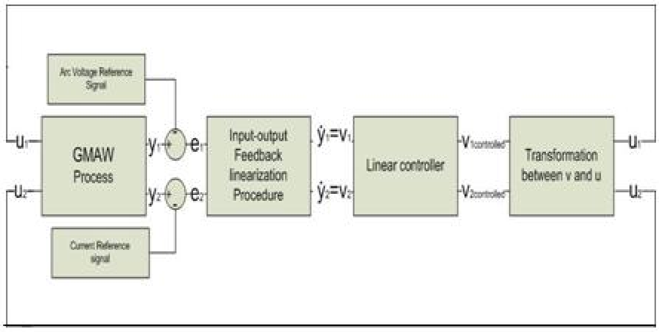

Fig. 6.Control structure

5. SIMULATION

To validate the designed controller in the previous section a simulation of the process was performed. This simulation has been done in two parts:

- Regulation
- Tracking

The regulation part was previously been done by (AbdelRahman., 1998) which did not cover drop detachment dynamic. To achieve a more realistic simulation, drop detachment should be considered. For an uncontrolled process (constant voltage) the drop growth and detachment will result in an arc length which becomes smaller during the growth period. Then, at drop detachment, the arc length jumps to a larger value. Thus, the arc length has a saw – toothed shape (it should be noted that here the arc length is controlled indirectly by controlling the arc voltageV_{arc}).When an arc voltage controller is applied such a controller tries to compensate for the changing arc length caused by the drop growth and detachment. However, we want to control the arc length process as if no drop was present, and thus the arc voltage controller can be improved by making the arc voltage reference signal , V_{ar} , having saw-toothed shaped. This is shown in Fig. 4.The reference is at its high just after expected drop detachments, but, at its low before expected detachment. The difference between the low and the high reference values must be equal to the difference between the arc voltage of the process just before and after of the detachments.

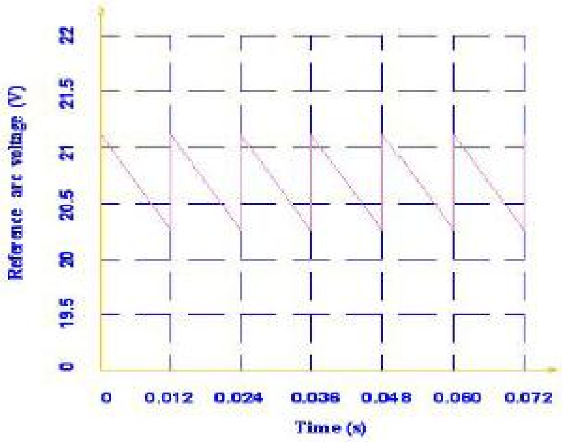

Fig. 4.Reference voltage to model the drop detachments

Results of the simulation for the arc voltage, tracking error of the arc voltage, the regulated current, are brought here for illustration in Fig. 7, Fig. 8, Fig. 9, Fig. 10. Values used in the simulations are brought in Table 1.

Table 1. Parameters used in simulations

Symbol	Unit	Value	Description
R_s	Ω	0.004	Wire resistance
L_s	H	15e-6	Wire inductance
ρ_r	Ω/m	0.2821	Electrode resistivity (steel)
C_1	$m/(sA)$	3.7e-4	Melting speed constant
C_2	$1/A^2m$	6.6e-4	Melting speed constant
r_w	m	5e-4	Electrode radius
U_b	V	15.7	Arc voltage constant
R_a	Ω	0.022	Arc resistance
E_a	V/m	636	Arc length factor
CT	m	0.015	Nominal tip to work piece dist.
S	m/s	0.267	Electrode speed.

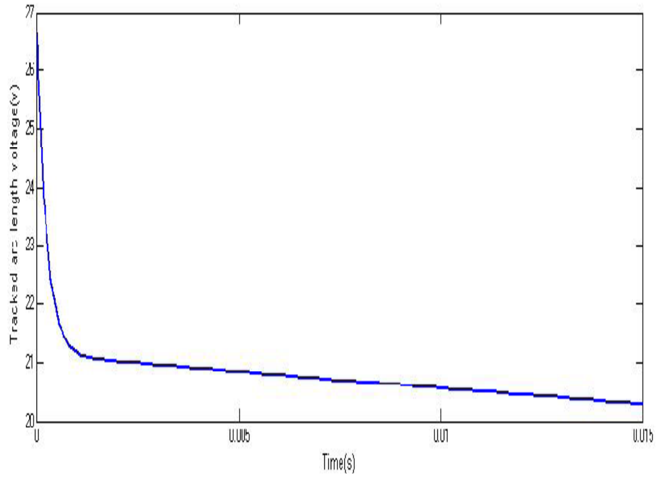

Fig. 7.Tracked arc voltage for one drop detachment

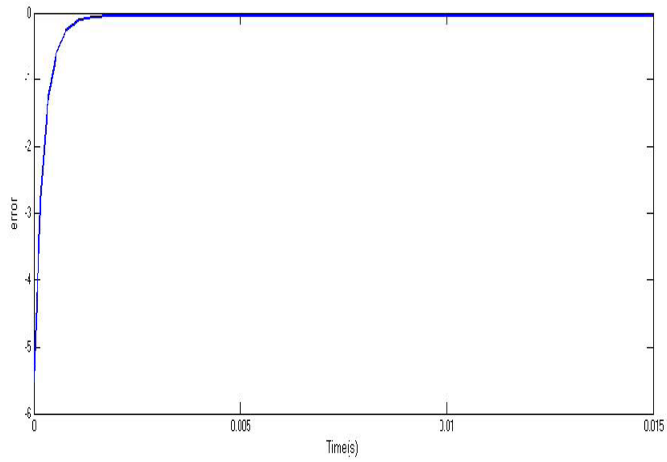

Fig. 8.Tracking error for arc voltage for one drop detachment

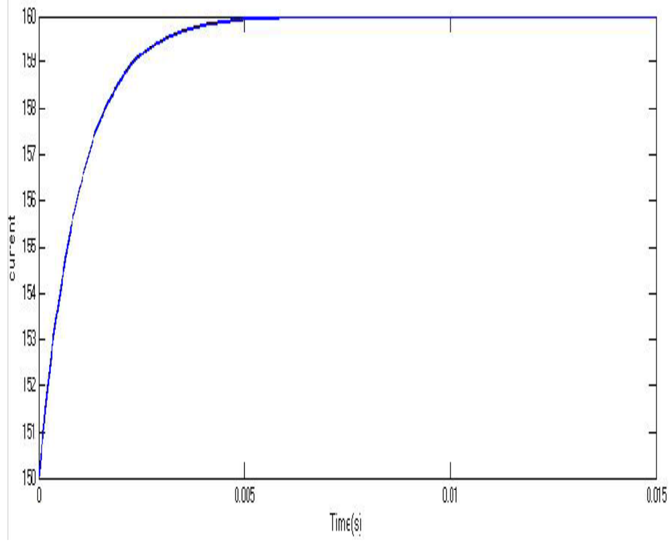

Fig. 9.Regulated Current to a value of 160(A)

6. CONCLUSIONS

In this paper, a model-based nonlinear controller was designed by carefully examining stability of the internal dynamics associated with the system by considering a mass rate of vaporizing and oxidizing electrode. Tracking performance of a saw-toothed signal for arc voltage which models the drop detachments was also investigated.

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