Implementation of Four-Phase Interleaved Balance Charger for Series-Connected Batteries with Power Factor Correction

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Abstract. A four-phase interleaved balance charger for series-connected batteries with power factor correction is proposed in this dissertation. In the two phases of two buckboost converters, the rectified ac power is firstly converted to a dc link capacitor. In the other two phases of two flyback converters, the rectified ac power is directly converted to charge the corresponding batteries. Additionally, the energy on the leakage inductance of flyback converter is bypassed to the dc link capacitor. Then, a dual-output balance charging circuit is connected to the dc link to deliver the dc link power to charge two batteries in the series-connected batteries module. The constant-current/constant-voltage charging strategy is adopted.

Finally, a prototype of the proposed charger with rated power 500 W is constructed. From the experimental results, the performance and validity of the proposed topology are verified. Compared to the conventional topology with passive RCD snubber, the efficiency of the proposed topology is improved about 3% and the voltage spike on the active switch is also reduced. The efficiency of the proposed charger is at least 83.6 % within the CC/CV charging progress.

1. Introduction

In view of vehicle batteries' demand for charging power, the charger must have the function of PFC to meet the standard of electric power utilization and reduce the power loss caused by the virtual work current [1]-[2]. Based on many techniques of single-phase AC PFC, input current is operated in DCM. Because its peak current changes in proportion to the input AC current to achieve the effect of PFC, it's not necessary to perform the AC exchange feedback control on input current. Therefore, the use of PFC techniques of DCM can simplify the circuit controller, reducing the burden of micro-control chip. However, when operated in DCM, the current peak is much larger than in continuous conduction mode, and it is likely to cause more severe switching loss and conduction loss at higher power conversion. It is necessary to add a filter circuit on the input side of supply mains, to filter out the high-frequency current in discontinuous current and reduce the pollution of the mains power [3]-[5].

2. Circuit architecture for homogeneously charging four-phase interlaced batteries in series

The system architecture of the four phase interlaced homogeneous charger with PFC developed for this paper is shown in Fig. 1. The first part consists of a LC filter and a bridge rectifier. The filter is used to filter out the high-frequency switching ripple in input current. The second part consists of two flyback converters, each of which charge a battery respectively. The third part consists of two buck/boost converters. The fourth part is a double-output homogeneous charging circuit, charging the other two batteries of the batteries in series. The micro-controller is used as the control center of the homogeneous charging system, input the five different voltage feedback and four different current feedback, and output

seven gate signals.

The circuit architecture of multi-output homogeneous charger is shown in Fig. 2. The input is 110V AC power, passing through the LC filter, a bridge rectifier, a four-phase interlaced PFC circuit and a double output homogeneous charging circuit, and then supply power to four batteries in series.

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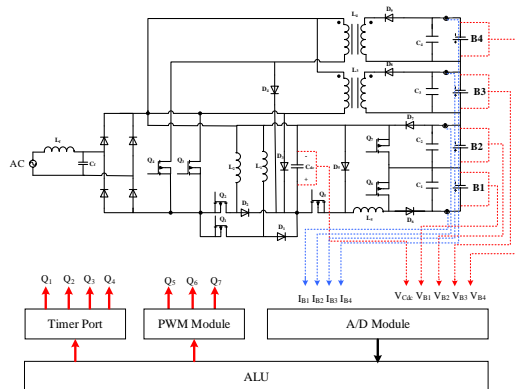
**Fig. 1** Topology and digital control scheme of the proposed converter.
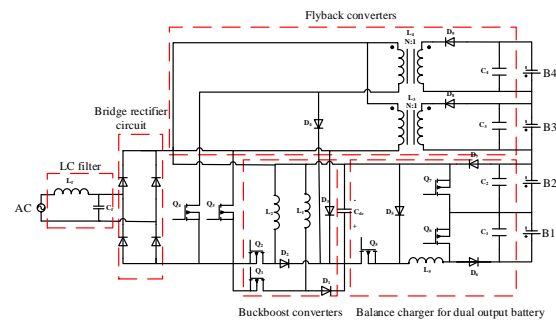
Fig. 2 Topology of the proposed converter.

3.   Experimental Results

For this paper, a real four-phase interlaced homogeneous charging circuit with PFC funtion is made, the physical circuit shown in Fig. 3. Its main architecture consists of four parts. The first part is the LC filter and bridge rectifier. Its filter is able to effectively filter out high frequency switching ripple. The second part consists of the two 2 flyback converters, charging one battery respectively. The third part consists of two buck/boost converters output to a DC link. The fourth part is the double output homogeneous charging circuit. The controller is dsPIC30F4011, which is used as the system center to control the circuit. Its PWM resolution is 16 bits and the operating frequency is 50 kHz. Therefore, the switching frequency is 50 kHz. In this paper, the parameters related to the circuit as shown in Table 1. The input 110V AC is from the supply mains and the output is put on the four 12V/16.7 Ah lithium iron oxide batteries in series for homogeneous charging. In addition, in the design the constant charging current is set at 8.35 A (0.5 C), the constant charging voltage is set at 14.4 V.

In this section, a waveform measurement is carried out for the four-phase interlaced PFC circuit. The circuit includes a LC filter circuit, a buck/boost converter, a fly-back converter and a double output homogeneous charging circuit. Each of them in different conditions will be measured and described. In addition, the circuit efficiency of consumed leakage inductance of this circuit and that of traditional RCD will be compared in this paper.
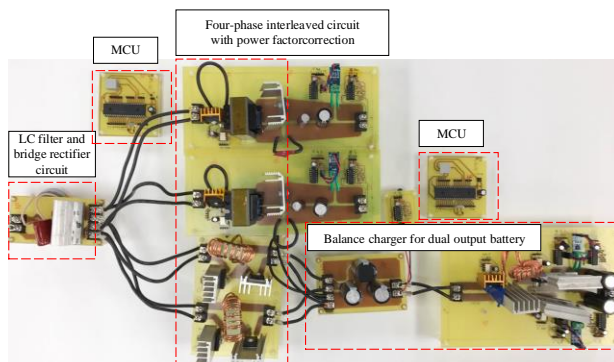

Fig. 3 Prototype of the proposed circuit

Table 1. Circuit specification

| V_{IN}	110 VAC
Lithium iron batteries	12 V / 16.7 Ah
Cut-off voltage	14.4 V
Charging current	8.35 A (0.5 C)
V_{CDC}	100 V

As shown in Fig. 4, the input voltage and current waveforms indicate that current I_m and voltage V_m have almost no phase difference. In the interlaced PFC circuit, inductance current $i_{L1} \sim i_{L4}$ will follow the input voltage V_m, and the peak current is in proportion to the input voltage, so a sine wave is formed. Four switches operate in an interlaced way. The turn-on time of each phase switch interlacedly operates over one fourth cycle as shown in Fig. 5.

The buck/boost converter is used to turn on and cut off signals and the gross surveyed waveform of inductive current is shown in Fig. 6. The buck/boost converter is used to turn on and cut off signals and the gross surveyed waveform of the primary side inductive current is shown in Fig. 7.It can verify that the current is operated in DCM.
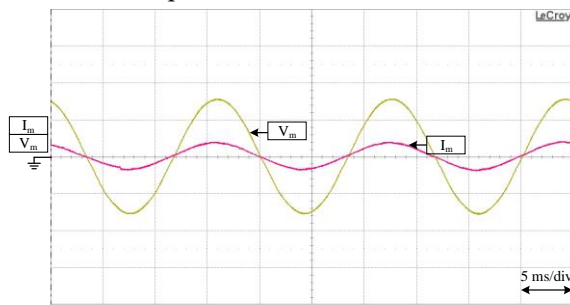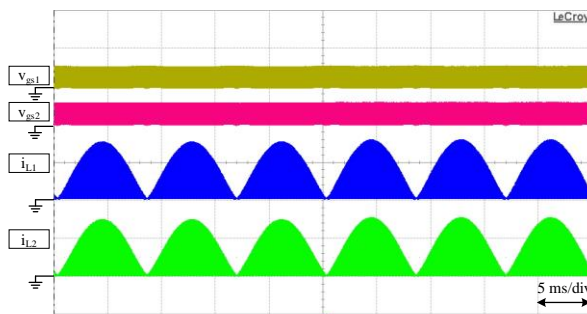

V_m : 100 V/div，I_m : 20 A/div

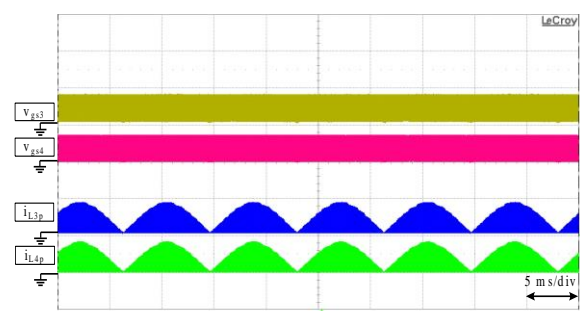**Fig. 4** Experimental waveforms of V_{IN} and I_{IN}.
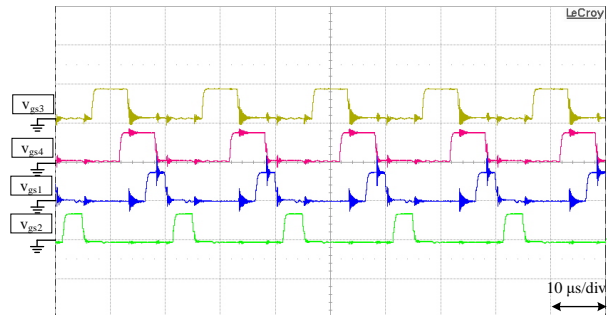
$v_{gs1} \sim v_{gs4}$: 20 V/div

Fig. 5 Experimental waveforms of $v_{gs1} \sim v_{gs4}$.

v_{gs1}、v_{gs2} : 20 V/div，i_{L1}、i_{L2} : 5 A/div

Fig. 6 Experimental waveforms of buckboost converters in DCM.

vgs3、vgs4 : 20 V/div，iL3p、iL4p : 10 A/div

Fig. 7 Experimental waveforms of Flyback converters in DCM

The gross surveyed waveforms of the third phase switch signal, the primary side inductive current, the secondary side inductive current and the recovered leakage inductance current of flyback converter.It can verify that it operates in DCM. The microscopic surveyed waveforms of switch signals, the primary side inductive current, the secondary side inductive current and the recovered leakage inductance current are shown in Fig. 8. The Fig. 8 shows that when the switch Q_3 is turned on, it supplies energy to the coupling inductor L_{3p} for energy storage. When Q_3 is cut off, diode D_8 is forward-biased, so it is turned on. Diode current i_{D8} is equal to the primary side inductive current i_{L3p} multiplied by N, i_{L3m} mapping to the secondary side. Diode D_3 is forward-biased, so it is turned on. The leakage inductance energy is guided to the DC-link capacitor C_{dc}.

v_{gs3} : 20 V/div，i_{L3p} :10 A/div，i_{D8} : 50 A/div，i_{D3} : 5 A/div
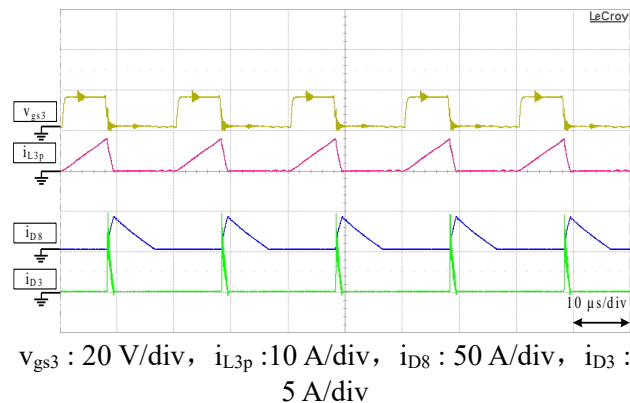
Fig. 8 Experimental waveforms of Flyback converter v_{gs3}, i_{L3p}. $i_{D8\ and}$ i_{D3}.

Fig. 9 shows the measured overall efficiency in constant current mode. When the battery is charged, the voltage rises from the lowest voltage of 10V to 14.4V and the battery is charged with constant current of 8.35A. Fig. 10 shows the measured overall efficiency in the constant voltage mode. When the battery is charged, the current decreases from the highest current of 8.35A to 2A and the battery is charged at the constant voltage of 14.4V. The circuit recovering leakage inductance is mentioned in this paper and the highest efficiency is achieved when the voltage is at 13.5V with constant current of 8.35A. The efficiency is 82.5%. The efficiency of the circuits using resistance for consumption is about 3% lower than the proposed circuit in this paper.
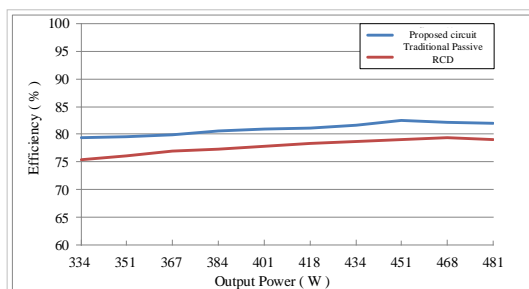
Fig. 9 Efficiency of the proposed circuit in cc mode.
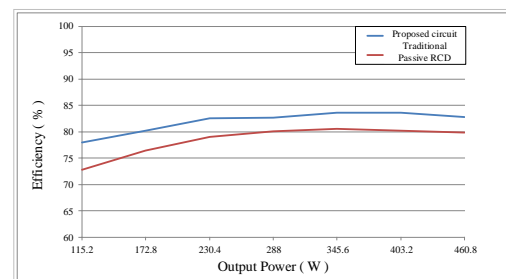
Fig. 10 Efficiency of the proposed circuit in cv mode.

4.   Conclusion

For this paper, a four-phase interlaced homogeneous charging circuit with PFC function is developed. On the issue of leakage inductance energy, 2 circuits are made as contrast. One is the circuit where the leakage inductance is consumed by resistance. The other is the circuit where the leakage inductance is guided by the diode to the output of the buck/boost converter to recover energy. After actual measurement, the circuit architecture proposed in this paper can effectively recover the leakage inductance energy to the DC-link capacitor, the efficiency of which is about 3% higher than the traditional passive RCD buffer circuit and reduces the switching surge voltage. The overall efficiency of the circuit proposed in this state is 83.6% in constant current mode and 80.5% in constant voltage mode. The power factor values of four-phase interlaced charging circuit are greater than 0.976 in any mode.

References

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