Novel AC-DC Converter Design with PF Correction

Y. Kobori, L. Xing, H. Gao, T. Shishime, M. Ohshima, H. Kobayashi, N. Takai and K. Niitsu

Abstract— This paper proposes a new AC-DC converter with Power Factor Correction (PFC) circuit. It requires few components (five switches, one inductor and one capacitor) to convert AC to DC directly. In this low-output-voltage H-bridge AC-DC converter, inductor current always flows in the same direction. We investigated two types of PFC circuits; boundary conduction mode (BCM) and continuous conduction mode (CCM). The new PFC circuit for BCM does not use an analog multiplier. We describe circuit topologies, operation principles and simulation results.

Keywords— AC-DC converter, Buck-boost converter, PFC, Switched-mode power supply

I. INTRODUCTION

AC-DC converters are indispensable for virtually all electronic devices, from cell phones to large manufacturing machinery. AC-DC converters produce steady direct current (DC) from alternating current (AC). In a typical converter, the AC input is rectified, drives a high-voltage high-frequency switching circuit connected to a transformer, and the desired DC voltage is output. However, this type of converter is bulky and has low efficiency, because it contains a switching DC-DC converter, a transformer, and a rectifier.

In this paper we propose a new circuit to realize direct AC-DC conversion: a non- inverting buck-boost converter with H-bridge circuit comprising five switches operated by changes in input voltage polarity, to make current flow in the inductor in one direction.

We also added a power factor correction (PFC) circuit. We investigated two PFC circuits: boundary conduction mode (BCM) and continuous conduction mode (CCM). We introduce their operating principles and show simulation results to verify their basic operation and performance. We also calculate the voltage-conversion ratio and compare it with that of a commonly-used buck-boost converter.

II. DIRECT BUCK-BOOST AC-DC CONVERTER

A. Proposed Circuit and Operation

The proposed direct buck-boost AC-DC converter is shown in Fig.1 and Fig.2, where the red solid line shows current flow when the inductor is charged, and the blue dashed line shows the current flow when the inductor is discharged. Five switches operate at a frequency of 200 kHz and the operation mode varies with changes in input voltage polarity and the charging or discharging of the inductor.

Let us consider the case when the input voltage is positive, as shown in Fig.1 and Fig.3 (a). First, S1 and S3 are ON for a time of D*Ts (D is the duty ratio, the ON part of the duty cycle, and Ts represents the switching period) and the inductor is charged. Next S1 and S3 are turned OFF and S2 and S5 are turned ON so that the inductor is discharged into the capacitor and the resistor. For a positive input, S1 and S3, S2 and S5 are alternately turned ON and OFF as shown in Fig.3 (a). The operation is just like the common buck-boost converter, and we obtain a steady output voltage.

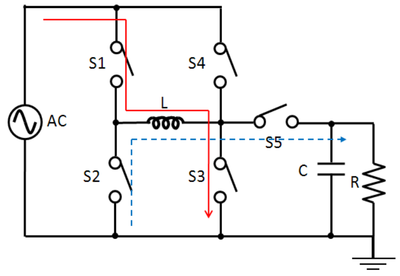


Fig.1 H-Bridge AC-DC converter (Current when $V_{in} > 0$)

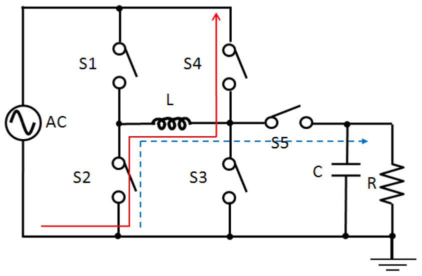
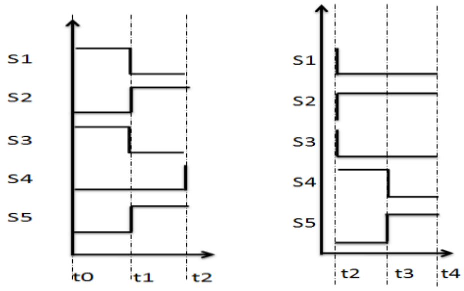


Fig.2 H-Bridge AC-DC converter (Current when $V_{in} < 0$)



（ａ） $V_{in} > 0$　　（ｂ） $V_{in} < 0$

Fig.3 Timing chart of switches

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B. Simulation Results

The circuit schematic for simulation is illustrated in Fig4. The input voltage is 100Vrms with a frequency of 50 Hz and we use PWM operating at 100 kHz. The other parameters are shown in Table 1. We set the output voltage to 50V and the output resistor current to Io=0.5A.

Table Ⅰ

Simulation Parameters of Figure 3

C	220 uF
R1	9 kΩ
R2	1 kΩ
L	220 uH
VREF	5.0 V

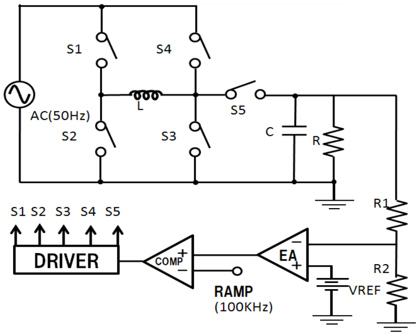


Fig.4 Simulation circuit

The waveforms of input voltage Vi and output voltage, output voltage ripple, the inductor current waveform and load transient response are shown in Fig.5, Fig.6, Fig.7 and Fig.8 respectively. These figures show the transient responses when the input voltage is near the peak. The output voltage ripple is 6mVpp, which is very small, and the inductor current ripple is under 1.7App.

For the transient response, we set the current change just as ⊿I=1.0 x 0.5A. The voltage ripple is 15mVpp / 0.5A in Fig.7, which is very small compared with the output voltage. We see in Fig.8 that when the inductor current is large (1.oA), it operates in continuous mode. When the inductor current is small (0.5A), it operates in intermittent mode.

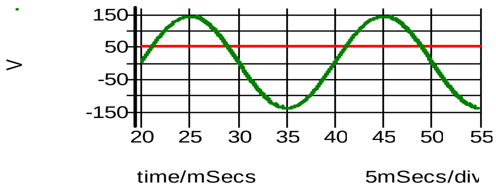


Fig.5 Waveform of input voltage and output voltage.

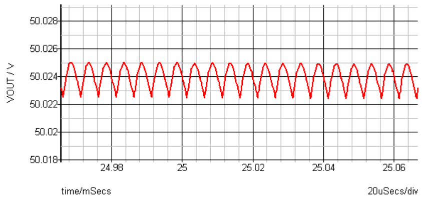


Fig.6 Output voltage ripple.

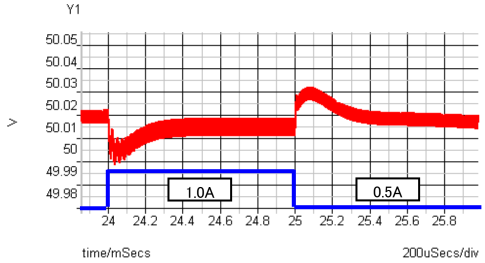


Fig.7 Load transient response.

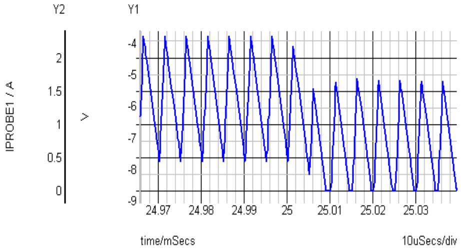


Fig.8 Waveform of inductor current

C. Voltage Conversion Ratio

Compared with the PWM clock frequency, the frequency of the input sine wave is very low; hence the instantaneous input voltage can be considered to be almost constant. Then the output voltage Vo can be calculated as follows:

$$Vo = \frac{D}{1-D} \cdot Vi$$

$$= \sqrt{2} \cdot \frac{D}{1-D} \cdot Vrms \cdot \sin(\theta) \qquad (1)$$

$$D(\theta) = \frac{1}{1 + \sqrt{2} / M \cdot \sin(\theta)} \qquad (2)$$

Here D is the duty ratio, and M is given by

$$M = Vo / Vrms \qquad (3)$$

Thus the average duty ratio D* in a half period is obtained as follows:

$$D^* = \frac{1}{\pi} \int D(\theta)\, d\theta$$

$$= \frac{1}{\pi} \int_0^{\pi} \frac{d\theta}{1 + \sqrt{2} / M \cdot \sin(\theta)} \qquad (4)$$

Since we cannot solve the above equation analytically, we solved it approximately by using interval integration. In Fig.9 we compare the result with that of a commonly-used non-inverting buck- boost converter, where the lateral axis indicates the average duty ratio and the vertical axis shows output voltage. We see that, compared with the common buck-boost converter, the output voltage is a little bit smaller for the same duty ratio; in other words a larger duty ratio is used for a given low output voltage, which makes it possible for our circuit to convert to a low output voltage directly, and this is an advantage over the commonly-used PWM-controlled buck-boost converter.

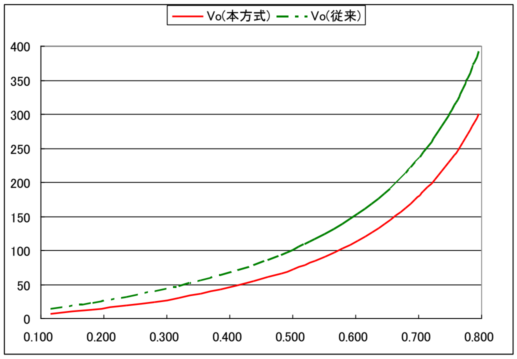
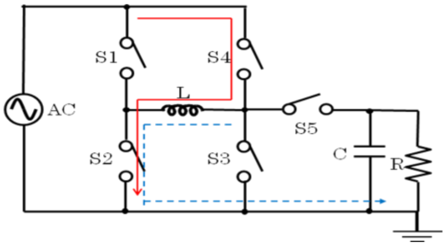


Fig.9 Average duty ratio vs. output voltage (Vrms=100V).

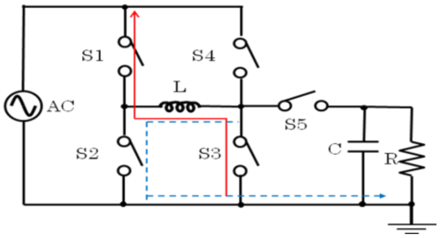
III. INVERTING H-BRIDGE AC-DC CONVERTER

A. Proposed Circuit and Operation

We can obtain negative outputs with the same circuit topology by reversing the direction of the inductor current. The circuit schematic is shown in Fig.10. We can reverse the inductor current just by changing the operation of the switch groups.



（a） Current flow when Vi＞0



（b） Current flow when Vi＜0

Fig.10 Inverting H-Bridge AC-DC converter

The operation of the switch groups are as follows: (1)When Vi ＞0 , first S4-S2 are ON、then S2-S5 are ON; (2) Vi＜0, first S3-S1 are ON, then S2-S5 are ON.

B. Simulation Results

We have performed circuit simulations to check the operation and performance of the proposed inverting H-Bridge AC-DC converter (Fig.10) with the same simulation conditions as the non-inverting one. The waveforms of input and output voltages and output voltage ripple for a load current of 220mA are shown in Fig.11 and Fig.12. We see that output ripple is under 3mV, which is very small, and the characteristics are similar to those of the non-inverting H-Bridge AC-DC converter.

The direct AC-DC converters described above have no problems when the input voltage is high enough. However, when the input is lower than 20V, output ripple becomes a bit larger than 3mV; we will find out the reason and solve this problem in the near future.

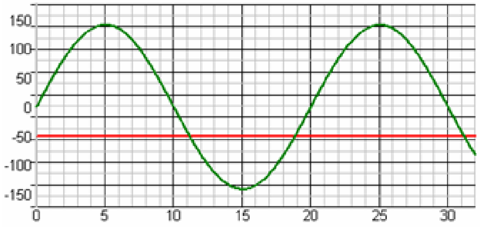


Fig.11 Output voltage of inverting converter.

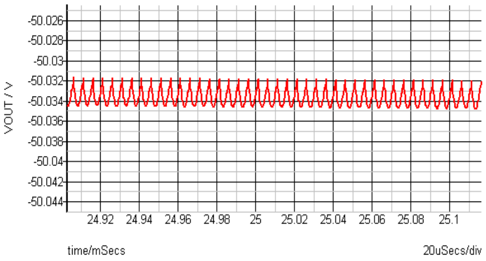


Fig.12 Output ripple of the inverting converter.

IV. POWER FACTOR CORRECTION (PFC) CIRCUIT

For AC-DC converters, distortion of the input current, and spurious current at clock frequencies should be reduced below the level permitted by EMI (Electro Magnetic Interference) regulations, because the AC-DC converters are connected directly to the power lines. We have designed PFC circuits to meet this requirement.

A. New PFC Circuit in BCM

(1) Conventional PFC in Boost Converter

In conventional AC-DC converters, a boost- type PFC circuit with an active filter is frequently used as shown in Fig.13. It consists of an analog multiplier, an op-amp, two comparators and D, L, C components. In this circuit, on-time of PWM signal should be constant, to keep the waveform of the input current similar to that of the input voltage (=Sinewave). The waveform of the inductor current is shown in Fig.14 that is a series of triangle waveforms in BCM. The current is zero at switching timing from off to on. The solid line represents the charge current to the inductor and the dashed line shows the discharge. So the input charges in a single triangle waveform and the voltage source is shown below.

$$Q_{in}(t)=T*(T_{on}*V_i*\sin\omega t)/2L \qquad (5)$$

The on-time T_{on} of PWM signal is designed to be constant but the off-time is variable, and thus the clock frequency varies in phase. In this case, the PWM period is given below,

$$T = T_{on} + T_{off}$$

$$= T_{on} + L{*}T_{on}{*}V_i{*}\sin\theta / (V_o - T_{on}{*}V_i{*}\sin\theta) \qquad (6)$$

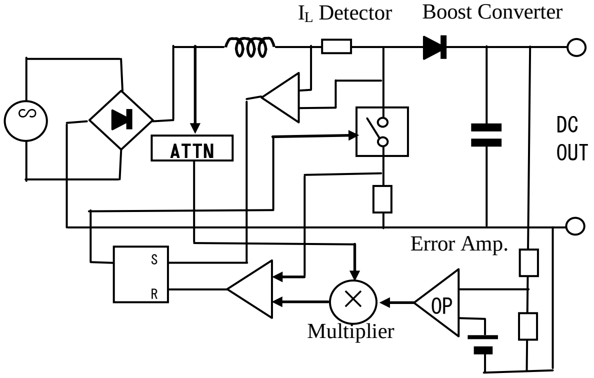


Fig.13 Conventional PFC circuit in BCM

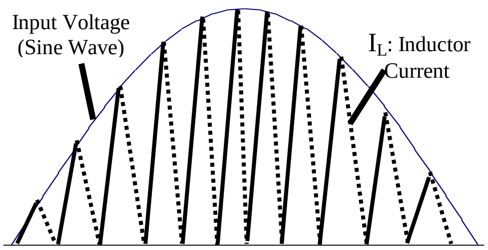


Fig.14 Waveform of inductor current in BCM.

(2) New PFC in Buck-Boost Converter

Since our proposed circuit is a buck-boost converter different from the above boost converter, it needs a new PFC circuit. In our proposed circuit, the input current is not equal to the inductor current, because the on-time current is input current and the off-time current is load current. Thus the on-time is constant and the off-time is given by

$$I_{off}(t) = I_p - t{*}V_o/L$$

$$= T_{on}{*}V_i{*}\sin(\theta_i)/L - t{*}V_o/L$$

$$\therefore T_{off} = (V_i/V_o){*}T_{on}{*}\sin(\theta_i) \qquad (7)$$

Here, Ip represents the peak current of IL.

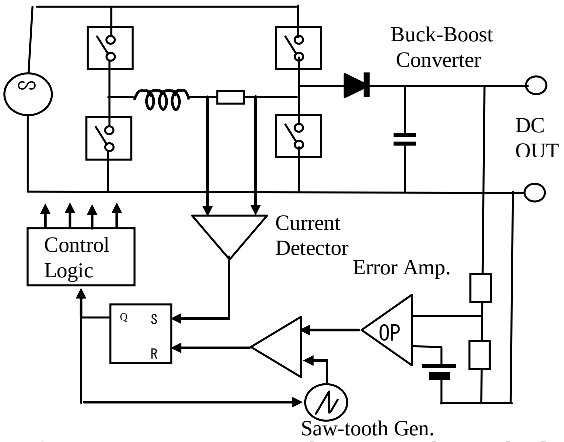


Fig.15 New BCM PFC without an analog multiplier.

Eq.(7) tells us that Toff is proportional to the input sin(θ i) wave. Thus the input current is shaped nearly the same as the input voltage because the average of Vi/Vo is much larger than 1 in Eq.(7). This means that a multiplier is not needed in the new PFC system shown in Fig.15. We note that conventional AC-DC PFC correction requires large capacitors to hold the input AC power and to output the DC power, and our proposed converter also requires a large capacitor of 47mF.

(3) Simulation Results of New Converter

In general, AC-DC converters have many output voltages and the most popular level is 24V output. Fig.16 shows the input voltage and the output voltage as well as the input current. The input current is of saw-tooth shape with clock frequency of about 100 kHz. In Fig.16, the input current represents the waveform of the source current through a LPF.

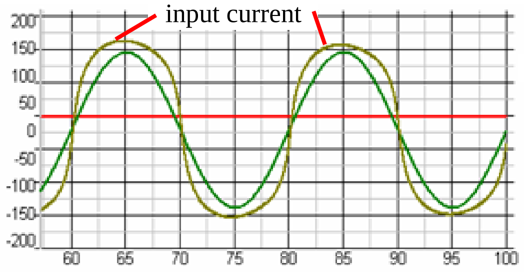


Fig.16 Waveform of input voltage, output voltage, and input current.

In this waveform, the power factor calculated from simulation is about 0.97. The output voltage ripple caused by clock signals is small enough, and ripple caused by input signals is 25mVpp at Io=0.25A. and 60mVpp at Io=1.0A. The ripple frequency is 100Hz. Fig.18 shows the waveform of the input voltage and the inductor current while Fig.19 shows the wide scope waveform of the inductor current.

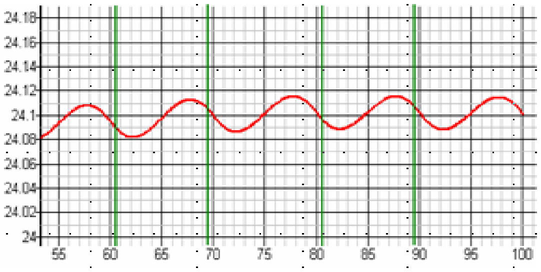


Fig.17 Output voltage ripple (100Hz).

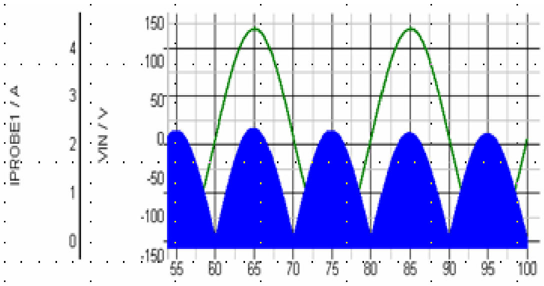


Fig.18 Input voltage and inductor current.

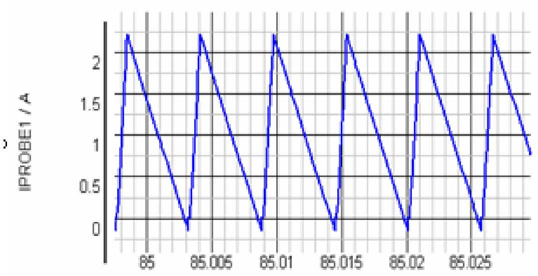


Fig.19 Inductor current in BCM.

B. New PFC Circuit in CCM

(1) Conventional PFC in the Boost Converter

Fig.20 shows a conventional AC-DC converter with CCM PFC. This circuit consists of an analog multiplier, two op-amps, a comparator and several components like in a normal boost converter. There the inductor current and the input current are the same and they flow as shown in Fig.21. Usually the frequency of the PWM signal is kept constant and the off-time Toff is controlled to be proportional to the input voltage wave.

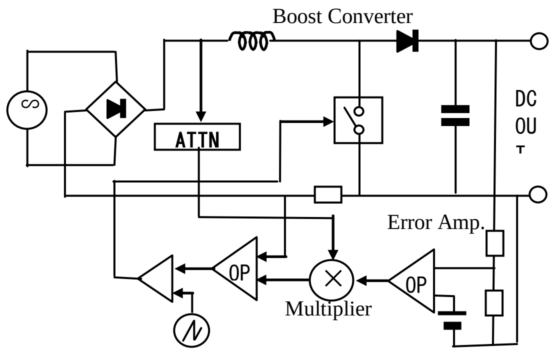


Fig.20 Conventional PFC circuit in CCM.

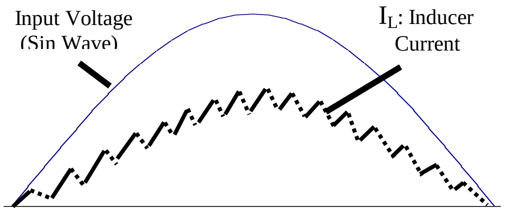


Fig.21 Waveform of inductor current in CCM.

(2) New PFC in Buck-Boost Converter

We have developed a new PFC circuit for our AC-DC direct converter shown in Fig.22. This PFC circuit consists of a new multiplier, two op-amps and a comparator to generate the PWM signal. The multiplier circled by the red dashed line consists of a pulse generator controlled by the output of the error amp, a time-to-voltage converter.

(3) Simulation Results of New Converter

Fig.23 shows the output voltage, the input current through a LPF and the inductor current. The input current is almost similar to the input sinewave shape except for zero-crossing points. Output voltage ripple caused by the input voltage is 60mVpp at Io=1.0A shown in Fig.24. The waveform of the inductor current is shown in Fig.25 at the timing of the inductor current peak at t=95ms. The ripple of the inductor current is about 0.2App. In this case, the power factor in our simulation is 0.99.

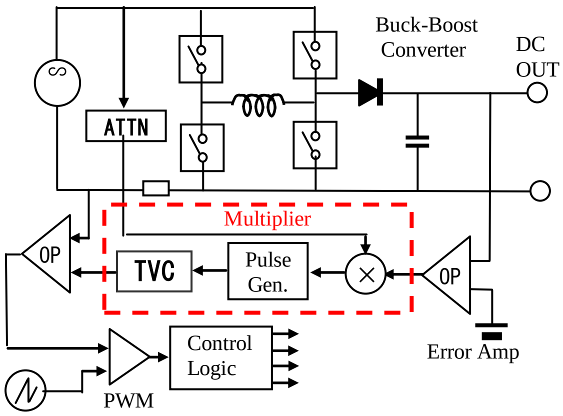


Fig.22 CCM PFC with new multiplier.

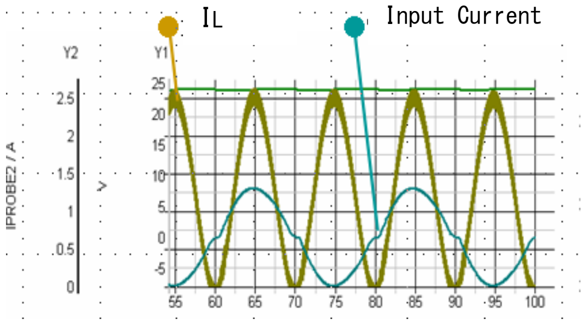


Fig.23 Input current and inductor current.

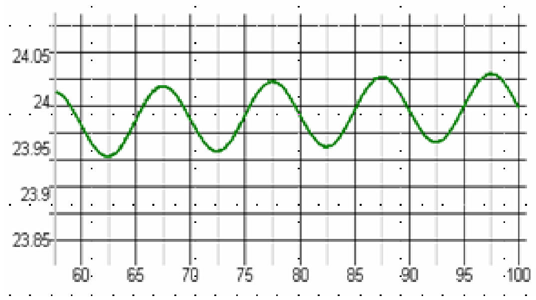


Fig.24 Output voltage ripple.

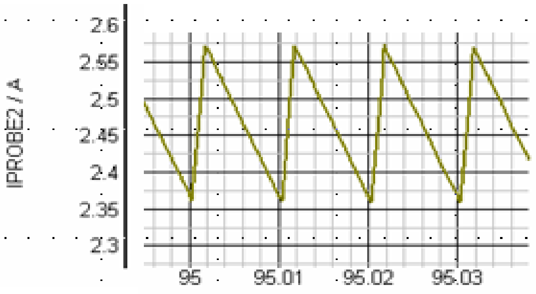


Fig.25 Inductor current in CCM.

V. CONCLUSION

In this paper, we have described a direct AC-DC converter with H-bridge topology and PFC circuits. We have investigated and proposed two PFC circuits in BCM and CCM. We explained their principles of operation and verified their basic operation by simulations. Simulation results show that the output voltage ripple is 60mVpp for BCM and 50mVpp for CCM at Io=1.0A. Furthermore we have developed a new PFC circuit in BCM converter and a new multiplier with time-to-voltage converter in CCM. Our simulations show that the power factor is 0.96 in BCM and 0.99 in CCM at $Vi=100V_{rms}$, Vo=24V and Io=1.0A.

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