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Integrated Models of a Gas Metal ARC Welding Process and Inverter based Power Supply for Process Control Simulation Studies

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***Abstract*—The objective in this paper was to combine the simulation of a Gas Metal Arc Welding (GMAW) process model with the simulation model of an inverter-based power machine. The GMAW process was considered as an electrical circuit and the mathematical model was based on physical descriptions of several parts of the GMAW process, as were the electric circuit of the power supply, the arc dynamics, and the electrode melting process. A simple welding application was simulated and the welding parameters were derived from several experimental conditions. Next, the dynamic behaviour of a full-bridge DC-DC converter was simulated and a suitable discrete PI controller proposed for welding current feedback control. Both models, the GMAW model and the inverter power supply model, were combined into a new simulation model of the GMAW process application together with an inverter based welding machine.**

***Index Terms*—Power system modelling, process control, simulation, welding.**

I. INTRODUCTION

The gas metal arc welding process is also called the MIG/MAG welding process, and is almost a substitute for the stick-electrode arc welding process within industry nowadays. This process is often used to weld aluminium using an inert shielding-gas (MIG - metal inert gas) or for welding certain ferrous metals using active shielding-gases (MAG). GMAW is an economical process suitable for welding most of metals at all positions using lover energy variations of the process. It is appropriate for usages in semi-automatic or automatic welding applications applied throughout high production industry.

Several research studies, for example [1]–[4], categorize the GMAW process as an electrical circuit. A mathematical model of the GMAW process is normally developed first. A description of the electric arc is then presented and all equations are combined into a general model that describes the GMAW process. Simulation methods are used to illustrate the behaviour of the GMAW process. During these simulations the welding power source's dynamic behaviour is often simplified. Today, in modern welding machines the inverter-based transformer technologies are used for transforming a high voltage and a low current into low voltage and a strong current. The main advantages are the small volume, being lightweight, excellent control performance and good dynamic characteristics, which allow fast adaptation ability to arc load's change. This is important for welding process stability and for the possibility of realizing different welding applications, such as pulsed DC welding, pulsed AC welding, and others. The quality of the output welding current and voltage of a GMAW power source has an important influence on the dynamic behaviour of the GMAW process and on the quality of the welded product. With the aim of maintaining a high quality of welding results, the output welding current and voltage must be controlled during the welding process. Furthermore, a real time control system is an important element of modern GMAW welding machine [5], [6].

Modern GMAW equipment is the combination of a sophisticated power electronic device and high performance microprocessor-based control systems. The development process of inverter-based welding power source with the corresponding control system is a complex and expensive process that requires extensive human and material resources [7]. When using the simulation technique the quality of design process can be improved and the design cost can be significantly reduced. Therefore, with the aim of improving the design process, an attempt was made to combine the simulation model of GMAW process with the simulation model of an inverter based welding power source [8].

This paper studies the dynamic behaviour of full-bridge inverter circuit together with the GMAW model. Both models are combined into a simulation model of the GMAW welding application with an inverter-based welding machine. The simulation results are useful for the rapid development of control algorithms of new power sources.

II. MODELLING OF THE GMAW PROCESS

As the GMAW process consists of several subsystems including the power supply, the melting process of the feeding wire, the dynamics of welding arc, the drop dynamics and the material transfer process, as illustrated in Fig. 1, its dynamic behaviour depend on the characteristics of each subsystems.

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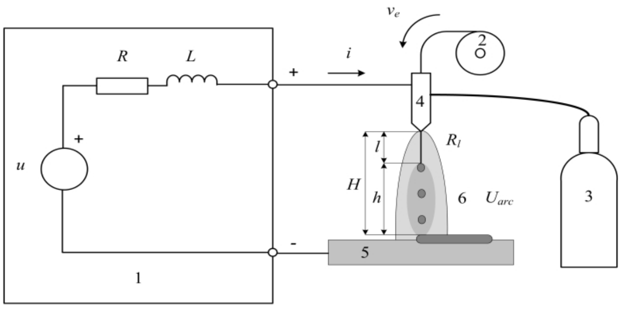

Fig. 1. GMAW process with basic equipment. (1) Power source; (2) Wire feed unit; (3) Shielding gas; (4) Welding gun; (5) Workpiece; (6) Welding arc and material transfer process.

The GMAW process can be presented as an electrical circuit with control voltage u as the input variable. The circuit consists of the power source inductance L and resistance R, i is the welding current, R_l is the electrode stick-out resistance, and U_{arc} is the arc voltage. Electrode stick-out resistance R_l is dependent on the electrical resistivity of the electrode stick °, cross-sectional area of the electrode wire A, and the electrode stick-out length l, and can be calculated as $R_l = l°/A$. It is assumed that u, R, L, °, and A are constant parameters and i, l, U_{arc} are dependent variables. We assume that welding process is stationary process and welding signals features are time invariant: $E(i(t)) = const.$, and $Var(i(t)) = \sigma^2$. A model of the electrical circuit is described using (1)

$$u = R \times i + L\frac{di}{dt} + i \times R_l + u_{arc}. \quad (1)$$

The electrode resistance R_l depends on total the length of the electrode stick-out length and drop length $l = l_s + l_d$. The dynamics of l_s depend on the feeding speed of electrode v_e, the melting speed v_m, and on the vertical velocity of the contact tip v_c. The contact tip to workpiece distance (CTWD) is indicated by H, and by ignoring the length of the drop ($l_d = 0$ and $l = l_s$) the length of the arc h is

$$h = H - l. \quad (2)$$

The dynamic of electrode stick-out is given by (3)

$$\frac{dl}{dt} = v_e - v_m + v_c. \quad (3)$$

With respect to (2) and (3), the arc length speed is

$$\frac{dh}{dt} = v_m - v_e - v_c. \quad (4)$$

In regard to the presented model, the dynamics of the melting speed v_m and arc voltage U_{arc} need to be described in greater detail. When the current flows through the electrode and the arc the electrode is heated by the current flowing through it. This heat depends on the resistance of the electrode. Numerous studies have described the physical background of this phenomenon. In [9] the research results from a study of anode and cathode melting rates are presented and in [10] the characteristic of melting rate as a function of current, type of gas, and other parameters is reported. In these and other related works [11] the expression for the total melting velocity v_m is proposed as

$$v_m = k_1 \times i + k_2 \times i^2 \times l. \quad (5)$$

An arc appears during the welding process between the electrode-stick (anode) and the workpiece (cathode). It can be presented as a discharge of electricity between the electrodes, characterized by a high current density and a low voltage drop between electrodes. The simplest model of the electrical arc is a voltage equation

$$u_{arc} = u_{a+c} + E \times h + i \times R_{arc}. \quad (6)$$

The total arc voltage u_{arc}, is made up of three separate parts: the anode and cathode drop voltage u_{a+c}, the drop voltage in the arc column, which is a function of the electric field strength E and the arc length h, and the drop voltage, that depends on current i and arc resistance R_{arc}. In our model we suppose that u_{a+c} is constant.

The model of the consumable electrode GMAW process is composed of (1), (4)–(6) and is

$$u = R \times i + L\frac{di}{dt} + i \times \frac{°}{A} \times l + u_{a+c} + E \times h + i \times R_{arc}. \quad (7)$$

Further parts of GMAW process dynamics, for example the welding drop dynamics, or drop detachment process are also important, but in this model are neglected. On the other hand, in GMAW not only the spray transfer conditions are widely employed but also the short-circuiting arc’s conditions with a relatively small current. This type of material transfer is within the mainstream of high-speed welding regarding thin sheet or overhead position welding of line pipes. Short-circuiting welding is a complicated process in which short-circuiting and arc generations are repeated intermittently. This should be the subject of our further research and will be included in the model.

III. Model of Inverter Power Supply

The inverter-based welding power supply consists of a rectifier, an inverter switch circuit, a high-frequency ferrite transformer, high-frequency rectifier, and an inductor as is presented in Fig. 2.

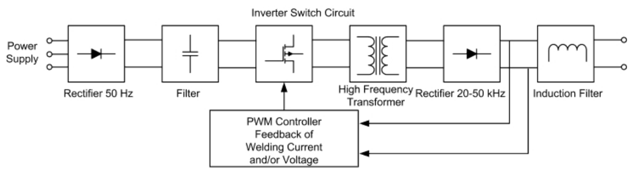

Fig. 2. Power supply architecture of modern-inverter based welding machine.

Most inverter switch circuits are realized with full-bridge DC-DC converters based on semiconductor power elements such as MOSFETs, or IGBT transistors. The switch circuits are controlled by microprocessor-based PWM controller units. The schematic of a simulation model of a full-bridge DC-DC converter is shown in Fig. 3.

The conventional DC-DC converter operates using a Pulse Width Modulation (PWM) current controller.

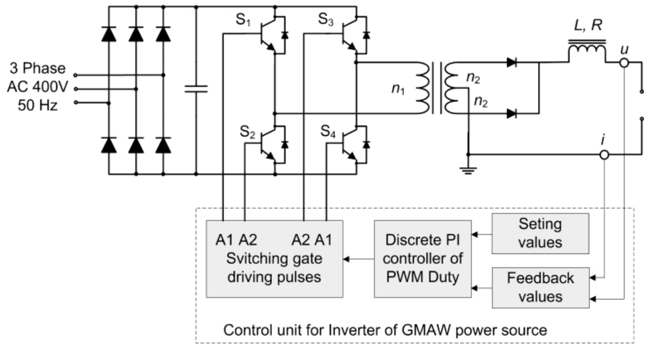

Fig. 3. DC-DC converter circuit using full-bridge PWM inverter with corresponding control unit.

The DC-DC converter operates at constant switching frequency, which is usually limited to 20 kHz–50 kHz. The amplitude of the welding current depends on the change of the phase shift between transistors S_1, S_2, S_3, and S_4. The PWM signals are generated using a simple circuit and are used for driving four transistors by changing the duty cycle. In paper [12] the authors investigated the implementations of different PWM control techniques on a microcontroller. These modulation techniques are used in order to enhance the performances of three-phase inverters. The duty cycles are usually controlled using feedback controller (voltage, current, or both). In [13] and [14] the implementation studies of *proportional-integral-derivative* (PID) controller are presented, but we decided to use a PI controller because it satisfies control performances well, and the lack of derivative action may make the control system stabile in the case of noisy data. The discrete parallel form is

$$C_{PI}\left(z\right)=K_p+\frac{T_S}{T_I\cdot}\times\frac{1}{\left(z-1\right)}, \qquad (8)$$

where K_P is the proportional gain, T_I is the integral time constant, and T_S is the sampling time.

IV. Simulation Results

An automatic welding application was assumed. Those parameters derived from the experimental conditions are shown in Table I.

TABLE I. GMAW PROCESS SIMULATION PARAMETERS.

Parameter	Descr. of the parameter	Value
R	Power source resistance	0.07 Ω
L	Power source inductance	0.02 mH
∘	Specific electrical resistance of the electrode	0.1 Ω/m
A	Cross-sectional area of the electrode wire	1.02×10^{-6} m^2
E	Electric field strength	675 V/m
u_{a+c}	Arc voltage constant	11.55 V
R_{arc}	Arc resistance	0.03 Ω
v_e	Feeding speed of electrode	0.5 m/min
k_1	Empirical constant	0.626 m/(As)
k_2	Empirical constant	7.55×10^{-5} (A^{2}s)$^{-1}$
H	Contact tip to workpiece distance (CTWD)	0.16 m
l	Electrode stick-out length	0.10 m

A constant welding speed was supposed. The welding torch was positioned 16 mm (H) from the work distance. The selected welding wire feed rate v_e 50 mm/s and the open circuit voltage u = 24 V were set. The first simulation was performed to find the welding current response when the CTWD was changed from 16 mm to 12 mm (at time 2.5 s) and back (at time 7.5 s). In addition, the electrode feeding speed v was changed from 50 cm/min to 75 cm/min at time t = 5 s.

Fig. 2 shows the changes in the welding voltage and current time responses, and the changes of the arc length.

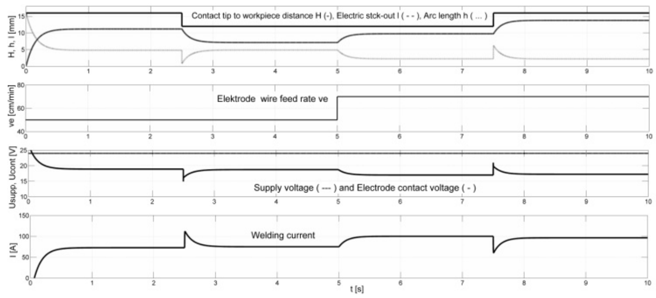

Fig. 4. Simulated results of contact to workpiece voltage waveform (third plot) and welding current waveform (fourth plot). Simulation response of the GMAW model when the CTWD was changed from 16 mm to 12 mm (first plot) and the electrode feeding speed ve was changed from 0.5 m/min to 0.7 m/min (second plot).

The welding current rose and fell with the changes of H and v_e, as expected. It can be seen from the first plot in Fig. 2 that the arc length h (dotted curve) decreased after the H changed from 16 mm to 12 mm and then increased back to the previous length. Accordingly, the electrode length l changed from 11.25 mm to 7.5 mm, which meant that the electrode melted at a higher speed when the current increased. In the second plot of Fig. 2 the electrode feeding speed was increased from 50 mm/s do 70 mm/s. This led a reduction of the arc resistance and an increasing of welding current.

A full-bridge circuit is simulated as the topology of the main inverter circuit. The load of the inverter depended on GMAW simulation model and was continuously changing. In Table II the design specification of the DC-DC converter and the circuit parameters are described, respectively.

TABLE II. DC-DC CONVERTER AND OTHER CIRCUIT PARAMETERS.

Parameter	Descr. of the parameter	Value
f_s	Switching frequency	40 kHz
C	Capacitance	1 μF
Pn	Transformer nominal power	5 kW
$n_1 : n_2 : n_2$	Transformer turns ratio	3,5 : 1 : 1
S_1 - S_4	Ideal switch, IGBT	
R_{on}	Switch internal resistance	140 mΩ
R_s	Snubber resistance	1MΩ
C_{sd}	Snubber capacitance	4,7 nF
T_s	Control sample time	0.1 ms
T_I	PI controller Integral constant	2 ms
K_P	PI controller proportional gain	0,2 %/A

The simulation results from the welding using current control feedback and the PWM full-bridge DC-DC converter are shown in Fig. 5.

Constant welding speed was supposed. The welding torch was positioned at 16 mm (H) from work distance (CTWD) and after 5 ms H was increased to 18 mm, as is presented in the first graph of Fig. 5. The welding wire feed-rate v_e was set at 70 mm/s. After 1 ms the welding current's set point was increased to 100 A, after 3 ms to 200 A, and finally after 7 ms to 150 A. The fourth plot in Fig. 5 presents the current control system transient response, which was stable with a small overshoot and was sufficiently fast. On the fifth plot the time response of the primary current is shown.

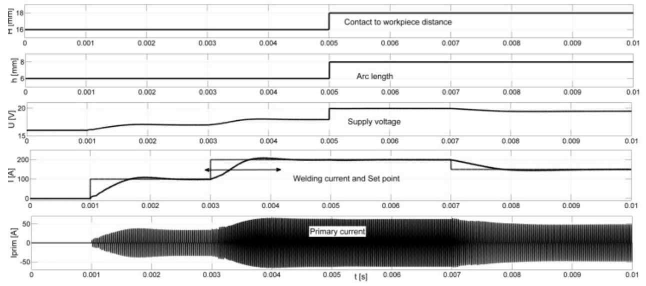

Fig. 5. Simulation results of the welding process with current control feedback and PWM full-bridge DC-DC converter-based welding power source. The upper plot shows the change of the CTWD from 16 mm to 18 mm. The forth plot presents the welding current transient response, and on the fifth plot the time response of the primary current is shown.

For a better presentation of the generated PWM signals the same simulation results were plotted within a time window from about 3 ms to 4 ms, and marked with an arrow in the fourth graph in Fig. 5.

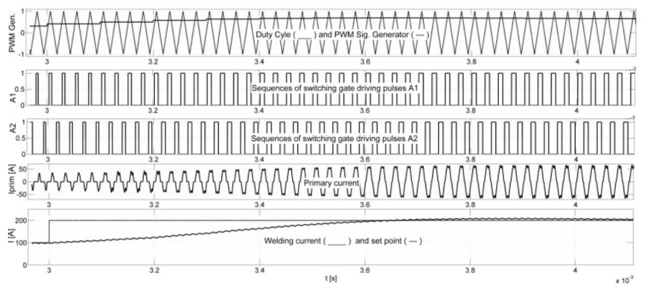

Fig. 6. Simulation results of generated PWM signals, which depend on the duty cycle controlled with simple PI controller. The second and third plots show the PWM signals for driving the full-bridge DC-DC converter switches. The fourth and fifth plots show the corresponding changes of primary current and secondary-welding current.

In the first plot of Fig. 6, the PWM frequency generator is compared with current controller output (duty cycle). In second and third plots the PWM signals for driving the full-bridge DC-DC converter switches are presented. The periods of pulses A1 and A2 changes depended on the duty cycle determined by the discrete PI controller. The maximum simulation step-size was 0.1 μs and the discrete PI controller sample time was 100 μs.

V. CONCLUSIONS

A simulation application has been developed for simulating the GMAW process and inverter-based welding source. The mathematical model is based on physical descriptions of several parts of the GMAW process, as are the electric circuits of the power supply, the arc dynamics, the electrode melting process, etc. Further process parts, for example the welding drop dynamics and drop detachment process will be the subject of further research and should also be included in simulation model of the GMAW process. The simulation of inverter power source for welding power supply has been proposed and tested together with the GMAW simulation model. The simulation results showed that the conventional full-bridge DC-DC converter with appropriate current feedback controller makes the output welding current follow the set references.

The proposed models and simulations, which are combine together to simulate the power source circuits using simulations of the GMAW process, are suitable for the development new power source circuits, for example resonant converters. By establishing appropriate models of the GMAW process and the full-bridge DC-DC converter model, simulation is an effective tool for investigating new welding technologies, for example the Pulsed GMAW process, or Surface Tension Transfer welding process (STT). Simulation results could be very useful for the rapid development of new control algorithms and for the designing of new inverter control units.

REFERENCES

[1] K. L. Moore, D. S. Naidu, R. Yender, J. Tyler, "Arc Welding Control: Part 1 – Modelling and Analysis", *Nonlinear Analysis: Theory, Methods & Applications*, vol. 30, pp. 3101–3111, 1997. [Online]. Available: http://dx.doi.org/10.1016/S0362-546X(97)00372-6

[2] K. L. Moore, D. S. Naidu, S. Ozcelik, *Modelling, Sensing and Control of Gas Metal Arc Welding.* Oxford, UK: Elsevier Science Ltd., 2003.

[3] M. Golob, A. Koves, A. Puklavec, B. Tovornik, "Modelling, simulation and fuzzy control of the GMAW process", in *Conf. Proc. 15th Int. Federation of Automatic Control (IFAC) - Triennial World Congress on Automatic Control*, Barcelona, Spain, 2002, vol. 13, pp. 253–258.

[4] J. S. Thomsen, "Control of Pulsed Gas Metal Arc Welding", *Int. Journal of Modelling, Identification and Control*, vol. 1, no. 2, pp. 115–125, 2006.

[5] J. Zhang, B. L. Walcott, "Adaptive Interval Model Control of Arc Welding Process", *IEEE Trans. On Control Systems Technology*, vol. 14, pp. 1127–1134, 2006. [Online]. Available: http://dx.doi.org/10.1109/TCST.2006.880215

[6] J. Scemeliovas, "Determination of Optimal Pulse Current for Arc Welding", *Elektronika Ir Elektrotechnika*, no. 7, pp. 87–90, 2009.

[7] M. D. Ngo, V. H. Duy, N. T. Phuong, H. K. Kim, S. B. Kim, "Development of digital gas metal arc welding system", *Journal of Materials Processing Technology*, vol. 198, no. 1–3, pp. 384–391, 2007. [Online]. Available: http://dx.doi.org/10.1016/j.jmatprotec.2007.02.010

[8] M. Golob, B. Tovornik, "Modelling, simulation and control of gas metal arc welding", in *Proc. 7th Congress on Modelling and Simulation EUROSIM*, Prague, Czech Republic, 2010, pp. 347–352.

[9] A. Lesnewich, "Control of the Melting Rate and Metal Transfer in Gas Shielded Metal Arc Welding - Part 1", *Welding Journal*, vol. 37, pp. 343s–354s, 1958.

[10] J. Tusek, M. Suban, "Dependence of Melting Rate in MIG/MAG Welding on the Type of Shielding Gas Used", *Journal of Materials Processing Technology*, vol. 119, pp. 185–192, 2001. [Online]. Available: http://dx.doi.org/10.1016/S0924-0136(01)00940-2

[11] E. Halmoy, "Wire melting rate, droplet temperature and effective anode potential", in *Proc. Int. Conf. Arc Physics and Weld Pool Behaviour,* London, England, 1979, pp. 49–57.

[12] C. Aghion, O. Ursaru, "Three-Phase inverter Controlled by ISCPWM and DPWM-S1", *Elektronika Ir Elektrotechnika*, no. 3, pp. 87–90, 2012.

[13] O. Krejcar, I. Spicka, R. Frischer, "Implementation of Full-Featured PID Regulator in Microcontrollers", *Elektronika Ir Elektrotechnika*, no. 7, pp. 77–82, 2011.

[14] A. Petrovas, S. Lisauskas, R. Rinkeviciene, "Digital Automatic Control System with PID Controller", *Elektronika Ir Elektrotechnika*, no. 4, pp. 13–16, 2011.