전기자동차 응용을 위한 6.6KW 저가형 브리지 없는 인터리빙 방식의 역률보상 컨버터

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A 6.6kW Low Cost Interleaved Bridgeless PFC Converter for Electric Vehicle Charger Application

ABSTRACT

In this paper, a low cost bridgeless interleaved power factor correction topology for electric vehicle charger application is proposed. With the proposed topology the number of switches, inductors, current sensors and associated circuits can be reduced, thereby reducing the cost of the system as compared to the conventional bridgeless PFC circuit. The reduced input current ripple by the proposed interleaved topology makes it suitable for high power applications such as electric vehicle chargers since it can reduce the size of the inductor core and the Electro Magnetic Interference (EMI) problem. In the proposed topology only one current sensor is required. All the boost inductor currents can be reconstructed by sampling the output current and used to control the input current. Therefore the typical problem caused by the unequal current gain of each current sensor inherently does not exist in the proposed topology. In addition the current sharing between converters can be achieved more accurately and the high frequency distortion is decreased. The performance of the proposed converter is verified by the experimental results with a prototype of 6.6kW bridgeless interleaved PFC circuit.

Index Terms – digital control, high power PFC, single current sensor, interleaved bridgeless PFC

1. Introduction

In conventional PFC, the input bridge diode contributes up to 37% of total losses. In order to improve the efficiency of PFC, the bridgeless PFC (BPFC) converters without an input rectifier are preferred. Interleaved Bridgeless PFC (IBPFC) topology uses two PFCs with interleaved configuration. With high efficiency and low current ripple, IBPFC is highly suitable for high power application such as electric vehicle charger. However, the high efficiency can only be achieved at the cost of low device utilization and complex feedback circuitry. Consequently, BIPFC suffers from high cost and bulky volume.

IBPFC topology consists of two bridgeless PFCs (BPFC) with interleaved configuration. In each half of line cycle, two legs perform PWM operation while the other two work as rectifiers. The return current paths for the low frequency input current through inductors and body diodes cause extra losses and low utilization of devices. In [1], the author merged two inductors and two MOSFETs by using four extra diodes. However, it comes with some limitations such as higher conduction loss, working in critical conduction mode which is not suitable for high power application. In [2], an effective method is introduced to reduce the size of inductors of bridgeless PFC with integrated magnetics. However, it reduces the efficiency and only applies for semi-bridgless PFC with clamp diodes.

Other challenge for IBPFC is the difficulty in current feedback circuitry. In IBPFC, four current transformers are typically used as a low cost solution to indirectly sense four inductor currents through the MOSFET currents. The multiple current sensor technique will result in not only high cost and large volume of the converter but also the high frequency distortion caused by tolerance of current sensors. Some authors developed the sensorless control algorithms. However, the reliability of the inductor current estimation highly depends on the accuracy of the model parameters. With typical swing inductor design in PFC, the inductance may vary widely during the half of line cycle. Consequently, the waveforms are highly distorted in this method.

In this paper, a 6.6kW low cost IBPFC with single current sensor is proposed. By employing two slow diodes, the number of inductors and MOSFETs can be reduced. The average value of the inductor current can be reconstructed by using only one current sensor at the output of converter with digital sampling strategy. Based on the reconstructed currents, the conventional digital control scheme with current sharing strategy can be applied. A 6.6 kW PFC for level 2 on-board charger is developed to prove the validity of the proposed topology.

2. Proposed Bridgeless Interleaved PFC with Single Current Sensor

The proposed IBPFC topology is shown in Fig. 1. D_{a1} and D_{a2} are two additional diodes. Due to their function of blocking the low frequency circulating current caused by the input voltage source, low cost, slow diodes can be used. L_2 and L_3 are integrated in the same core, which reduces the volume of the circuit. Comparison of proposed topology with the conventional counterparts is shown in Table 1.

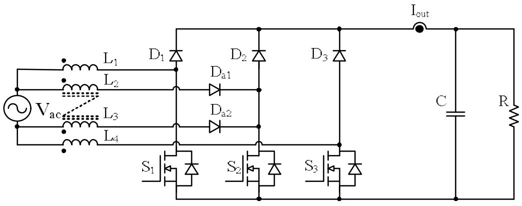

Fig. 1 Proposed Interleaved Bridgeless PFC topology with single current sensor

Table. 1 Comparison of PFC topologies

Component	IBPFC	Proposed IBPFC	2-phase Interleaved PFC
MOSFET	4	3	2
Fast Diode	4	3	2
Slow Diode	None	2	4
Boost Inductor	4	3	2
Current Sensor	4	1	2
Efficiency	Best	Good	Low
Cost	Highest	High	Low

For the simplicity of the circuit, S_1 and S_3 are driven by one PWM signal. The PWM signal of S_2 is 180^0 out of phase with the first PWM channel. Assuming that the input voltage is positive, the operation of the proposed converter can be explained by the key waveforms of converter when the duty < 0.5 (Fig.2a) and duty > 0.5 (Fig.2b), respectively. When the duty < 0.5, energized intervals of inductor L_1 and L_2 are separated as shown in the interval 1 (t_0~t_1) and 3 (t_2~t_3). In the interval 2 (t_1~t_2) L_1 releases its energy to the output. L_2 delivers its energy to the output in the interval 4 (t_3~t_4). The output current equals to the input current of L_1 or L_2 in the interval 2 or 4, respectively.

Similarly, when the duty > 0.5, the L_1 and L_2 work with overlap energized intervals. In these overlap intervals 1 and 3, all switches are turned on, thus the output current equals zero. In the other intervals 2(t_1~t_2) and 4(t_3~t_4), inductor L_2 or L_1 delivers its energy to the output. Thus the output current will equals to I_{L2} in the interval 2 or I_{L1} in the interval 4, respectively.

By sampling the output current at the center of interval 2 and 4, the average value of input currents can be calculated for the control of the system.

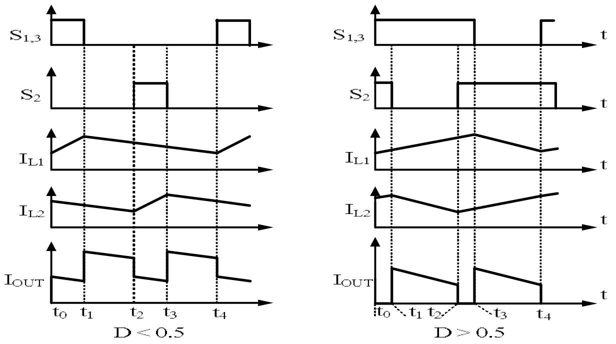

Fig. 2 Key waveforms in the BIPFC with the duty D < 0.5 and duty D > 0.5

In order to guarantee the operation of the proposed topology, the system needs to be designed to work in CCM mode with the inductor calculated by Equ. (1). The output ripple is limited to 5% by the capacitance calculation shown in Equ. (2). The specification of the proposed IBPFC is shown in Table 2.

Table 2 Specification of proposed 6.6 kW BIPFC.

Input voltage	V_{in}	220 V
Input frequency	f_{line}	60 Hz
Output voltage	V_{out}	400 V
Rated power	P_{out}	6.6kW
Switching frequency	f_s	70 kHz
Output capacitor	C_{out}	3400 µF
Boost inductor	L_{boost}	120 µH

$$L_{boost} = \frac{V_{out} \times \sqrt{2} \times D_{LL\min}}{\Delta I_L \times f_s} \qquad (1)$$

$$C_{out} = \frac{2 \times P_{out}}{\eta} \frac{1}{V_{out} \times 2\pi \times 2 f_{line} \times \Delta V_{ripple}} \qquad (2)$$

3. Digital control and current sharing strategy

The digital control strategy for proposed topology is shown in the Fig. 3.

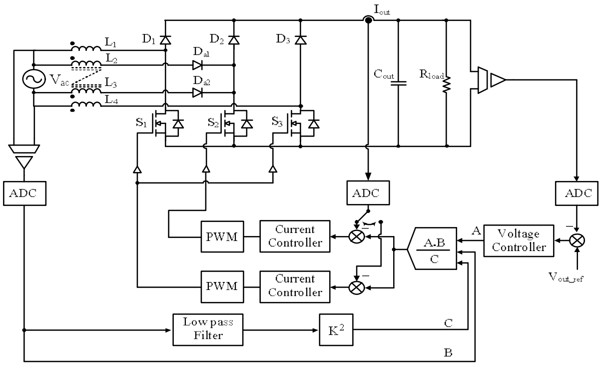

Fig. 3 Control strategy for proposed bridgeless PFC

One outer voltage loop with low bandwidth is designed to regulate the output voltage. Meanwhile, two inners current loops with high bandwidth help the input current tracks the input voltage. Each current controller is sequentially updated within a switching period. Since the current controllers share the common reference, the average value of input currents of all boost leg can be balanced.

4. Experimental results

A 6.6kW proposed IBPFC with specification in Table 2 is designed. The experiment results are shown in Fig. 4 to Fig.6. The key waveforms in Fig. 4 show the proper operation of proposed topology with input sinusoidal current following the input voltage. The output voltage is regulated at 400V.

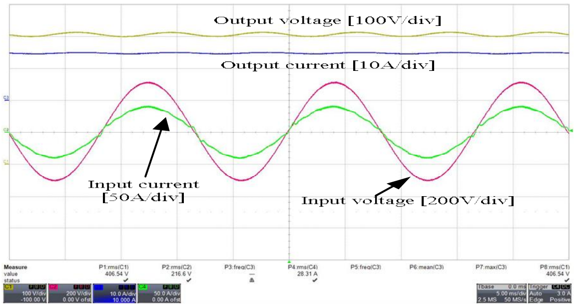

Fig. 4 Key waveforms with V_{in} = 220V, Pout = 6.6 kW

The efficiency and power factor profiles compared with conventional IBPFC are showed in Fig.5 and Fig.6. In Fig.5, the highest efficiency of proposed topology is 98.4% at 240V input voltage. It is slightly lower than conventional IBPFC efficiency (98.7%). The power factor profiles in Fig. 6 show high value and similarity between proposed IBPFC and conventional counterpart.

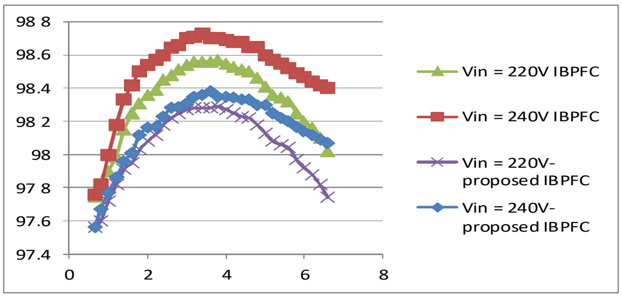

Fig. 5 Efficiency profile of proposed IBPFC

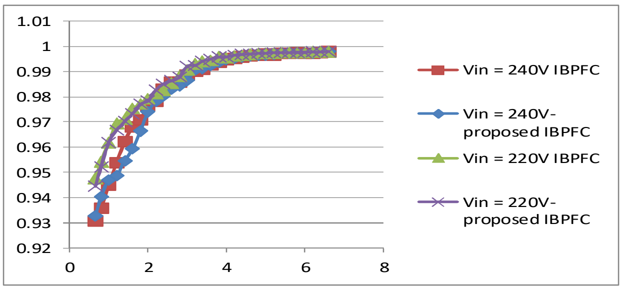

Fig. 6 Power factor profile of the proposed IBPFC

5. Conclusion

In this paper, a 6.6kW low cost IBPFC is proposed. The current sampling technique and digital control scheme with a single current sensor are proposed. The reduction in number of inductors, switches, and current sensors help reduce cost and volume of system. The multi current sensor issue does not exist, thus the performance of controller is improved. These features make the proposed IBPFC suitable for high power applications such as level 2 on-board charger of electric vehicle.

References

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