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# MIMO Stabilization of the Pulsed Gas Metal Arc Welding Process via Input-Output Feedback Linearization Method By Internal Dynamics Analysis

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**Abstract:** In this study, stability of Gas Metal Arc Welding (GMAW) process and its internal dynamics 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. 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 are maintained at zero which is called zero dynamics. Details of zero dynamics matter because if unstable, it can invalidate many control design procedures such as input-output feedback linearization method. At the present study, the stability of zero dynamics of the process which was ignored in the previous works will be investigated. Also, the state space model of the GMAW process will be modified by considering mass rate of the vaporizing electrode, which has a critical influence on the stability of the internal dynamics. Furthermore an input-output feedback linearization method will be used to design a controller for regulation of the arc length and current of the process and simulations results will be presented to illustrate the controller performance.

**Key words:** GMAW process, feedback linearizaton, internal dynamics, zero dynamics, stability analysis

## INTRODUCTION

There exists a wide variety of welding processes. Each one represents some advantages and is usually best suited for 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 provide 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 facts 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 the following subjects:

- Arc length control
- Control of mass and heat transfer (Linden *et al*., 1980; Smartt and Einerson, 1993)
- Control of weld temperature and/or cooling rate (Nishar *et al*., 1994; Einerson *et al*., 1992)
- Control of weld pool and its geometry. (Aendenroomer, 1996; Henderson *et al*., 1993; Hale and Hardt, 1992)
- Control of droplet transfer frequency (Phillips and Nagle, 1995; Johnson *et al*., 1991)
- Control of weld penetration (Barnett *et al*., 1995; Chen and Chin, 1990)
- Control of joint profile (fill rate) and trajectory (Fujimura *et al*., 1987; Tomizuka, 1988)

This study 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 has to be controlled. Because of the nonlinear nature of the melting process, the controller must be able to handle nonlinearities.

Arc length control for a GMAW process can be performed by either a PID control strategy as reported by Naidu *et al.* (1998), Madigan (1994) and Greene (1990), or another linear control strategy reported by Zhang *et al.* (2002), in which robustness is also considered. Basically

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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, these are avoided for the nonlinear controller presented in this study. The GMAW process was considered as a nonlinear SISO system and a feedback linearization controller was proposed for regulation (Thomsen, 2005). In the GMAW process was considered as a nonlinear MIMO system and nonlinearities were 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 (Abdel Rahman, 1998; Naidu *et al.*, 1999; Moore *et al.*, 2003). To achieve robustness, sliding mode control was also suggested by Ebrahimirad *et al.* (2003). In this study, 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.

## 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
- The ability to join a wide range of material types and thicknesses
- All-position welding capability
- Excellent weld bead appearance
- Less welding fumes when compared to SMAW (Shielded Metal Arc Welding) and FCAW (Flux-Cored Arc Welding) processes

## MATHEMATICAL MODEL OF GMAW PROCESS

**Before detachment:** Detailed discussion for deriving the state-space equations of the GMAW process before drop detachment is given by Abdel Rahman (1998) and the result is adopted here. The GMAW process can be approximated by the following model:

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

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

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

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

$$\dot{x}_5 = \dot{I} = \frac{u_2 - R_L x_5 - V_{arc} - R_s x_5}{L_s} \tag{5}$$

where, the state variables are:

$x_1 = x$ : Droplet displacement (m)
$x_2 = \dot{x}$ : Droplet velocity (m sec$^{-1}$)
$x_3 = m_d$ : Droplet mass (kg)
$x_4 = l_s$ : Stick out (m)
$x_5 = I$ : Current (A)

and

$$M_r = C_1 x_5 + C_2 x_5^2 \rho_w x_4 \tag{6}$$

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

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

The output variables are:

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

$$y_2 = I = x_5 : \text{Current (A)} \tag{10}$$

and the control input variables are:

$u_1 = S$ : Wire feed speed (m sec$^{-1}$)
$u_2 = V_{oc}$ : Open circuit voltage (volts)

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

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

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

**Drop detachment:** Throughout the welding process liquid metal is continuously added to the drop at the tip of the electrode and at some point, the drop is detached from the electrode. Detachment happens when the surface tension of the drop is no longer able to support the drop attached to the electrode. Typically, drop detachment has been modeled by two different models:

- Static Force Balance Model (SFBM)
- A model based on the Pinch Instability Theory (PIT) (Lancaster, 1984)

The SFBM predicts drop detachment by comparing the surface tension of the drop with the external forces exerted on the drop. Thus, in the SFBM the dynamics of the drop is not taken into account when predicting the occurrence of drop detachment. However, dynamics are taken into account by including the inertia force in the SFBM (Yoo *et al*., 2001). These results in a dynamic model, which is called the dynamic force balance model (DFBM). Both the SFBM and the DFBM predicts drop detachment by evaluating forces affecting the drop against the surface tension supporting the drop. However, the Pinch Instability Theory (PIT) results in a different detachment criterion. Based on the pinch instability theory, a detachment criterion can be derived that does not rely on balance of axial forces, but rather relies on radial forces. The SFBM does not include any dynamics of the pendant drop. Hence, detachment occurs if the maximal surface tension force, $F_s$, is exceeded by the total force, $F_{tot}$, affecting the drop; so,

SFBM, detachment if $F_{tot} > F$

In the DFBM, described in the inertia force is included in the detachment criterion (Yoo *et al*., 2001). So, the following criterion is obtained.

DFBM, detachment if $F_{tot} + m_d \ddot{x}_d > F$

In the detachment criterion, based on the pinch instability theory, is derived (Lancaster, 1984). Detachment occurs if critical drop radius, $r_{dc}$, is exceeded.

PIT, detachment if $r_d > r_{dc}$

Where:

$$r_{dc} = \frac{\pi(r_d + r_w)}{1.25\left(\frac{x_d + r_d}{r_d}\right)\left(1 + \frac{\mu_0 I^2}{2\pi^2 \gamma (r_d + r_w)}\right)^{\frac{1}{2}}} \tag{13}$$

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

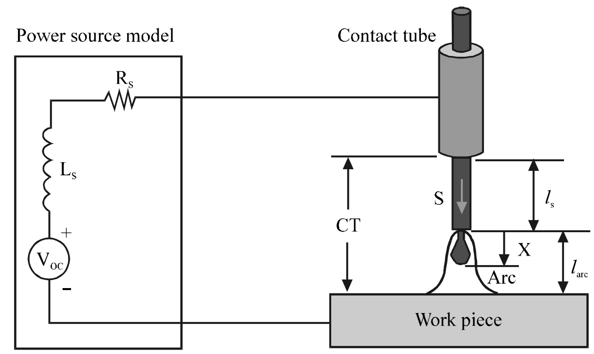


Fig. 1: Some of the parameters and Variables used in the GMAW modeling

Where:
$r_d$ : Droplet radius (m)
$r_w$ : Electrode radius (m)
$\gamma$ : Surface tension of liquid steel (N m$^{-2}$)

The SFBM and the DFBM do not take the pinch effect into account and therefore, at strong currents, where the pinch effect is especially strong, the PIT model is the best drop detachment estimator, as drops tend to detach at the strong current pulses. Some of the parameters and Variables used in the equations are shown in Fig. 1

## 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 ν (Slotine and Li, 1991). Given the nonlinear system in Eq. 11 and 12, input-output feedback linearization of the system is obtained by first differentiating the output $y_i$ until all the inputs appear. Assume that $r_i$ is the smallest integer such that at least one of the inputs appears in $y_i^{r_i}$; then,

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

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

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

Where:
$L_f h$ : $\nabla h.f$
h : $R^n \rightarrow R$ be a smooth scalar function

$f\ : R^n \rightarrow R^n$ be a smooth vector field on $R^n$

and the n×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 the input u ) $r_i$'s are all well defined. Furthermore, if E(x) is invertible, then, input transformation is (Slotine and Li, 1991):

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

which yields m equations in the following simple form

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

Since the input $v_i$ only affects the output $y_i$ as in Eq. 17, it is called a decoupling control law and the invertible matrix E(x) is called the decoupling matrix of the system (Slotine and Li, 1991). The system in Eq. 11 and 12 is then said to have relative degrees $(r_1, r_2 ... r_m)$ at $x_0$ and the scalar $r = (r_1 + r_2 + ... + r_m)$ is called the total relative degree of the system at $x_0$.

**Internal dynamics:** When input-output linearization method is performed, the dynamics of the nonlinear system is decomposed into an external (input-output) part and an internal (unobservable) part (Slotine and Li, 1991). Since the external part consists of a linear relation between y and υ, it is easy to design input υ 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.

**Controller design:** To apply the input-output feedback linearization procedure, the output is differentiated until the inputs are all appeared in the outputs or their derivatives:

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

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

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

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 dynamics 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 Eq. 16 to be:

$$u_1 = \frac{R_a(-V_0 - E_a(CT - x_4) + (-R_a - R_s - \rho x_4)x_5)}{L_s E_a} - \frac{E_a(-C_1 x_5 - \rho C_2 x_4 x_5^2) + \upsilon_1}{\pi r_w^2 E_a} + R_a\left(\frac{-V_0 - E_a(CT - x_4) + (-R_a - R_s - \rho x_4)x_5}{L_s E_a} + \frac{\upsilon_2}{E_a}\right) \tag{21}$$

$$u_2 = L_s\left(\frac{-V_0 - E_a(CT - x_4) + (-R_a - R_s - \rho x_4)x_5}{L_s} + \upsilon_2\right) \tag{22}$$

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

**Zero-dynamics:** 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 zeros to nonlinear systems. A way to extend this concept is to define a so-called zero-dynamics for a nonlinear system (Slotine and Li, 1991). 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 $(u_1, u_2)$:

$$x_5 = 0$$

$$x_4 = CT + \frac{V_0}{E_a}$$

$$\upsilon_1 = 0$$

$$\upsilon_2 = 0$$

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:

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

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

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

At higher welding currents, significant vaporization at the surface of the molten droplet can occur in the arc root area; therefore, $M_{ve}$ which is the mass rate of vaporizing electrode during melting, it is important to note that $M_{ve}$ has a negative value since it reduces the mass rate that is transferred to the droplet and should be considered in the system dynamic equations (Fig. 2).

So, by applying the zero input, Eq. 24-26 become:

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

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

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

where, $r_d$ is replaced by $\left(\frac{3x_3}{4\pi\rho_w}\right)^{0.333}$ in Eq. 28, (Agarwala, 2000).

The last Eq. 29, by knowing that $M_{ve}$ is negative and $x_3$ cannot be negative, represents a stable equation. The first two Eq. 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 shown in Fig. 3-5. The results 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 shown in Fig. 6.

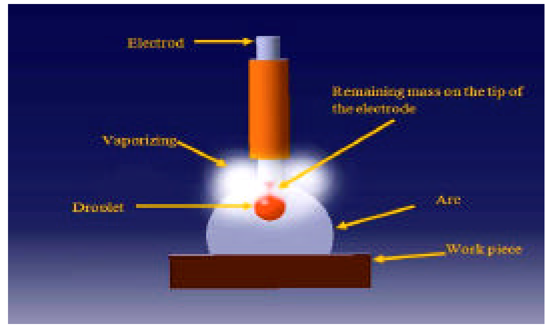


Fig. 2: Vaporization of the electrode during welding

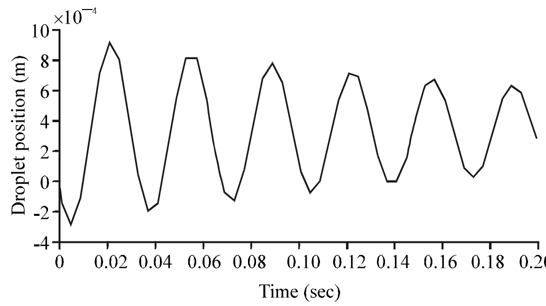


Fig. 3: Droplet position ($x_1$)

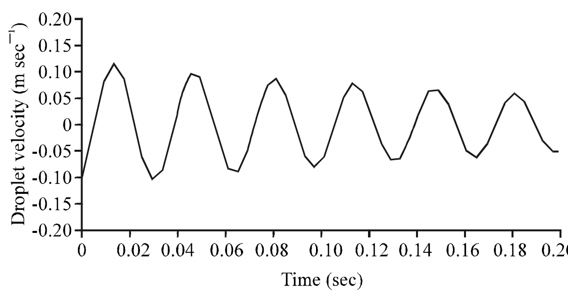


Fig. 4: Droplet velocity ($x_2$)

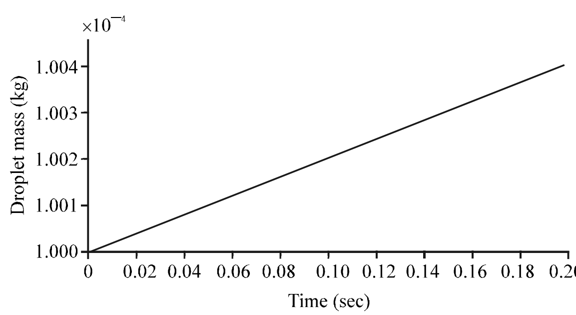


Fig. 5: Droplet mass ($x_3$)

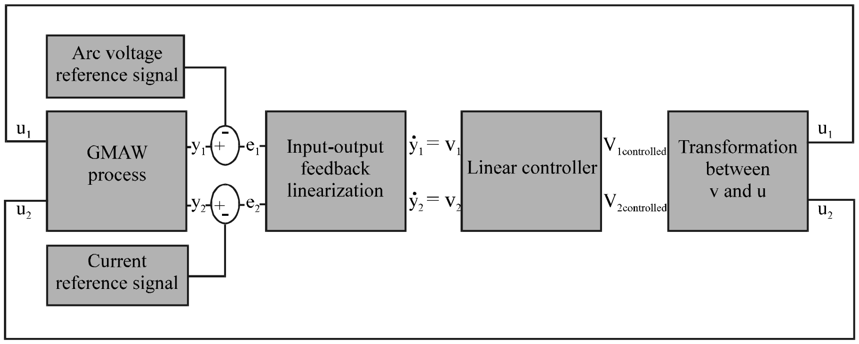


Fig. 6: MIMO feedback linearization of GMAW process

## SIMULATION

The metal transfer modes during the GMAW process are described by the following categories:

Free-Flight Transfer

- Globular
- Spray
- Combination of Globular and Spray
- Streaming

Short-Circuiting Transfer
Pulsed Transfer

As shown in Fig. 7. for GMAW, globular transfer (characterized by a drop size bigger than the diameter of the electrode wire and at the rate of few drops per second) takes place when the current is relatively low compared to the current levels associated with spray transfer but larger than the current levels associated with short circuit transfer. At higher welding currents, the drop size decreases and the electrode tip becomes tapered and a very fine stream off droplets is projected axially through the arc leading to streaming transfer. This transfer is seen with high-resistivity and small-diameter wires operating at welding currents above 300 A (Norrish, 1992).

In this study, focus is on pulsed GMAW. This type of welding falls within the spray mode, as drops in pulsed welding are detached by the strong current as in the spray mode. However, in contrary to the spray mode, the current is shifted between a low level and a high level. The advantage of using pulsed GMAW, when compared to the spray mode, is the heat input into the weld pool and also, the pulses used make it possible to control the drop detachment process. To validate the designed controller in the previous section, a simulation of the process is performed. The arc length regulation was previously carried out by Abdel Rahman (1998) without considering the stability of the internal dynamics of the GMAW process which is investigated in the present study.

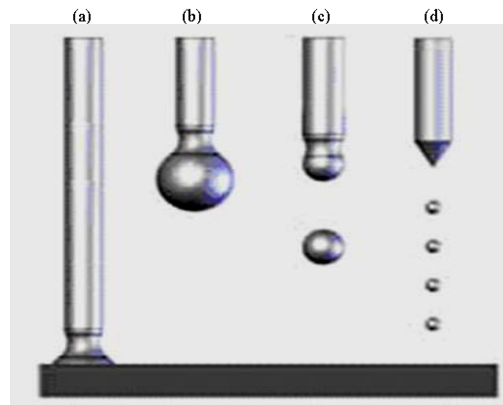


Fig. 7: Conceptual schematic of metal transfers in GMAW: (a) short circuit, (b) globular, (c) pulse and (d) spray

Table 1: Parameters used in simulations

| Symbol | Unit | Value | Description |
|---|---|---|---|
| $R_S$ | Ω | 0.004 | Wire resistance |
| $L_S$ | H | 15e-6 | Wire inductance |
| $\rho_r$ | $\Omega\, m^{-1}$ | 0.2821 | Electrode resistivity (steel) |
| $C_1$ | m/(sA) | 3.7e-4 | Melting speed constant |
| $C_2$ | $1/A^2\, m$ | 6.6e-4 | Melting speed constant |
| $r_w$ | m | 5e-4 | Electrode radius |
| $U_0$ | V | 15.7 | Arc voltage constant |
| $R_a$ | Ω | 0.022 | Arc resistance |
| $E_a$ | $V\, m^{-1}$ | 636 | Arc length factor |
| CT | m | 0.015 | Nominal tip to work piece dist. |
| S | $m\, sec^{-1}$ | 0.267 | Electrode speed |

## RESULTS

Results of the simulation for the current regulation, current error and voltage error are brought here in Fig. 8-10. Also block diagram of the simulation is presented in Fig. 11. Values used in the simulations are brought in Table 1.

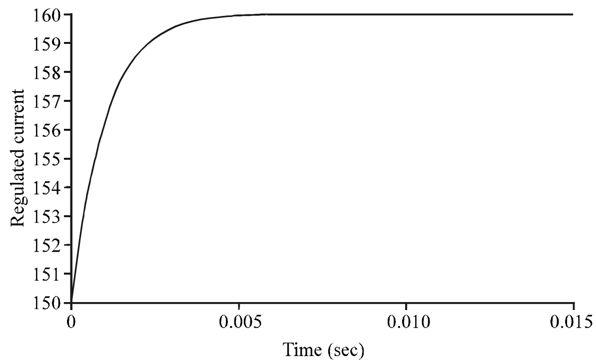


Fig. 8: Regulation of the current to the value of 160 A

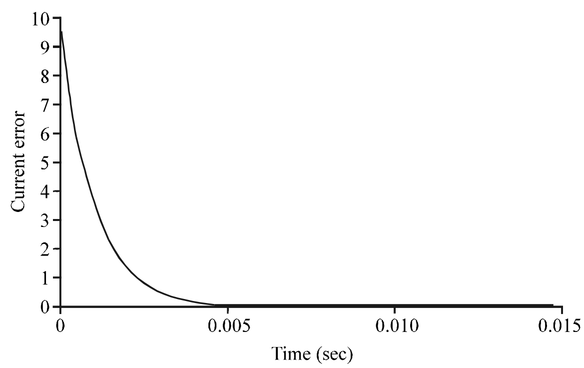


Fig. 9: Error present in regulation of the current

## CONCLUSION

In this study, a model-based nonlinear controller was designed for regulation of the arc voltage and the current. As it was mentioned in this study the feasibility of the feedback linearization scheme is dependent on the stability of the internal dynamics which was ignored by other works in this process; but, here by carefully examining stability of the internal dynamics associated with the system, it was indicated there were three internal dynamics state variables which their stability was analytically and numerically investigated. During the study of the internal dynamics stability it was

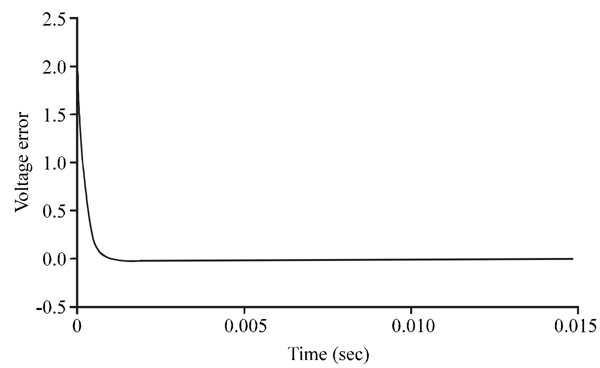


Fig. 10: Error present in regulation of the arc voltage

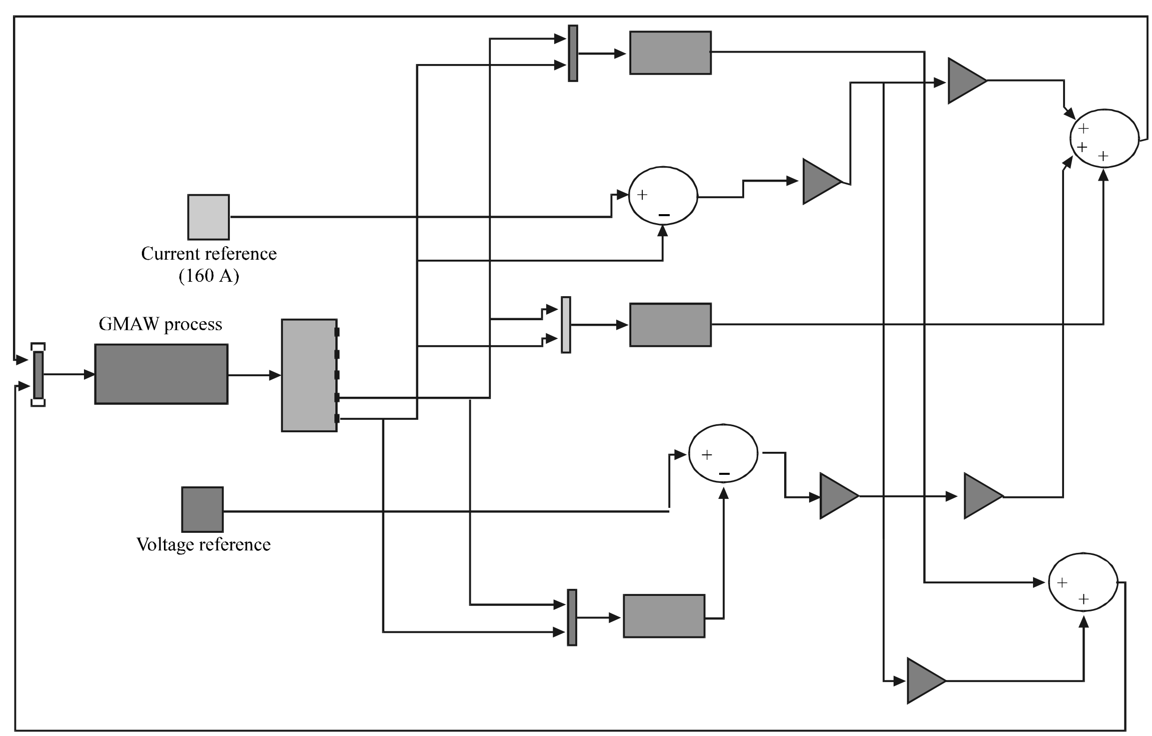


Fig. 11: Simulation flow-chart

demonstrated that mass rate of vaporizing and oxidizing electrode was to be considered. Simulations were presented to show the performance of the designed controller.

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