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A Comparative Study of Simple Ac-Dc PWM Full-Bridge Current-Fed and Voltage-Fed Converters

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ABSTRACT

Ac-dc PWM single-stage converters that integrate the PFC and dc-dc conversion functions in a single switching converter have been proposed to try to minimize the cost and complexity associated with implementing two separate and independent switch-mode converters. In this paper, two simple ac-dc single-stage PWM full-bridge converters are considered - one current-fed, the other voltage-fed. The operation of both converters is explained and their properties are noted. Experimental results obtained from simple lab prototypes of both converters are presented, then compared and discussed.

Keywords: single-stage converters, ac-dc power conversion, power factor correction

1. Introduction

In recent years, regulatory agency requirements have been pressuring power converter manufacturers to implement some form of power factor correction (PFC) in their products due to the rise in the use of electrical equipment. High input power factor and low input current harmonics are more and more becoming mandatory performance criteria for power converters so that agency standards such as EN61000-3-2 can be satisfied. The traditional ac-dc full-bridge converter, shown in Fig. 1, has been replaced by a two-stage approach with an ac-dc boost converter in place of the traditional passive diode rectifier/LC filter input combination shown in Fig. 1. The boost converter can shape the input current so that it is almost sinusoidal, but this increases the cost and complexity of the overall two-stage converter because an additional switching converter must be implemented.

Ac-dc PWM single-stage full-bridge converters that integrate the power factor correction (PFC) and dc-dc conversion functions in a single switching converter have been proposed to try to minimize the cost and complexity associated with implementing two separate and independent switch-mode converters. Single-stage resonant and PWM full-bridge converters have been proposed [1]-[8], but resonant converters are not as suitable as PWM converters because they operate with variable switching frequency control, have high switch voltage and current stresses, and have a limited input line/output load operating range.

Single-stage PWM full-bridge converters can either be current-fed or voltage-fed, depending on whether the input of the full-bridge is connected to a large inductor or a large capacitor. The converter shown in Fig. 2(a) is the simplest possible ac-dc single-stage current-fed PWM

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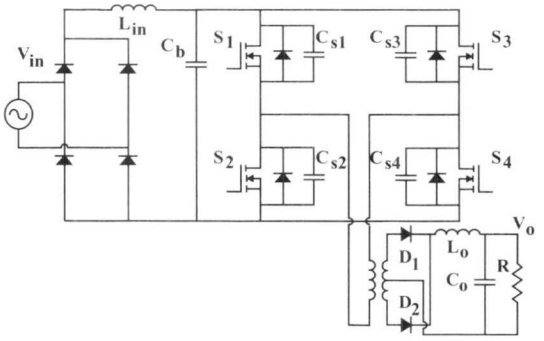


Fig. 1 Ac-dc PWM converter with diode rectifier/LC filter front-end.

full-bridge converter. Other converters of this type are variations on this converter with extra circuitry added to improve performance. For example, a possible variation of the converter shown in Fig. 2(a) would be one with an auxiliary circuit added to help the main power circuit switches operate with soft-switching. Likewise, the converter shown in Fig. 2(b) is the simplest possible ac-dc single-stage voltage-fed PWM full-bridge converter. Since the development of single-stage converters is motivated by cost reduction and simplicity, the objective of this paper is to consider the simplest and cheapest possible single-stage PWM current-fed and voltage-fed full-bridge converters and to compare their performance. In this paper, the operation of the converters shown in Fig. 2(a) and (b) is briefly explained, their properties are noted, and experimental results obtained from simple prototypes of both converters are presented, then compared and discussed.

2. Converter Operation

The operation of the full-bridge converters shown in Fig. 2 is explained in this section.

A. Current-fed PWM converters

The current-fed ac-dc single-stage PWM full-bridge converter shown in Fig. 2(a) has two basic modes of operation: If the dc bus is shorted (Fig. 3(a)), either by turning on all the converter switches or by turning on at least two switches in the same converter leg at the same time, then the input inductor current will rise as the full input voltage is put across L_{in}, and no energy is

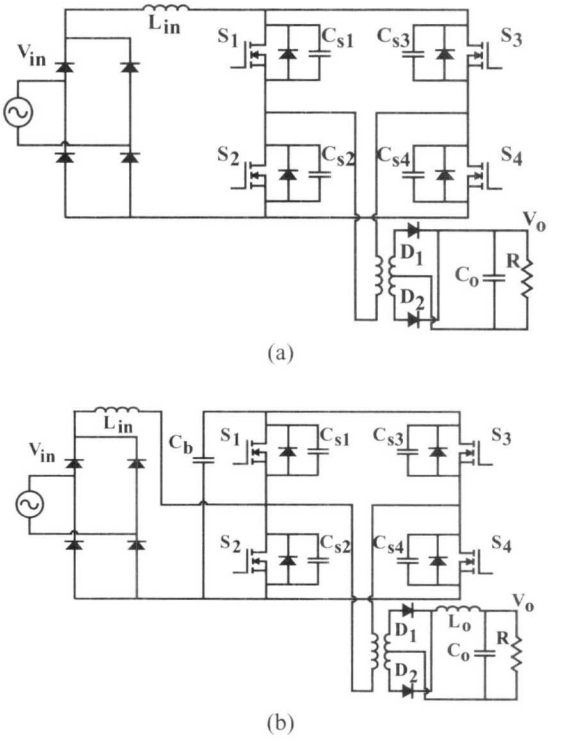


Fig. 2 Simple ac-dc PWM full-bridge converter with PFC (a)Current-fed converter. (b)Voltage-fed converter.

transferred to the load. If a pair of diagonally opposed switches is on, as shown in Fig. 3(b), then the current flowing through the input inductor L_{in} will fall as energy will be transferred from the primary side of the converter to the output. The operation of the current-fed PWM full-bridge converter can be considered to be analogous to that of a one-switch PWM boost converter because the boost converter has the same two key modes of operation - one mode where the dc bus is shorted, and another mode where the dc bus is not shorted and energy from the input is transferred to the load. The input current can be made to be fully discontinuous, bounded by a sinusoidal envelope, or it can be made to be fully continuous and almost purely sinusoidal. Typical converter waveforms are shown in Fig. 4.

B. Voltage-fed PWM converters

The voltage-fed converter shown in Fig. 2(b) is almost the same as the PWM full-bridge converter shown in Fig. 1, except that input inductor, L_{in}, is connected to switch S_2 instead of energy-storage capacitor, C_b. This

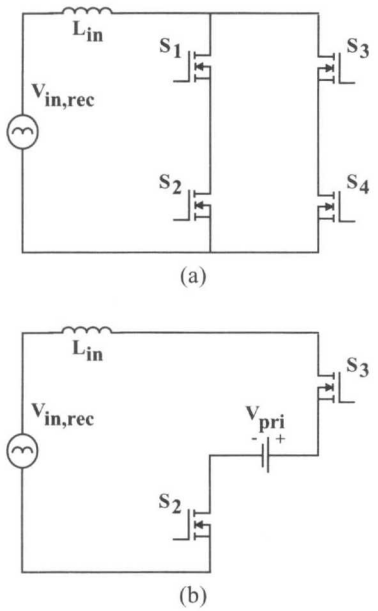


Fig. 3 Equivalent primary-side circuits showing fundamental current-fed converter operation modes: (a) Dc bus short mode. (b) Energy-transfer mode.

modification allows switch S_2 to perform the same current-shaping function as the switch in a boost converter while the converter performs dc-dc conversion in a manner similar to a standard PWM full-bridge converter. Energy is transferred from capacitor C_b to the load whenever a pair of diagonally opposed pair of switches is on (S_1 and S_4 or S_2 and S_3), and none is transferred whenever the voltage across the transformer primary is zero and the converter is in a freewheeling mode of operation.

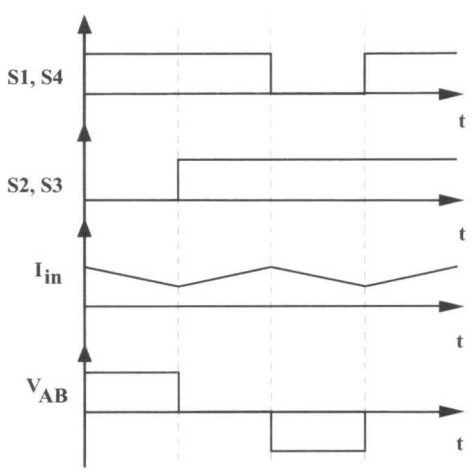


Fig. 4 Current-fed converter gating signals and waveforms

The voltage-fed converter passes through several distinct intervals of operation during a single steady-state switching cycle, and has more modes of opration than does the current-fed converter. These intervals, which can be seen from the circuit diagrams shown in Fig. 5, are as follows:

a) Interval 1 (t_0-t_1): At $t = t_0$, switches S_2 and S_3 are on and energy is being transferred from capacitor C_b to the load. While this is happening, input current I_{in} is rising as the full rectified input voltage is placed across inductor L_{in}.

b) Interval 2 (t_1-t_2): At $t = t_1$, switch S_2 is turned off and capacitors C_{s1} and C_{s2} begin to discharge and charge respectively. Both the input current and the transformer primary current do the charging and discharging of these capacitors.

c) Interval 3 (t_2-t_3): At $t = t_2$, the converter enters a freewheeling mode of operation and there is no energy transfer to the load. The input current flows through the body-diode of S_1 into capacitor C_b while the transformer primary current is circulating through switch S_3. This interval is bypassed if capacitors C_{s1} and C_{s2} cannot be fully discharged and charged respectively

d) Interval 4 (t3-t4): At t = t3, switch S1 is turned on and the converter continues to operate as it did during Interval 3.

e) Interval 5 (t4-t5): At t = t4, switch S3 is turned off and capacitors Cs3 and Cs4 are charged and discharged, respectively, by the transformer primary current.

f) Interval 6 (t_5-t_6): Current begin to flow through the body-diode of S_4 at $t = t_5$. This interval is bypassed if capacitors C_{s3} and C_{s4} cannot be fully charged and discharged respectively.

g) Interval 7 ($t_6 - t_7$): At $t = t_6$, switch S_4 is turned on. Both the input and transformer primary currents continue to flow through switch S_1 in the direction indicated in Fig. 5(g).

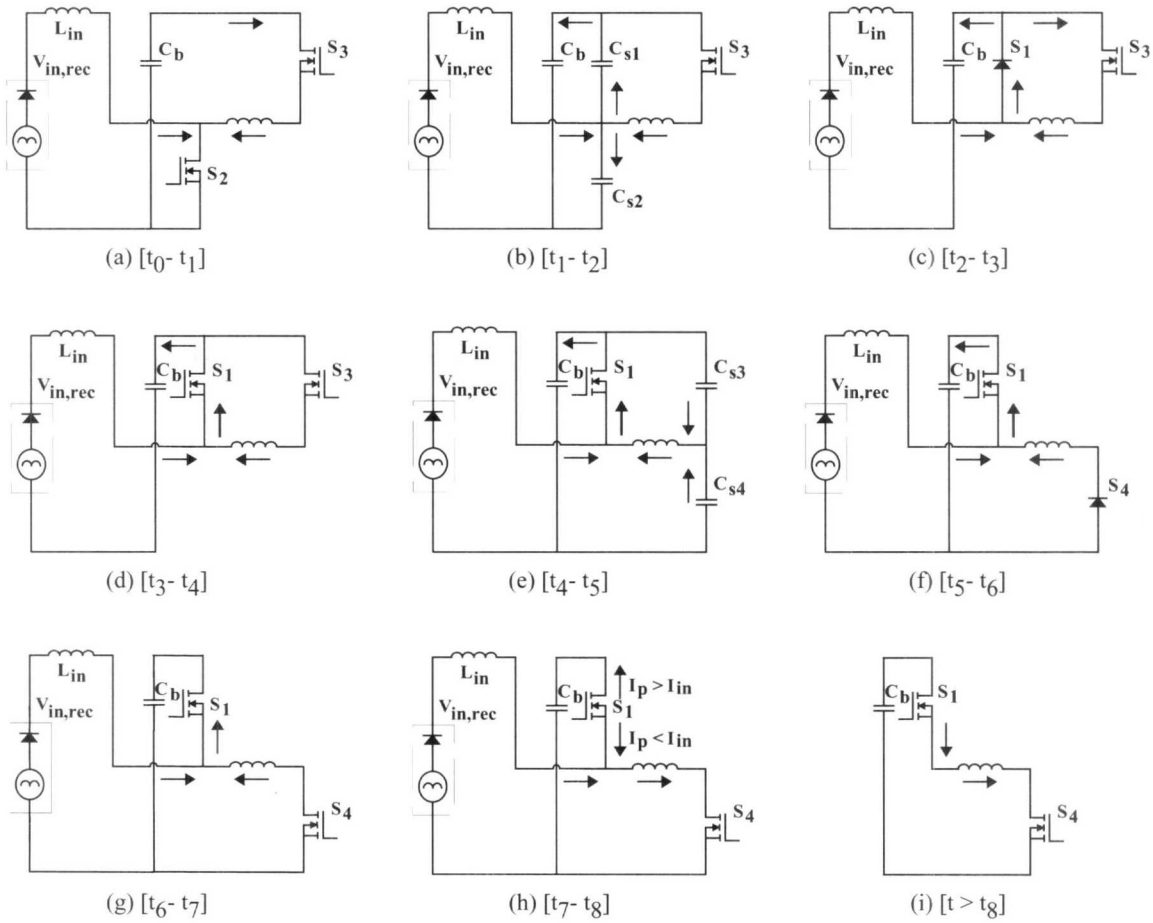


Fig. 5 Equivalent primary-side circuits showing voltage-fed converter operating intervals in a half-switching cycle.

h) Interval 8 ($t_7 - t_8$): At $t = t_7$, the transformer primary current reverses direction. The direction of the current through S_1 depends on whether the input current is greater or less than the transformer primary current. If the input current is discontinuous, then it becomes zero sometime after $t = t_2$. If this is the case, then the equivalent circuit during Interval 7 is the one shown in Fig. 5(i) where the converter is shown to act exactly like a standard PWM full-bridge converter, with no interaction from the input. If the input current is continuous, then there will be a net current flow into C_b while S_1 and S_4 are on.

The gating signals used for the switches in the proposed converter are different from the phase-shift control technique typically used in a PWM full-bridge converter. As can be seen in Fig. 6, the gating signals of the switches in a leg of the proposed converter are asymmetrical with the top switch having a pulse width of $(1\text{-}D)T_{SW}/2$ (with D = duty-cycle and T_{SW} = switching period) and the bottom switch having a pulse width of $DT_{SW}/2$. The gating signals of the switches in a leg are complementary with some "dead-time" added to avoid the possibility of cross-conduction.

3. Converter Properties

In this section, the properties of the two converters shown in Fig. 2 are compared.

A. Number of times power is processed

In the current-fed converter, there is a direct link between input and output as current from the input

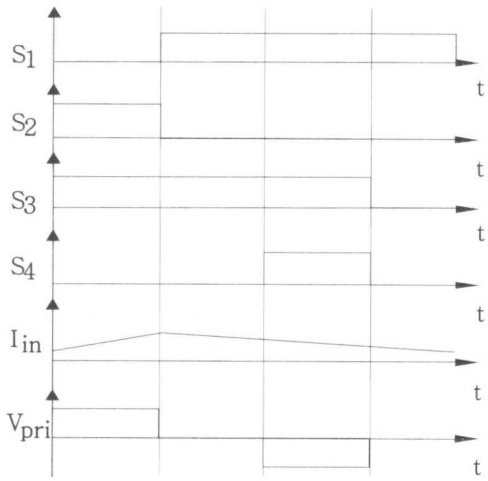


Fig. 6 Voltage-fed converter gating signals and waveforms

inductor flows directly through to the converter transformer primary, and the reflected current flows through the secondary and rectifier diodes to the output. As a result, power from the input of the current-fed converter is processed only once as it flows directly through the output without passing through any intermediate stage that can result in additional losses.

This is not the case for the voltage-fed converter where there is a dc bus capacitor located between the input inductor and full-bridge converter. In this case, there is no direct link between input and output so that power from the input must be processed twice: once when energy from the input inductor is transferred to the primary-side dc bus capacitor, and again when energy from the capacitor is transferred to the output. Since the converter processes power twice, there are two opportunities for power to be lost instead of just one.

B. Output voltage ripple

The current-fed converter is fundamentally a boost converter with a direct link between input inductor and output. The current fed to the output capacitor is therefore a rectified sinusoidal waveform with a large low frequency 120 Hz component. This is so, even though the main power transformer is a high-frequency transformer that does not handle a 60 Hz or 120 Hz component; the 120 Hz component is reconstructed at the transformer secondary. The output current is similar to the one that exists for a boost diode in a standard PWM boost

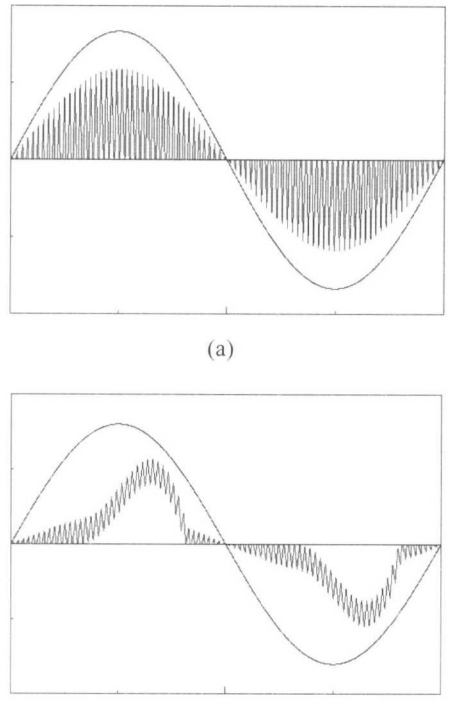


Fig. 7 Types of input current waveforms for the voltage-fed converter (a)Discontinuous current (b)Semi-continuous current.

converter except that it is stepped up by the transformer (which typically steps down the primary voltage). As a result, the output current ripple of the current-fed converter is very large and this, in turn, results in a considerable output voltage ripple. Since there is only one capacitor that serves as an output filter, this capacitor must be very large to reduce the voltage ripple.

In the case of the voltage-fed converter, if the duty cycle is kept constant throughout the input line cycle, as opposed to varying it throughout the cycle to try to maintain a near perfect continuous sinusoidal waveform, then there will be no low frequency 120 Hz harmonic component in the output current. The output inductor current may be either discontinuous or continuous, but it will only have high frequency components that can be filtered out by the output filter; this means that a smaller filter can be used. Fixing the duty-cycle through the input voltage line cycle, however, may cause significant harmonic distortion of the input current, as will be discussed below.

C. Input power factor

Any PWM technique that can be used in a conventional PWM boost converter can also be used in the current-fed converter shown in Fig. 2(a) because the two converters are very similar. Since the boost converter can be made to operate with a near unity power factor, so too can the current-fed converter.

The voltage-fed converter can be made to operate with a fully continuous, sinusoidal input current waveform by tracking the input current and appropriately adjusting the converter duty cycle throughout the input line cycle. It is not, however, recommended that this be done because the output current of the converter, in this case, would have a considerable low frequency component, similar to what is found in a current-fed converter. Operating the converter with a fixed duty cycle throughout the line cycle will result in the input current being either fully discontinuous or semi-continuous as shown in Fig. 7. If the waveform is semi-continuous, then there will be a significant amount of harmonic distortion, but the converter can be designed to ensure that the input current waveform will still conform to the standards set by regulatory agencies.

D. Dc bus voltage overshoot and ringing

No current flows through the transformer in the current-fed converter when the dc bus is shorted, but current does flow through the transformer when the converter makes the transition from the dc bus short mode to the energy-transfer mode. This occurs when a pair of diagonally opposed switches is simultaneously turned off. Current, however, does not flow instantaneously through the transformer after the switches have been turned off because of the presence of leakage inductance in the transformer. It flows, instead, through the output capacitances of the switches that have been turned off while the transfer of current to the transformer is taking place. This continues until the current is completely transferred to the transformer.

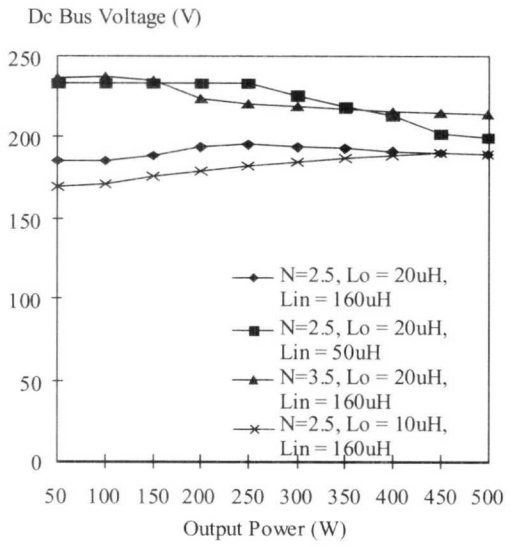


Fig. 8 Graph of dc bus voltage vs output power for V_{in} = 100 Vrms and V_o = 48 V.

While current is flowing through the output capacitances of the turned-off switches, the dc bus voltage can rise to a considerable level as a resonance exists between the leakage inductance of the isolation transformer and the full-bridge switch capacitances, and there is nothing inherent in the converter to clamp the voltage. Moreover, the resonance can also cause severe ringing to appear in the dc bus voltage waveforms as energy is transferred back and forth between the leakage inductance and the output switch capacitances. In order to suppress the severe dc bus voltage overshoots and ringing, a voltage clamp must be placed across the dc-bus on the primary side to reduce these effects. One can choose either a simple resistor-capacitor-diode (RCD clamp), which increases converter losses, or a more sophisticated non-dissipative clamp, which increases converter costs.

Issues related to dc bus voltage overshoots and ringing are entirely avoided in the voltage-fed converter because the converter has a large energy-storage capacitor at its primary-side dc-bus. This capacitor will suppress any voltage overshoot or ringing that might appear on the dc bus so that no additional clamp is required.

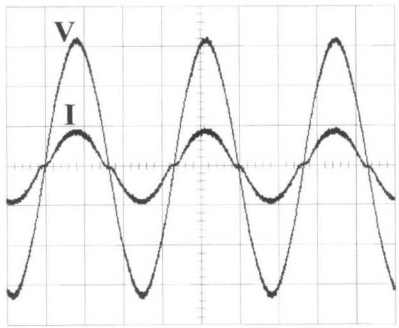
E. Dc bus voltage level

With some sort of clamp in place to suppress any voltage overshoots or ringing that would otherwise appear across the dc bus, the level of the dc bus voltage in the current-fed converter is approximately equal to the product of the output voltage and the transformer turns ratio. This is true regardless of input line and output load conditions. In the case of the voltage-fed converter, however, the dc bus voltage is very dependent on input

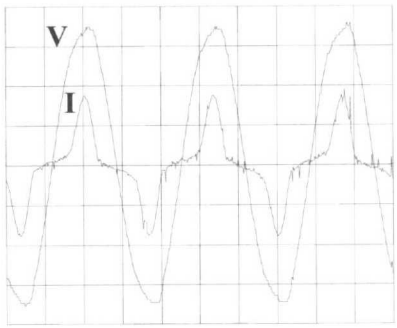
line and output load conditions because the dc bus capacitor is separated from the input source and output load by inductors. There is, therefore, nothing in the converter that directly regulates the dc bus voltage level.

What determines the dc bus voltage level in the voltage-fed converter is the energy equilibrium that must exist at the dc bus capacitor when the converter is in steady-state operation. The energy pumped into the capacitor from the input section must be equal to the energy that the capacitor provides to the output, so that the net dc current flowing in and out of the capacitor is zero during a half-line cycle. The relationship between dc bus voltage and load can be seen in the graph shown in Fig. 8, which is a graph of dc bus voltage vs. output power for various combinations of N, L_{in}, and L_o, and can be summarized as follows:

1) The voltage is constant regardless of what the load is if both output current and input current are discontinuous. It is dependent on the ratio of L_{in}/L_o and on the transformer turns ratio N in this case.
2) The voltage is constant regardless of what the load is if both the output current and the input current are continuous. In this case, it is dependent mainly on the transformer turns ratio N, and less so on the ratio of L_{in}/L_o.
3) The voltage increases when the load is decreased if the input current is discontinuous and the output current is continuous.
4) The voltage decreases as L_{in} is increased and the other component values are kept constant. This property is most apparent when the input current has considerable ripple so that a change in L_{in} has a greater effect on this current.
5) The voltage decreases as L_o is decreased and the other component values are kept constant. This property is most apparent when the output current has a considerable ripple so that a change in L_o has a greater effect on this current.
6) The voltage decreases as N is decreased and the other component values are kept constant.



(a)

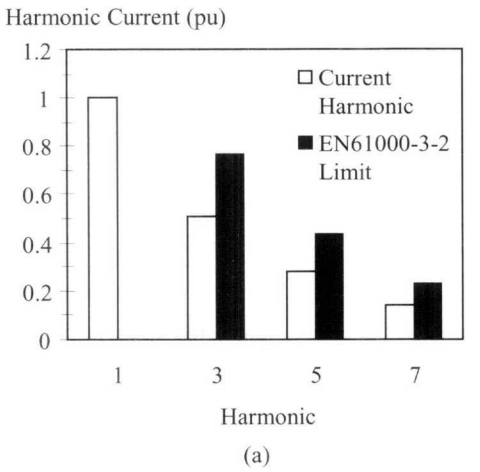


(b)

Fig. 9 Typical input voltage and current waveforms (a)Single-stage current-fed PWM full-bridge converter(scale: V: 50 V/div., I: 5 A/div., t: 5 ms/div.) (b)Single-stage voltage-fed PWM full- bridge converter(scale: V : 40V/div, I : 10A/div., t : 5ms/div).

4. Experimental Results

Simple experimental prototypes of the two converters shown in Fig. 2 were built according to the following specifications: input voltage V_{in} = 100 – 230 Vrms, output voltage V_o = 48 V, maximum output power P_o = 500 W, and switching frequency F_{sw} = 50 kHz. The current-fed converter was implemented with the following component values: transformer turns ratio N = 8, input inductor L_{in} = 750 μH, output capacitor C_o = 5.75 mF. In order to suppress any dc bus voltage overshoots or ringing an RCD snubber was used because it is the simplest and least expensive snubber possible. The voltage-fed converter was implemented using the following component values N = 2.5, L_{in} = 140 μH, output inductor L_o = 32 μH, dc bus capacitor C_b = 1000 μF, and C_o = 1000 μF.



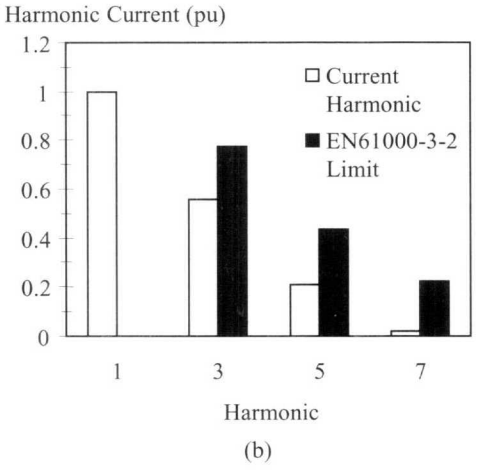
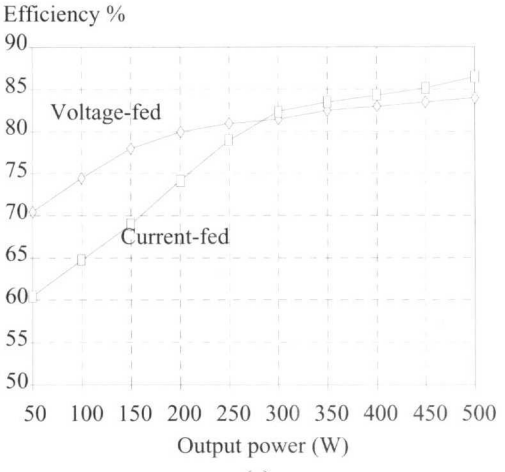


Fig.10 Input current harmonic content at output power P_o = 500 W for (a) V_{in} = 230 Vrms and (b) V_{in} = 100 Vrms.



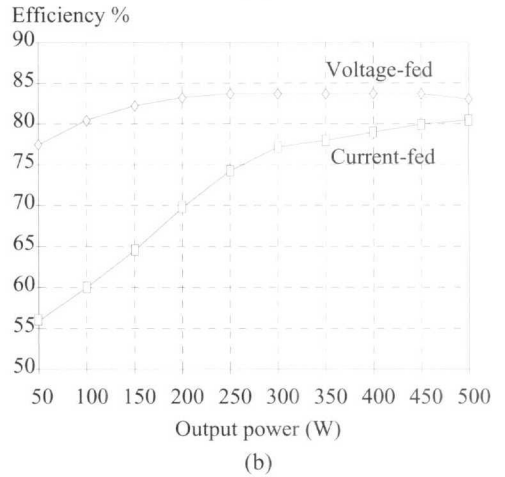


Fig. 11 Graphs of converter efficiency vs. output power with input voltage (a) V_{in} = 230 V (b) V_{in} = 100 V.

Fig. 9 shows typical input waveforms for both single-stage PWM full-bridge converters. It can be seen that the input current waveform of the current-fed converter is almost sinusoidal while that of the voltage-fed converter is not. The power factor of the voltage-fed converter was found to be between 0.8 and 0.95, and its input current satisfied EN61000-3-2 Class D standards as can be seen from Fig. 10. This shows the worst-case input current harmonic content for input voltages V_{in} = 100 Vrms and 230 Vrms. This occurs at the maximum load of P_o = 500 W.

Fig. 11 shows graphs of efficiency vs. output power for both converters. Fig. 11(a) shows efficiency curves for the case where V_{in} = 230 V. It can be seen that the current-fed converter is less efficient than the voltage-fed converter under light-load conditions, but more efficient under heavy-load conditions. The current-fed converter has low efficiency when operating with a light load because the losses caused by the RCD snubber at the dc bus are dominant with respect to the power delivered to the load. These losses become less significant as the load is increased.

Fig. 11(b) shows graphs of efficiency vs. output power when both converters operate with V_{in} = 100 V. It can be seen that the voltage-fed converter is more efficient than the current-fed converter throughout the load range. If the efficiency of both converters operating with V_{in} = 100 V is compared to the efficiency curves shown in Fig. 11(a),

it can be seen that in some cases the current-fed converter operates with greater efficiency when V_{in} = 230 V in some cases, but the voltage-fed converter is always more efficient when V_{in} = 100 V.

These results can be explained as follows: the current-fed converter will always operate with a primary-side dc-bus voltage approximately equal to the product of the regulated output voltage and the transformer turns ratio regardless of the input and line conditions. In the case of the experimental prototype, this voltage was about 380-390 V. For the same output load, the current-fed converter will always operate with a greater efficiency when V_{in} = 230 V than it will when V_{in} = 100 V because the amount of current circulating in the circuit is greater in the latter case. This greater current leads to increased conduction and switching losses than when V_{in} = 100 V.

Unlike the current-fed converter, the primary-side dc bus voltage of the voltage-fed converter will vary depending on the load and line conditions - especially the input line conditions. The dc bus voltage of the prototype voltage-fed converter was approximately equal to 175 V when the input voltage was V_{in} = 100 V and 375 V when V_{in} = 230 V, throughout most of the load range. Although the amount of current circulating in the converter is greater when V_{in} = 100 V than it is when V_{in} = 230 V, the dc bus voltage is considerably less and therefore so too are the switching losses, which are dependent on the square of the voltage across the converter switches before they are turned on. It is only under heavy-load conditions when the conduction losses caused by the greater amount of current circulating in the converter become more significant that the voltage-fed converter becomes less efficient than when V_{in} = 100 V. The voltage-fed converter operating with V_{in} = 100 V is more efficient than the current-fed converter operating with this voltage because of the lower switching losses caused by the lower dc bus voltage.

It should be noted that if both converters were designed to operate with a greater load range (i.e. with a maximum load of 1 kW instead of 500 W), then the RCD snubber implemented in the current-fed converter in the current-fed converter would need to be able to handle the increase in energy trapped in the transformer leakage inductance due to the greater load current. This, in turn, would mean that the RCD snubber would also need to dissipate a greater amount of energy, and that the efficiency curves for the converter operating at the greater load range would remain very similar. When V_{in} = 230 V, the voltage-fed converter would be more efficient than the current-fed converter under light-load conditions, but less efficient under heavy-load conditions, and the voltage-fed converter would always be more efficient then the current-fed converter when V_{in} = 100 V, except perhaps under near maximum load conditions.

The efficiency of the current-fed converter could be improved if a more sophisticated "non-dissipative" snubber was used at the dc bus, but this would add cost and complexity. Moreover, any improvement in efficiency would be modest as such a snubber generally tends to create a large amount of additional circulating current in the converter that leads to an increase in conduction and turn-off losses. As a result, the general efficiency characteristics of the two converters would remain the same, although the crossover point when the current-fed converter becomes more efficient than the voltage-fed converter could occur at a lighter load.

5. Conclusion

Two types of ac-dc single-stage PWM full-bridge converters were considered in this paper: current-fed converters and voltage-fed converters. Since the main motivation behind the implementation of single-stage converters is the reduction of cost and complexity, the simplest possible current-fed single-stage PWM full-bridge converter and the simplest possible voltage-fed single-stage PWM full-bridge converter were examined. The operation of both converters was explained, their properties were reviewed, and experimental results obtained from simple lab prototypes of both converters were presented, then compared and discussed.

It was seen that the current-fed converter, which required a primary-side dc bus RCD snubber to suppress bus voltage overshoot and ringing, was less efficient than

the voltage-fed converter under light-load conditions, but more efficient under heavy-load conditions when the input voltage was V_{in} = 230 V. It was also seen that the voltage-fed converter was always the more efficient converter throughout the load range when the input voltage was V_{in} = 100 V because it operated at a lower primary-side dc bus voltage and therefore with lower switching losses.

References

[1] M. J. Schutten, R. L. Steigerwald, and M. H. Kheraluwala, "Characterisitcs of load resonant converters operated in a high power factor mode," IEEE Trans. Power Elec., vol. 7, no. 2, pp. 304-314, Apr. 1992.

[2] H. Benqassmi, J.-P. Ferrieux, and J. Barbaroux, "Current source resonant converter in power factor correction," *IEEE PESC Conf. Rec*, 1997, pp. 378-384.

[3] J. G. Cho, C. Y. Jeong, J. W. Baek and G. H. Rim, "Novel zero-voltage-transition isolated PWM boost converter for single stage power factor corrector," *IEEE PESC Conf Rec.,* 1998, pp. 1023-1029.

[4] P. K. Jain, J. R. Espinoza, and N. A. Ismail, "A single-stage zero-voltage zero-current-switched full-bridge DC power supply with extended load power range," *IEEE Trans. on Ind. Elec.,* vol. 46, no. 2, pp. 261-270, Apr. 1999.

[5] L. Rosetto and S. Buso, "Single-phase ac/dc integrated PWM converter", in *IEEE INTELEC Conf. Rec.*, 2000, pp. 411-418.

[6] K. L. Fontoura et. al., "A pplication of the non-dissipative snubber in the ac/dc full-bridge converter and high power factor application", in *IEEE INTELEC Conf. Rec.*, 2000, pp. 665-669.

[7] C. Qiao and K. M. Smedley, "An isolated full-bridge boost converter with active soft-switching", in *IEEE PESC Conf. Rec.*, 2001, Vol. 2, pp. 896-903.

[8] G. Moschopoulos, "A simple ac-dc PWM full-bridge converter with integrated power factor correction," in *IEEE INTELEC Conf. Rec.* 2001, pp. 376-383.

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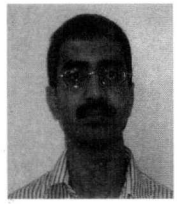

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