APPLICATION OF SLIDING CONTROL METHOD TO AN ARC WELDING MACHINE AND COMPARING ITS PERFORMANCE WITH THAT OF CONVENTIONAL PI METHOD

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ABSTRACT

In this study, the performance of a high-frequency arc welding machine including a two-switch inverter is analyzed. The state space equations of the system are derived for different states of the inverter switches and used in obtaining the overall mathematical model of the system using the averaging technique. The duty cycle of the converter is derived based on Phase-Shift Pulse-Width-Modulation (PSPWM) technique combing the derived mathematical model with the sliding control rule. The performance of the system is analyzed by simulating the system using SIMULINK tool box of MATLAB. The simulation results of this method are compared with those of the conventional PI method. The simulation results show that the proposed control method performs well and satisfies the control requirement being the adjusting load current at the set value.

I. INTRODUCTION

Welding machines performance and their circuit configurations vary with development of high-frequency power semiconductor devices. Operating the converters of the arc machines at high frequency increases the control performance of the systems. In arc welding, the main problem of concern during the control design is complexity and strong uncertainty. Reliable models that could relate process control input and output weld properties are not very well known [1]. Modern electronic welders are required to feature lightness, safety, reliability, cheapness and flexibility of operation. According to the developments of power electronics technology, new circuit topologies and control strategies are possible to achieve higher quality in this area [2]. There are lots of methods to improve welding performance.

The load current is controlled using state-space averaging based sliding mode and the conventional PI control methods. The advantage of sliding mode controller is their switching control actions, which are appropriate to the on-off behavior of power switches. Ideally, the switching of control occurs at infinitely high frequency. In practice, the frequency can not be infinitely high due to the finite switching time and the undesired parasitic effects causing undesired chattering of the control. Infinitely high frequency is the main obstacle of sliding mode controllers and can be surmounted by applying a constant switching frequency. In this study, this is achieved by designing the controller using sliding average method. The proposed control method is used in adjusting the load current by varying the duty cycle of only one of the switches, since the duty cycle of the another switch is constant and is equal 50%.

II. CIRCUIT CONFIGURATION OF THE ARC WELDING MACHINE

The main system of the arc welding machine is shown in Fig. 1. The system consists of an uncontrolled rectifier, a two-switch single-phase inverter, a step-down high-frequency transformer, a mid-point rectifier, a filtering inductor and the load.

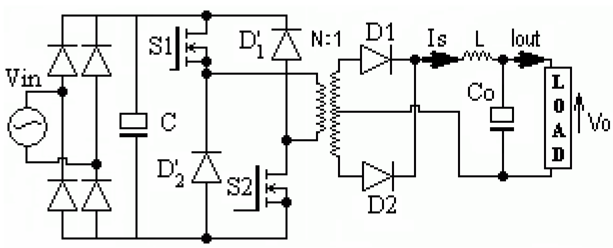
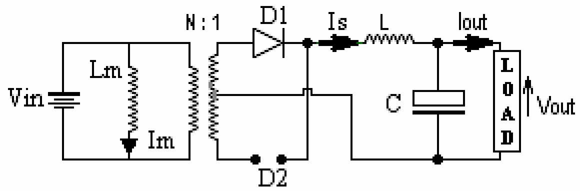


Figure1. Main system of arc welding machine

The first stage is an uncontrolled rectifier connected to ac mains of $220V_{rms}$ and 50 Hz. There is a filter capacitor connected at the output of the rectifier to decrease the peak-to-peak ripple of the dc-link voltage. The second stage is a two-switch single-phase inverter that converts dc-link voltage into a high frequency (20 kHz) square waveform ac signal. The third stage of the system is a high-frequency step-down transformer. The primary and secondary windings of the transformer are connected to the inverter and the mid-point rectifier, respectively. The purpose is to adjust the load current at the set value by varying the phase-shift angle of the inverter based on the sliding mode and PI control methods.

III. MATHEMATICAL MODEL AND CONTROL

The operation of inverter is divided into 3 modes depending on the “on” and “off” states of the semiconductor switches as shown in Fig. 2.



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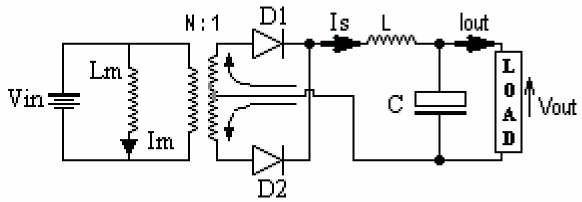

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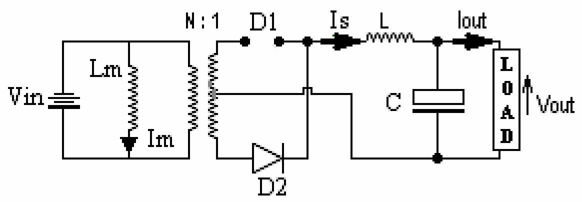

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Figure2. Different operating modes of the converter a)S1:on,S2:on b) S1:on,S2:off c)S1:off,S2:off

The operating modes of the inverter are given in Table1.

Table1. Operating modes

MODES	SW ON	SW OFF
Mode 1	S1,S2	-
Mode 2	S1	S2
Mode 3	-	S1,S2

Mode1- Both switches are in ON state (S1&S2) and the diodes are reverse-biased. The energy is charged in the magnetizing inductance and transferred to secondary windings of transformer. D1 is forward and the D2 is reverse biased.

Mode2- In this mode of operation S1 is conducting and S2 is in OFF state and the current links through S_1 and D'_1. In this duration the energy stored in the magnetic field is constant. The load current is equally shared between the mid-point rectifier diodes.

Mode3- Both switches are in OFF state (S1&S2). The voltage across the primary winding becomes negative generating a decreasing linear magnetizing current. In this period the magnetic energy is discharging. D2 is forward and D1 is reverse biased.

The difference between the welding converter topology proposed in this study and the conventional one is to insert an energy storage time of (1-D-K)T. By this method the stability and dynamic response of the system can be much improved when compared with the conventional welding converter [3]. Fig. 3 shows the time sequence of gate drive voltages waveforms of switches S1, S2 and the transformer magnetizing current, Im.

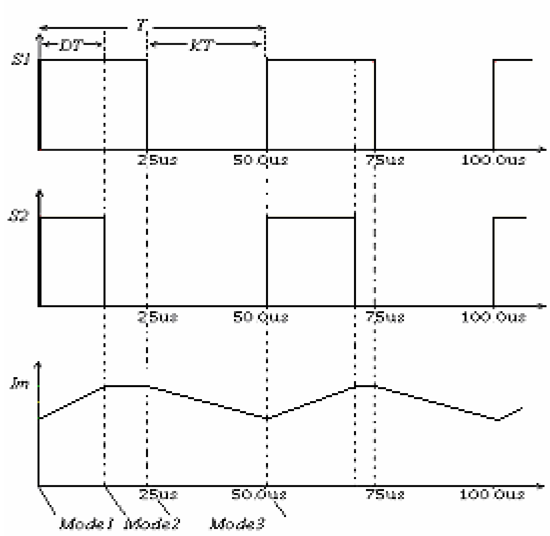

Figure3. PWM phase- shift control strategy and magnetizing current waveform

The parameters of the welding machine used in this study are shown in Table2.

Table2- System parameters

System Parameters	Values
Ac Source	220Vrms.
C input	3000µF
Turn Ratio	6
V primary	215V
V secondary	36V
C output	25µF
R Load	0.1778 Ω
Switching frequency	20kHz

In Fig. 3, T and D are switching period and the duty cycle of the welding inverter. The state space equations of the system for the case where the switches are in ON state and the current of the transformer is continuous are as:

$$\left.\begin{aligned} \frac{dI_m}{dt} &= \frac{V_{in}}{L_m} \\ \frac{dIo}{dt} &= \frac{I_m N}{RC} - \frac{Io}{RC} \end{aligned}\right\} \begin{array}{l} \mathbf{0 < t < DT} \\ \mathbf{S1 : ON \ \& \ S2 : ON} \end{array} \qquad (1)$$

The state equations corresponding to the case where S1 is ON and S2 is OFF are obtained as follows,

$$\left.\begin{aligned} \frac{dI_m}{dt} &= 0 \\ \frac{dIo}{dt} &= \frac{I_m N}{RC} - \frac{Io}{RC} \end{aligned}\right\} \begin{array}{l} \mathbf{DT < t < (1\text{-}K)T} \\ \mathbf{S1 : ON \;\&\; S2 : OFF} \end{array} \tag{2}$$

The state equations corresponding to case where both switches are in off state are as follows,

$$\left.\begin{aligned} \frac{dI_m}{dt} &= -\frac{V_{in}}{L_m} \\ \frac{dIo}{dt} &= \frac{I_m N}{RC} - \frac{Io}{RC} \end{aligned}\right\} \begin{array}{l} \mathbf{(1\text{-}K)T < t < T} \\ \mathbf{S1 : OFF \;\&\; S2 : OFF} \end{array} \tag{3}$$

In Eqn. 4 the moving averages of Im and Io are shown by X1 and X2, respectively.

$$X1 = Im \quad , \quad X2 = Io \tag{4}$$

$$\dot{X1} = \frac{dI_m}{dt} \quad , \quad \dot{X2} = \frac{dIo}{dt} \tag{5}$$

State space averaged equations can be obtained by combining equations 1, 2, 3 as;

$$\dot{X1} = \frac{V_{in}}{L_m}(D - K) \tag{6}$$

$$\dot{X2} = \frac{N}{RC} X1 - \frac{1}{RC} X2 \tag{7}$$

III-a SLIDING AVERAGE MODE CONTROL

In this study the moving average of the load current is used. This will significantly simplify the design. X2 is the moving average of the output current, and R is the desired output current. The sliding surface in the state space is given by X2 = R. The following conditions can be written according to the sliding-mode control rules given in [4].

$$\begin{aligned} \dot{X2} &< 0 \quad \text{if} \quad X2 > R \\ \dot{X2} &> 0 \quad \text{if} \quad X2 < R \end{aligned} \tag{8}$$

A first order path can be selected based on the following equation and the convergence speed is controlled according to the Eqn. 9.

$$\dot{X2} = -\lambda\,(X2 - Iref) \tag{9}$$

λ is a positive real number and is called the convergence factor. (Fig. 4)

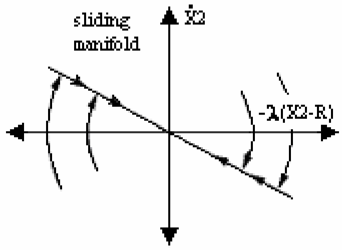

Figure4. Convergence relation for control of arc welding

Based on Eqn. 9, the larger the convergence factor the faster the system will reach its steady state. However, due to limits on the system parameters such as duty cycle, it is not possible to increase the convergence factor beyond a certain value [4]. Duty cycle can not be greater than %50 of the switching period.
The control parameter of this technique can be obtained by combining Eqns. 6, 7 and 9.

$$D = \frac{L_m}{V_{in}}\left[\frac{-\lambda\,(X2 - Iref)}{N}(1 - \lambda RC) + \frac{V_{in}}{L_m} K\right] \tag{10}$$

The controller given in Eqn. 10 is a function of time and does not depend on the state variables. The controller regulates the welding output current by means of duty cycle. Sliding average control strategy eliminates the main disadvantage of sliding mode control being variable switching frequency.

III-b PI CONTROL MEDHOD

The PI control method scheme is shown in Fig. 5. The parameters used in this method (Kp, Ki) affect the controller performance. By adjusting these parameters we are able to minimize the rise time and the steady state error of the load current. Effects of PI controller parameters on the output current are shown in Table3.

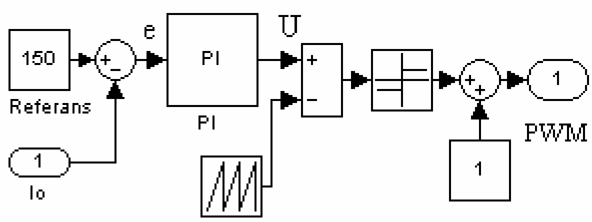

Figure5. Scheme of PI control method

The variable **e** represents the tracking error, the difference between the desired input value **R** and the actual output **Io**. The error signal **e** is sent to the PI controller, and the controller computes both the derivative and the integral of the error. The controller output signal (**U**) determines according to Eqn. 11.

Table3. Effects of PI controller parameters on the output current

CL Response	Rise Time	Overshoot	Settling Time	S-S Error
Increase in Kp	Decrease	Increase	Small Change	Decrease
Increase in Ki	Decrease	Increase	Increase	Eliminate

These correlations may not be exactly accurate, because Kp and Ki depend on each other. In fact, changing one of these variables changes the effect of the other. For this reason, the table should only be used as a reference when one is searching for suitable Ki and Kp values.

$$U = Kpe + Ki \int edt \tag{11}$$

IV. SIMULATION RESULTS

The system was modeled and simulated in MATLAB/SIMULINK. The load of the system is considered to be linear and resistive. In the simulation the load current is kept constant at the set value by controlling the phase-shift angle (or the duty-cycle) of the inverter switch. The simulations were performed using two different control methods and different cases of operation. Simulation results corresponding to different control methods are compared in the following sections.

IV-a RESULTS OF SLIDING AVERAGE METHOD

Fig.6 shows the dc link voltage, load current and load voltage waveforms of the welding machine for the parameters given in Table2. At instant of 0.01 sec. a 15% decrease occurs in the load resistance.

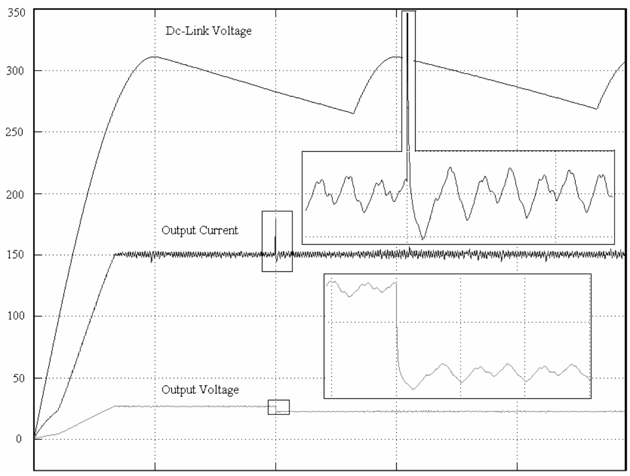

Figure6. Load voltage, load current and dc-link voltage waveforms

It is shown that the decrease in load resistance causes an increase in the load current for a very small period, which decreases to its set value by controlling the phase shift angle of the inverter.

Fig.7 is corresponding to the case where a 15% increase in the load resistance occurs at instant of 0.01 sec.

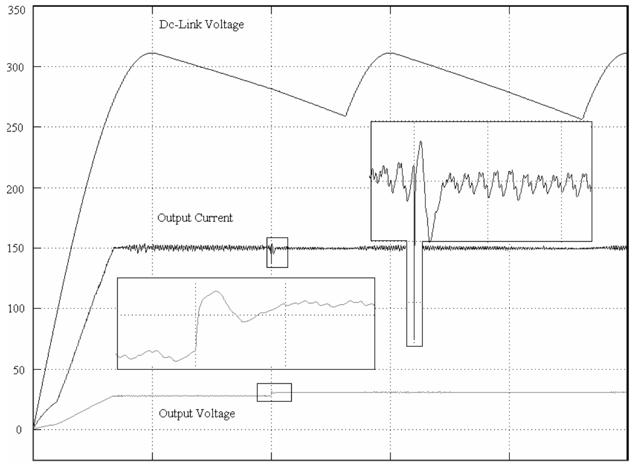

Figure7. Load voltage, load current and dc-link voltage waveforms

Fig.8 and 9 are similar to Fig.6 and 7. In these figures load resistance is constant and the changes occur in the ac mains voltage level.

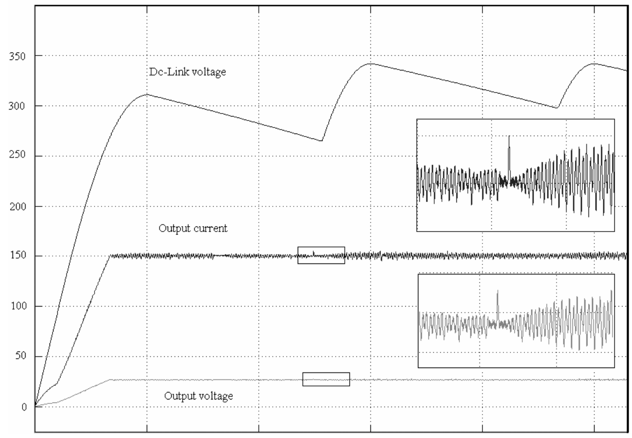

Figure8. Load voltage, load current and dc-link voltage waveforms for the case when the input voltage level increases by 10% at instant of 0.001 sec. (load is constant)

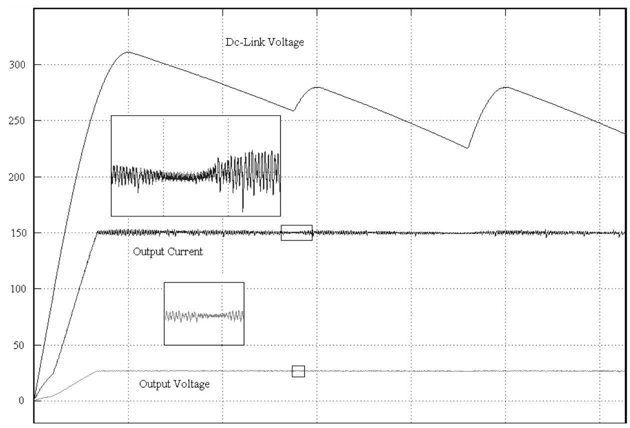

Figure9. Load voltage, load current and dc-link voltage waveforms for the case when the input voltage level decreases by 10% at instant of 0.001 sec. (load is constant)

IV-b RESULTS OF PI CONTROL METHOD

In this section of paper the simulation results of using PI control method are given. The conditions of figures 10, 11, 12, 13 are corresponding to those of figures 6, 7, 8 and 9, respectively.

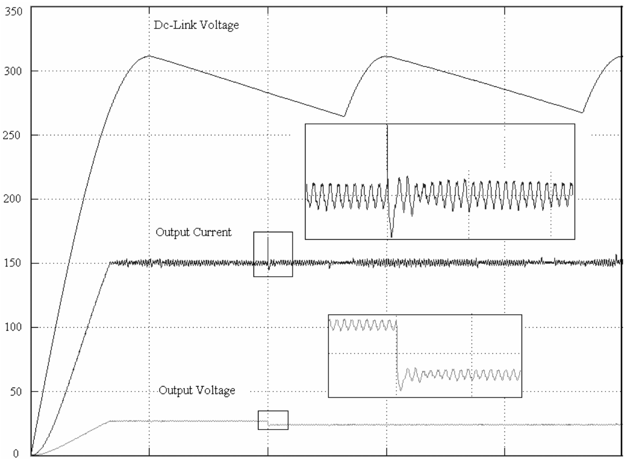

Figure10. Load voltage, load current and dc-link voltage waveforms

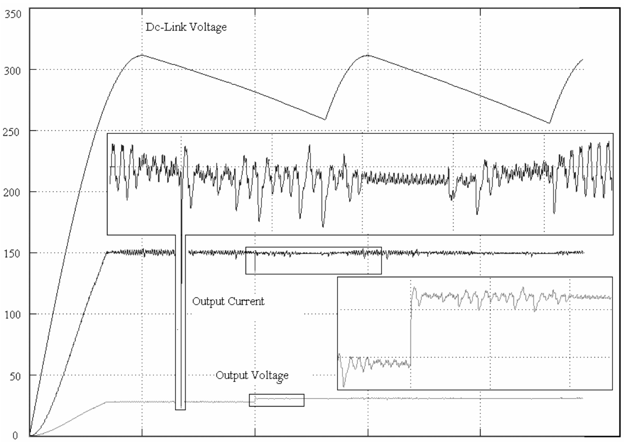

Figure11. Load voltage, load current and dc-link voltage waveforms

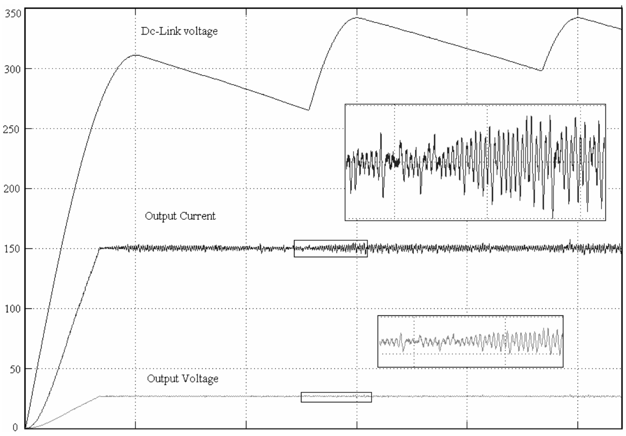

Figure12. Load voltage, load current and dc-link voltage waveforms

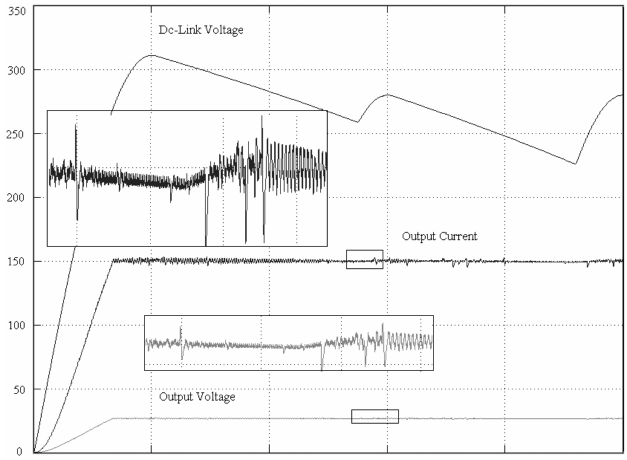

Figure13. Load voltage, load current and dc-link voltage waveforms

V. CONCLUSION

The welding machine was modeled and simulated by means of MATLAB/SIMULINK using a new control strategy of PWM technique (Two-switch phase-shift technique). The proposed model is a new and different from the conventional one in which the duty cycle of both inverter switches are changed. In this model, only the duty cycle of one of the inverter switches is changed while the duty cycle of the another inverter switch is constant (50%). The simulation results corresponding to the two different control methods are given in Section IV. The results show that the proposed PWM phase-shift technique performs well and satisfies the load current adjustment. In addition, comparing the results of two control methods applied to the arc welding machine confirms that the sliding average control technique is more robust than the conventional PI method.

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