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A Study of AC-DC PWM Full-Bridge Integrated Converter Topologies

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ABSTRACT

Two AC-DC PWM full-bridge converters that can shape the input current to improve input power factor while performing dc-dc conversion are investigated in this paper Both converters are simple in that they are similar to the standard PWM full-bridge converter with a diode rectifier/LC low-pass filter input, and both can operate with a simple method of PWM control. In the paper, the operation of the converters is explained and their steady-state characteristics are discussed. The feasibility of the converters and their ability to meet EN61000-3-2 Class D standards for electrical equipment are shown with results obtained from experimental prototypes The performance of both converters in terms of dc bus voltage level, input power factor and efficiency is compared and discussed.

Key Words : AC-DC PWM full bridge converter, power factor correction

1. Introduction

Power converter manufacturers are being pressured by regulatory agencies to implement some form of power factor correction (PFC) in their products. The increasing use of electrical equipment such as computers, telecommunications systems, consumer electronics, etc by society threatens to increase the amount of harmonic pollution in the ac utility grid, and regulatory agency standards on current harmonic content such as EN61000-3-2 are being enforced to try to reduce the problem For conventional two-stage ac-dc converters with output isolation where an ac-dc rectifying stage and an isolated dc-dc conversion stage are used, this has meant replacing the traditional passive diode rectifier/LC filter input combination with a boost converter in the rectifying stage. The boost converter can shape the input line3-2, but an additional switching converter must be current so that it is more sinusoidal and with a harmonic content compliant with agency standards such as EN61000- implemented. and the cost complexity of the overall two-stage converter are therefore increased

Converters that integrate the PFC and dc-dc conversion functions in a single switching converter have been proposed to try to minimize these disadvantages [1]-[14]. Most of this research, however, has focused on low power, "integrated" forward converters, and there has been much less investigation done on higher power full-bridge type converters (≥ 500 W). Of the full-bridge integrated converters that have been previously proposed [8]-[14], most have at least one of the following major drawbacks: (i) They produce an output voltage with a large low frequency (120 Hz) ripple, which limits them to applications where a tightly regulated output voltage is not required. (ii) They do not have an energy storage capacitor across the dc bus, which causes high voltage overshoots and ringing to

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appear across the dc bus unless damped by a lossy snubber (iii) They do have an energy storage capacitor across the bus, but the voltage across this capacitor is excessive (i e > 500-600 V) (iv) They are complex and require the addition of auxiliary transformers and extra components

PWM full-bridge converters that can operate with integrated PFC and satisfy the EN61000-3-2 Class D standards for electrical equipment, but without the above disadvantages have been proposed by the authors and studied in detail in [15] and [16] Both converters are simple in that they are similar to the standard PWM full-bridge converter with a diode rectifier/LC low-pass filter input, and both can operate with a simple method of PWM control In the paper, the operation of the converters is explained and their steady-state characteristics are discussed The feasibility of the converters and their ability to meet EN61000-3-2 Class D standards for electrical equipment are shown with results obtained from experimental prototypes The performance of both converters in terms of dc bus voltage level, input power factor and efficiency is compared and discussed

2. Converter Operation

The two converters, which will henceforth be referred to as Converter A and Converter B in this paper, are shown in Fig 1 and Fig. 2 respectively. Converter A, is representative of typical integrated forward and full-bridge converters where the number of energy-transfer modes in a single switching cycle is matched by the number of times energy from the input inductor is transferred to the energy storage capacitor. Converter B is a simplified version of Converter A and has the property of having a lower number of times in a switching cycle that energy is transferred from the input inductor to the energy storage capacitor This is a property that is possible only in full-bridge type integrated converters and not in forward-type integrated converters, and can result in a lower dc bus voltage V_{Cb} than that found in other integrated converters The main difference between these converters and the conventional PWM full-bridge converter with a diode rectifier/LC filter input is that the input inductor, L_{in}, is connected to both bottom converter switches in the case of Converter A and it is connected to a single bottom switch in the case for Converter B This allows the bottom

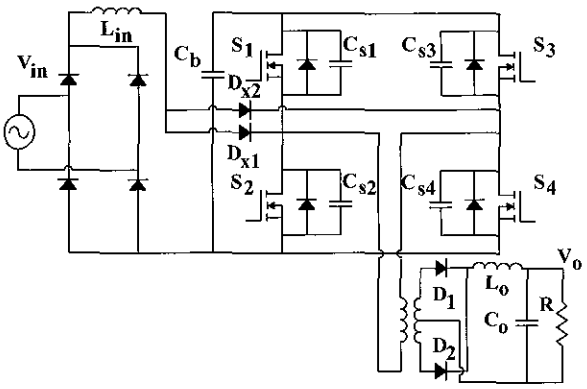

Fig 1 Integrated PWM full-bridge Converter A

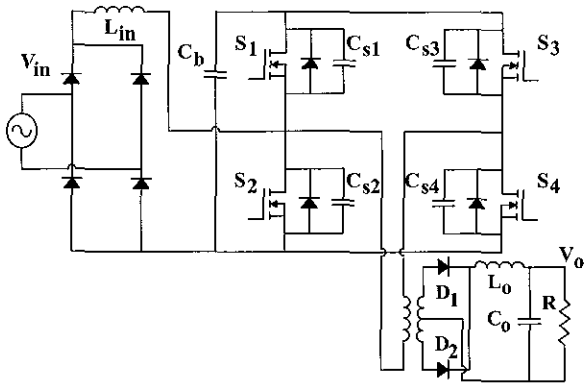

Fig 2 Integrated PWM full-bridge Converter B

switch(es) to shape the input current while the converter is performing dc-dc conversion in a way that is similar to that of a standard full-bridge converter In order for this to happen, however, a different PWM technique than the standard phase-shift control technique typically used in a full-bridge converter must be used In the standard phase-shift PWM technique, the gating signals have the same duration and the control is performed by shifting the gatings signals of the switches in one converter leg with respect to those of the other leg. For Converters A and B, the gating signals of the switches in a converter leg are asymmetrical with the bottom switch having a pulse width of $DT_{SW}/2$ (where D is the converter duty cycle and T_{SW} is the switching period) in order to perform the input current shaping.

The converter is in an energy-transfer mode and energy is transferred from the dc bus capacitor on the primary side to the output whenever a pair of diagonally opposed switches are on It is in a freewheeling mode whenever both bottom switches are off. In the case of Converter A,

energy stored in L_{in} is transferred to C_b whenever the converter is in a freewheeling mode. In the case of Converter B, the transfer of energy from L_{in} to C_b may occur only after every other freewheeling mode, depending on whether the instantaneous input current is larger or smaller than the transformer primary current

Converters A and B can operate in any one of several possible combinations of operating modes. The output section of the converter can operate in either the discontinuous conduction mode (DCM) or the continuous conduction mode (CCM) The input section can operate in DCM, CCM, or a semi-continuous conduction mode SCM, which is a combination of DCM and CCM Regardless of the combination of input and output section modes, both converters pass through several distinct intervals of operation during a single steady-state switching cycle The operating intervals for Converter A are as follows with the case when the instantaneous input current is greater than the instantaneous transformer primary current being presented first, then the case when the input current is the smaller current

2.1 Input current (I_{in}) is greater than the transformer primary current (I_p)

The primary-side equivalent circuits and the operating waveforms of the converter for this case are given in Figs. 3 and 4 respectively

(a) Interval 1 [t_0 - t_1], (Fig 3(a)):

Switches S_1 and S_4 are on at $t = t_0$, and the voltage across the transformer primary is equal to the voltage across C_b, V_{bus}. The input current rises as power is being transferred to the load. Its value at t_1 is

$$I_{in,k(t1)} = I_{in,k(t0)} + \frac{V_{in,rec,k} D_k T_{sw}}{2L_{in}} \qquad (1)$$

where, $I_{in,k(t0)}$ is the original input current before the start of Interval 1 (this is zero if the input current is discontinuous), $V_{in,rec,k}$ is the diode bridge rectifier voltage during Interval 1, D_k is the duty-cycle, and T_{sw} is the switching period of the full-bridge converter The current flowing through S_1 is $I_{p,k}$, the transformer primary current (the sum of the reflected secondary current and the magnetizing current, assumed here to be negligible) and

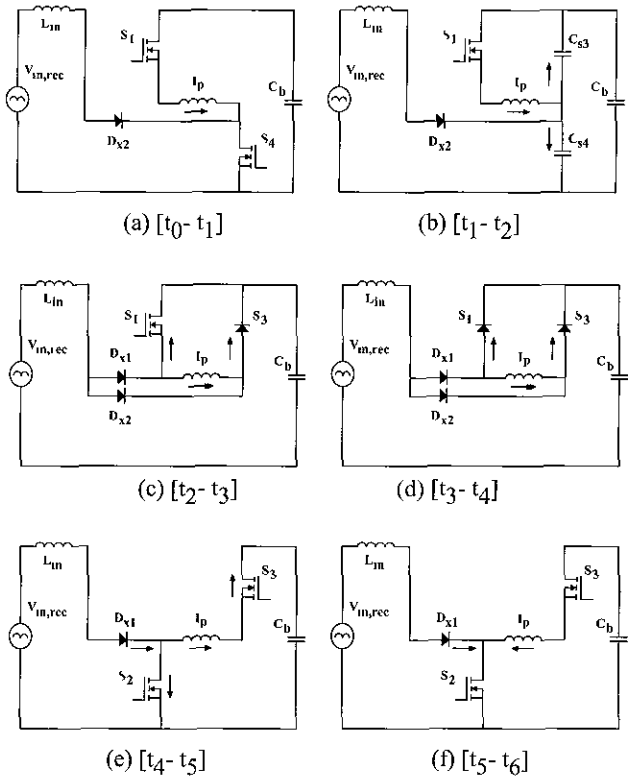

Fig 3 Operating intervals for a half-switching cycle for Convert-er A when the instantaneous input current is greater than the instantaneous transformer primary current

the current flowing through S_4 is

$$I_{S4,k} = I_{in,k} + I_{p,k} \qquad (2)$$

(b) Interval 2 [t_1 - t_2], (Fig. 3(b)):

Switch S_4 is turned off at $t = t_1$ and capacitors C_{s3} and C_{s4} discharge to zero and charge to V_{bus} respectively Energy from the input inductor L_{in}, the output inductor L_o, and the transformer leakage inductance L_{lk} is available for this task

(c) Interval 3 [t_2 - t_3], (Fig. 3(c)):

The converter is in a freewheeling mode as the voltage across the transformer primary is zero The current flowing through D_{x1} is $I_{p,k}$. The remaining current, $I_{in,k}$-$I_{p,k}$, is divided between S_1 and D_{x2}, with the voltage drop across S_1 clamped by D_{x2} The current flowing into energy-storage capacitor C_b is

$$I_{Cb} = I_{Sl,k} + I_{Ds3,k} = I_{in,k} \qquad (3)$$

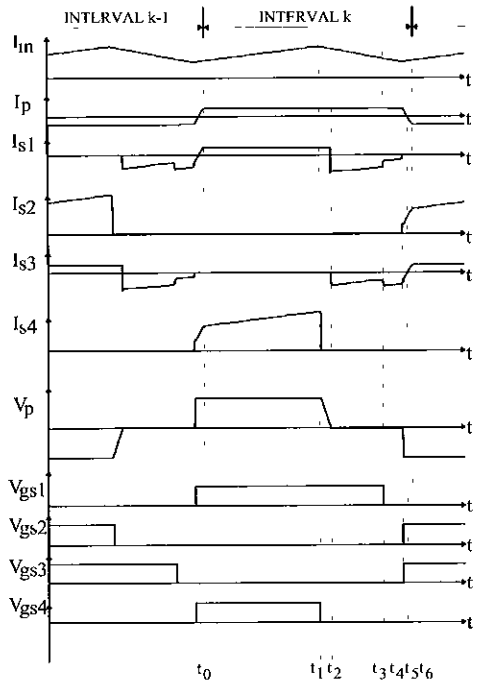

Fig 4 Typical waveforms for Converter A when the instantaneous input current is greater than the instantaneous transformer primary current

The input current falls because the voltage across the input inductor is equal to the difference between the input voltage and V_{bus} (which is larger than the input voltage). The input current at the end of Interval 3, t_3, is

$$I_{in,k(t3)} = I_{in,k(t2)} - \frac{(V_{bus} - V_{in,rec,k})d_k T_s}{2L_{in}} \quad (4)$$

where, $I_{in,k(t2)}$ is the input current value at the beginning of Interval 3 and $d_k T_s$ is the duration of the interval. $I_{in,k} = 0$ and $D_k + d_k < 1$ when the input current is discontinuous,

(d) Interval 4 [t_3 - t_4], (Fig. 3(d)):

Switch S_1 is turned off at $t = t_3$. The converter is still in a freewheeling mode, but the distribution of the current between the anti-parallel diode of S_1 and D_{x2} is different

(e) Interval 5 [t_4 - t_5], (Fig. 3(e)):

Switch S_2 is turned on at $t = t_4$, and the current that was flowing through S_1 and D_{x2} now flows through this switch The current flowing through S_2 during this interval is

$$I_{S2,k} = I_{in,k} - (I_{p,k} - \frac{V_{bus}(t - t_4)}{L_{lk}}) \quad (5)$$

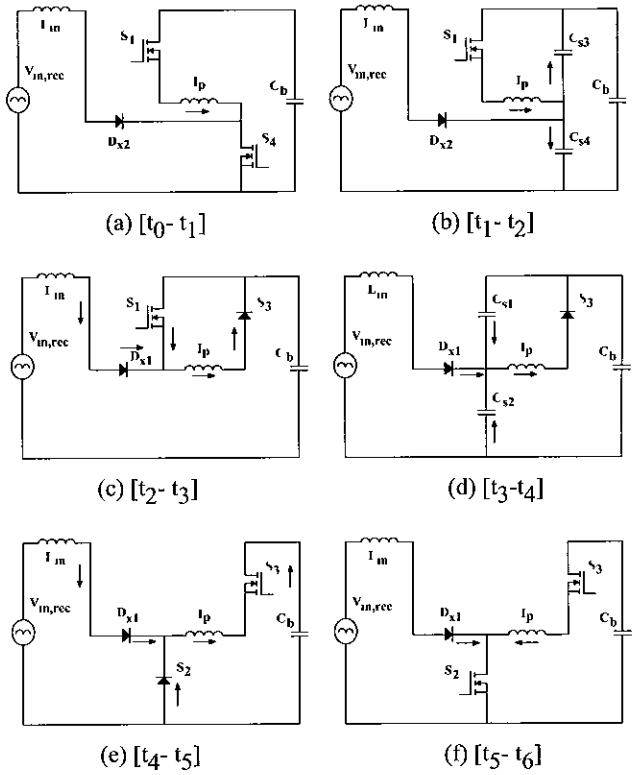

Fig 5 Operating intervals for a half-switching cycle for Converter A when the instantaneous input current is less than the instantaneous transformer primary current

and the current flowing through the anti-parallel diode of S_3 decreases, reaching zero at $t = t_5$.

(f) Interval 6 [t_5- t_6], (Fig. 3(f)):

At $t = t_5$, the transformer primary current begins to flow in the opposite direction and continues to rise until $t = t_6$ After $t = t_6$, the converter is in the same state as it was after $t = t_0$, except that switches S_2 and S_3 are on instead of S_1 and S_4.

2.2 Input current (I_{in}) is less than the transformer primary current (I_p)

The primary-side equivalent circuits and the operating waveforms of the converter for this case are given in Fig 5 and Fig. 6 respectively. The operating intervals during a half switching cycle when the instantaneous input current, $I_{in,k}$, is less than the transformer primary current, $I_{p,k}$, are very similar to those when $I_{in,k} > I_{p,k}$ with one exception The flow of current in the full-bridge switches when the converter is in a freewheeling mode is different. During Intervals 3-5 (Figs. 5(c)-(e)), the difference between

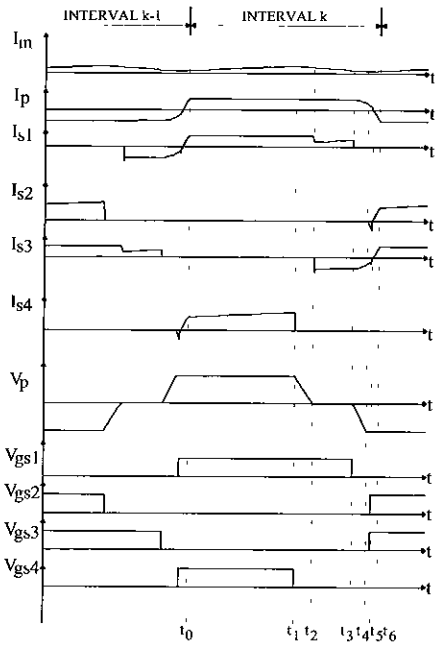

Fig 6 Typical waveforms for Converter A when the instantaneous input current is greater than the instantaneous transformer primary current

the transformer primary current and the input current flows through S_1 then discharges and charges C_{s1} and C_{s2} respectively after S_1 is turned off. This current eventually flows through the anti-parallel diode of S_2. Regardless of how current flows in the full-bridge during a freewheeling mode, the flow of input current through the converter remains the same when $I_{in,k} >$ or $< I_{p,k}$.

2.3 Operating intervals for Converter B

The operating intervals of Converter B are a combination of those of Converter A for one leg, and those for a conventional PWM full-bridge converter for the other because Converter B has input inductor L_{in} attached to only one of its legs. These intervals will therefore be not be discussed in detail except to explain the circuit operation during the particular intervals shown in Fig 7. In Fig 7(a), the converter is shown to be operating with switches S_2 and S_3 on. In this case, the converter is in an energy-transfer mode as the dc bus voltage is placed across the transformer primary and energy from capacitor C_b is transfer to the output. While this is occurring, the full rectified input voltage is placed across L_{in}, and the input current will rise. In Fig. 7(b) the converter is shown to operate with switches S_1 and S_4 on.

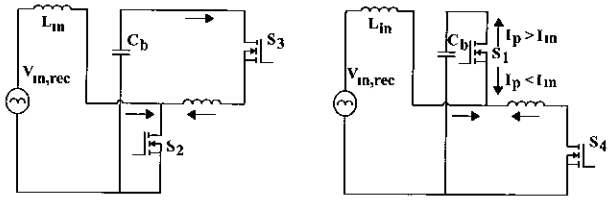

Fig 7 Energy transfer mode operating intervals for Converter B

This is also an energy- transfer mode, but the net amount of energy transfer is dependent on whether the instantaneous input current $I_{in,k}$ is greater or less than the instantaneous transformer primary current $I_{p,k}$. If $I_{in,k}$ is greater than $I_{p,k}$, then the difference between the two current will flow into capacitor C_b If $I_{in,k}$ is less than $I_{p,k}$ then the difference between the two current will flow out of C_b. If the $I_{in,k}$ is zero, which may be the case if the input current is discontinuous, then the converter operates in the same manner as a standard PWM full-bridge converter.

3. Steady-State Characteristics

An analysis of the characteristics of Converters A and B was performed in [15] and [16]. The key parameter that was derived in both cases was the dc bus/storage-capacitor voltage V_{Cb} because it is only when this is determined that the values for the other parameters can be determined. Special efforts have to be made to determine V_{Cb} because is not solely regulated by an independent ac-dc boost PFC stage like a conventional two-stage converter, and therefore cannot be kept constant. This voltage was derived by noting that an energy equilibrium must exist for storage-capacitor C_b 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 C_b provides to the output, so that the net dc current flowing in and out of C_b must be zero during a half-line cycle

From the analysis of the converters, the following general characteristics were noted

1) When output current I_o and input current I_{in} are both discontinuous, V_{Cb} remains constant regardless of what the load is. It is dependent on the ratio of L_{in}/L_o, and on the transformer turns ratio N
2) When I_o and I_{in} are both continuous, V_{Cb} again remains almost constant regardless of what the load is

It is dependent mainly on the transformer turns ratio N, and slightly on the ratio of L_{in}/L_o This is particularly true if I_{in} and I_o are deep in continuous current mode CCM.

3) The voltage across capacitor C_b, V_{Cb} will increase when the load decreases if I_{in} is discontinuous and output current I_o is continuous.
4) V_{Cb} decreases as L_{in} is increased and the other component values are kept constant, especially when I_{in} is fully discontinuous
5) V_{Cb} decreases as L_o is decreased and the other component values are kept constant, especially when I_{in} is fully discontinuous
6) V_{Cb} decreases as transformer turns ratio $N = N_1/N_2$ is decreased and the other component values are kept constant.

Several of these properties can be seen in the graph shown in Fig. 8, which is a graph of dc bus voltage V_{Cb} vs output power for various combinations of transformer turns ratio N, input inductor L_{in}, and output inductor L_o for Converter B For example, it can be seen that when L_o = 20 μH and L_{in} = 160 μH and N is changed from 2 5 to 3.5, the dc bus voltage will in fact be increased Also as an example, it can also be seen that the curve for N = 2.5, L_o = 20 μH and L_{in} = 50 μH is more constant under light load conditions than the other curves due to the fact that L_{in} is smaller and both input and output current are in discontinuous current mode (DCM)

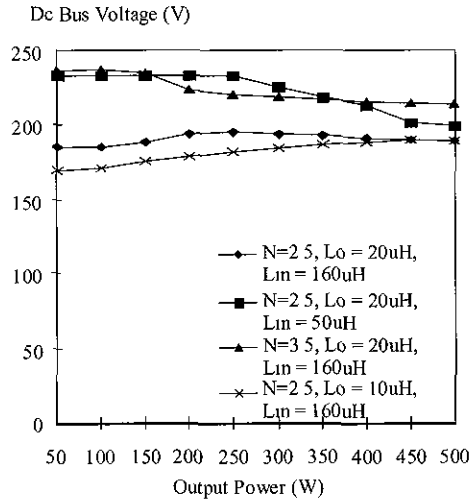

Fig 8 Dc bus voltage vs output power for V_{in} = 100 Vrms and V_o = 48 V for Converter B

4. Experimental Results

In order to compare the performance of Converters A and B, an experimental prototype was built to operate under the following conditions

Input voltage V_{in} = 85 – 265 Vrms
Output voltage V_o = 48 V
Maximum output power P_o = 500 W
Maximum dc bus voltage V_{Cb} < 450 V
Switching frequency F_{sw} = 50 kHz

Three different sets of results were obtained· The first set was for the case of Converter A designed to operate across the full input voltage range with L_{in} = 203 μH and L_o = 4.5 μH (Case 1)

The second set was for the case of Converter B designed to operate across the full input voltage range with L_{in} = 140 μH and L_o = 32 μH (Case 2)

The third case was for the case of Converter A designed to operate with the same set of values as those used for Case 2 except with the input voltage range restricted to V_{in} = 85 – 132 Vrms (Case 3) A common value of transformer turns ratio of N = 2.5 was used for all three cases in order to facilitate the investigation

Figs 9(a) and (b) show the input current waveforms for Converter B in Case 2 when it is operating with P_o = 500 W and with V_{in} = 230 Vrms and 100 Vrms respectively The input current waveforms for the other two cases are very similar

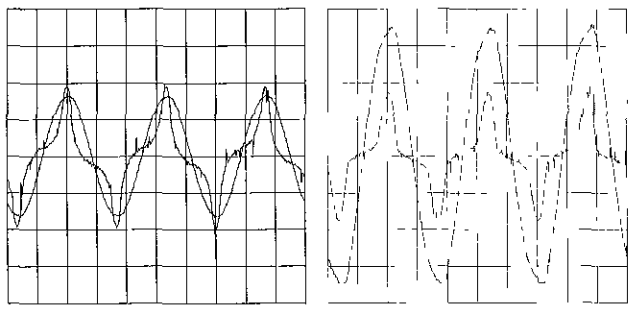

Fig 9 Input voltage and current waveforms for Converter B operating at P_o = 500 W, (a) V_{in} = 230 Vrms, scale V 200 V/div , I 4 A/div , t 5ms/div , (b) V_{in} = 100 Vrms, scale V 40 V/div , I 10 A/div , t 5ms/div

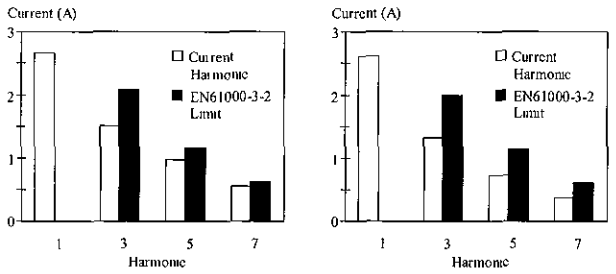

Fig 10 Input current harmonic content at V_{in} = 230 Vrms and P_o = 500 W; (a) Case 1 (b) Case 2

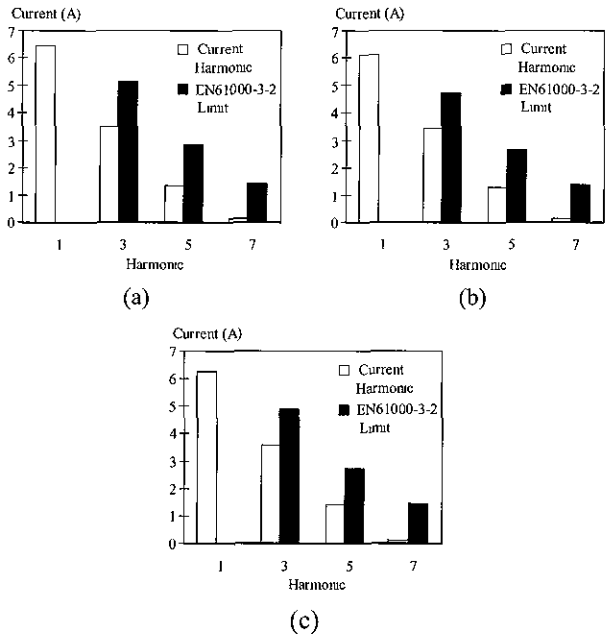

Fig 11 Input current harmonic content at V_{in} = 230 Vrms and P_o = 500 W, (a) Case 1 (b) Case 2 (c) Case 3

Figs. 10 and 11 show the worst-case input current harmonic content for V_{in} = 230 Vrms and 100 Vrms for all three cases This will occur under full-load conditions at P_o = 500 W for all three cases Fig 10 shows the harmonic content for Cases 1 and 2 when V_{in} = 230 Vrms and Fig. 11 shows the harmonic content for Cases 1, 2, and 3 when V_{in} = 100 Vrms. Although the EN61000-3-2 standard for Class D electrical equipment is valid up to an input power of 600 W (after which Class A standards apply), and the input power in some of the cases exceeded the 600 W level, the Class D standard was used since the maximum input power is close to the 600 W level and it is more stringent than the Class A. Since the Class D limits

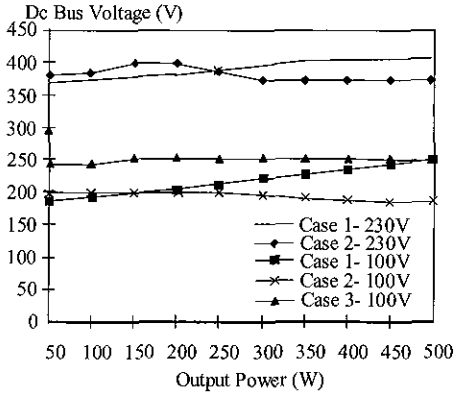

Fig 12 Experimental dc bus voltage vs output power

are satisfied for the worst-case current in all three cases under investigation, then so too will the limits be met under lighter load conditions

Figs. 12, 13, and 14 show graphs of dc bus voltage V_{Cb}, input power factor, and converter efficiency vs. load for various values of V_{in}, ranging from 100 Vrms to 230 Vrms (which was the maximum input voltage available to investigate Cases 1 and 2) It can be seen that the dc bus voltage can be kept at a maximum of about 400 V with a 230 V input (and can be kept at below 450 V for a 265 V input), that the input power factor can range from approximately 0.8 to 0 95, and that a maximum converter efficiency of approximately 85% can be achieved

The characteristics of Converter A and B operating in the three cases described above and somewhat different than those found in a standard two-stage converter system with a boost converter front end supplying power to a full-bridge dc-dc converter These differences come from the fact that the dc bus voltage in an integrated converter is not constant since there is no independent means of controlling this voltage as there is in a two-stage converter. The dc bus voltage will vary depending on operating condition.

When looking at Figs 12 –14 and comparing all three cases, it can be seen that Converter B (Case 2) generally has the better performance Most of the improvement in performance is a result of the fact that Converter B can operate with a lower dc bus voltage than Converter A because energy from the input inductor is pumped less often into the energy storage capacitor for the same operating point. In order to maintain the dc bus voltage of Converter A at a level less than 450 V for a high line

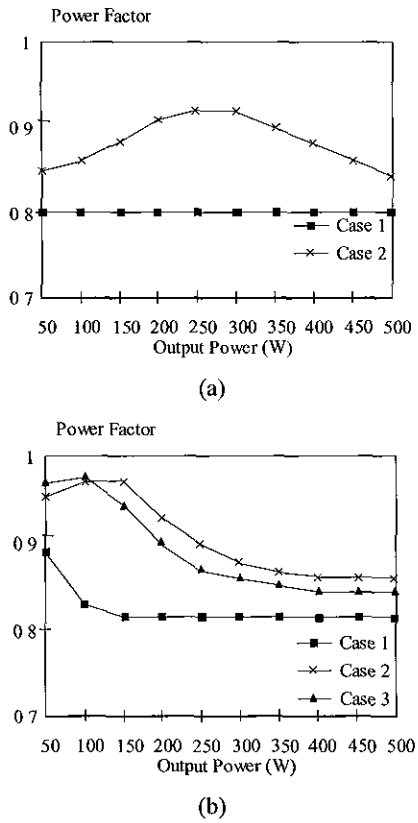

Fig 13 Experimental input power factor vs output power, (a) input voltage V_{in} = 230 Vrms, (b) input voltage V_{in} = 100 Vrms

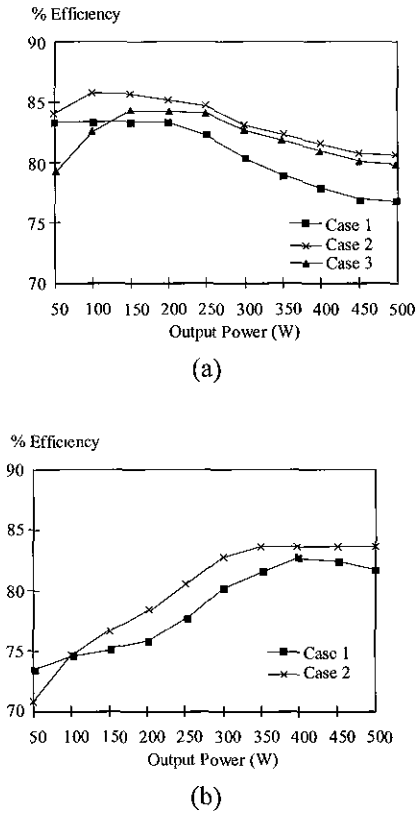

Fig 14 Experimental efficiency vs output power, (a) input voltage V_{in} = 230 Vrms, (b) input voltage V_{in} = 100 Vrms

input, the output inductor has had to have been made fairly small to produce a highly discontinuous output current The output current is much more continuous for Converter B

Converter B has a higher efficiency than Converter A operating both in Case 1 and in Case 3 mainly because it can be more easily designed to have a lower dc bus voltage than Converter A Since Converters A and B were implemented experimentally without soft-switching, a lower dc bus voltage would result in less voltage being placed across the converter switches and therefore fewer switching losses This phenomenon also explains the fact that both Converters A and B exhibit a higher light load efficiency at low line input voltage when the dc bus voltage is lower than at high line input voltage. Converter B can also operate with a higher input power factor than Converter A when it is operating in Case 1 or in Case 3 In the case of Case 1, Converter A is operating with a larger input inductor that Converter B is in Case 2 (L_{in} =203 μH vs L_{in} = 140 μH).

Since Converter B is operating with a smaller input inductor, its input current is much more likely to follow a sinusoidal envelope than is Converter A, therefore it will operate with a higher input power factor When Converter A is operating as it is in Case 3 with the same input inductor as Converter B in Case 2, then Converter B will operate with a higher input power factor for the following reason Since Converter B can be made to operate with a lower dc bus voltage for a particular operating point, it will operate with a higher duty cycle than Converter A will for the same duty cycle D. If output voltage V_o = $V_{Cb}D/N$ then D will be higher for Converter B than it will be for Converter A for the same V_o Since the shape of the input current for an integrated converter is determined by the converter duty-cycle, operating with a larger duty-cycle means that the input current will start to rise sooner in the line cycle, making its overall shape more spread out and therefore more sinusoidal and/or making its fundamental component more in phase with the input voltage The latter situation can be seen in Figs 10, 11 and

13 for the graphs of the various cases when P_O = 500 W where there is little variation in input harmonic content among the various cases but there is variation in power factor.

5. Conclusion

Two PWM full-bridge converters that simultaneously perform input power factor correction and dc-dc conversion were examined in this paper Both converters have a simple topology as they are very similar to the standard PWM full-bridge with a diode rectifier/LC filter front-end except for some slight modifications. The first converter, Converter A, is representative of typical integrated forward and full-bridge converters where the number of energy-transfer modes in a single switching cycle is matched by the number of times energy from the input inductor is transferred to the energy storage capacitor. The second converter, Converter B, is a simplified version of Converter A and has the property of having a lower number of times in a switching cycle that energy is transferred from the input inductor to the energy storage capacitor

In the paper, the operation of both converters was explained and their general steady-state characteristics were discussed. Both converters were implemented with an experimental prototype. It was shown that both converters are feasible, and that both can be designed to meet EN61000-3-2 Class D standards for electrical equipment while maintaining a dc voltage of less than 450 V, an input power factor ranging from 0.8 to 0.95, and a maximum efficiency of approximately 85% Converter B was found to have a superior overall performance than Converter A, mainly because of its ability to operate with lower dc bus voltages for the same operating points

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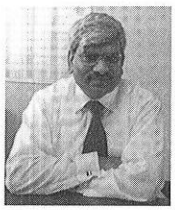

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