# POWER FACTOR CORRECTION OF CO2 WELDING MACHINE USING SINGLE-SWITCH THREE-PHASE AC/DC CONVERTER


Jae-Mun Kim*, Yuen-Chung Kim*, Jung-Jun Ahn*, Chung-Yuen Won* and Sei-Chan Kim**
*Sung Kyun Kwan University, **Bucheon College
300 Chunchun-dong, Jangan-Ku, Suwon 440-746, Korea
Phone +82-331-290-7169 Fax +82-331-290-7179
Email: kjmun@nature.skku.ac.kr



**ABSTRACT** - *This paper describes for reducing harmonic distortion in $CO_2$ welding machine with nonlinear load characteristic using single-switch three-phase AC/DC converter. The low-order harmonic component amplitude of the phase current of single-switch three-phase discontinuous mode is calculated.*

*Experimental results show that $CO_2$ welding machine with single-switch three-phase AC/DC converter is effectively controlled with power factor correction for phase current during welding time.*


## 1. INTRODUCTION

Recently, because of the increasing of nonlinear loads in the utility systems, the power quality has drawn many attentions like as three-phase and single-phase system. The low power factor and large harmonic phase currents generated by uncontrolled rectifiers are well-known problems that can lead to voltage distortion, increase losses in the utility systems[1]. Generally, inverter $CO_2$ welding machine with nonlinear load characteristic has diode rectifier for AC/DC conversion. Therefore phase current with low-order harmonics which has a harmful effect on power distribution system and cause incorrect operation on the other equipments.

To overcome the above problems, active current waveshaping techniques have been developed to provide nearly sinusoidal source current. Several simple topologies that operate in discontinuous current mode(DCM) and require only single-switch have been studied to reduce the converter cost and avoid the complexity of full bridge three-phase AC/DC converters. Due to its simplicity and relatively good performance, the single-switch three-phase AC/DC converter is the most popular topology[2-3].

In this paper, power factor correction(PFC) for $CO_2$ welding machine with nonlinear load characteristic using single-switch three-phase AC/DC converter is described.

Experimental results show that $CO_2$ welding machine using single-switch three-phase AC/DC converter is effectively controlled with reduced harmonic components during welding time for phase current.

## 2. SYSTEM OPERATION ANALYSIS

The $CO_2$ welding system with single-switch three-phase AC/DC converter as shown in Fig. 1 are proposed to reduce the low-order harmonic components about phase current. The circuit can be divided into two parts. The first part is a pulse-width-modulated discontinuous current mode single-switch three-phase AC/DC converter which is composed of filter inductor $L_f$, filter capacitor $C_f$, boost inductor L, switching device S, rectifier diode, output capacitor. The second part is half-bridge inverter including transformer secondary side, which is composed of full bridge rectifier, filter inductor.

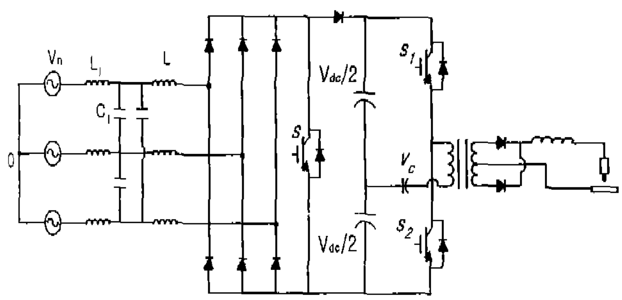



Fig. 1. The $CO_2$ welding machine system with single-phase three-phase AC/DC converter

Principle of AC/DC converter operation

The power circuit configuration of single-switch three-phase AC/DC converter is shown in Fig. 2. The principle can be easily understood by assuming that the switch $S$ is operated at constant frequency $f_s$ and with a fixed duty ratio $d$. Since discontinuous current mode operation is assumed, all three phase currents are zero at the beginning of a switching period and change linearly at a rate proportional to the corresponding phase voltage when $S$ is turned on.

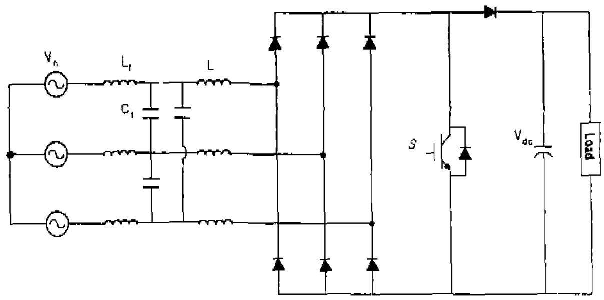



Fig. 2. The single-switch three-phase AC/DC converter

Therefore, each phase current reaches a peak value proportional to its phase voltage at the time when $S$ is turned off, then falls down due to the fact that the output voltage $V_{dc}$ is higher than the amplitude of phase voltage $\sqrt{6}\ V_n$, $V_n$ being the rms phase voltage. All phase currents return to zero before the end of the switching cycle [3-4].

## Phase Current Harmonics

Using the local average model, low-frequency harmonics of the phase current can be determined[4-6].

$$M = \frac{V_{dc}}{\sqrt{6}V_n} \tag{1}$$

The total harmonic distortion(THD) of phase current decreases with increasing $M$. For THD to be lower than 10%, $M$ must be larger than 1.7. For $M>5$, we have approximately purely sinusoidal current shape. Due to $V_{dc}$ being relatively high compared to $\sqrt{6}\ V_n$ the demagnetization of boost inductor $L$ will need only a minor part of the switching cycle. For $M<1.25$, high amplitudes of the low frequency harmonics of phase current occur.

Suppose that each phase voltage is as follows :

$$v_a = \sqrt{2}V_n \cos\omega t \tag{2}$$

$$v_b = \sqrt{2}V_n \cos(\omega t - 2\pi/3) \tag{3}$$

$$v_c = \sqrt{2}V_n \cos(\omega t - 4\pi/3) \tag{4}$$

The normalized phase currents as averaged over each switching cycle are calculated to be [3].

$$i_a(\omega t) = \frac{d^2}{n_s}\frac{\sqrt{2}\pi[M\cos\omega t + \sin(2\omega t - \pi/3)]}{[M + \sqrt{3}\sin(\omega t - \pi/6)][M - \cos(\omega t - \pi/6)]} \tag{5}$$

$$i_a(\omega t) = \frac{d^2}{n_s}\frac{\sqrt{2}\pi M\cos(2\pi/3 - \omega t)}{M + \sqrt{3}\sin(\omega t - \pi/6)} \tag{6}$$

$$i_c(\omega t) = \frac{d^2}{n_s}\frac{\sqrt{2}\pi[M\cos(\omega t + \frac{2\pi}{3}) - \frac{1}{2}\sin(2\omega t - \pi/3)]}{[M + \sqrt{3}\sin(\omega t - \pi/6)][M - \cos(\omega t - \pi/6)]} \tag{7}$$

where $n_s = f_s / f_1$ is the ratio of switching frequency to the line frequency.

Referring to (5)-(7), since each phase current is proportional to $d^2$ and the 5th, 7th, ..., (6i±1)th harmonics, it can be expanded using Fourier series as

$$i_a(\omega t) = \frac{d^2}{n_s}a_1\cos\omega t + \sum_{i=1}^{\infty}\frac{d^2}{n_s}a_{6i\pm1}\cos(6i\pm1)\omega t \tag{8}$$

where $a_1$ and $a_{6i\pm1}$ are constants that depend on $M$ only.

By the Eq. (8), It contains several side-band harmonics besides the fundamental modulation.

## The operation principle of half-bridge inverter including welding load

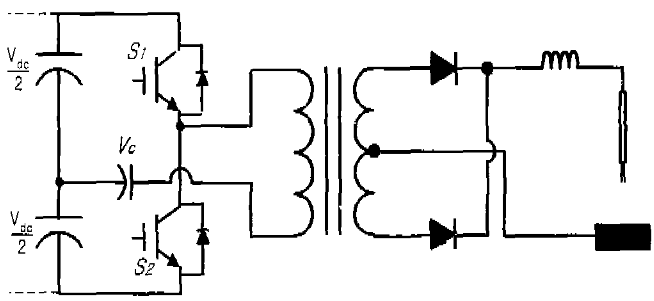
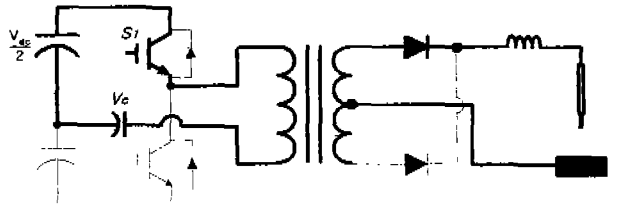
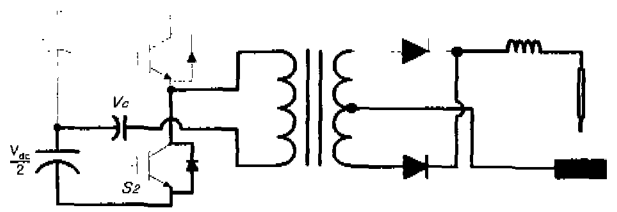



Fig. 3. The half-bridge inverter including welding load

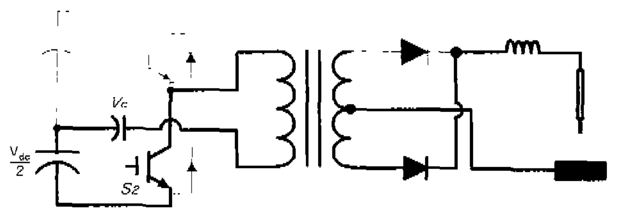
The half-bridge inverter including welding load is shown in Fig. 3. In the half-bridge inverter, as compared with full-bridge inverter, the number of switches is reduced to two by dividing the dc source voltage into two parts with capacitors. Each capacitor has voltage $V_{dc}/2$ across it. When $S1$ is closed, the transformer primary voltage is $+V_{dc}/2$ - Vc. When $S2$ is closed, the transformer primary voltage is $-V_{dc}/2$ - Vc. Thus, a square-wave is produced in the transformer primary side. The voltage across an open switch is twice the transformer primary voltage. As with the full-bridge inverter, dead time for the switches is required to prevent a short circuit across the source, and anti-parallel diodes are required to provide continuity of current for inductive loads. Also, To avoid the DC current bias, the small DC blocking capacitor is placed in series in the primary. When looking into the operation of the half-bridge inverter including transformer secondary side during welding time , its operation can be devided into four modes as shown in Fig. 4.



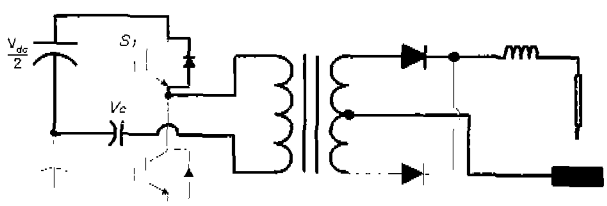

(a) Mode 1( Switch $S_1$ Turn On, $S_2$ Turn Off )




(b) Mode 2( Switch $S_1$ Turn Off, $S_2$ Turn Off )




(c) Mode 3( Switch $S_1$ Turn Off, $S_2$ Turn On )




(d ) Mode 4( Switch $S_1$ Turn Off, $S_2$ Turn Off )

Fig. 4. The operation of half-inverter including welding load

## 3. EXPERIMENTAL RESULTS

The total $CO_2$ welding system with single-switch three-phase AC/DC converter including control part as shown in Fig. 5 has been implemented to reduce the low-order harmonic components about phase current.

Control part can be divided into two, which are composed of DC link output control of AC/DC converter and welding current control during welding time.

The system parameters are as follows:

- Rated output power: 30 kW
- Rated input voltage: 3ϕ 220V
- Boost inductor: 40 uH
- Filter inductor: 100 uH
- Blocking capacitor: 40 uF
- Switching frequency :10 kHz

Decision of boost inductor value

The RMS current value of boost inductor is determined by rated output power, rated input voltage. Therefore, the peak current of boost inductor is two times the value of RMS current for duty ratio 50%.

$$i_{peak} = \frac{p_{out}}{\sqrt{3}v_{l-l}} * 2 \qquad (9)$$

where, $i_{peak}$ is peak value of input current, $p_{out}$ is rated output power and $v_{l-l}$ is rated line to line of input voltage. Therefore, boost inductor value can be designed as follow;

$$L = \frac{dt}{di} * v_{i,peak} \qquad (10)$$

where, $dt$ is maximum on-time of switching cycle, $di$ is peak value of input current for on-time and $v_{i,peak}$ is peak value of input voltage.

Decision of blocking capacitor value

To avoid the DC current bias, the DC blocking capacitor is placed in series in the primary. Selection of the magnitude of the capacitor is done as follows;

$$C_{blk} = \frac{i_{pft} * 0.4T}{dv} \qquad (11)$$

where, $i_{pft}$ is the peak equivalent flat-topped primary current pulse of transformer, $T$ is switching cycle and $dv$ is permissible drop value for on-time.

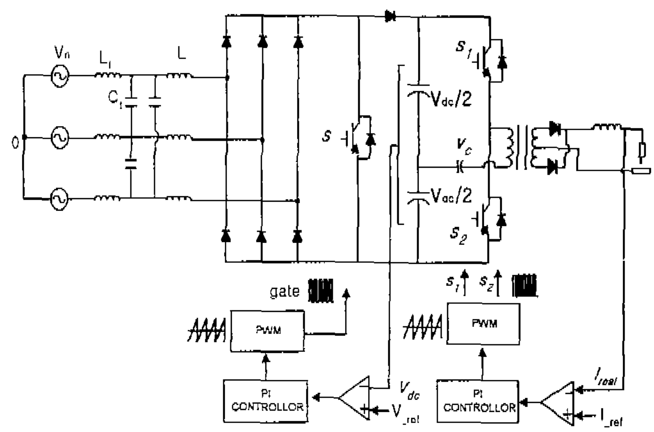



Fig. 5. The total $CO_2$ welding machine system

*The performance of the system is compared with that of* conventional diode rectifier only and PFC using single-switch three-phase AC/DC converter. Fig.6 shows welding current and phase current about conventional method, when welding conditions are welding wire 1.2$\phi$, welding reference current 180A, welding voltage 30V, respectively. The welding current waveform show during short circuit in load side and phase current is flowed with large low-order harmonic components. Fig. 7 shows FFT analysis of phase current about Fig. 6. By viewpoint of Fig. 7, it contains low-order harmonic components in phase current. Fig. 8 shows welding current and welding voltage during short circuit. As shown in Fig. 8, when it is shorted between pieces and torch, it is increasing in welding current and welding voltage is dropped at the same time.

Fig. 9 shows phase current about single-switch three-phase AC/DC converter when converter dc voltage is controlled with 600V in resistive load(10kW). As shown in it, phase current and voltage of system are in phase.

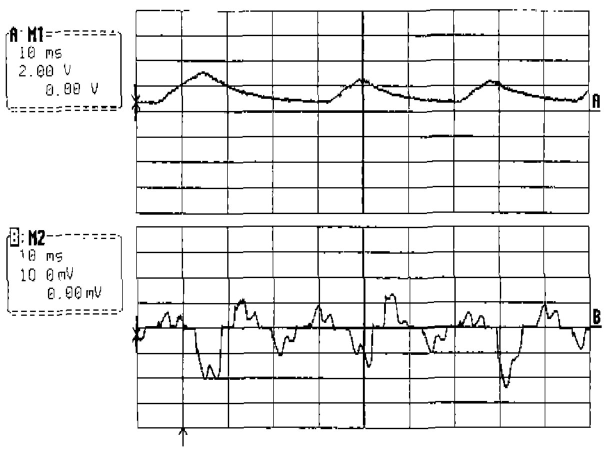


Fig. 6. Output current and phase current waveforms during welding time.(300A/div :upper, 20A/div :lower)

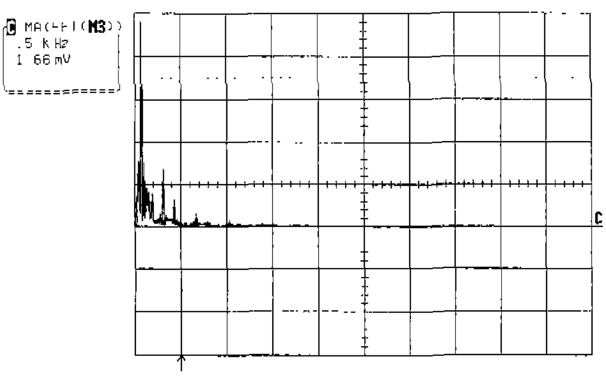


Fig. 7. Phase current FFT analysis about Fig. 6.

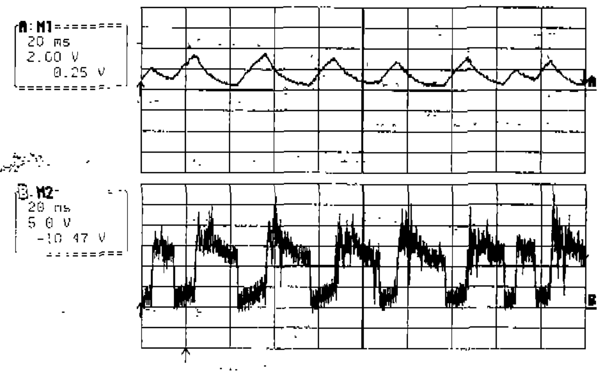


Fig. 8. Welding current & voltage during welding time. (300A/div :upper, 5V/div :lower)

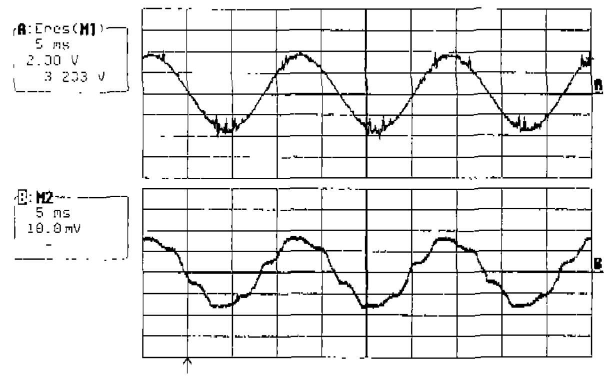


Fig. 9. Phase voltage, and phase current waveforms about single-switch three-phase AC/DC converter in resistive load. (100V/div :upper, 20A/div :lower)

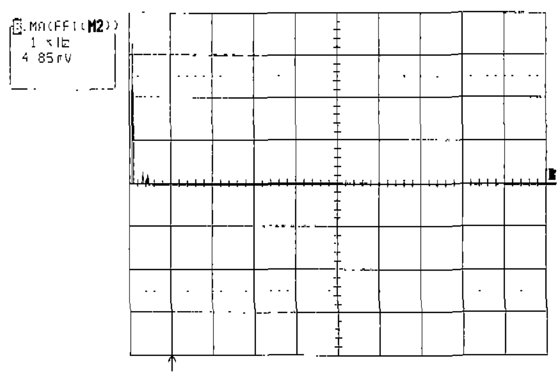


Fig. 10. Phase current FFT analysis about Fig. 9.

Fig. 10 shows FFT analysis of phase current about Fig. 9. Compared with Fig. 7 and Fig. 10, low-order harmonic components are reduced by using single-switch three-phase AC/DC converter. Fig. 11 show phase voltage and phase current waveforms about single-switch three-phase AC/DC converter when welding conditions are welding wire 1.2$\phi$, welding reference current 100A, welding 20V, respectively. Fig. 12 show phase current FFT analysis about Fig. 11. As shown in Fig. 11 and Fig. 12, phase voltage and phase current are in phase. Also, low-order harmonic components are reduced in phase current. Fig. 13 shows experimental system for power factor correction of $CO_2$ welding machine using single-switch three-phase AC/DC converter.

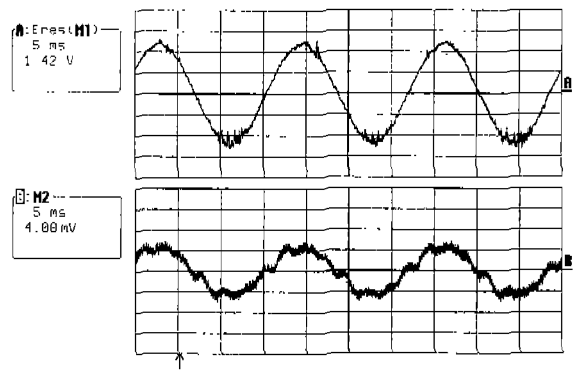



Fig. 11. Phase voltage, and phase current waveforms about single-switch three-phase AC/DC converter during welding time.(70V/div :upper, 20A/div :lower)

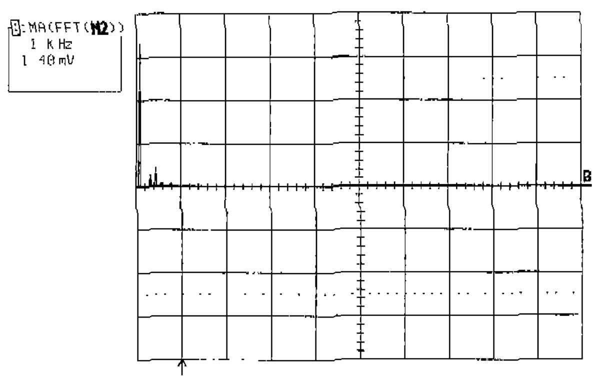



Fig. 12. Phase current FFT analysis about Fig. 11.

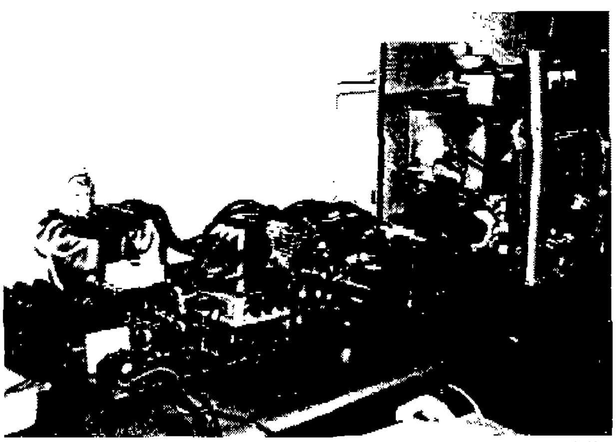


Fig. 13. Experimental system for PFC of $CO_2$ welding machine with single-switch three-phase AC/DC converter.

## 4. CONCLUSIONS

To reduce low-order harmonic components in phase current, the $CO_2$ welding machine with nonlinear load characteristic using single-switch three-phase AC/DC converter is presented in this paper.

The low frequency harmonic components amplitude of the phase current of single-switch three-phase discontinue mode is calculated.

Experimental results show that AC/DC converter with single-switch three-phase rectifiers is effectively controlled with low-order harmonic components in phase current.

## ACKNOWLEDGMENT

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