Isolated Bridgeless Cuk Converter with Improved Power Quality for Welding Power Supply

Swati Narula [1] G. Bhuvaneswari [2] Bhim Singh [3]

Abstract– This paper deals with a new single-phase bridgeless AC-DC converter for AWPS (Arc Welding Power Supply) with an ability to improve the power factor at AC mains. The PFC (Power Factor Correction) converter is based on high frequency isolated Cuk converter topology. The conduction losses are reduced by eliminating the DBR (Diode Bridge Rectifier) in classical converter topology. The proposed converter topology is designed to operate in DCM (Discontinuous Conduction Mode) for simple control and to minimize the EMI (Electromagnetic Interference). The DCM operation also facilitates to achieve a unity power factor at AC mains. This converter regulates constant voltage at the output in the range of welding currents and inherent parametrical short-circuit current limit to improve the weld bead quality. The dynamic and steady state responses of the proposed AC-DC converter are included to validate the capability of converter for welding power supply.

Keywords–Bridgeless rectifier, Cuk converter, high frequency transformer, power factor correction, power quality, total harmonic distortion, welding power supply

I. INTRODUCTION

Now-a-days welding power supplies with active PFC (Power Factor Correction) are preferred to meet harmonics regulations and standards as per IEC 61000-3-2 [1]. Significant efforts have been made in developing PFC based converters to reduce the harmonics contents in AC Mains [2-3]. Generally, PFC based power supplies consist of a DBR followed by a high frequency transformer of the DC-DC converter [4]. However, the efficiency of this conventional PFC converter is low because of the conduction losses caused by the diode bridge. Moreover in high power applications, the high conduction loss in the DBR degrades the overall system efficiency. Moreover, the diodes may be destroyed due to the heat generated within the diode bridge. The bridgeless topologies discussed in [5-7], have been implemented as boost rectifier to achieve high power factor. But it suffers from the drawbacks such as high inrush current, lack of current limiting during overload conditions and no galvanic isolation. In proposed bridgeless PFC converter, the current flows through a minimum number of switching devices which in turn minimizes the conduction losses. Furthermore, its cost is also reduced [8-9].

In order to stabilize the arc length in welding power supply, a welding power source with constant voltage output characteristic is usually preferred [10]. Initially, the electrode is too cold to emit electrons to establish the arc. Generally, an arc is initiated by scratching or touching the electrode on the base metal, which causes a short-circuit condition while the load current should be controlled to a desired value [11-12].

Even during normal welding condition, there is a possibility that the electrode comes into contact with the work-piece which arises a short circuit condition. High short circuit current results in increased spatter generation and poor weld quality [13]. This makes arc welding a stochastic process and it becomes indispensable to analyze the dynamic characteristics of the entire welding process. This paper presents a bridgeless Cuk converter based AWPS. The proposed topology consists of two isolated Cuk converters, one conducting for each half line period of the AC mains voltage. The Cuk converter has several commendable features such as reduced EMI, less conduction losses, inherent protection against inrush current, low switching current ripple, easy implementation of galvanic isolation and high overall conversion efficiency [14-16].

The short circuit protection has been incorporated in proposed power supply which appreciably improves the weld bead quality. The double loop control scheme aids in limiting the output current to 1.25 p.u. even during short circuit conditions. Moreover, eliminating the DBR at the front end reduces the conduction losses. It offers improved thermal utilization of the semiconductor switches as switch rms current is bifurcated into two switches and being a single stage PFC configuration, it minimizes the complexity of the system. Furthermore, the high frequency isolation leads to an excellent voltage control and safe operation, desired for the welding equipment. Besides, input current shaping is inherent in Cuk converter operating in DCM (Discontinuous Conduction Mode) [17]. Therefore, the proposed converter is made to operate in DCM and the duty cycle is mainly decided by the DC output voltage follower. The design, control and modeling of the single phase bridgeless Cuk converter using PWM (Pulse-Width Modulation) are carried out using MATLAB-Simulink environment developed by MathWorks [18]. In order to illustrate the performance of proposed topology, some design aspects are discussed in relation to different loads and supply voltage conditions during welding process.

II. SYSTEM CONFIGURATION

The proposed bridgeless Cuk converter based AWPS is shown in Fig. 1. This topology is formed by connecting two isolated Cuk converters in such a way that one conducts with a positive half cycle of input AC mains while the other one with a negative half cycle of input AC mains. It comprises of AC mains, Cuk converters, high frequency rectifier, output filter and welding load. High frequency isolation provides improved voltage control and

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safety of welding load equipment. The high operating frequency also results in a significant reduction in the dimensions and mass of the welding power supply compared to the conventional ones which operate at the mains frequencies.

A single stage isolated bridgeless Cuk AC-DC converter consists of two conversion processes, one during positive half cycle and the other one during negative half cycle. For the positive half cycle switch S_1 is turned on and for the negative half cycle switch S_2 conducts.

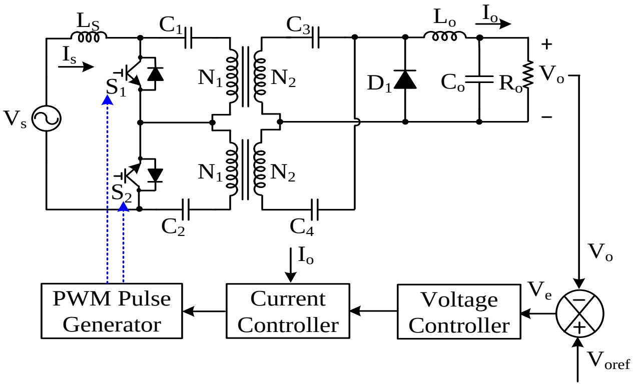


Fig.1: Circuit configuration of isolated bridgeless Cuk converter based AWPS.

Fig. 2 shows the operating modes of bridgeless Cuk converter for positive and negative half cycles of the supply voltage Referring to Fig. 2a, during the positive half-line cycle of input AC mains voltage, S_1, C_1, C_3, D_1 and body diode of switch S_2 are conducting, which connects the input ac source to the output welding load, R_o. Similarly, during the negative half cycle, S_2, C_2, C_4, D_1 and body diode of switch S_1 conduct as shown in Fig. 2b. Thus there is a reduction in the current stress on the power switches as each one is operating for half of the cycle only. These two switches can be driven from the same control signal which adds simplicity to the circuit. The output inductor, L_o and capacitor, C_o reduces the output voltage ripple.

During positive half cycle of the supply voltage, the switch S_1 is turned on and the diode, D_1 remains reversed biased as shown in Fig. 2a(i). When switch S_1 is turned off and diode D_1 becomes forward biased. The inductor freewheels its stored energy to the load as presented in Fig. 2a(ii). In Fig. 2a(iii), the inductor enters into the DCM and the switch S_1 and the diode D_1 remain turned off during this period. Similarly, the operation of the proposed converter during negative half cycle of the supply voltage is shown in Fig. 2b(i)-(iii).

PWM (Pulse Width Modulation) technique has been used to ensure DCM operation of the proposed converter. The double loop control has been implemented to avoid the problems such as spattering, instability of arc length, poor weld bead quality etc.

The sensed output DC voltage, V_o is compared with the reference DC voltage, V_{oref} then the generated voltage error, V_e is given to PI (Proportional-Integral) voltage controller. The output of the PI voltage controller acts as a reference current signal for the PI current controller. This reference current is compared with the output current which generates the error and this error is given to PI current controller to restrict the output current in the desired limit. The output of current controller is compared with ramp signal to generate gating pulses for Cuk converters.

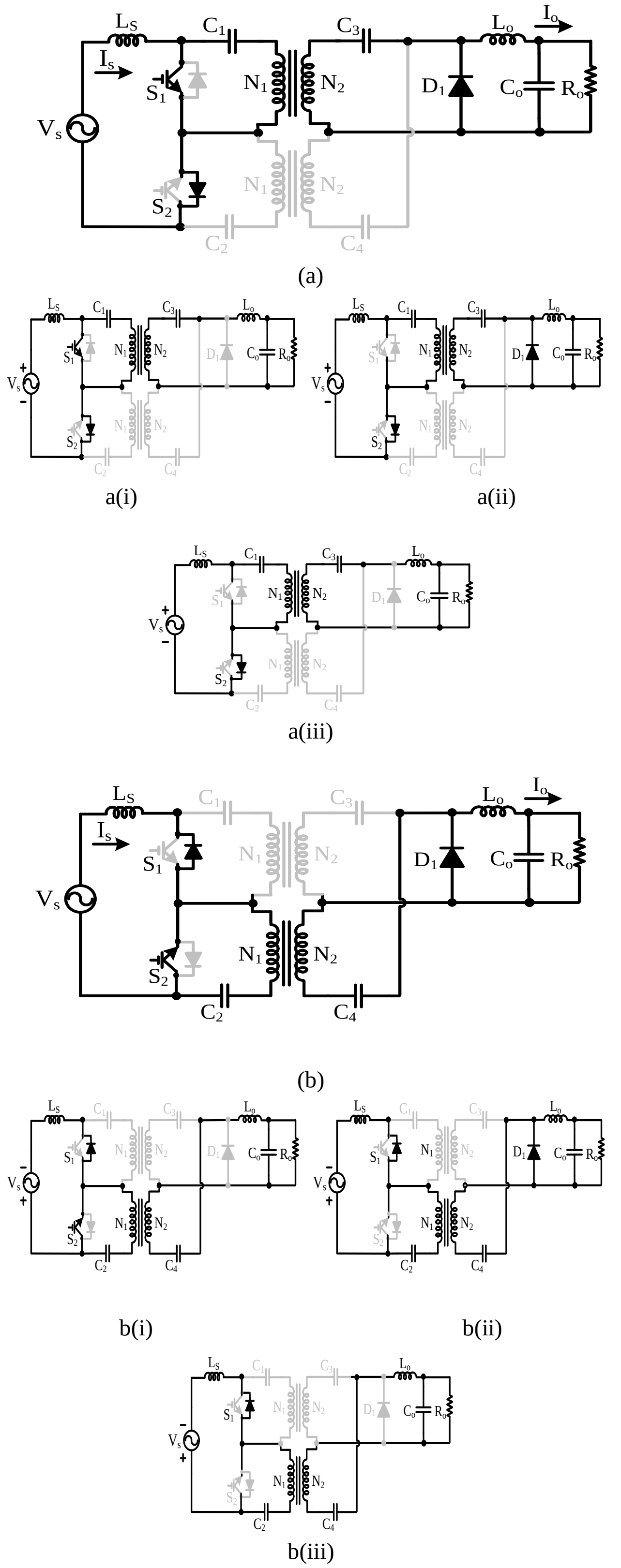


Fig.2a: Bridgeless Cuk converter based AWPS operation during positive half cycle 2a (i)-(iii).
2b: Bridgeless Cuk converter based AWPS operation during negative half cycle 2b (i)-(iii).

III. DESIGN EXAMPLE OF PROPOSED AWPS

In this section, the design and analysis of the proposed single phase welding power supply have been discussed in detail. For the sake of simplicity, a single module of isolated Cuk converter has been considered and a pure resistance is taken as a welding load. Due to the symmetry of the proposed circuit, the circuit is analyzed during positive half cycle of the input voltage only. For analysis purposes, the supply voltage, v_{in} is considered to be a constant within each switching cycle; this is because the line frequency f(=50 Hz) is much lower than the switching frequency f_s (=50 kHz).

In steady state condition, the average voltages across the primary and secondary windings of the high frequency transformer and inductors L_S and L_o and the transformer primary and secondary windings are equal to zero. Thus,

$$V_1(avg) = V_2(avg) = V_{Ls}(avg) = V_{Lo}(avg) \quad (1)$$

$$V_{sav} = \frac{2\sqrt{2}V_s}{\pi} = \frac{2\sqrt{2}*220}{\pi} \cong 198\ V \quad (2)$$

By applying the constant volt-second relationship, the voltage conversion ratio of the isolated Cuk converter can be derived to calculate the turns ratio of the high frequency transformer operating at 50 kHz.

For an isolated Cuk converter, this relation is as,

$$V_o = \frac{V_s N_2 D}{(1-D)N_1} \quad (3)$$

where D is the duty ratio of an isolated Cuk converter, which decides the turn on and off period of the switch.

In order to ensure DCM operation, the value of duty cycle D is considered to be 0.2, then the turns ratio of the HFT is calculated as,

$$\frac{N_1}{N_2} = \frac{V_{s\max}D}{(1-D)V_o} = \frac{198*0.2}{0.8*20} = 3.887 \quad (4)$$

Initially, when the switch S_1 is turned on, input voltage, V_S is applied to the input inductor, L_S resulting in linear increase in input current. Simultaneously, the intermediate capacitor, C_1 is discharged through switch S_1. On the secondary side of the high frequency transformer, the capacitor C_3 discharges its stored energy while diode D_1 remains reverse biased.

If the permissible ripple current flowing through the input inductor is Δi_{LS} (30% of I_S), then the value of L_S is given as,

$$L_S = \frac{V_{s\max}D}{f_s \Delta i_{Ls}} = \frac{311*0.2}{50000*4.62} = 0.27\ mH \quad (5)$$

The selected value of input inductor is 0.32 mH to minimize the input current ripple.

When switch S_1 is turned off, the diode D_1 becomes forward biased. The input inductor, L_S discharges through intermediate capacitor, C_1 and the body diode of switch S_2. Furthermore, the output inductor, L_o delivers its stored energy to the welding load, R_o. Thus, the inductor current, i_{Lo} falls continuously and the rate of change in inductor current can be obtained from off period condition, which is as,

$$\frac{di_{Lo}}{dt} = \frac{-V_o}{L_o} \quad (6)$$

Thus value of output inductance at the boundary between CCM and DCM is given as,

$$L_{o\min} = \frac{V_o(1-D)^2 N_1^2}{2Df_s I_o N_2^2} = \frac{20*(0.8)^2(3.887)^2}{2*0.2*50000*120} = 80.58\ \mu H \quad (7)$$

Thus, the value of output inductor is estimated as L_{omin} = 80.58 μH.

To ensure DCM operation of an isolated Cuk converter,

$$L_o < L_{o\min} \quad (8)$$

Thus, the selected value of L_o is 26 μH. The output capacitor value can be calculated from eqn. (9) for a given voltage ripple (ΔV_o = 4% of V_o) as,

$$C_o = \frac{I_o}{4\pi f_L(\Delta V_o)} = \frac{120}{4*\pi*50*0.8} = 238.73\ mF \quad (9)$$

where f_L is the line frequency = 50 Hz.

The value of output capacitor is calculated as C_o = 238.73 mF to reduce the output voltage ripple.

Intermediate capacitance,

$$C = \frac{C_1 C_3 \left(\frac{N_2}{N_1}\right)^2}{C_1 + \left(\frac{N_2}{N_1}\right)^2 C_3} \quad (10)$$

The main function of the intermediate capacitor is to maintain nearly constant voltage within a switching period. The value of intermediate capacitance has a major impact on the input line current waveform. In order to minimise the input current oscillation, the resonant frequency of C, L_S and L_o' (referred value of L_o) should be greater than the line frequency.

Furthermore, the resonant frequency of C and L_o' must be less than the switching frequency to attain constant voltage during every switching cycle. Hence, the value of the capacitance can be approximated as,

$$C = \frac{1}{\omega_r^2 (L_s + L_o')} \tag{11}$$

$$= \frac{1}{5000^2 * \left\{0.32x10^{-3} + (26x10^{-6} * 3.887^2)\right\}}$$

$$= 56.12\ \mu F$$

where

$\omega_L < \omega_r < \omega_s$;

ω_L = line frequency, ω_r = resonant frequency

and ω_s = switching frequency

Thus, the resonant frequency is selected to be 5000 Hz. For optimum operation, the calculated parameters are adhered to so that PFC feature of the proposed topology operating in DCM is maintained at different loads and AC mains voltages. These selected design parameters of the proposed converter system are summarized in Appendix.

IV. PERFORMANCE ANALYSIS OF PROPOSED AWPS

In this section, the effectiveness of proposed bridgeless converter based AWPS is evaluated by simulating the proposed topology in MATLAB-Simulink environment. The converter circuit has been simulated for the calculated values of the bridgeless converter as given in Appendix to achieve unity power factor and low value of total harmonics distortion.

Figs 3-12 show the steady state and dynamic performances of the proposed converter. The converter operates in DCM to ensure improved power quality and high level of weld quality. The dynamic performance of the converter has been demonstrated by suddenly switching the welding load. The simulated results for light load and rated load conditions are shown in Figs. 3-7.

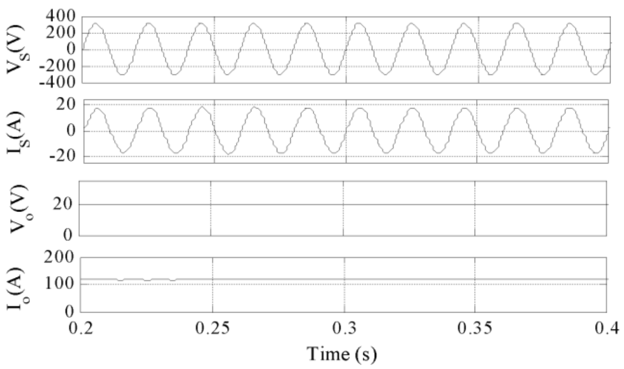


Fig. 3: Performance of proposed AWPS at 220 V AC mains and 100% load.

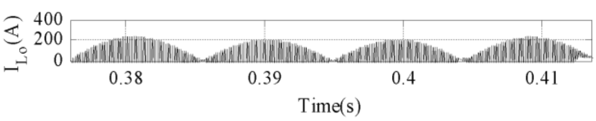


Fig. 4: Output inductor current of bridgeless Cuk converter demonstarting DCM.

In Fig. 4, it can be clearly seen that the converter is operating in DCM. The input and output voltage and current waveforms of proposed 2.4 kW welding power supply for a 20 V/120 A load is shown in Fig. 3. The input current waveform along with its harmonic spectrum and THD (Total Harmonic Distortion) of AC mains current for rated load condition are shown in Fig. 5. It is evident from Fig. 6 that even on varying loads, the system exhibits fast dynamic response. Moreover, the PI controller successfully maintains a constant DC voltage at output.

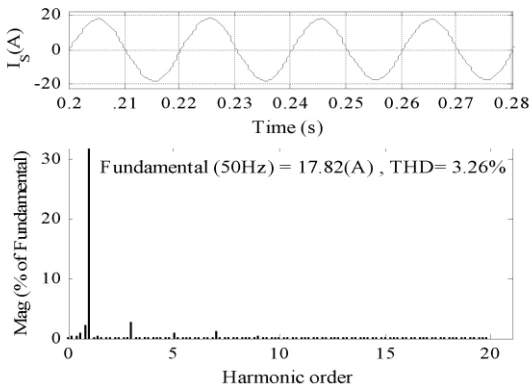


Fig. 5: Waveform and harmonics spectrum of AC mains current (I_S) at full load.

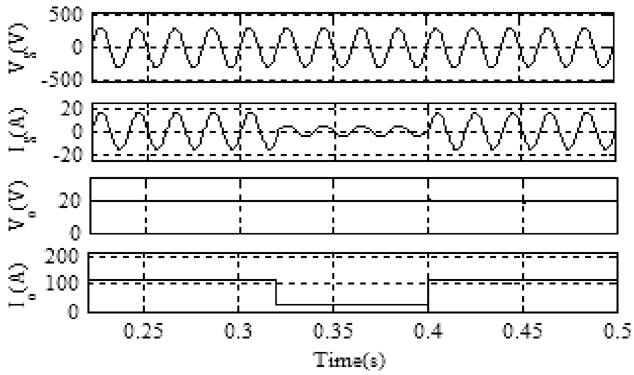


Fig. 6: Performance of proposed AWPS at 20% load.

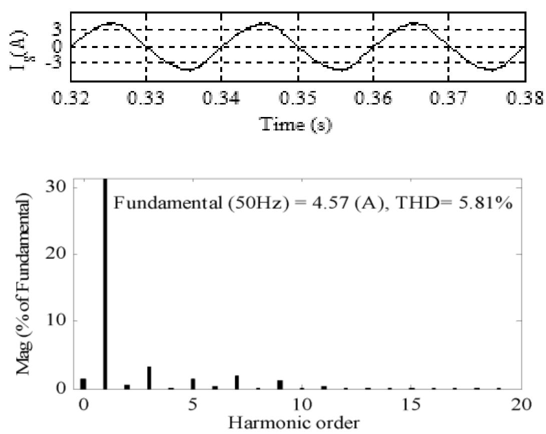


Fig. 7: Waveform and harmonics spectrum of AC mains current (I_S) at light load condition.

The harmonics spectrum of AC mains current along with its THD at light load condition is shown in Fig.7. The dynamic performance of welding power supply along with AC mains current frequency spectrum at varying supply conditions has been demonstrated in Figs. 8-11.

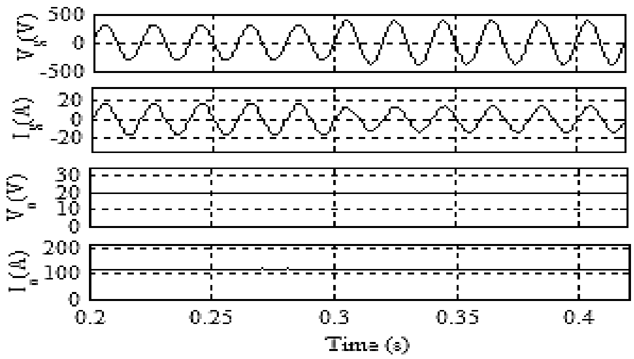


Fig. 8: Dynamic performance of the proposed AWPS at V_s of 270 V.

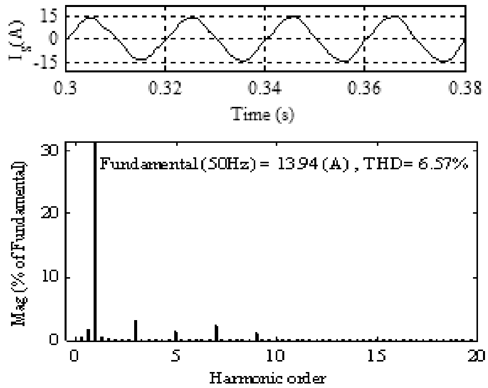


Fig. 9: Waveform and harmonic spectrum of AC mains current (I_S) at V_S of 270 V.

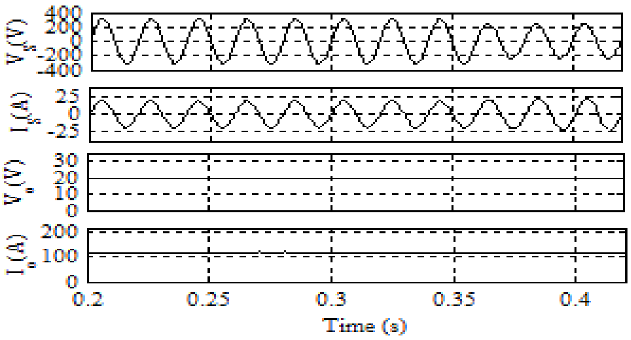


Fig. 10: Dynamic performance of the proposed AWPS at V_S of170 V.

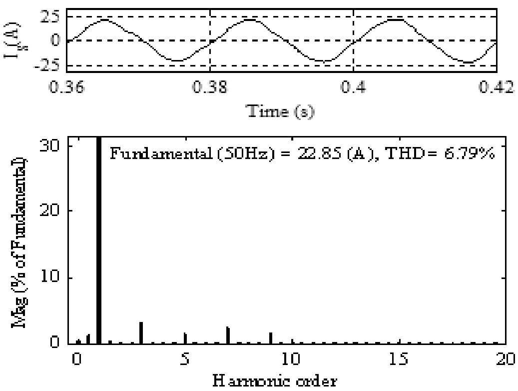


Fig. 11: Waveform and harmonic spectrum of input ac mains current (I_S) at supply voltage = 170 V.

The short circuit occurs when the electrode accidentally comes in contact with the welding pad and gets stuck to the molten metal. While designing an AWPS, it is beneficial to have a short circuit current slightly higher than the rated load current to inhibit the electrode from sticking to the work-piece during the arc striking process. Whenever the output current becomes more than 1.25 times the rated current, the PI current controller adjusts the duty cycle of the switches in such a way as to limit the output current to safe value.

The transition from short circuit to rated load condition is shown in Fig. 12. The controller aids in fast transition from short circuit to rated load and it restricts the output current to 150 A during short circuit period which results in less spatter generation and thus improves the weld quality.

Figs. 13-14 demonstrate the variation of PQ indices at various loads and input AC voltage variations. It can be clearly seen that the input AC mains current THD is below 5.81% under the variable load conditions while the input AC mains current THD is between 3.26% and 6.79% under the varying AC mains voltage.

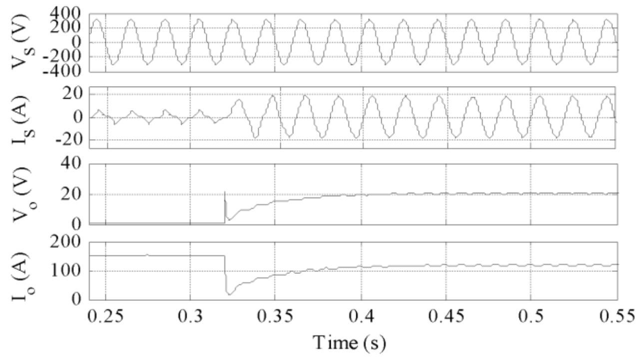


Fig. 12: Dynamic performance of proposed AWPS under short circuit condition.

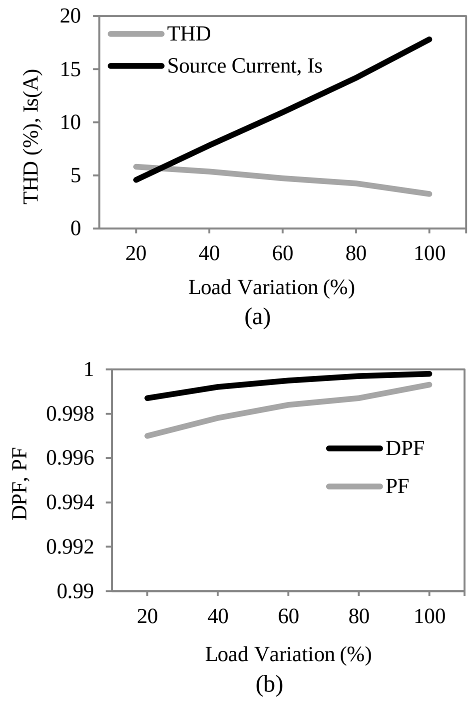
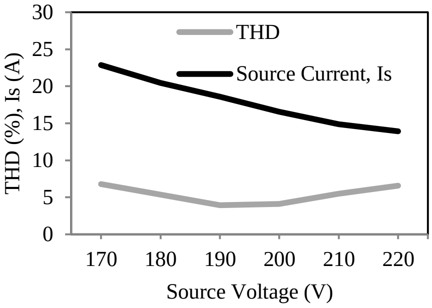
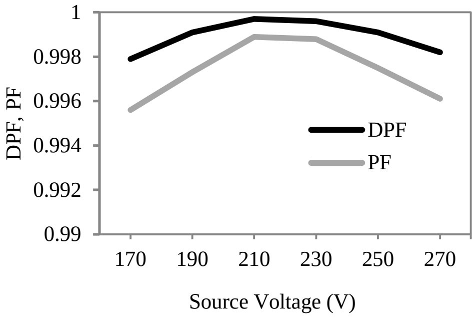


Fig. 13: Variation of PQ indices of bridgeless Cuk converter based AWPS under different load conditions.
(a) I_S and its THD at AC mains
(b) DPF and PF



(a)



(b)

Fig. 14: Variation of PQ indices of bridgeless Cuk converter based AWPS under various source voltage conditions.
(a) I_S and its THD at AC mains
(b) DPF and PF

V. Conclusion

An exhaustive performance of a bridgeless Cuk converter based power supply for welding applications has been carried out for different loads and AC mains voltages conditions. It has been found that the THD of the input AC mains current falls within 7% for both full load as well as light load conditions for the wide range of operating AC mains voltage from 170V to 270V. Fast dynamic response of proposed welding power supply has been achieved hereby improving the reliability of the system. In addition, the proposed welding power supply has been found capable of operating even in the short circuit condition which makes the system more efficient and appropriate for welding applications. An effectual designing method to arc welding power supplies has been put forward.

VI. Appendix

Specifications of Proposed Welding Power Supply

Input AC mains voltage, V_s(rms): 220 V, 50Hz; Output Power, P_o: 2.4 kW; Output Voltage, V_o: 20V; Output Current, I_o: 120A; Switching frequency of DC-DC converter, f_S : 50 kHz; Transformer primary to secondary turns ratio, N_1/N_2: 3.887; Input Inductor, L_S = 0.32 mH; Intermediate Capacitor, C: 56.12 μF; Output Inductor, L_o: 26 μH; Output Capacitor, C_o: 238.73 mF.

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