A Study on Power Factor and Dynamics in Arc Welding System Using Single Switched PFC Converter

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Abstract

An arc welding machine using single switched PFC converter is presented in this paper. First, the basic operation and principle is reviewed. Controller design is intended to force voltage ripple to minimize, and dynamic response to enhance. Feed-forward strategy for arc welding machine is developed, and that is verified by simulation. The improved power factor characteristics of arc welding machine known as low power factor system with nonlinear property, are shown and evaluated compared to conventional one.

I. Introduction

An arc welding machine consists of preregurater part, inverter part , transformer and postregulator part. Because conventional arc welding machine uses diode rectifier as preregulator and then load varies remarkably, it results in low power factor and unstable inverter operation.[1] Among many problems, low-order harmonics and output voltage ripple must be considered deliberately because these problems deteriorate utility quality and total system performance. As countermeasure, the control techniques optimizing utility condition and improving dynamic response can be considered[2,3]. Due to above reasons it is proper to apply PFC converter for arc welding machine in three phase application. But as 6-switched three-phase converter has demerits of high cost and complex control scheme, there is a limitation adopting this topology[4,5]. So, in this paper novel arc welding system adopting single switched converter is proposed and implementated. That is evaluated with numerical method, simulation and experiment. Single-switched boost converter involving the economical merit of diode rectifier and the high power factor characteristics of PWM converter are studied through numerical method and also analyzed in terms of operation and input currents conditions in boost reactor.[6,7]

Enhanced control algorithm considering feed-forward compensation is expressed in detail. From a obtained transfer function of voltage controller, one can select controller gain. Voltage control scheme is plotted as diagram and verified through simulation, which reduces eminently output voltage ripple and serves stable power supply. Finally, in section IV power factor correction compared with conventional one is confirmed through experiment.

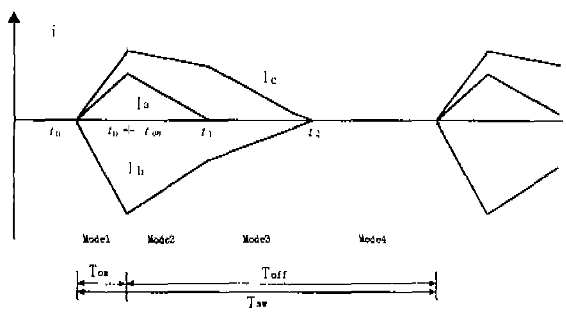


Fig. 1 input currents for a switching cycle.

II. Operation and Analysis

2.1 Operation

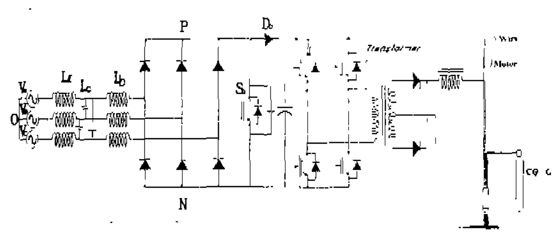


Fig 2. proposed arc welding machine

Like in Fig.2, single switched boost converter constitutes input filter(L_f - C_f), boost reactor, switch(S_b) and blocking diode(D_b). Based upon the theory of DC-DC boost converter, single switched boost converter can obtain excellent filtering performance with less reactive component by harmonic conversion from low order to high order. Fig.1. represents input current for a switching cycle in $[0, \frac{\pi}{6})$ and total four states are obtained as to switching and three-phase conditions. Assuming that phase-voltage for a switching cycle is constant, it comes to linear relations between phase voltage and line current respectively during T_{on} and energy is absorbed in reactor. For T_{off}, the current of a line current reaches zero first of all and then residual b, c line current reach zero.

2.2 Input current

The analysis of input current is carried out assuming that

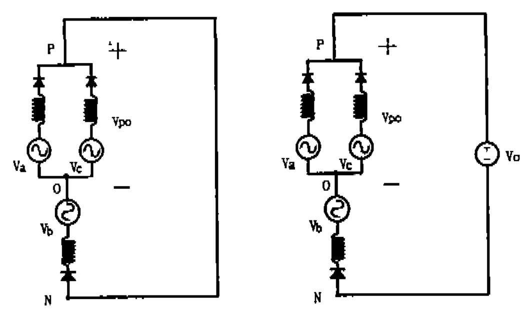
1) Voltage source is Symmetric
2) DC-link capacitor is as much as ripple is depreciated .
3) Input current operate in discontinuous conduction mode
4) All devices in circuit are ideal.

Fig.3 is equivalent circuit according to on/off state assuming that output capacitor is the same as the voltage source. By averaging equivalent circuits, state equation is as follows. During Switch On-Time, KVL is expressed as (1).

$$V_{PO} = -L\frac{di_a}{dt} + V_a = -L\frac{di_b}{dt} + V_b = -L\frac{di_c}{dt} + V_c \qquad (1)$$

Also, during Switch Off-Time, KVL is expressed as (2) respectively.

$$\begin{aligned} V_{PO} - V_a &= -L\frac{di_a}{dt} \\ V_{PO} - V_b - V_o &= -L\frac{di_b}{dt} \\ V_{PO} - V_c &= -L\frac{di_c}{dt} \end{aligned} \qquad (2)$$



(a) Switch On-time (b) Switch Off-time

Fig. 3. equivalent circuits as to switch state

$[0 \leq \omega t < \frac{\pi}{6}]$

$$I_A = \frac{\sin(\omega t)}{\sqrt{3}M - 3\sin(\omega t)} \frac{V_o T_{ON}^2}{2LT_{SW}} \qquad (3)$$

$[\frac{\pi}{6} \leq \omega t < \frac{\pi}{3}]$

$$I_A = \frac{M\sin(\omega t) + \frac{1}{2}\sin(2\omega t - \frac{2\pi}{3})}{[\sqrt{3}M - 3\sin(\omega t + \frac{2\pi}{3})][M - \sin(\omega t + \frac{\pi}{6})]} \frac{V_o T_{ON}^2}{2LT_{SW}} \qquad (4)$$

$[\frac{\pi}{3} \leq \omega t < \frac{\pi}{2}]$

$$I_A = \frac{M\sin(\omega t) + \sin(2\omega t + \frac{2\pi}{3})}{[\sqrt{3}M + 3\sin(\omega t + \frac{2\pi}{3})][M - \sin(\omega t + \frac{\pi}{6})]} \frac{V_o T_{ON}^2}{2LT_{SW}} \qquad (5)$$

$$where \quad M = \frac{V_o\ (dc\ link\ voltage)}{\sqrt{3}V_{LN}\ (peak\ value\ of\ L-L\ voltage)}$$

Reflecting on equation (3)(4)(5), the factors affecting power factor are boost reactor and voltage gain(M) under constant frequency and load.

Equation (6) and Fig.4 show the boundary of duty dependent on selected voltage gain(M). It is clear from Fig.4 that high value of M yields Continuous Conduction Mode(CCM). On the contrary low value of M yields Discontinuous Conduction Mode (DCM).

$$d_b = 1 - \frac{1}{M} \qquad (6)$$

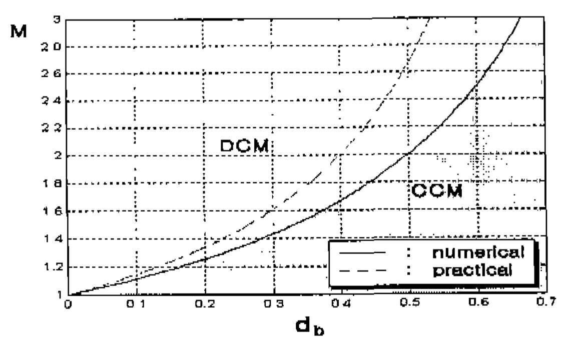


Fig. 4. boundary condition as to voltage gain & duty ratio.

Theoretical boundary is plot as a solid line, but practical boundary based on experimental experience is plot as a dotted line. Through Input current analysized by numerical method, one knows that higher value of M causes the more sinusoidal waveform in Fig.5.

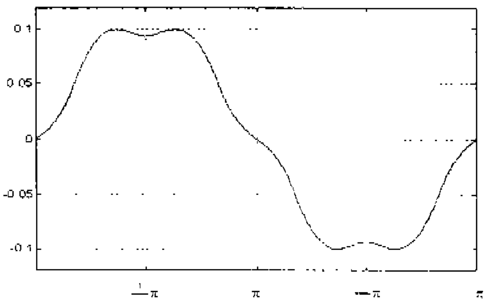


Fig. 5. numerically analysed input current.

III. Feed-forward strategy

Differential equation considering power is as follows.

$$C\frac{dV_c}{dt} = i_i - i_o = \frac{P_i}{V_c} - \frac{P_o}{V_c} \tag{7}$$

if linearization is accomplished by following equations,

$$V_c = V_c^* + \Delta V_c \qquad P_i = P_i^* + \Delta P_i \qquad P_o = P_o^* + \Delta P_o \tag{8}$$

$$P_i = P_o \qquad \frac{dV_c}{dt} = 0 \qquad V_c = V_c^*$$

(where V_c P_i P_o : *operating point*)

$$C\frac{dV_c}{dt} = \frac{1}{V_c}(P_i - P_o) = P_g(P_i - P_o) \tag{9}$$

where $P_g = \frac{1}{V_c^*}$

linealized model of dc output port is as follows. The reference of input power is obtained as summation of controller output and feed-forward term of load.

$$P_i^* = (k_p + \frac{k_i}{s})(V_c^* - V_c) + V_c i_o \tag{10}$$

Also, the gains of voltage controller can be obtained as (12). The transfer function of voltage controller is as follows.

$$\frac{V_c}{V_c^*} = \frac{\frac{P_g k_p}{C}s + \frac{P_g k_i}{C}}{s^2 + \frac{P_g k_p}{C}s + \frac{P_g k_i}{C}} \tag{11}$$

$$k_i = \omega^2 \frac{C}{P_g} \qquad k_p = \frac{2\zeta\omega C}{P_g} \tag{12}$$

(ω : natural frequency, ζ : damping ratio)

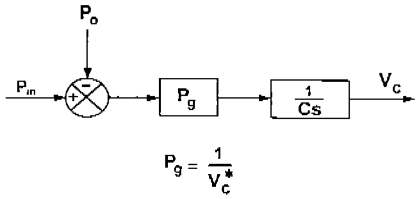


Fig. 8. Linearlized Model of DC side.

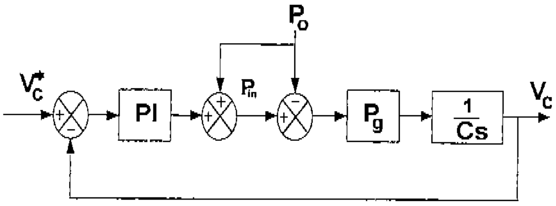


Fig. 9. block diagram of Voltage controller.

IV. Simulation and Experiment

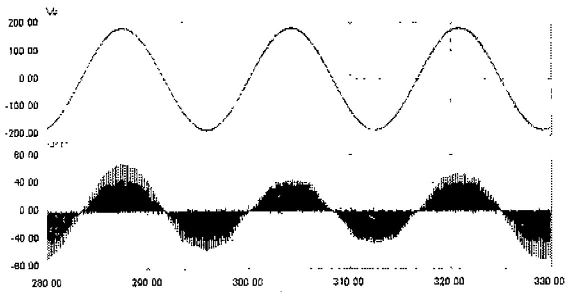
4.1 Simulation

Table 1. constants selection
(for both simulation and experiment)

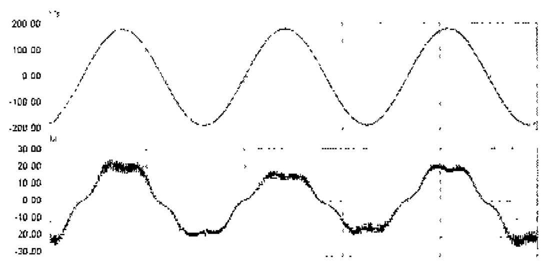
f_{cutoff}	4.5kHz
C_{out}	1000uF
f_{SW}	10kHz
L_f	45uH
C_f	25uF
V_o	400V
P_o	5-15kHz
L_b	15uF

Simulation analysis is accomplished by PSIM(Power Simulation) which has rapid calculation speed using ideal and simplified model and then verified theoretical proprioty. Maximum power and load characteristics of arc welding machine proposed as applied example are approximated because of nonlinear load property. The characteristics of Input/Output and harmonics contents by simulation is represented to well fit with theoretical expression. The constant used at simulation is shown table 1. Filtered by Low-pass filter and unfiltered currents are described by Fig. 10. Fig. 11,12 are comparative waveforms considering

Feed-forward compensation. From rapid response and diminished ripple, one can know that dynamics and stability is enhanced like table 2.



(a) discontinuous input current(50% load variation)



(b) continuous input current(50% load variation)

Fig. 10. input side current waveform

Table 2. Simulation results

With F-F compensation		Without F-F compensation	
■ L-L voltage	220V	■ L-L voltage	220V
■ output voltage	500V	■ output voltage	500V
■ ripple rate	±0.4%	■ ripple rate	± 3%
■switching freq.	10kHz	■switching freq.	10kHz

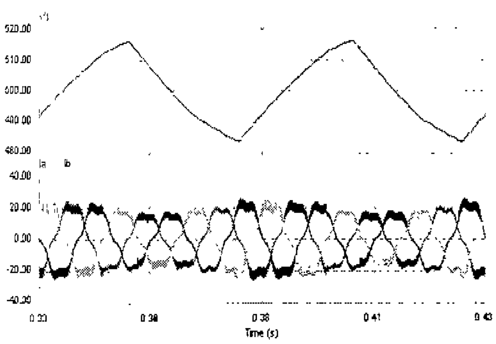


Fig. 11 output/Input waveform without Feedforward term

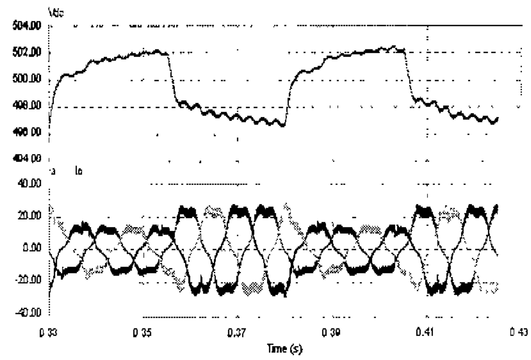
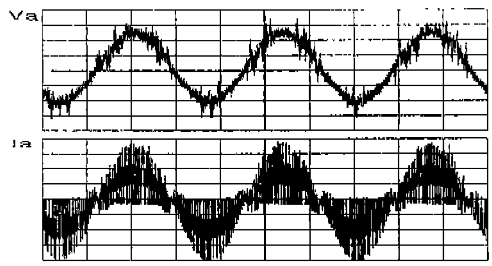


Fig. 12 output/Input waveform with Feedforward term

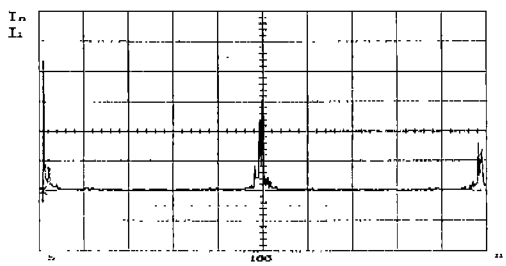
4.2 Experimental Results

4.2.1 resistive load

The experimental prototype of single switched boost converter is built and the experiment is conducted in the object of resistive load. The experimental constant is the same that table 1. shown before.



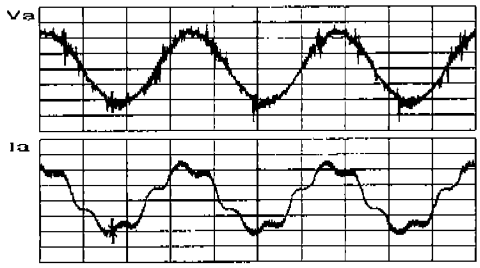
(a) voltage/current



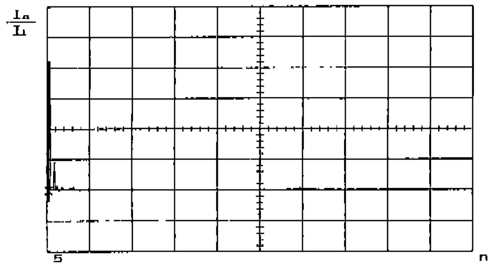
(b) frequency spectrum

Fig. 13. unfiltered input waveform

Fig13,14 shows the waveforms and frequency spectrum of input current. As like Fig. 13(a), low order harmonics has been reduced while the funmental components of current is in phase with phase voltage. Additionally the experiment confirms that the operation under boundary condition insures DCM current and minimized current ripple. The cutoff frequency selected in input filter is 4.5k[Hz] and a filtered current waveform is represented in Fig.14. But which waveforms inform of the restriction of power factor correction because of 5,7th-order components in filtered current. Fig.15 shows that DC link voltage is being controlled constantly for resistive load.



(a) voltage/current



(b) frequency spectrum

Fig. 14. filtered input waveform.

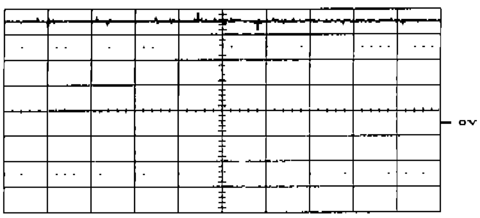


Fig. 15. output voltage. (100V/div)

4.2.2 Arc welding machine

The output characteristics of general inverter arc welding system is illustrated in Fig.16,17. A short and a arc stage in metal transfer power are reiterated with about 20Hz even though not periodically. It is short state that output voltage drops a vicinity of zero, and arc state that output voltage rises to maximum again. The output power that is the product of voltage and current , is shown and oscillates repeatedly. Owing to this property , single switched boost converter in welding system continues transient state due to load variation(50~100%) and hence a voltage controller considering feed-forward term must be designed with high response.

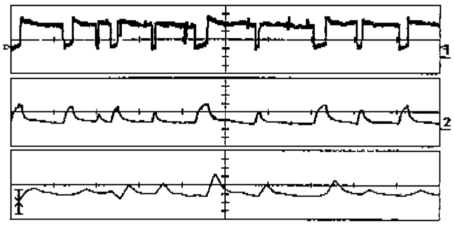


Fig.16. short transfer mode

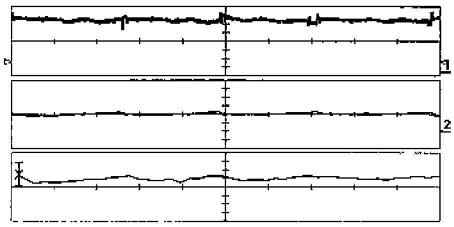
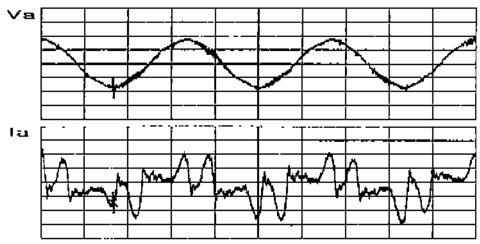
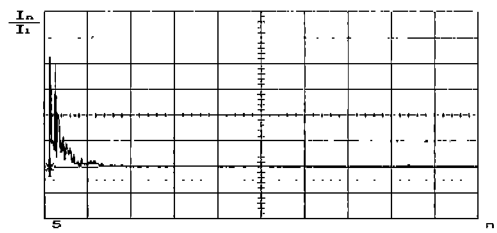


Fig.17. globular transfer mode

Fig.18 shows input waveforms of conventional arc welding machine known as low power factor instrument. In this figure, the low power factor property of diode rectifier appears remarkably. Fig.19 is a case of applying single-switched boost converter to arc welding machine, and shows considerable decrease of low-order harmonics. Output voltage is selected as 400V considering voltage rate of inverter and transformer. From an experiment, reduction of low-order harmonics results in power factor correction and economical implementation is also possible compared to full-bridge PWM converter.

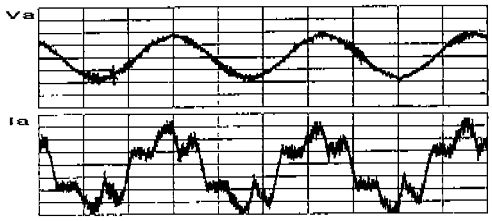


(a) input voltage/current

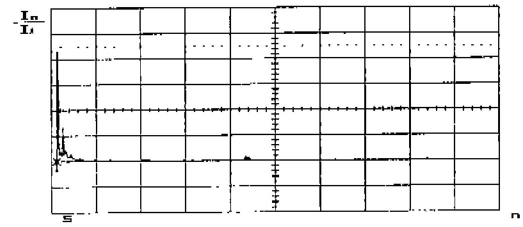


(b) frequency spectrum

Fig. 18. conventional arc welding machine.



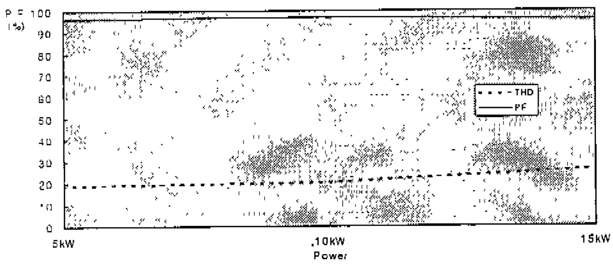
(a) voltage/current



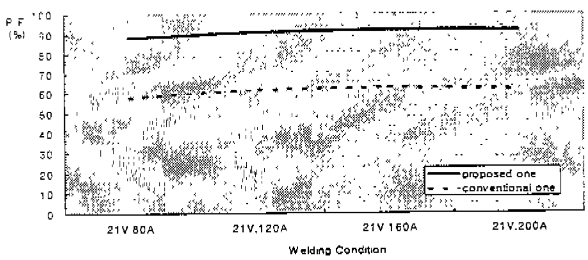
(b) frequency spectrum

Fig. 19. proposed arc welding machine.

Assuming that power perturbation is regular, input state is measured and analyzed in case of arc welding system. From these results, eminent correction of the power factor can be obtained like Fig. 19.
Measurement is performed for each welding conditions and classified harmonics, and then the p.f. characteristics for resistive and welding are shown in Fig. 20.



(a) resistive load



(b) arc welding machine

Fig. 20. Variation of power factor to load conditions.

V. Conclusion

In this paper, the operation characteristics of arc welding machine which limits low order harmonics is studied through numerical method and simulation/experiment. And the results are in the following.

1. parameter induction for power factor correction
2. advanced THD prior to diode rectifier
3. design of voltage controller based upon power for rapid response
4. available implementation of arc welding machine

Consequently, singe switched boost converter is suitable for arc welding system and is anticipated to increase system performance even though single control switch.

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