Interleaved PFC balance charger with passive lossless snubber for series-connected batteries

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Abstract An interleaved balance charger for four series-connected batteries is proposed in this study. Each battery can be charged individually in the proposed charger for balance charging process. The charger is operated in the discontinuous conduction mode (DCM) for power factor correction (PFC). Two flyback and two buckboost converters are input parallel-connected and controlled with multi-phase interleaving technique. The input current ripple is then greatly reduced. Each flyback converter is used to convert the charging power from the grid to one corresponding battery. The two buckboost converters are output parallel-connected and followed by a dual output converter. Two batteries in the series-connected battery tank are charged by the dual output converter. Moreover, a passive lossless snubber is proposed to recover the leakage inductance energy in the flyback converters. A 500W prototype is constructed and corresponding experiments are carried out. From the experimental results, it can be seen that the efficiency is improved by about 3% compared with the topology with common RCD snubbers. The measured power factor of the proposed charger is higher than 0.976.

key words: power factor correction, multiphase interleaved, balance charger, lossless snubber

Classification: Power devices and circuits

1. Introduction

In recent years, electric vehicles got a lot of attraction because of the fossil fuel crisis. The energy storage composed of rechargeable batteries is one of the most important devices in electric vehicles. The batteries are usually connected in series to meet specific voltage requirement. However, the characteristic differences among the batteries would cause voltage imbalance during charging. The series-connected batteries might be overcharging by common chargers without charge equalization. It would cause damage to the batteries and shorten the lifetime.

Various topologies of balance charger for series-connected batteries were proposed. In conventional balance chargers composed of dc converters, such as buck-boost, flyback and other kinds of dc converters, the configuration would become more complex while the number of series-connected batteries is increased [1-6]. Multi-output chargers are used to directly charge the series-connected batteries and eliminate the voltage imbalances during charging. Charge equalization circuits are proposed to transfer the charges among the series-connected batteries to eliminate the voltage imbalance [7-11]. However, the energy transferring between each battery would cause additional power losses. The voltage imbalance can easily be reduced by using multi-winding transformer and without increasing the control complexity [12-14]. However, the parameters variation among the windings would cause inconsistent output voltage on the secondary windings. The multi-output charger with voltage multiplier is composed of diodes and capacitors. The output voltages can be more uniform because less parameter variations among diodes and capacitors [15-17].

Multi-phase parallel converters with phase interleaved control are widely used to enhance reliability and efficiency. The required EMI filter can also be reduced because of the reduced current ripple. To achieve unity power factor, a common topology composed of a EMI filter, a full-bridge diode rectifier and a DC converter operated in DCM was usually adopted for reducing the complexity of feedback controller [18-24].

In this paper, an interleaved input-parallel output-series balance charger with PFC is proposed to charge a four series-connected battery pack. The flyback and buck-boost converters are integrated into this charger and a lossless snubber is also proposed to clamp the voltage spike and recover the energy on the leakage inductances. The input current ripple is greatly reduced by the adopted multi-phase interleaving control. The charger is operated in DCM for nearly unity input power factor. The configuration and operation principles of the proposed balance charger are described as following sections. A prototype for charging four series-connected batteries is constructed and experimental results are also provided for validity and performance verification.
2. Circuit Configuration of Proposed Charger

Fig. 1 shows the configuration of the proposed balance charger. A LC filter and a full bridge diode rectifier are connected to the AC source for filtering out the high frequency components and providing a rectified voltage $V_{in}$. The rectifier is followed by a four-phase interleaved converter which is composed of two flyback and two buck-boost converters. The two buck-boost converters convert the rectified power to the DC link for a dual-output converter. The dual-output converter is composed of three active switches $Q_3-Q_5$, three diodes, $D_3-D_7$, an inductor $L_5$ and two capacitors $C_1$ and $C_2$. Switch $Q_6$ is used to control the inductor current of inductor $L_5$. The duty ratios of switches $Q_6$ and $Q_7$ would be adjusted to control the charging current to batteries $B_1$ and $B_2$, respectively. The other two batteries $B_3$ and $B_4$ are charged by the two flyback phases respectively. Each one flyback converter directly converts and delivers the required charging power to corresponding battery from the rectified AC source.

Two flyback and two buck-boost converters are operated in DCM and with phase interleaving technique. The peak value of each phase input current would be proportional to the rectified AC voltage $V_{in}$. The ripple of the total input current would be reduced because of the phase interleaving control. The requirement of LC filter can also be reduced by the increased equivalent frequency of the input current ripple. Moreover, a lossless snubber composed diodes $D_8$, $D_9$ and capacitor $C_{dc}$ is integrated into the charger to recover the energy on leakage inductances of coupled inductors $L_3$ and $L_4$ to the DC link. The voltage spike of active switches in the two flyback phases could then be clamped as well.

In this paper, the constant-current/constant-voltage (CC/CV) charging method shown in Fig. 2 is used to charge each battery [24-27]. The charging process of each battery in the developed circuit can be independently controlled by the corresponding active switch. The current and voltage of each battery are fed back to the micro-controller unit to determine the corresponding duty ratio of the active switch. When the battery voltage is lower than the rated charging voltage, the charging current is regulated to the rated current value for constant-current charging, and the battery voltage will increase with time in this interval. When the battery voltage increases to the rated charging voltage, the controller will reduce the battery charging current for regulating the battery charging voltage to the rated charging voltage. Finally, when the charging current is further reduced to the cut-off current value, the charging process of the battery is then completed.

3. Operation Principles of Proposed Balance Charger

The relative waveforms of the four-phase interleaved charger are shown in Fig. 3. The gating signals of the active switches in the four phases are interleaved with a quarter of one switching period. The first two buck-boost phases, phase 1 and phase 2, are used to convert power from the rectified AC source $V_{in}$ to the DC link $V_{dc}$. The relative waveforms of the four-phase interleaved charger.
for the dual-output converter to charge the series-connected batteries B₁ and B₂. The other two flyback phases, phase 3 and phase 4, are worked independently to provide charging power to series-connected batteries B₃ and B₄, respectively. It can be seen that the operational principles of phase 1 and phase 3 are similar to phase 2 and phase 4, respectively. Therefore, for simplifying the analysis of the charger, phase 1 and phase 3 are taken as examples to illustrate the operational principles. The operation modes of phase 1 and phase 3 with respective to the time intervals in Fig. 3 are illustrated in Fig. 4 and Fig. 5 respectively.

The equivalent circuits in one switching period of phase 1 are shown in Fig. 4. Fig. 4(a) shows the operation mode of phase 1 when the active switch Q₁ is turned on in the interval of t₀ ≤ t ≤ t₁. The inductor L₁ is charged by the input source |Vᵢn| and the inductor current increases from zero. When the active switch Q₁ is turned off in the interval of t₁ ≤ t ≤ t₂, the corresponding equivalent circuit is shown in Fig. 3(b). The energy pre-stored in inductor L₁ is released to the DC link. While the energy stored in inductor L₁ is totally released, i.e. iL₁=0, diode D₁ and switch Q₁ are both turned off in the interval of t₂ ≤ t ≤ t₆ as shown in Fig. 3(c).

![Fig. 4 Equivalent circuits of phase 1 in intervals of (a) t₀ – t₁, (b) t₁ – t₂, and (c) t₂ – t₆.](image)

Fig. 5 shows the four operation modes of phase 3. In the first mode of the interval t₃ ≤ t ≤ t₄, switch Q₃ is turned on and diode D₃ is revised biased as shown in Fig. 5(a). The primary side inductance is charged by the input source and the current increases from zero. In the second mode of the interval t₄ ≤ t ≤ t₅, switch Q₃ is turned off, the energy stored in the leakage inductance L₃k is recovered to the DC link through the flywheel diode D₃ as shown in Fig. 5(b). This mode ends when the energy in the leakage inductance is totally released. In the third mode of the interval t₅ ≤ t ≤ t₆, diode D₃ is forward biased for the magnetizing inductance to release energy to the output side, as shown in Fig. 5(c). When the energy of magnetizing inductance is fully released, the converter would be worked into the last mode from t₆ to the end of the switching cycle shown in Fig. 5(d).

![Fig. 5 equivalent circuits of phase 3 in intervals of (a) t₁ – t₄, (b) t₄ – t₅, (c) t₅ – t₇, and (d) t₇ – Tₐ.](image)

The operation principles of the dual-output converter can be divided into two charging modes, namely the dual CC mode and CC/CV hybrid mode, as shown in Fig. 6 and Fig. 7, respectively. While the two batteries B₁ and B₂ are both in the constant-current charging stage, the dual-output converter would be operated in the dual CC mode, as shown in Fig. 6. Fig. 6(a) shows the circuit operation while switch Q₃ is turned on and the inductor L₅ is charged by the input source, i.e. the DC link. When switch Q₃ is turned off, diode D₅ would be forward-biased for inductor L₅ as shown in Fig.
6(b) to release energy to the series-connected batteries \( B_1 \) and \( B_2 \) simultaneously. In the dual CC mode, switches \( Q_6 \) and \( Q_7 \) are always turned off.

If one of the two batteries has been charged into the constant-voltage stage, the corresponding switches \( Q_6 \) or \( Q_7 \) would be activated to adjust the charging current. For example, Fig. 7 shows the operation principles of the dual-output converter under the condition that battery \( B_1 \) is in the CV charging stage. The main switch \( Q_5 \) is still used to remain a constant current for charging battery \( B_2 \). To reduce the charging current for battery \( B_1 \) for constant-voltage charging, switch \( Q_6 \) would be activated. Fig. 7(a) shows the equivalent circuit of the converter while switches \( Q_6 \) and \( Q_6 \) are both turned on. Fig. 7(b) shows the equivalent circuit under the condition that switch \( Q_6 \) is turned off and switch \( Q_6 \) is still turned on to bypass the charging current of battery \( B_1 \). Therefore, the effective charging current to battery \( B_1 \) can be reduced by adjusting the duty ratio of switch \( Q_5 \) to keep battery \( B_1 \) being charged in the constant-voltage stage. In this operation mode, battery \( B_1 \) is still charged in the constant-current stage because switch \( Q_7 \) is always turned off and the inductor current is remained constant by adjusting the duty of switch \( Q_5 \).

**Fig. 6 Equivalent circuits in dual CC operation with (a) switch \( Q_5 \) turned-on and (b) switch \( Q_5 \) turned-off**

**Fig. 7 Equivalent circuits in hybrid CC/CV operation with (a) switch \( Q_5 \) turned-on and (b) switch \( Q_5 \) turned-off**

4. **Experimental Results**

The circuit parameters of the constructed hardware are shown in Table I. The DC link voltage is set to 100V for effectively clamping the voltage spike caused by the leakage inductances. Fig. 8 shows the gating signals and inductor currents of phase 1 and phase 2 with respective to the grid period. By adopting the DCM PFC technique, it can be seen that the peak value of the inductor current is proportional to the rectified grid voltage. Basically, the AC input current would be nearly in phase with the input AC voltage after filtering out the switching frequency ripple components. To verify the operations in one switching period, the relative waveforms of phase 1 and phase 2 are shown in detail in Fig. 9 and Fig. 10. In phase 1, while switch \( Q_1 \) is turned on, the inductor current is increased and the reverse-bias voltage on diode \( D_1 \) is equal to the summation of the rectified grid voltage and the dc link voltage. When switch \( Q_1 \) is turned off, diode \( D_1 \) will be forward biased to release the inductor energy. Once the inductor current is reduced to zero, switch \( Q_1 \) and diode \( D_2 \) are both turned off to share the reverse bias voltage.

**Fig. 11 shows the gating signal, inductor current, primary side current, secondary side diode current and the flywheel diode current. The flywheel diode is forward biased by the primary side current while switch \( Q_1 \) is turned off. The energy of the leakage inductance is then recovered to the dc link through flywheel diode \( D_6 \). Meanwhile, the energy on the magnetizing inductance is also transferred to the secondary side. Diode \( D_6 \) is turned off when the energy of the leakage inductance is totally released and the magnetizing inductance current would reduce to zero before the end of switching cycle.**

**Fig. 12(a) and Fig. 12(b) show the measured waveforms of the dual-output converter in dual CC and hybrid CC/CV modes, respectively. Fig. 12(a) shows the gating signals of switches \( Q_5 \) and \( Q_6 \), the inductor current \( i_{L5} \) and the battery current \( i_{B1} \). In dual CC charging mode, inductor current \( i_{L5} \) is controlled to the rated charging current by adjusting the duty ratio of switch \( Q_5 \). Switches \( Q_6 \) and \( Q_7 \) are both turned off for charging batteries \( B_1 \) and \( B_2 \) at the same time. Fig. 12(b) shows the waveforms of the gating signals of switches \( Q_5 \) and \( Q_6 \), the inductor current \( i_{L5} \) and the battery current \( i_{B2} \) when battery \( B_1 \) is already charged into the constant-voltage region. It can be seen that switch \( Q_6 \) is then activated to reduce the charging current for battery \( B_1 \). The charging current for battery \( B_2 \) still remains the rated value.

The measured power factor of the proposed charger in CC and CV charging modes for four series-connected batteries are shown in Fig. 13. In the CC charging measurement, all batteries are assumed to be charged from 10V to 14.4V with constant current simultaneously. The output power is in the range between about 330W and 480W and the power factor is higher than 0.988. In the CV charging measurement, the charging current of each battery is charging from 8.35A to 2A for remaining constant charging voltage 14.4V. The output power is in the range between 115W and 480W. The corresponding power factor is higher than 0.976.

To compare the efficiency performance, a conventional dissipative RCD snubber is also constructed. The efficiency of the proposed charger in CC and CV charging modes are shown in Fig. 14(a) and Fig. 14(b). The efficiency of the proposed charger with the proposed lossless snubber is at least 3% higher than that with a conventional RCD snubber both in CC and CV modes.
Table I. Parameters of the developed circuit

| Parameter                                      | Value                  |
|------------------------------------------------|------------------------|
| Input AC Voltage \( V_{\text{in}} \)          | 110 V AC               |
| Batteries                                      | 12 V /16.7 Ah          |
| Rated charging voltage \( V_{\text{dc}} \)     | 14.4 V                 |
| Rated charging current \( I_{\text{dc}} \)     | 8.35 A (0.5C)          |
| DC link voltage \( V_{\text{dc}} \)           | 100 V                  |
| Inductor of filter \( L_{\text{f}} \)         | 27.2 μH                |
| Capacitor of filter \( C_{\text{f}} \)        | 2200 nF                |
| Inductors L1, L2 \( L_{\text{1}}, L_{\text{2}} \) | 35μH                   |
| Inductors L5 \( L_{\text{5}} \)               | 100μH                  |
| Primary inductance of L3, L4 \( L_{\text{3}}, L_{\text{4}} \) | 100μH                  |
| Secondary inductance of L3, L4 \( L_{\text{3}}, L_{\text{4}} \) | 2.6μH                  |
| Leakage inductance of L3, L4 \( L_{\text{3}}, L_{\text{4}} \) | 3.46μH, 3.2μH          |

5. Conclusion

A four-phase interleaved charger for four series-connected batteries was proposed in this paper. Two flyback, two buckboost and a dual-output converters are
integrated into the proposed charger. The flyback and buckboost converters were working in DCM. After filtering out high frequency ripple components, the AC input current is nearly sinusoidal and in phase with the input voltage. The measured power factor was high than 0.976. Moreover, a lossless snubber is also proposed for the two flyback converter to recover the leakage inductance energy. The efficiency of the charger with proposed lossless snubber is at least 3% higher than that with a conventional dissipative RCD snubber.

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