한국해양공학회 2006년도 추계학술대회 국제워크샵 pp. 60~66

Control Gas Metal Arc Welding System Using Decentralized Method

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KEY WORDS: decentralized control method, sliding mode controller, proportional controller, PS-GMAW, WFU.

ABSTRACT: This paper presents a new way achieving better welding results of gas mental arc welding (GMAW) system by using a decentralized control method. In this paper, the GMAW system is considered as two separated subsystems such as a power source of GMAW (PS-GMAW) and a wire feed unit (WFU). The mathematical modeling of PS-GMAW and WFU are presented. Based on the modeling of two subsystems, a sliding mode controller and a proportinal controller is designed for controlling the PS-GMAW and the WFU, respectively. Two decentralized controllers have to be designed to control the out welding arc of the GMAW to be stable and tracking the setting value accurately during the welding process. Furthermore, the simulation and experimental results are shown to prove the effectiveness of the proposed controlers.

1. Introduction

The GMAW process was developed and made commercially available in 1948 although the basic concept was actually introduced in the 1920's. In its early commercial applications, the process was used to weld aluminum with an inert shielding gas, giving rise to the term "MIG" (metal inert gas) which is still commonly used when referring to the process. Variations have been added to the process. One among the variations was the use of active shielding gases, particularly CO2, for welding certain ferrous metals. This eventually led to the formally accepted term as gas metal arc welding (GMAW) by American welding system. The GMAW process uses either semiautomatic or automatic equipment and is principally applied in high production welding. Most of metals can be welded with this process in all positions with the lower energy variations of the process. GMAW is an economical process that requires little or no cleaning of the weld deposit. Warpage is reduced and metal finishing is minimal compared to stick-electrode welding [W.H. Chu, etc.].

Usually, a conventional GMAW system using analog control circuit, based on the thysistor (SCR) technology which has an operated frequency (50~60Hz). Base on this operated frequency, the quality of output welding current and voltage is very rough and the main transformer which changes the input voltage level into the welding voltage level is very big and heavy. However, this kind of welding machine has much no good influence on the power network. Furthermore, the conventional GMAW requires a well-trained technician to adjust the parameters of this machine [W.H. Chu, etc.]. To solve these problems, a new digital intelligent GMAW system using insulated gate bipolar transistor (IGBT) technique which has an operated frequency (20 kHz) is developed. Based on this technique, the main ferrite transformer with small mass is used for handling a big power output and this kind of welding machine nearly has no effect on the power network. The parameters of developed GMAW system are automatically established when the setting condition such as a welding voltage, a welding current, a welding mode and diameter of wire electrode are chosen. The developed GMAW has the rank of the setting values for welding voltage from 16VDC to 36VDC and welding current from 50A to 220A. The error vector is defined as the difference between the setting values and the output values. Based on the error vector, the nonlinear controller with closed loop system is used in order that the output welding current and voltage achieve the setting values very fast and without overshot. To obtain controller, the developed digital intelligent GMAW system is considered as two separate subsystems such as PS-GMAW and WFU. Based on a decentralized control method, a sliding mode controller and a proportional controller are designed for WFU and PS-GMAW, respectively. Two decentralized controllers have to be designed to control the welding arc of GMAW to be stable and accurate tracking the setting values during the welding process. Furthermore, the developed GMAW includes some functions such as anti electrode wire stubbing on the starting function, burn back function (needless to electrode wire cut after welding process), etc., . the simulation and experimental results are shown to prove the effectiveness of the proposed controlers.

2. Dynamic System Modeling

Based on the flow chart for a welding process of the developed GMAW system is shown in Fig. 1, the DC motor of the WFU adjusts the electrode wire feed-rate in order to compensate an electrode wire melting-rate to continuously keep a welding arc during the welding process. Assumption if the output welding voltage which is supplied by PS-GMAW is kept constantly, the changing electrode feed-rate makes the output welding current change. To illustrate this concept, the graphs between the welding current and electrode feed-rate are built by Lincoln Electric Company as shown in Fig. 3. Furthermore, assumption if the electrode feed-rate is kept constantly, the changing power output of PS-GMAW will change the output welding voltage. The developed PS-GMAW is shown in Fig. 4. This PS-GMAW is based on AC to DC inverter using insulated gate bipolar transistor (IGBT) technique. The average power output of PS-GMAW proportional to the % of duty ON of PWM of IGBT gate. However, the % of duty ON of PWM of IGBT gate is proportional to the average output voltage of the AC to DC inverter. So to control the output welding voltage, the average output voltage of the PS-GMAW is controlled.

For this reason, in this part, the WFU is modeled as a transfer function between the DC voltage supply for DC motor of the WFU and the output welding current. Then, the PS-GMAW is modeled as a transfer function between the average output voltage of the PS-GMAW and the output welding voltage. The flow chart for the welding process of the developed digital intelligent GMAW system is as follows:

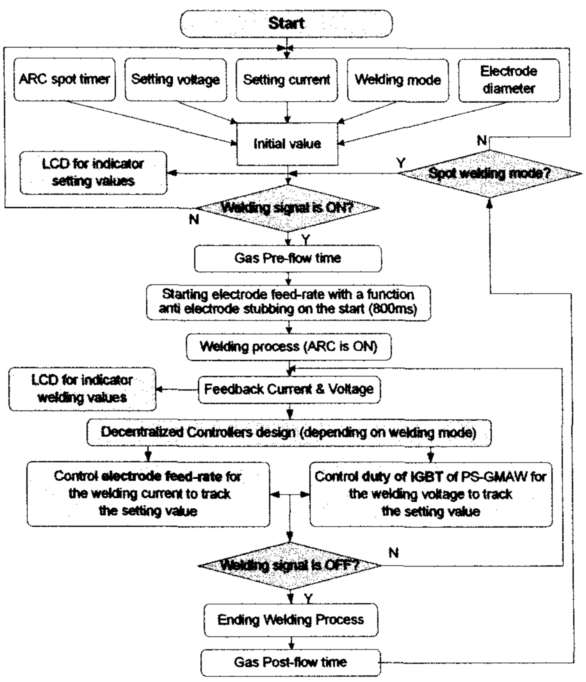
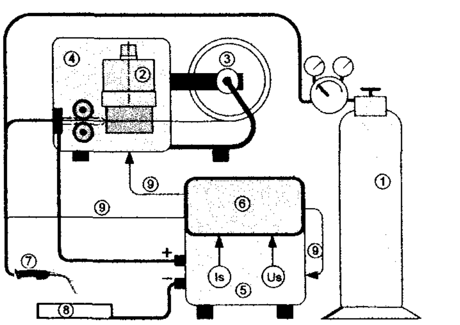


Fig. 1 Flow chart for controlling the GMAW



① Shielding gas; ② DC motor & gear box; ③ welding electrode roll; ④ WFU
⑤ PS-GMAW; ⑥ Control box; ⑦ Welding gun; ⑧ workpiece; ⑨ control cable

Fig. 2 Basic GMAW equipment

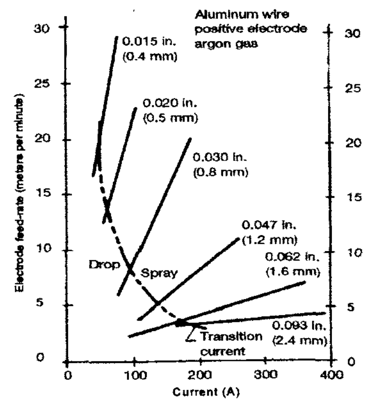


Fig. 3 Relationship between the electrode feed-rate and welding current

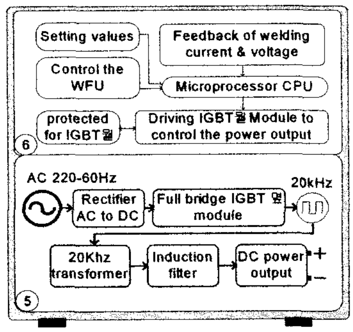


Fig. 4 Scheme of PS-GMAW and control box

2.1 Dynamic model of WFU

The DC servomotor is used to control the DC motor of WFU which controls the electrode feed-rate to keep the welding arc. The dynamic relationship between the electrode feed-rate and the voltage of a DC servomotor can be expressed into a second-order dynamic equation as the following:

$$G_m(s) = \frac{W_f(s)}{V_m(s)} = \frac{b_0}{s^2 + a_1 s + a_0} \tag{1}$$

where $W_f(s)\,[m/\min]$ and $V_m(s)\,[Voltage]$ denote the electrode feed-rate and the DC voltage of a DC servomotor, respectively. The purpose of controlling WFU is to change the electrode feed-rate in order to achieve the welding current I_w tracking the setting value I_s. In the GMAW process, in order to maintain a stable arc length, the electrode feed-rate must be equal to the electrode melting-rate.

$$W_f = W_m \tag{2}$$

where W_m is the electrode melting-rate

The electrode melting-rate W_m can be expressed in a function of welding current I_w and welding voltage U_w as the following:

$$W_m = K_i I_w - K_u U_w \tag{3}$$

where K_i and K_u are the coefficient ratios of the melting-rate to the welding current and welding voltage, respectively.

From Eq. (2) and Eq. (3), the electrode feed-rate can be expressed as follows

$$W_f(s) = K_i I_w - K_u U_w \tag{4}$$

Therefore, the welding current can be expressed as follows

$$I_w = \frac{W_f(s)}{K_i} + \frac{\Delta G}{K_i} \tag{5}$$

where $\Delta G = K_u \times U_w$

In practice, the welding current effects the electrode feed-rate much more than the welding voltage. If the welding voltage is considered as a disturbance in Eq. (4), the block diagram for an open loop transfer function of the WFU is shown in Fig. 5.

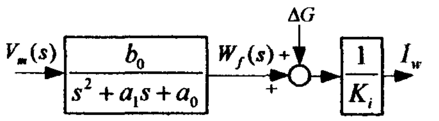


Fig. 5 Block diagram of open loop of WFU.

If ΔG is considered as disturbance of the system, the transfer function $G(s)$ of the WFU between the $V_m(s)$ and I_w can be expressed as follows:

$$G(s) = \frac{I_w(s)}{V_m(s)} = \frac{1}{K_i}\left[G_m(s) + \Delta G_d\right] \tag{6}$$

$$G(s) = \frac{I_w(s)}{V_m(s)} = \frac{1}{K_i}\left[\frac{b_0}{(s^2 + a_1 s + a_0)} + \Delta G_d\right] \tag{7}$$

where $\Delta G_d = \Delta G / V_m$

2.2 Dynamic Model of PS-GMAW

The circuit layout of the GMAW system can be expressed as Fig. 7. U_a, R_a, R_P, R_n and L represent the average output voltage of PS-GMAW, resistance of PS, parasitic resistance in the circuit, resistance between contact tip and wire, and inductance of the PS-GMAW, respectively. The Kirchhoff's voltage law for welding circuit can be expressed as follows.

$$U_a = L\frac{dI_w}{dt} + (R_a + R_p + R_n) \times I_w + (U_w + U_{sheath}) \times \Psi \tag{8}$$

where U_{sheath} is given as a constant value of 14.5V [H. Terasaki], Ψ is a switch parameter and defined as follows:

$$\Psi = \begin{cases} 1 & \textit{if arc is on} \\ 0 & \textit{if short circuit} \end{cases} \tag{9}$$

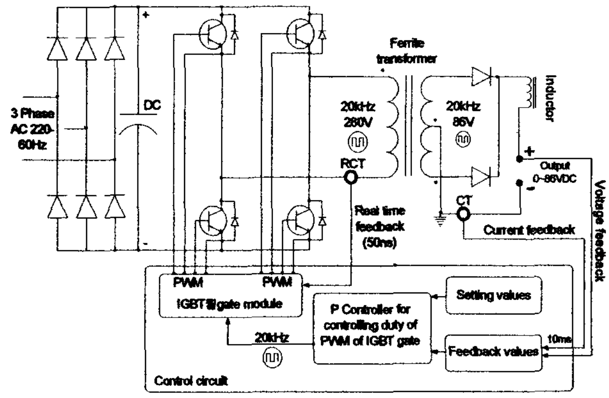


Fig. 6 Schematic circuit of PS-GMAW

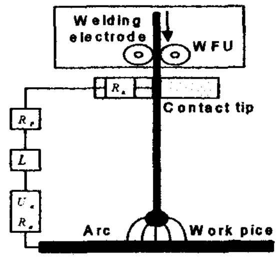


Fig. 7 Circuit layout of the GMAW system

3. Design of Decentralized Controllers

The flow char of GMAW process is shown in the Fig. 1. After all the setting welding conditions are chosen, the initial value of an electrode feed-rate of the WFU is calculated via experimental database similar to the Fig. 3. Furthermore, the initial voltage of DC servomotor of WFU (V_m) can be estimated through the transfer function of WFU and the initial average voltage output for PS-GMAW (U_a) can be calculated through the transfer function of PS-GMAW. When welding arc is on, the errors of current and voltage are established. Based on these errors and their transfer functions, decentralized controllers are designed. The main objective of this part is how to design the decentralized controllers for WFU and PS-GMAW then these controllers stabilize the welding arc and make the errors of the GMAW system converge to zero as $t \to \infty$.

3.1 Controller design for WFU

From Eqs. (1) and (7), the state-equation with zero initial values of system can be expressed as follows:

$$\begin{cases} x_1 = W_f \\ x_2 = \dot{W}_f \\ \dot{x}_1 = x_2 \\ \dot{x}_2 = -a_1 x_2 - a_0 x_1 + b_0 u_i \\ y = I_w = c \times [x_1 + \Delta G] \end{cases} \tag{10}$$

where $x \in R^2 = [W_f \quad \dot{W}_f]^T$ is the state vector, $y = I_w$ is the scalar output, and $u_i = V_m$ is the scalar controller for WFU, and

$c = 1/K_i$.

The current error e_i is defined as follows:

$$e_i = (I_s - I_w)/c \qquad (11)$$

where I_s is the constant setting current value.

Derivative of the error is as the following:

$$\dot{e}_i = -\dot{x}_1 - \Delta G \qquad (12)$$

In order to obtain the controller of sliding mode, the sliding surface is defined as follows:

$$s = \dot{e}_i(t) + \lambda e_i(t) \qquad (13)$$

where λ is a positive constant value.

It is easy to see that the error e_i in the (13) converges to zero along the trajectory of s equals to zero. From Eq. (13). if $s = 0$, $\dot{e}_i$ is negative when e_i is positive, and vice versa. That is, $\dot{e}_i e_i \le 0$. Thus, the equilibrium point of e_i converges to zero as $t \to \infty$.

Derivative of sliding surface can be calculated as follows:

$$\dot{s} = [(\lambda - a_1)\dot{e}_i + \frac{a_0}{c}(I_s - ce_i) - b_0 u_i] + \bar{d} \qquad (14)$$

where $\bar{d} = -a_0\Delta G - a_1\Delta\dot{G} - \Delta\ddot{G}$ is bounded value

Now our objective is to design a controller u_i which stabilizes the system and makes the sliding surface converge to zero based on Lyapunov's method with the Lyapunov's function as $V = 1/2s^2$. The sliding mode controller can be drawn from the Lyapunov's condition:

$$\dot{V} = s\dot{s} \le 0 \qquad (15)$$

The proposed controller is given as follows:

$$u_i = \frac{\dot{e}_i}{b_0}(\lambda - a_1) + \frac{a_0}{cb_0}(I_s - ce_i) + Qs + \bar{\beta} \times sign(s(t)) \qquad (16)$$

where $\bar{\beta}$ and Q are positive constant values, and $\bar{\beta}$ is named as upper bound of the disturbance.

Eq. (16) satisfies the condition in Eq. (15) if $|\bar{d}| \le \bar{\beta}$.

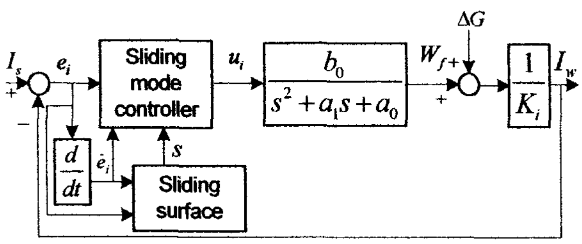


Fig. 8 Block diagram of a closed loop WFU

3.2 Controller design for PS-GMAW

When the arc is ON, the average voltage output of PS-GMAW in Eq. (8) can be rewriten as follows:

$$U_a = (R_s + R_p + R_n)I_w + (U_w + U_{sheath}) \qquad (17)$$

The PS-GMAW in Fig. 6 is based on the DC converter. So the average output voltage of PS-GMAW can be expressed as follows:

$$U_a = 2 \times D \times 86 \qquad (18)$$

where D is duty of PMW $D = [0\% \;\; to \;\; 48\%]$.

From Eq. (17) and (18), Eq. (19) is obtained.

$$D = \frac{1}{172}[(R_s + R_p + R_n)I_w + (U_w + U_{sheath})] \qquad (19)$$

In this system, the duty of PWM is coded by 8 bit digital number in the microprocessor. So the relationship between the controller u_u and D is as follows:

$$u_u = \frac{256 \times 100}{48} D = \frac{256 \times 100}{48} \times 2 \times 86 \times U_a = \frac{U_a}{H} \qquad (20)$$

where $H = 129/400$

From Eqs (17), (18) and (20), the average voltage output of PS-GMAW can be rewritten as follows:

$$u_u = \frac{400}{129}\left[(R_s + R_p + R_n)I_w + (U_w + U_{sheath})\right] \qquad (21)$$

$$U_w = U_a - U_{sheath} - R \times I_w = H \times u_u - U_{Fix} + \Delta U \qquad (22)$$

where $R = R_s + R_p + R_n$, $U_{Fix} = R \times I_s + U_{sheath}$,
$\Delta D = R \times c \times e_i$ is considered as disturbance.

If ΔD is considered as a disturbance, the Eq. (22) says that the controller u_u is directly proportional to the output welding voltage U_w.

The error voltage e_u is defined as follows:

$$e_u(t) = (U_s - U_w) \times K_w \qquad (23)$$

The proportional controller u_u is applied to adjust the average output voltage of PS-GMAW such that the welding voltage achieves the setting value. The proposed controller is as follows:

$$u_{u(i)} = u_{u(i-1)} + K_p \times e_{u(i-1)} \qquad (24)$$

where K_p, K_w are positive constant values. $u_{u(i-1)}, e_{u(i-1)}$ are the values of controller and the error at period of $(i-1)^{th}$, respectively.

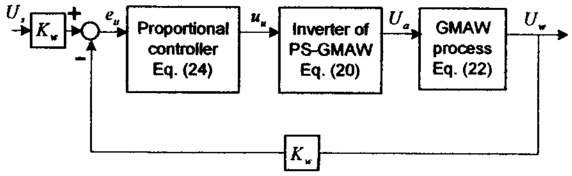


Fig. 9 Proportional controller for PS-GMAW

4. Simulation and Experimental Results

4.1 Hardware design

A developed full automatic GMAW system is shown in Fig. 10.

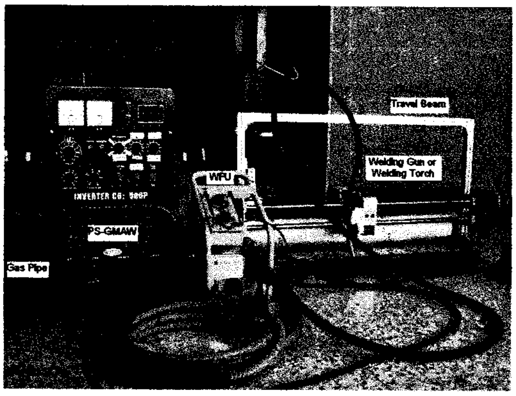


Fig. 10 Developed GMAW system

It includes GMAW and a travel beam. The travel beam moves the welding torch along the welding line with constant velocity. The PS-GMAW has LCD display and analog display for showing the welding current and welding voltage to easily compare the digital values with analog values.

4.2 Identification of parameters for the transfer function

The transfer function in Eq.(1) can be rewritten as follows:

$$G_m = \frac{\omega_{motor} \times b'}{V_m} = \frac{W_f}{V_m} = \frac{b'/k_e}{(s\tau_m + 1)(s\tau_e + 1)} \quad (25)$$

For the specific WFU, the rate of gear box is 1/34, $K_{gear} = 1/34$, the feed roll's diameter is 40mm, $D_{roll} = 40 \times 10^{-3}[m]$ and DC motor's parameters of WFU are shown in Table 1, k_e is back electromotive force constant, k_T is motor torque constant, R_{am} is armature resistance, J_m is moment of inertia, τ_m is mechanical time constant and τ_e is electrical time constant.

The parameters of transfer function $G_m(s)$ can be calculated as follows:

$$b_0 = b \times b' = 119{,}631 \quad (26)$$

where

$$b = \frac{1}{k_e \times \tau_m \times \tau_e} = 3{,}389{,}002$$

$$b' = \frac{W_f}{\omega_{motor}} = \frac{D_{roll}}{2} \times K_{gear} \times 60$$

$$= 20 \times 10^{-3} \times \frac{1}{34} \times 60 = 0.0353\,[(m/\min)/(rad/s)]$$

$$a_1 = \frac{\tau_m + \tau_e}{\tau_m \tau_e} = 1{,}378.7 \quad (27)$$

$$a_0 = \frac{1}{\tau_m \tau_e} = 194{,}189.8 \quad (28)$$

Parameters	values	Units
k_e	57.3×10^{-3}	$[V\sec/rad]$
k_T	4.8×10^{-2}	$[N \times m/A]$
R_{am}	1.1	$[\Omega]$
L_{am}	0.9×10^{-3}	$[H]$
J_m	0.157×10^{-4}	$[kgm^2]$
$\tau_m = \frac{R_{am} J_m}{k_e k_T}$	6.28×10^{-3}	$[s]$
$\tau_e = \frac{L_{am}}{R_{am}}$	0.82×10^{-3}	$[s]$

Table 1 Numerical values of DC motor of WFU

The K_i depends on a diameter of welding electrode. Based on experimental results, the gain K_i can be approximated ranging from 0.041~0.046 for 1.2 mm aluminum electrode. In this paper, $K_i = 0.043$ is chosen.

The nominal mathematical model of the transfer function $G_m(s)$ is as follows:

$$G_m(s) = \frac{119{,}631}{s^2 + 1{,}387.5s + 194{,}189.8} \quad (29)$$

4.3 Simulation and experimental results

To verify the effectiveness of the proposed controllers, simulation and experiment are done for the developed GMAW system in Fig. 10.

Numerical values and initial values used in simulation and experiment are shown in Table 1-3.

Parameters	values	Unit
Setting current	110	$[A]$
Setting voltage	22	$[V]$
Diameter of Electrode	1.2	$[mm]$
R_a	0.019	$[\Omega]$
R_p	0.096	$[\Omega]$
R_n	0.017	$[\Omega]$
U_{sheath}	14.5	$[V]$
Sampling time	0.01	$[s]$
Initial u_i for WFU	7.67	$[V]$
Initial u_u for PS-GMAW	157	$[digit\ mum.]$

Table 2 Numerical values and initial values of system

Gains	value	Gains	value
K_i	0.043	λ	350
Q	30	K_w	0.14
$\overline{\beta}$	200,000	K_P	0.51

Gains	value	Gains	value
$\bar{d}_{Min}$	30,000	$\bar{d}_{Max}$	185,000

Table 3 The gains of GMAW syste

Fig. 11 shows that the simulation result of control signal input of u_i for WFU. The control signal becomes stable after 3.5 seconds and has the value about 7.5V.

The sliding surface and tracking error e_i are shown in Fig. 12 and Fig. 13. As we know, the control signal u_i make the sliding surface s converge to zero and then the tracking error e_i go to zero.

The control signal input u_u for PS-GMAW is shown in Fig. 14. The control signal u_u has 158 at steady state.

Fig. 15 shows that the simulation result for the tracking error e_u. The simulation result shows that the error converges to zero after 3.5 seconds.

Fig. 16 shows that the simulation results of output welding current and welding voltage are 110A and 22V, respectively.

The experimental results of welding current and voltage are shown in Fig. 17. These results show that the output values are stable after 3.5 seconds and track the setting values very well during the welding process. However, there is a little difference between the simulation and experimental results at the beginning of welding process because the welding arc is established at the beginning welding process.

The initial duty for experiment of PWM corresponding to the control signal input for $u_u = 158$ [digit num.] is shown in Fig. 18.

Fig. 19 shows that welding results of GMAW system

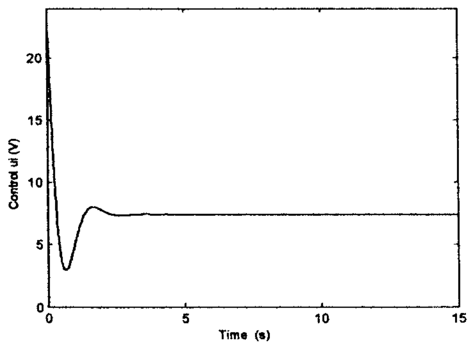


Fig. 11 Control signal input of u_i $[V]$

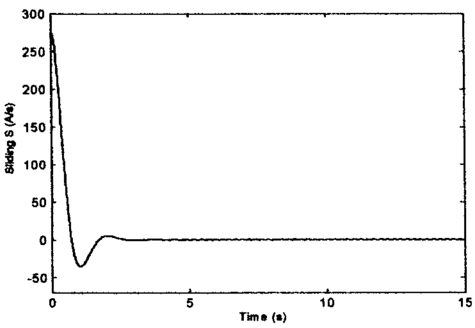


Fig. 12 Sliding surface s $[A/s]$

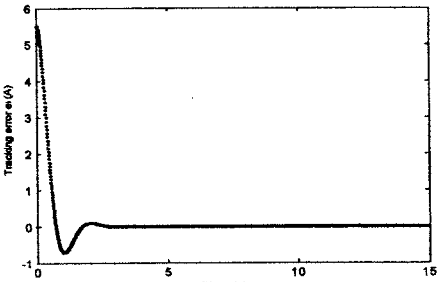


Fig. 13 Tracking error e_i $[A]$

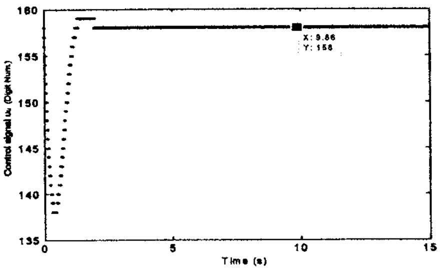


Fig. 14 Control signal u_u [digit num.]

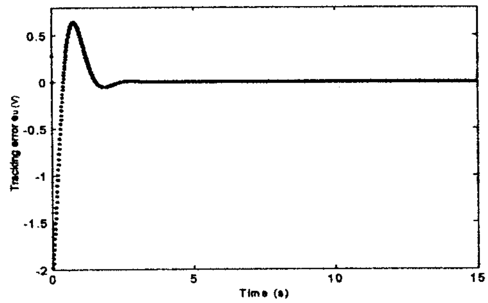


Fig. 15 Tracking error of welding voltage e_u $[V]$

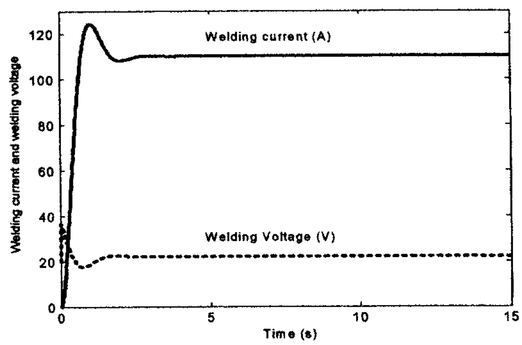


Fig.16 Tracking current and voltage

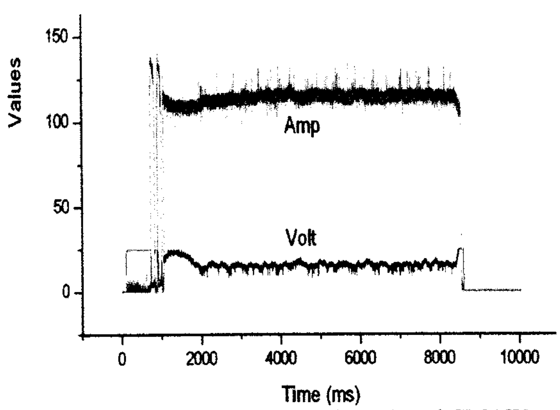


Fig. 17 Experimental results of developed GMAW

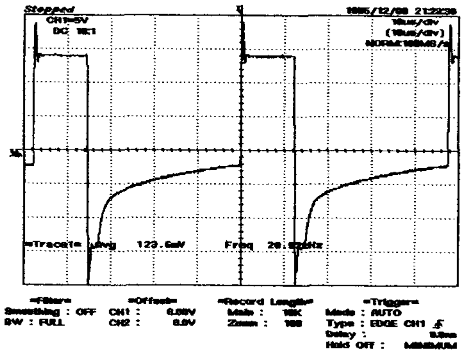


Fig. 18 Initial PWM for one gate of IGBT

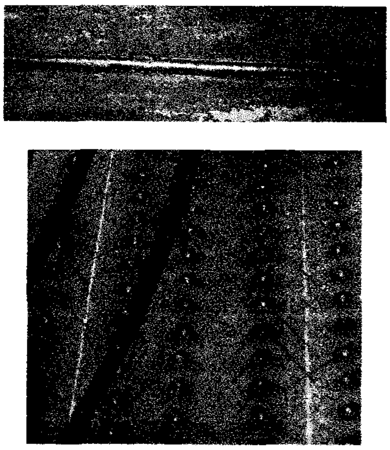


Fig. 19 Welding results of GMAW

5. Conclusion

In this paper, a developed digital automatic GMAW system is presented. A new way achieving better welding results by using a decentralized control method is proposed. The GMAW system is considered as two separate subsystems such as WFU and PS-GMAW. Furthermore, the mathematical models of two subsystems are presented. Based on these models, sliding mode control and proportional control methods are proposed and applied to control the output welding current and voltage for tracking the setting value. The simulation and experiment results show that the developed digital automatic GMAW makes the output welding values track the setting values very well. Furthermore, very nice and neat welding line is achieved by developed GMAW system.

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