Design and Analysis of a Front End AC-DC Switched Mode Converter For an Electronic Welding Machine

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Abstract

This paper presents design and analysis of a front end ac/dc switched mode converter for a dc electric welder. Constant dc link voltage is controlled by using a PI controller in conjunction with hysteresis band current control PWM for switching of two additional insulated gate bipolar transistors (IGBTs) in a full-bridge rectifier in order to improve input current waveform and input power factor. Derived equations for determining switching frequency limit are also included. Output dc arc current is controlled at constant level by using a PI controller to generate PWM signals with fixed switching frequency for power mosfet switching devices in a high frequency full bridge inverter. Design of feedback control for the front end switched mode converter is fully given in detail. The system performance is investigated which appears satisfactory.

Keywords: adaptive PWM current , IGBT , PI controller

1. Introduction

A dc electric welding machine has been widely used in general applications for joining material [1,3]. Typically, high arc dc current with low voltage in the range between 15 V to 75 V is used. Inverter arc welding machine with high frequency transformer offers various advantages such as improvement in welding performance and quality and a reduction in size and weight over the conventional transformer connected to ac mains. Generally, the conventional inverter welding machine includes AC/DC diode bridge rectifier as a front end converter which causes many problems such as harmonic currents and low input power factor[1,3]. Resonant switching techniques in order to increase the switching frequency and to reduce power losses were reported in[2]. However the system complexity and cost could be drawback. Therefore, to obtain high performance power converters having the abilities of A DC Electric Welder and power factor correction and harmonic content reduction,the front end switched mode converter is proposed in conjunction with high frequency inverter.

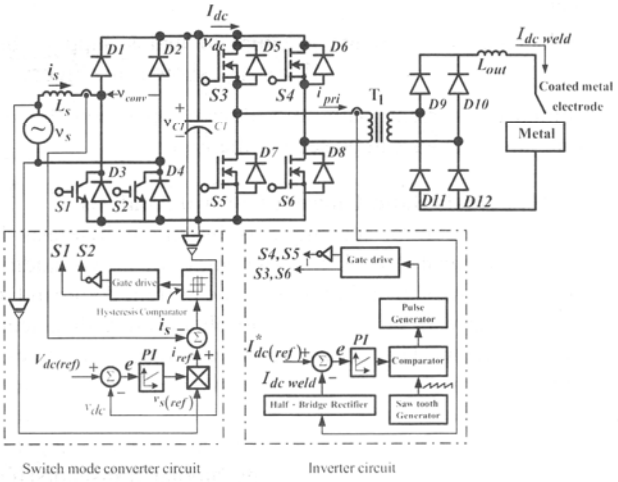

Fig. 1 Proposed electronic welding circuit

2. Main Power Circuit and Operation

The circuit configuration of the proposed system is shown in Figure 1. The system is composed of three main parts namely, an AC/DC front end switched mode converter, a DC/AC high frequency inverter and AC/DC diode bridge rectifier. The front end switched mode converter consists of four diodes and two IGBTs connected in anti-parallel with diodes at bottom of each leg of the full bridge[4]. The reason of selecting this configuration is low cost and uni-direction power flow which is appropriate for the welder machine. The proposed converter is controlled to achieve high power factor, current harmonic reduction and dc link voltage regulation. To obtain such performance, a hysteresis band current controller is employed in the inner loop control to track the line current command in phase with the mains voltage. A voltage controller is also used in the outer loop control to maintain the constant dc link voltage. The high frequency full bridge inverter using MOSFETs as switching devices is employed associated with the high frequency transformer to transfer power to the DC/AC diode bridge rectifier and the work piece to be welded. Current of the primary side of the transformer is controlled at required constant value through the PI controller to generate fixed switching PWM signals for all power mosfets. There are four operation modes for the proposed ac/dc switched mode converter as shown in Figure 2. The switching states of power devices. If the converter operates in the positive line current, the operation modes 1 and 2 are employed to track the line current command. On the other hand, operation modes 3 and 4 are used in the negative line current. All power switches and diodes are assumed ideal and dc capacitor voltages are controlled at required constant value ($v_{C1} = v_{dc}$). In the first operation mode, power switch *S1* is turned on and switch *S2* is turned off in the positive line current. The ac side voltage of converter is equal to zero ($v_{conv} = 0$). The inductance line voltage is equal to mains supply voltage ($v_{L_s} = v_s$).The current flows as shown in Figure 2(a). Similarly, current path and device operation for other operation modes can be seen in the Figure 2.

3. Hysteresis Band Current Control Analysis

A control technique is based on hyteresis band current control PWM for switching of two additional IGBTs[5]. As shown in Figure 3 the current command (i_{ref}) is in phase with ac mains (v_S) to obtain unity displacement power factor. The actual input current(i_s) will track the current command within hysteresis band. By considering operation point between 1 and 3, the input current will increase from lower hyteresis band at point 1 to upper band at point 2 and the Insulated gate bipolar transistors(IGBT) *S1* is switched on whilst *S2* is switched off. The linearly rising current(i_s+) then touches the upper band at point 2. The following equations can be written in the respective switching intervals t_1 and t_2.

$$L_s \frac{di_S^+}{dt} = v_S \tag{1}$$

$$L_s \frac{di_S^-}{dt} = v_s - v_{dc} \tag{2}$$

where L_s = input inductance , and i_s+ and i_s- are the respective rising and falling current segments.
From the geometry of Figure 3. The following equations can be obtained as

$$t_1 + t_2 = \frac{di_S^+}{dt} + \frac{di_S^-}{dt} = \frac{2v_S - V_{dc}}{L_S} \tag{3}$$

$$\frac{di_s^+}{dt} t_1 - \frac{di_r^*}{dt} t_1 = 2HB \tag{4}$$

$$\frac{di_S^-}{dt} t_2 - \frac{di_r^*}{dt} t_2 = -2HB \tag{5}$$

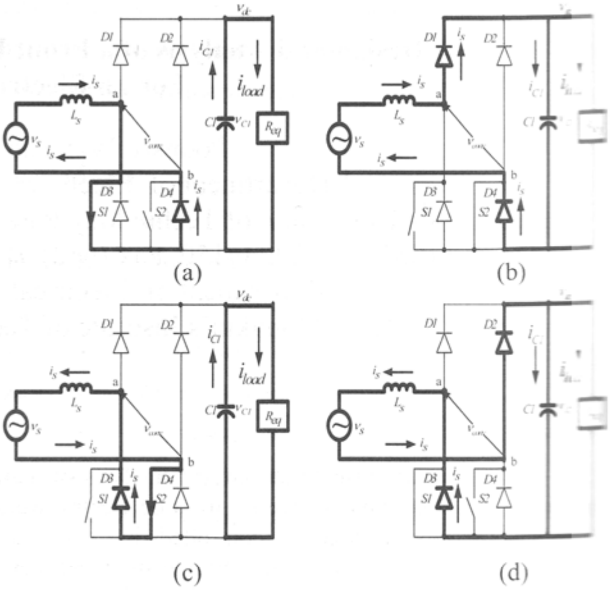

Fig. 2 Operation modes of the adopted converter
(a) Mode 1 (S1 "On" , S2 "Off" , $v_{conv} = 0$)
(b) Mode 2 (S1 "Off" , S2 "On" , $v_{conv} = v_{dc}$)
(c) Mode 3 (S1 "Off" , S2 "On" , $v_{conv} = 0$)
(d) Mode 4 (S1 "On" , S2 "Off" , $v_{conv} = -v_{dc}$)

$$t_1 + t_2 = T_S = \frac{1}{f_{S1}}$$

where t_1 and t_2 are the respective switching intervals, and f is the switching frequency.
Adding (4) and (5) and substituting (6), the equation can be written as

$$t_1 \frac{di_S^+}{dt} + t_2 \frac{di_S^-}{dt} - \frac{1}{f_{s1}} \frac{di_r^*}{dt} = 0$$

Subtracting (5) from (4), we can get

$$t_1 \frac{di_S^+}{dt} - t_2 \frac{di_S^-}{dt} - \left(t_1 - t_2\right) \frac{di_r^*}{dt} = 4HB$$

substituting (3) in (8) results in

$$\left[\left(\frac{1}{f_{s1}}\right)\left(\frac{di_s^+}{dt}\right)\right] - t_2 \left(\frac{2v_s - V_{dc}}{L_s}\right) - \left(t_1 - t_2\right) \frac{di_r^*}{dt} = 4HB$$

substituting (3) in (7) , we can get

$$t_1 - t_2 = \frac{\frac{\left(\frac{di_r^*}{dt}\right)}{f_{s1}} + t_2 \left[\frac{\left(2v_s - V_{dc}\right)}{L_s}\right]}{di_s^+/dt}$$

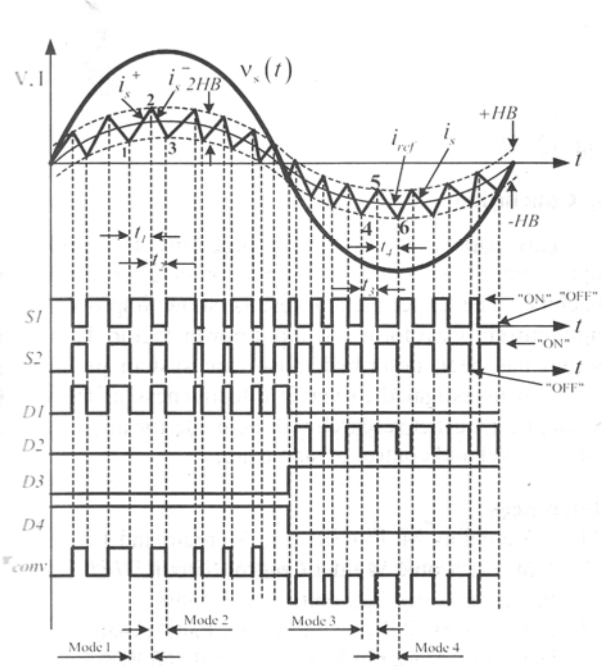

Fig. 3 Current control PWM technique and Timing pattern for each device

Substituting (10) in (9) , the equation can be rearranged as

$$\left[\left(\frac{v_s}{f_{s1}L_s}\right)\right]-t_2\left(\frac{2v_s-V_{dc}}{L_s}\right)\cdot\left(\left[\frac{m}{f_{s1}}\right]\cdot t_2\left(\cdot\frac{(2v_s-V_{dc})}{L_s}\right)\right)\left(\frac{L_s}{v_s}\right)(m)=4HB \quad (11)$$

By substituting (2) and (3) in (11) , current hyteresis band is

$$HB=\frac{0.25v_s}{f_{s1}L_s}\left[1-\left(1-\frac{V_{dc}}{v_s}\right)-\frac{m^2L_s^2}{v_s^2}-\left(1-\frac{V_{dc}}{v_s}\right)mL_s\right] \quad (12)$$

and switching frequency is

$$f_s=\frac{0.25v_s}{(HB)L_s}\left[1-\left(1-\frac{V_{dc}}{v_s}\right)-\frac{m^2L_s^2}{v_s^2}-\left(1-\frac{V_{dc}}{v_s}\right)mL_s\right] \quad (13)$$

Since

$$m^2=\left[\frac{d\left(I_{\mathrm{m}}\sin\omega t\right)}{dt}\right]^2=0.5\omega^2I_m^2\left(1+\cos2\omega t\right) \quad (14)$$

and

$$v_s=V_m\sin\omega t \quad (15)$$

Therefore, maximum switching frequency is

$$f_{s(\max)}=\frac{0.25V_{\mathrm{m}}}{(HB)L_s}\left[\frac{V_{dc}}{V_{\mathrm{m}}}\right]\text{at } \omega t=\frac{\pi}{2},\frac{3\pi}{2},\text{etc.} \quad (16)$$

Timing pattern for each device and input converter voltage (v_{con}) is also illustrated in Fig.3 corresponding to operation mode as mentioned in section 2.

4. Design of PI Controller

Figure 4 shows block diagram of the control system in the AC/DC switched mode converter for the dc electric welder. Simplified transfer function for regulated dc link voltage corresponding to the block diagram can be arranged as (17). Figure 5 illustrates root locus for determing PI compensator parameters. In order to obtain damping factor (ς) of 0.707 and natural frequency (ω_n) of 410 rad/s, proportional gain, K_p of 1.72 and integrator gain, K_i of 200 are chosen. Fig.6 shows step response giving settling time of 45 ms.

$$T(S)=\frac{V_{dc}(S)}{V_{dc(ref)}(S)}=\frac{R_{eq}V_sK(S+200)}{\left(R_{eq}CIS^2+S\right)V_{dc(ref)}+kR_{eq}V_s(S+200)} \quad (17)$$

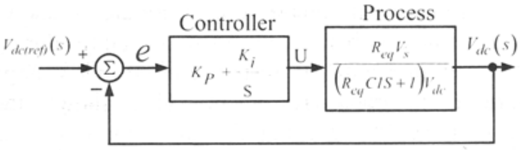

Fig. 4 Block diagram of the control system of the AC/DC switched mode converter

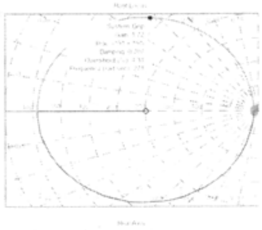

Fig. 5 Root locus of the control system

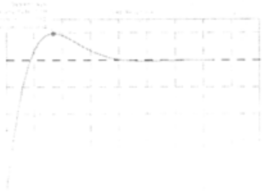

Fig. 6 Step response of the AC/DC switch mode converter using the designed PI compensator

Figure 7 shows block diagram of the arc current control loop. Simplified transfer function primary current in front side of the high frequency transformer with reference current corresponding to the block diagram can be arranged as (18).

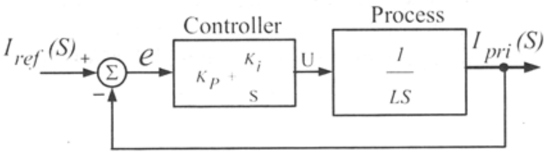

Fig. 7 Arc current control loop

$$T(S)=\frac{I_{pri}(S)}{I_{ref}(S)}=\frac{\left(K_p.S+(K_i/L_{pri})\right)}{\left(S^2+K_p.S+(K_i/L_{pri})\right)} \quad (18)$$

5. Experimetal Results

The experimental prototype of the AC/DC switched mode converter for the electric welder was built with designed circuit parameters and the initial stage of the experiment was conducted with metal work piece at dc arc current of 30 A. Maximum switching frequency of 25 k HZ for the switched mode converter is calculated with (16) to ensure that this value is below the maximum switching frequency of choosen IGBTs and fixed switching frequency of inverter is 50 kHz. This value is reasonable for Mosfets. DC link voltage is regulated at 311 V. Figure 8 and Figure 9 show the waveforms and harmonic spectrum of input current respectively. As shown in Figure 9 high order harmonics are reduced while the fundamental components of current is in phase with phase voltage. Figure 10 shows that DC link voltage is being controlled constantly during welding. Clearly, in Figure 10, response in dc link voltage with Figure 6 is good agreement. This shows the effectiveness of the PI controller design. Figure 11 and Figure 12 show output dc current waveform and welded metal work piece respectively.

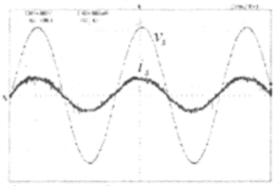

Fig. 8 Input voltage and current waveforms of the switch Mode converter , scale: 100 V/div and 5 A/div

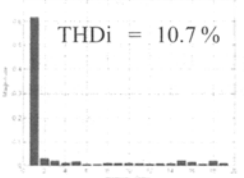

Fig 9 Corresponding harmonic spectra of the input current

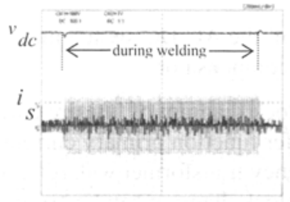

Fig. 10 Upper trace: dc link voltage, scale: 100V/div lower trace: input current scale : 5A/div : 200 ms/div. Measured with digital oscilloscope model DL1540/DL

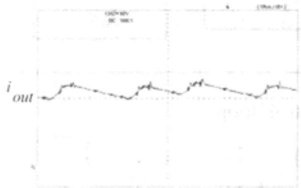

Fig. 11 Output dc arc current waveform scale 10 A/div

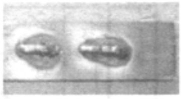

Fig. 12 Welded metal work piece

6. Conclusion

This paper has dealt with problems associated with input current of AC/DC converter for inverter arc welding machine. The experimental results show improvement of input current waveform and input power factor. The system design has been described. Also, the system performance has been investigated to verify effectiveness of the design. Attempt for further research will be made for increase in arc current level and control of stable arc.

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