Performance Improvements for MMA Welding Based on Self-Oscillating Inverter

Kais Seddiki, Hamed belloumi and Ferid kourda

Laboratoire Systèmes Electriques (L.S.E.-LR11ES15) Ecole Nationale d'Ingénieurs de Tunis, Université Tunis El Manar, BP.37-1002-Tunis le Belvédère, Tunisie

Summary
This paper describes improvements developed in a Manual Metal Arc welding machine based on self-oscillating resonant inverter. A new standby operation sequence based on a double modulation phase is proposed in order to reduce the size of the discharge capacitor. This standby solution also relieves the resonant inductor voltage specification. The proposed converter operates with soft switching at no load and full load. There is no need to use a passive snubber in the converter. Power control of the developed Manual Metal Arc welding machine technique consists in controlling the magnetic saturation of a saturable transformer, by using a DC-control current circulating through an additional winding, in order to ensure a variable asymmetrical control as a function of the dc-control current. Therefore we can regulate the output current while maintaining the switching frequency close to the resonant one. Test results are presented to confirm the viability of the proposed arc welding power supply. The experimental results show that the proposed MMA welding power supply has promising feasibility in industrial applications.
Key words:
Self-oscillating half bridge converter, zero-voltage-switched, standby operation, Asymmetrical control, Manual Metal Arc welding.

1. Introduction

This Manual metal arc welding uses ac, pulsed dc, or dc power supplies. Of these, dc sources provide constant polarity current, resulting in high arc stability. Currently, high-frequency inverter welding machines are preferred to conventional welding machines due to their high efficiency and high performance. The converter should operate at high frequency in order to realize high-performance control and decrease the size of magnetic elements. Resonant converters are applied in the control of discharges including lighting, induction heating, and arc welding. Using the resonant converters, lightweight, small-size, and high-efficiency systems can be obtained [1] [2]. Among these, half bridge series resonant converters (HBSRC) are the most popular ones, because of their simplicity of circuit configuration, easy design of the control system, and low switching losses [3] [4]. When this structure becomes self-oscillating, it has the advantage of operating at no load, at full load and at short circuit [5]. This article presents an evaluation of the half bridge series resonant converters applied to arc welding with coated electrode also known as Shielded Metal Arc Welding type (SMAW) or Manual Metal Arc (MMA). A high-performance single-phase arc welding machine is presented. A new standby operation sequence based on a double modulation phase is proposed in order to reduce the output capacitor size. This standby solution also relieves the voltage specification of the resonant inductor. Self-oscillating HBSRC does not allow the control of the power transfer. An interesting solution is that the self-oscillating circuit can provide the control of the power transfer, as well as retain the circuit simplicity. Thus, the aim of this paper is to propose a novel technique for controlling the transfer of power, based on asymmetric control to ensure a variable output current. The proposed system is a flexible power supply configured in current mode operation. The proposed system is able to adapt to other continuous current mode operations. The operation principles, theoretical analysis, and simulation results are completely verified by a prototype welding machine with 500W output power and 111 kHz switching frequency.

The paper is organized as follows. Section 2 describes the operation of the welding power supply. Section 3 describes the improvements in the proposed MMA converter in order to achieve a protection against output overvoltage. Section 4 describes the proposed control strategy. Section 5 shows the simulation results of the developed arc welding machine. Section 6 shows the main experimental results of the proposed solution, finalizing with conclusions.

2. Description and Operation of the Welding Power Supply

2.1 Circuit Description

To The system is a flexible power supply designed as a current source [8], corresponding to the block diagram shown in Fig.1 which consists of the following stages.

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Input stage: a power converter transforms the ac mains voltage into a stabilized dc voltage. The power factor corrector (PFC) is used to improve the input performance regarding the harmonic injection in the utility line. The objective of the PFC is to act as an ideal resistor emulator. This allows the power distribution system to operate more efficiently, reducing energy consumption.

The PFC section is a boost converter supplying constant voltage to the dc bus, V_{dc} = 300 V. This is a common solution in practical applications for two-stage power supplies connected to the mains in order to obtain the maximum efficiency and components utilization ratio.

Resonant inverter stage: The inverter uses a pair of bidirectional switches Q_1 and Q_2; each bidirectional switch has an active power switch K_1 and K_2 with respective body diodes D_1 and D_2. The resonant tank circuit consists of an inductance L and two capacitors C_H and C_L. The series resonant inverter achieves ZVS operation during the turn-on transition, resulting in the concentration of the switching losses during the switch-off transition. Thus, to improve the efficiency, small lossless capacitors C_1 and C_2 can be placed across the switches to act as snubbers, to eliminate turn-off losses. This circuit acts when the switches turn off, as it delays the voltage rise across the active power switches (dv / dt is reduced) [6].

HF Transformer: it increases the current to supply the weld with the specified current level. Output stage: it is a high-frequency rectifier that converts the ac current into a dc current with an overlapped high-frequency ripple. A discharge capacitor is required to establish the arc.

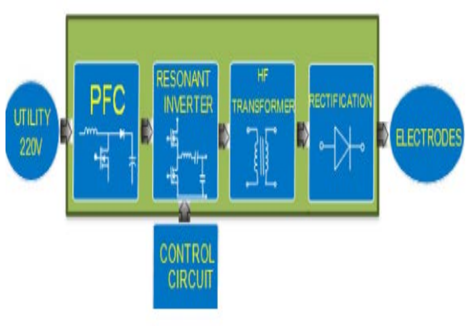


Fig. 1 Block diagram of the Arc Welding Power Supply.

2.2 Operating Principle

Fig. 2 shows the circuit diagram of the self-oscillating Manual Metal Arc welding machine. The circuit is based on a conventional half-bridge converter controlled by a small saturable core TS. The proposed circuit consists of an inverter and a current-driven rectifier.

In order to control both power switches Q1 and Q2, a saturable current transformer TS is used. The saturable current transformer is constituted by a single turn in the primary side TS1 and ten turns in each secondary winding TS21 and TS22.

The saturable current transformer is coiled in such a way that when the resonant current IP passes, a positive or negative voltage, depending on the direction of the current, appears across the gate–source of the power switches, allowing its turn-on or turn-off.

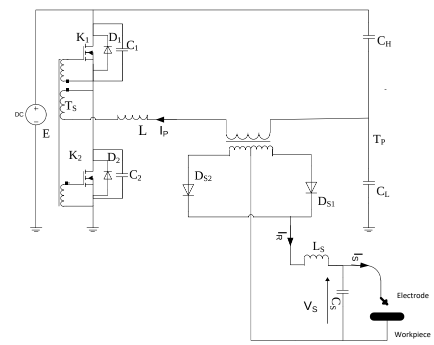


Fig. 2 Circuit of the self-oscillating DC–DC resonant converter with the arc model of MMA process.

In this section, the operating principle of the converters is discussed in detail. A complete self-oscillating operation is divided into six stages. It is described as follows.

Stage 1: t0 < t< t1

To start the operation of the self-oscillating Manual Metal Arc welding machine, a slight release of a turn-on voltage pulse across the gate of the power switch K_2 is sufficient. After the start and when the resonant tank current I_P flows through the primary winding of the saturable transformer. As a consequence, K_2 is turned-on under the ZVS condition and K_1 is turned off. During the positive half cycle of the resonant tank current I_P, the power is supplied to the MMA arc welding through output rectifier diode D_{S2} (Fig.3).

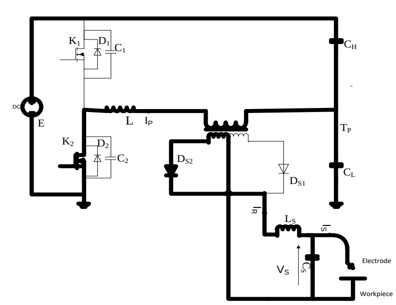


Fig. 3 Conducting path in interval 1

Stage 2: t1 < t < t2

At t1 the saturable core T_S saturates. As a consequence, the control signal of K_2 is removed and the power switches

K_2 starts to turn off. The primary positive current will charge the capacitor C_2 from zero to 300V and the capacitor C_1 is discharged from 300V to 0. The resonant current I_P is still positive, thus, the power is supplied to the MMA arc welding through output rectifier diode D_{S2} (Fig.4).

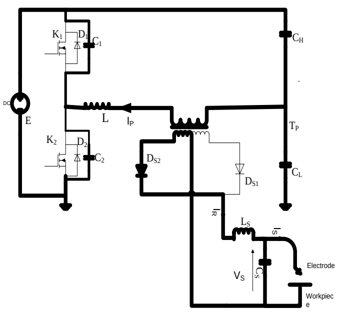


Fig. 4 Conducting path in interval 2

Stage 3: t2< t < t3

When the capacitor voltage V_{C1} reaches zero, the body diode D_1 of the switch K_1 is turned on, and ensures continuity of the inductive current.

The resonant tank current I_P is still positive, hence, the power is supplied to the MMA arc welding through the output rectifier diode D_{S2}. This stage is ended at $t=t_3$ when switch K_1 turns on (Fig.5).

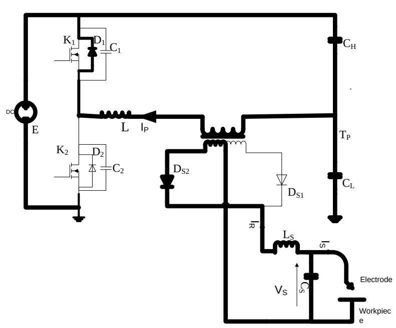


Fig. 5 Conducting path in interval 3

Stage 4: t3 < t < t4

When the resonant tank current I_P reaches zero, it flows through the resistance "$R_{DS(on)}$ " of K_1 and becomes negative. Thus, it flows through the primary winding of the saturable core, hence the driving signal across the gate-source of the switch K_1 becomes positive, which allows the turn-on of K_1. In this mode, the power switch is naturally turned on at zero voltage, which eliminates the turn-on losses. The resonant tank current I_P is negative, consequently, the power is supplied to the MMA arc welding through output rectifier diode D_{S1} (Fig.6).

Stage 5: t4 < t < t5

At t4 the operating point of the saturable core T_S reaches its saturation region. No energy is transferred to the gate–source of the active power switches; subsequently K_1 is turned off.

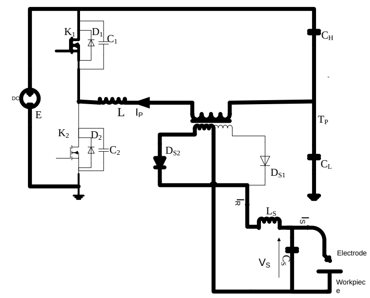


Fig. 6 Conducting path in interval 4

The primary negative current will charge the capacitor C_1 from zero to E=300V and the capacitor C_2 is discharged from E=300V to 0. The power is supplied to the MMA arc welding through the output rectifier diode D_{S1}. This stage is ended at t=t5 when V_{C2}=0 and V_{C1}=E (Fig.7).

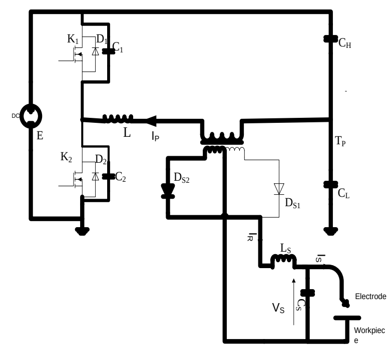


Fig. 7 Conducting path in interval 5

Stage 6: t5 < t < t6

The operation principle in this stage is similar to that in stage 3.

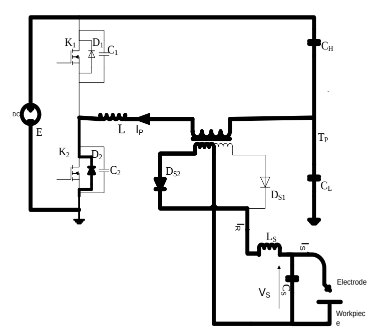


Fig. 8 Conducting path in interval 6

However, this time the inductive current continuity will be ensured through the body diode D_2, hence, the power is supplied to the MMA arc welding through output rectifier diode DS1(Fig.8). This stage ends when the resonant current I_P reaches zero, and the driving signal across the gate-source of the switch Q_2 becomes positive again, leading to the turning on of Q_2. As a result, the operation turns back to Stage 1 and a new switching period starts.

3. Improvements

3.1 Standby Operation

The arc welding process is composed of many states, such as standby operation, short circuit, generation of arc voltage. Before starting to weld, the reference current value must be adjusted according to the electrode diameter [11] [12]. The welding process starts when the electrode is touched to the piece, a short circuit occurs, and the current increases suddenly. The high current causes the electrode to melt and generates an arc.

The output voltage is imposed by the welding process, however in standby operation the circuit has to be protected against overvoltage. This voltage charges the output capacitor that provides the electric discharge necessary to establish the arc.

In standby operation, or when we pass from loaded operation to open circuit operation the gain becomes very high. Therefore, the output voltage increases very quickly to reach a destroying value [9] [10]. The output diodes are exposed to high voltage stress as well.

A new method is proposed to minimize the output voltage ripple, amplitude, and frequency under open-circuit conditions. The practical advantage of the method is the significant size reduction of the output capacitor.

In order to investigate the characteristics of the arc welding machine, a simulation is performed in PSIM simulator. Fig.9 shows the basic structure of the system used for the simulation. In the MMA converter, the input voltage is 300 V and the switching frequency is 111 kHz. High-frequency transformer output voltage is rectified by the diodes. The operating frequency of the DC-DC converter is high enough in respect to the arc welding dynamics.

In standby operation, due to the resonant circuit operation, the output voltage rises quickly, until reaching a threshold. A new technique is proposed to achieve a protection against output overvoltage. It consists of cutting off the converter when the output reaches 27V.

Thereafter the output decreases to meet 25v, then the converter is initiated. Hence the open circuit output voltage is maintained between 25 and 27v that is sufficient interval to initiate the arc. The arc voltage waveforms in open-circuit conditions from the PSIM simulation are shown in Fig.10.a. The initial operating voltage is 65 V at no-load. An improved operation mode is achieved when a standby operation method based on a double modulation phase is introduced, decreasing the resonant inverter voltage gain.

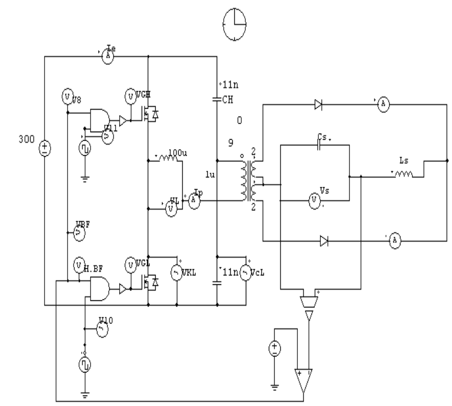


Fig.9: Arc welding simulation at standby operation in PSIM

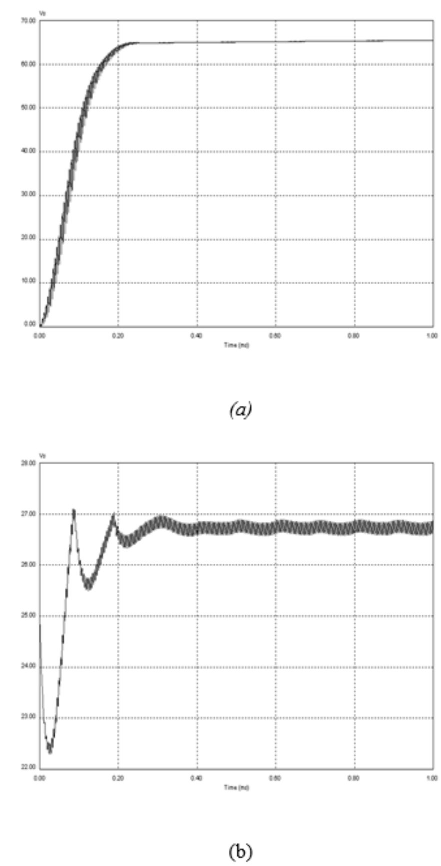
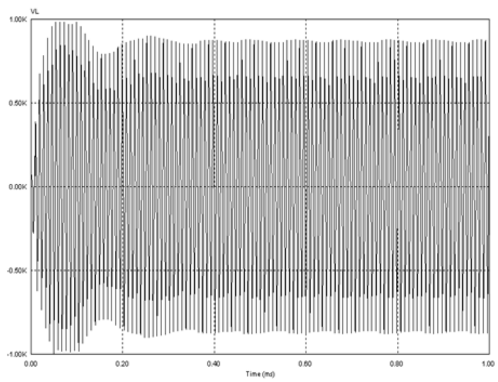


Fig. 10 Output voltage in standby operation: (a) Open circuit without double modulation phase and (b) open circuit with double modulation phase.

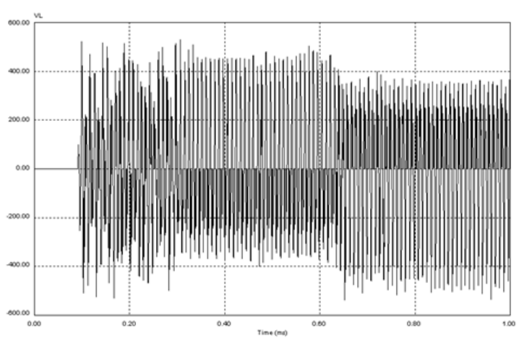
Fig. 10.b shows the output voltage in this operation mode. As observed, the amplitude is reduced (V_s=25V), which allows the size to be reduced and extends the life of the output capacitor.

3.2 Resonant Inductance Specifications

In nominal behavior, the drop voltage in the resonant inductor is about 500 V, but as shown in Fig.11.a, in standby operation, this voltage increases up to 1 kV,. Therefore, the specification in resonant inductor should be higher, increasing its weight and size.



(a)



(b)

Fig. 11 Resonant inductor voltage in standby operation: (a) Open circuit without sliding phase and (b) open circuit with sliding phase.

Through the proposed method described in Section 3.1, lower energy circulates in the resonant tank, reducing the maximum resonant inductor voltage; this voltage decreases to around 400V, as shown in the lower trace in Fig.11.b, which means that the voltage specification of the resonant inductor does not exceed the voltage required for the nominal operation.

4. Proposed Control Strategy

The series resonant inverter (Fig.2) can be modelled with the circuit shown in Fig.12 [5]. The load of the MMA converter formed by the HF transformer, the current rectifier, the filter and the electrode and the piece can be modelled as an effective resistance, R_{eq}, connected in series with an inductor L_{eq}, their values given by [5].

$$R_{eq} = \frac{8}{\pi^2 m^2} R \qquad (1)$$

$$L_{eq} = L + l_1 + l_2 \qquad (2)$$

The duty cycles of both switches Q_2 and $Q_1$are D and (1-D), respectively. When Q_1 is on, the power is transferred from the source to the load and then the output of the chopper sees a positive voltage of U_{AB} from the source. When the switch Q_2 turns on, the source is separated from the rest of the power circuit and the output of the inverter sees the voltage across the switch Q_2 which is zero volts (Fig.13). The resonant tank voltage is equal to the voltage across Q_2. This can be represented in terms of Fourier series by (3).

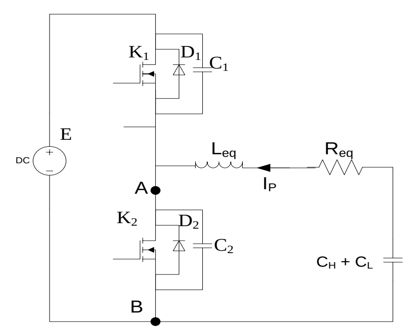


Fig. 12 Equivalent circuit of the dc-dc series resonant converter

$$U_{AB}(t) = D.E + \sum_{n=1}^{+\infty} \frac{\sqrt{2}.E}{n.\pi} .\sqrt{1-\cos(2\pi nD)}.\cos(n\omega_0 t) \qquad (3)$$

The DC component of the voltage U_{AB} is blocked by the series capacitor C. Consequently, the ac component of voltage U_{AB}, which causes the resonant current I_p to flow, is given by (4)

$$V_{ac}(t) = \sum_{n=1}^{+\infty} \frac{\sqrt{2}.E}{n.\pi} .\sqrt{1-\cos(2\pi nD)}.\cos(n\omega_0 t) \qquad (4)$$

Because a resonant circuit forces a sinusoidal current, only the power of the fundamental component V_{ac1} is transferred from the input source E to the resonant circuit. Consequently, only the fundamental component of this inverter needs to be considered. Equation (5) gives the fundamental component of voltage V_{ac}.

$$V_{ac1}(t) = \frac{\sqrt{2}.E}{\pi}.\sqrt{1-\cos(2\pi D)}.\cos(\omega_0 t) \quad (5)$$

Fig.14 shows the equivalent ac circuit of the MMA half bridge series resonant converter. Hence, the input impedance of this circuit is expressed as follows.

$$Z_{in}(j\omega) = R_{eq} + j\left(L_{eq}\omega - \frac{1}{C\omega}\right) = R_{eq}\left(1 + jQ\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right)\right) \quad (6)$$

$$\left|Z_{in}\right| = R_{eq}\sqrt{1 + Q^2\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right)^2} \quad (7)$$

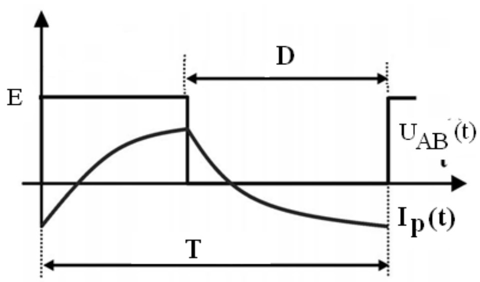


Fig. 13 main waveforms and parameters

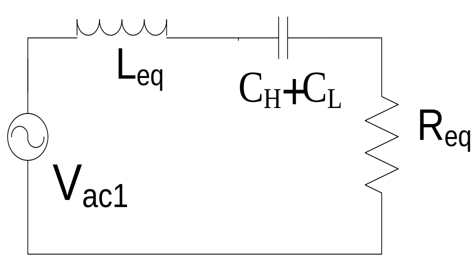


Fig. 14 Equivalent circuit simplified by first harmonic method

$$\text{Where } \omega_0 = \frac{1}{\sqrt{L_{eq}.C}} \text{ and } Q = \frac{L_{eq}.\omega_0}{R_{eq}} = \frac{1}{C.R_{eq}.\omega_0} \quad (8)$$

The fundamental current through the series resonant circuit is given by (9)

$$I_{P1}(t) = \frac{\sqrt{2}.E}{\pi\left|Z_{in}\right|}.\sqrt{1-\cos(2\pi D)}.\cos(\omega_0 t-\varphi) \quad (9)$$

From (9), the peak value of the fundamental series resonant current $I_{P1(max)}$ is given as

$$I_{P1(max)} = \frac{\sqrt{2}.E}{\pi\left|Z_{in}\right|}.\sqrt{1-\cos(2\pi D)} \quad (10)$$

The output current average value $I_{S(av)}$ which flows through the electrode is expressed as follows.

$$I_{S(av)} = \frac{2}{m.\pi} I_{P(max)} \quad (11)$$

$$I_{S(av)} = \frac{2.\sqrt{2}.E}{m.\pi^2.\left|Z_{in}\right|}\sqrt{1-\cos(2\pi D)} \quad (12)$$

$$I_{S(av)} = K.\sqrt{1-\cos(2\pi D)} \quad (13)$$

Where $K = \frac{2.\sqrt{2}.E}{m.\pi^2.\left|Z_{in}\right|}$.

Fig.15 shows that the average value of the output current can be controlled by changing the duty cycle D either from 0 to 0.5, minimum-to-maximum output current, or 0.5 to 1, maximum-to-minimum output current.

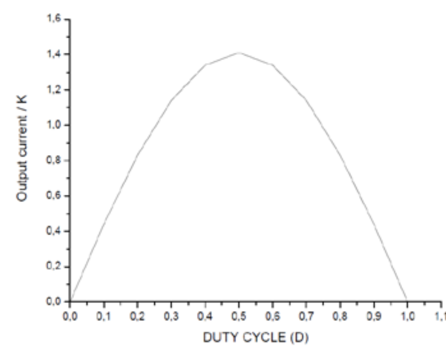


Fig. 15 Output current as a function of the duty cycle D

5. Experimental Results

By following the design procedure, a laboratorial prototype of a welding machine is implemented. Fig.16 displays the voltage waveform V_{DS1} across the power switch Q_1 and the voltage waveform V_{DS2} across the power switch Q_2, and the resonant current waveform I_P, for a duty cycle equal to 50%. A ZVS operation can clearly be observed in this figure, because the voltage across the drain-to-source reaches zero before the resonant current flows through the switch. The losses of the turn-off switching are attenuated, through the use of the snubber capacitors C_1 and C_2.

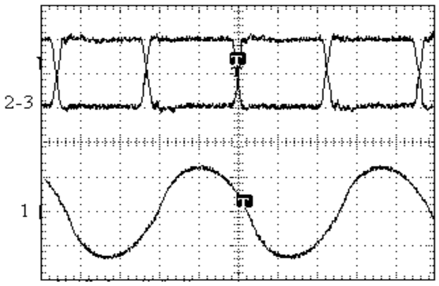


Fig. 16 ch1: I_P 5A/div, ch2: V_{DS2} :150V/div, ch3: V_{DS1} :150V/div, 1us/div

Fig.17, Fig.18 and Fig.19 show the resonant current waveform I_P and the drain-to-source voltage V_{DS2} for a 30% duty cycle, for a 60% duty cycle, and for a 75% duty cycle, respectively.

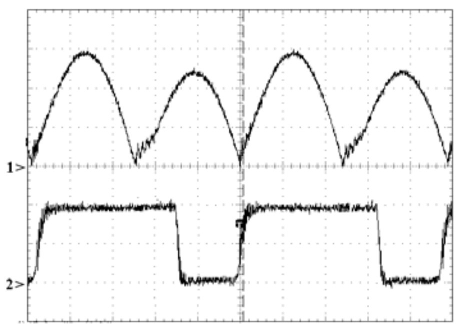


Fig. 17 ch1: I_R : 10A/div; V_{DS2} :150V/div; D=30%; 2us/ div

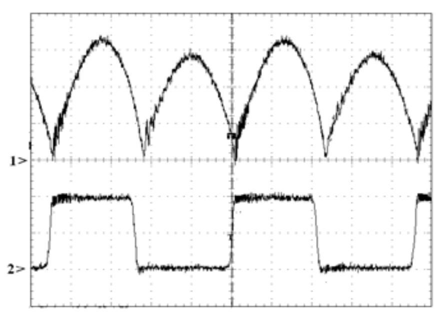


Fig. 18 ch1: I_R : 10A/div; V_{DS2} :150V/div; D=60%; 2us/ div

It is clear that the secondary diodes switch at zero current. However, it can be observed that the maximum value of the rectified current which flows through the rectifier diode D_{S1} and the maximum value of the rectified current which flows through the rectifier diode D_{S2} are different. Due to the existence of a dc-offset current which flows through the power transformer, the dc-offset current increases as operating duty cycle D decreases.

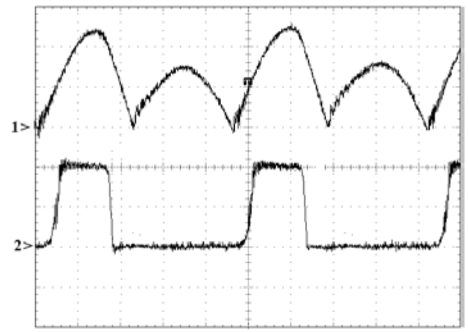


Fig. 19 ch1: I_R : 10A/div; V_{DS2} :150V/div; D=75%; 2us/ div

Table 1: Effect of the Duty Cycle Variation

D	$I_{S(av)}$ (A)
30%	17.8
50%	25
60%	20.7
75%	15.7

Table 1 shows the impact of the variation of the duty cycle on the average value of the output current $I_{S(av)}$. As shown in table I, as the duty cycle increases or decreases, the output current average value gradually decreases. This is verified based on (13). As a conclusion, these waveforms match up with the theoretical expected ones, and verify the proper operation of the MMA converter.

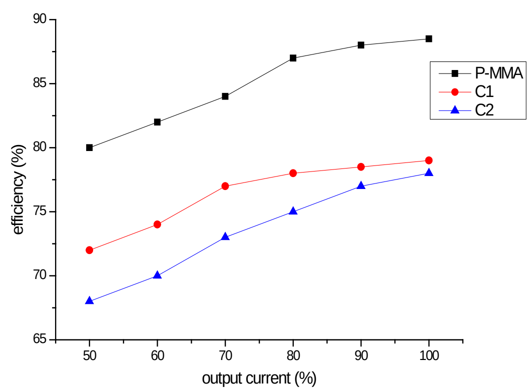


Fig. 20 Efficiency comparison of the welding machines.

One way to assess the effectiveness of the proposed arc welding machine (PMMA) is to measure the efficiency and to compare it with the efficiency of two commercial inverter welding machines (C_1 and C_2) at the same power level. Fig. 20 shows the results of this comparison. As shown in this figure, at full load, the efficiency of the proposed arc welding machine is a little higher than the two commercial inverter welding machines. However, efficiency with the proposed control scheme is remarkably higher than the two commercial inverter welding machines at light load. Therefore, the developed MMA welding machine with the proposed control scheme has higher efficiency than the other machines. The efficiency of the developed welding machine is 89% at nominal output current.

6. Conclusion

In this paper, improvements for an arc-welding power supply based on self-oscillating resonant inverters have been developed. The output voltage ripple, amplitude, and frequency under open-circuit conditions have been reduced by means of a new standby operation method based on a double modulation phase, which increases the lifetime of the output capacitor. The proposed solution allows the converter to operate at constant frequency, thus reducing the size of the EMI filter, which otherwise would be high in the case of using variable frequency control.

The validity of the proposed asymmetrical control scheme is verified through experimental results. It can be concluded that the presented work control technique has the following advantages.

1) The asymmetrical control can be used to control the output power to arc-welding power supply.
2) The control scheme is in a simple configuration and easy to implement.
3) The presented circuit configuration and proposed control scheme can also be used with other applications that require output-power regulation under load-parameter variation.

Acknowledgments

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Kais seddiki was born in Tunisia, in1977. He received the Degree of instrumentation and industrial maintenance Engineer from the National Institute of Applied Sciences and Technologie,Tunisie in 2003., and the Masters degree from the National Engineers School of Tunis in 2013.

He is currently a trainer, ATFP .His research interests are high-frequency switching converters, resonant converters, and soft switching techniques.

H.Belloumi was born in Tunisia in 1983. He received the Degree of Electrical Engineer from the National Engineers School of Tunis – ENIT in 2009, the Masters degree in 2010 and Ph.D degree in 2014 from the National Engineers School of Tunis.

Her research interests include high-frequency switching converters, resonant converters, and soft switching techniques. Since 2014, he is an assistant professor at the Faculty of Sciences of Bizerte, Tunisia since 2014.

F. kourda was born in Tunisia; He received his bachelors of Science and technics in electrical engineering from the Normal Superior School of Technical teeatching tunisia 1981 and the masters degree and Ph.D degree from the National Institute of Applied Sciences Lyon, France in 1989. His current research interests include High frequency converter, contactless electrical energy transmissions. Since 2010, he is a Full Professor in the Electrical Department of the National Engineers School of Tunis.