Optimized Coupling Factor for Minimizing Ripple Current of Coupled Inductor under Variable Duty in Rapid Traction Battery Charger

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Abstract

This paper investigates the design of coupled inductor for minimum inductor current ripple in rapid traction battery charger systems. Based on the general circuit model of coupled inductor together with the operating principles of dc-dc converter, the relationship between the ripple size of inductor current and the coupling factor is derived under the different duty ratio. The optimal coupling factor which corresponds to a minimum inductor ripple current becomes -1, i.e. a complete inverse coupling without leakage inductance, as the steady-state duty ratio operating point approaches 0.5. In an opposite manner, the optimal coupling factor value of zero, i.e. zero mutual inductance, is required when the steady-state duty ratio operating point approaches either zero or one. Coupled inductors having optimal coupling factor can minimize the ripple current of inductor and battery current resulting in a reliable and efficient operation of battery chargers.

1. Introduction

Plug-in Hybrid Electric Vehicle (PHEV) is becoming an attractive alternative to internal combustion engine vehicles in modern transportation industry. One way to achieve the practical all-electric cruising range of electric vehicles is to implement well distributed fast charger infrastructure. Therefore, battery chargers play a critical role in the development of EVs. EV battery chargers can be classified into on-board and off-board with unidirectional or bidirectional power flow. Unlike on-board chargers, off-board battery chargers are less constrained by size and weight. Charging time and battery life are closely linked to the characteristics of the battery charger. Various topologies and schemes have been reported for off-board chargers [1]-[4].

Among several topologies for off-board chargers, parallel connected multiple bidirectional dc-dc converters with active or diode bridge front-end rectifier are well adopted in industry. Phase-staggering operation of multiple bidirectional dc-dc converters is considered to reduce the ripple size of summed inductor currents and filtering requirement for the battery current. Inductor current ripple reduction using a coupled inductor in the interleaving structure has been also proposed. A coupled inductor can decrease the physical size of inductor itself while still complying with the peak switching current requirements from power semiconductor switches in dc-dc converters [5-7]. The coupling factor of coupled inductor has a significant impact on the phase-staggering operation of multiple bidirectional dc-dc converters. The selection of the optimal magnetic structure and coupling factor is regarded to be an important task in designing a coupled inductor. However, there has been a little work to focus on the optimal coupling factor of a coupled inductor and its relationship with the operation of dc-dc converters in previous literatures.

This paper investigates the design of coupled inductor for minimum inductor current ripple in rapid traction battery charger systems. The influence of coupling factor of coupled inductor on the operation of interleaved dc-dc converters is studied. The selection of optimal coupling factor under various operating conditions is also presented. This paper is structured in three main sections. Section 2 describes the modeling of coupled inductor. Section 3 explains the analysis and design process for the optimal coupling factor. Simulation as well as experimental result is presented in Section 4.

2. Modeling of Coupled Inductor

Figure 1 shows the schematic of rapid charger system proposed in this paper. Overall battery charging and discharging system consists of active front-end rectifier of neutral point clamped 3-level type and non-isolated bidirectional dc-dc converter of multi-phase interleaved half-bridge topology. As shown in Fig. 2 power can flow in both directions within a Battery Charging Unit (BCU), thus coping with charging and discharging mode of battery; buck-operation mode and boost-operation mode. The complete power converter system can deal with bi-directional power flow between the ac grid and energy storage devices.

The large ripple in battery charging current incurs stresses to a battery and eventually shortens the life time of battery. In order to reduce the ripple of battery charging current and filter inductor size, coupling of output inductors in two-phase interleaved dc-dc converters are employed. Interleaved bi-directional dc-dc converter with the coupled inductor core structure is shown in Fig. 3. The coupled inductor has the symmetric magnetic structure. The equivalent circuit of coupled inductor is illustrated in Fig. 4. The core structure has three legs of I core so that the coupling factor between two windings can be adjusted by the air gap distance in the center leg.

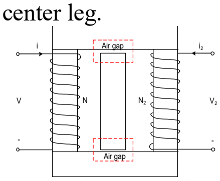

Fig 3 Magnetic structure of coupled inductor employed in dc-dc converter

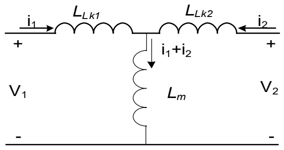

Fig 4 Equivalent circuit of coupled inductor

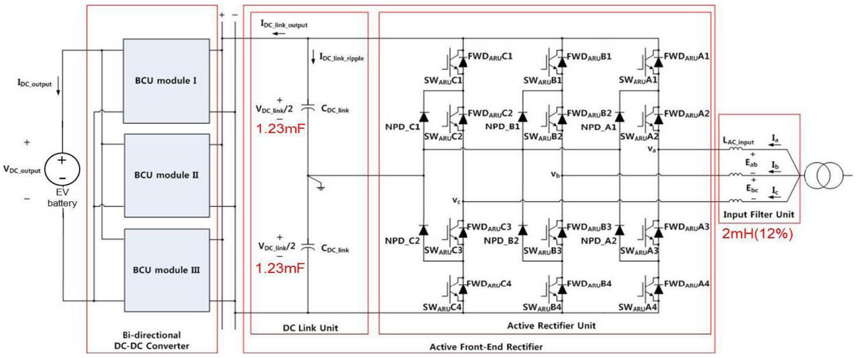

Fig 1 Battery charging and discharging inverter system

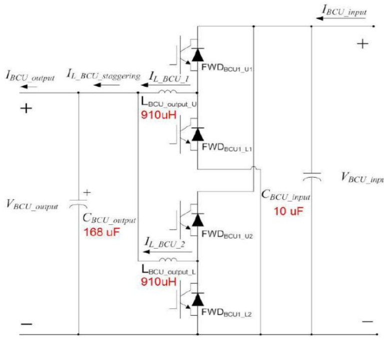

Fig 2 Bi-directional DC-DC converter

3. Design of Optimized Coupling Factor

Optimized coupling factor has been obtained through theoretical modeling of coupling inductor and circuit simulation as shown in the following.

$$V_{L\_BCU\_1} = \frac{d}{dt}(\lambda_{11} + \lambda_{21}) = L_{11}\frac{d}{dt}i_{L\_BCU\_1} + L_{21}\frac{d}{dt}i_{L\_BCU\_2} \quad (1)$$

$$V_{L\_BCU\_2} = \frac{d}{dt}(\lambda_{22} + \lambda_{12}) = L_{22}\frac{d}{dt}i_{L\_BCU\_2} + L_{12}\frac{d}{dt}i_{L\_BCU\_1} \quad (2)$$

$$\frac{\lambda_{12}}{i_{L\_BCU\_1}} = \frac{\lambda_{21}}{i_{L\_BCU\_2}} = L_{12} = L_{21} = M \quad (3) \qquad k = \frac{M}{\sqrt{L_{11}L_{22}}} \quad (4)$$

Using (3) and (4), inductor voltage equations of (1) and (2) can be simplified to (5). Because of the coupling mechanism of inductor, two inductor voltages($V_{L\_BCU\_1}$, $V_{L\_BCU\_2}$) are correlated to each other depending on the switching states of SW_{BCU_U1} and SW_{BCU_U2}. A total of four different combinations of switching states are possible. Using one of four coupled inductor voltage equations in Table I depending on the switching state, the inductor voltage equation of (5) can be written as (6).

$$V_{L\_BCU\_1} - kV_{L\_BCU\_2} = (1-k^2)L_{11}\frac{d}{dt}i_{L\_BCU\_1} \quad (5) \qquad V_{L\_BCU\_1} = L_{eq\_1}\frac{d}{dt}i_{L\_BCU\_1} \quad (6)$$

Table Ⅰ. Equivalent Inductance under Different Switch mode

Mode	Switch Voltage	Voltage Equation	Equivalent inductance
Mode1	$V_{L\_BCU\_1} = V_{in} - V_o$ $V_{L\_BCU\_2} = -V_o$	$V_{L\_BCU\_2} = -\frac{D}{1-D}V_{L\_BCU\_1}$	$Leq = \frac{1-k^2}{1+\frac{D}{1-D}k}L_s$
Mode2	$V_{L\_BCU\_1} = -V_o$ $V_{L\_BCU\_2} = -V_o$	$V_{L\_BCU\_2} = V_{L\_BCU\_1}$	$L_{eq} = (1+k)L_s$
Mode3	$V_{L\_BCU\_1} = -V_o$ $V_{L\_BCU\_2} = V_{in} - V_o$	$V_{L\_BCU\_2} = -\frac{1-D}{D}V_{L\_BCU\_1}$	$Leq = \frac{1-k^2}{1+\frac{1-D}{D}k}L_s$
Mode4	$V_{L\_BCU\_1} = V_{in} - V_o$ $V_{L\_BCU\_2} = V_{in} - V_o$	$V_{L\_BCU\_2} = V_{L\_BCU\_1}$	$L_{eq} = (1+k)L_s$

Minimum inductor current ripple is obtained when the equivalent inductance is at its maximum. Therefore, the optimal coupling factor of coupled inductor for the minimal current ripple is to set the equivalent inductance terms in Table I at its maximum values. The optimal coupling factors maximizing the corresponding equivalent inductance values under two different regions of duty ratio are obtained and expressed in (7) and (8).

$$k_{D<0.5} = \frac{-1 + D + \sqrt{1-2D}}{D} \quad (7) \qquad k_{D>0.5} = \frac{D + \sqrt{2D-1}}{D-1} \quad (8)$$

4. System Verification

Table Ⅱ. Specifications of Electric Vehicle Battery Charge System

Specification	Values	Specification	Values
Rated power	30kW	Pre-charging mode voltage	292V
AC input voltage	342~506V	Pre-charging mode current	0~78A
AC input current	77A	Constant voltage mode voltage	440V
DC-link voltage	858V	Constant current mode current	78A
Battery capacity	11 4kWh	DC output voltage	50~450V

5. Conclusion

Coupled inductors are often employed in several topologies for EV battery charger systems. Through an appropriate coupling factor and phase-staggering operation, coupled inductor can improve the performance of charging unit with smaller inductor ripple current. This paper investigates the design of coupled inductor for minimum inductor current ripple in rapid traction battery charger systems. Based on the general circuit model of coupled inductor together with the operating principles of dc-dc converter, the relationship between the ripple size of inductor current and the coupling factor is derived. Simulation and experimental result verify the theoretical derivation of the optimal coupling factor. The design guideline for selecting optimal coupling factor can be very useful in a battery charging system. Coupled inductors having optimal coupling factor can minimize the ripple current of inductor and battery current resulting in a reliable and efficient operation of battery chargers.

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Fig 5 EV and rapid charger of test

Fig 6 Photo of power stack

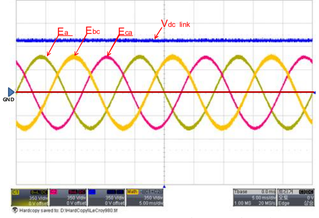

Fig 7 Experiment waveform of ac input voltage

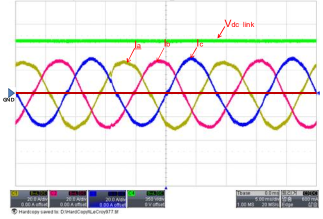

Fig 8 Experiment waveform of ac input current

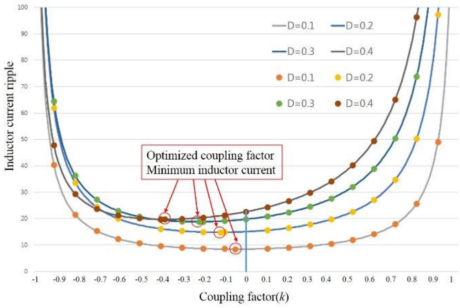

Fig 9 Simulation and mathematical Analysis waveforms of inductor current ripple Vs coupling factor under duty < 0 5

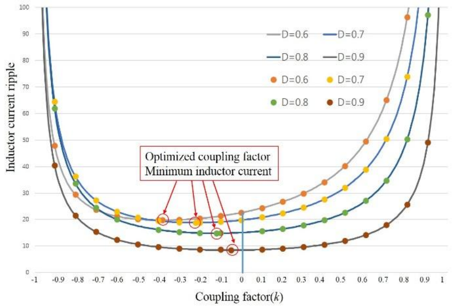

Fig 10 Simulation and mathematical Analysis waveforms of inductor current ripple Vs coupling factor under duty > 0 5

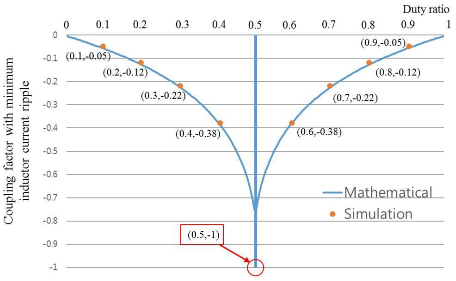

Fig 11 Coupling factor of the minimum inductor current ripple under variable duty[line : mathematical analysis, dot : simulation]

References

[1] M. Bojrup, P. Karlsson, M. Alakula, and B. Simonsson, "A dual purpose battery charger for electric vehicles," in *IEEE Power Electronics Specialists Conference*, vol. 1, pp. 565-570, 1998.

[2] C.C. Chan and K.T. Chau, "An overview of power electronics in electric vehicles," in *IEEE Trans. Ind. Appl.*,vol.44,no. 1, pp. 3-13, Feb. 1997.

[3] C. S. Lee, J. B. Jeong, B. H. Lee, and J. Hur, "Study on 1.5 kW battery chargers for neighborhood electric vehicles," in *Proc. IEEE Veh. Power and Propulsion Conf.*, pp. 1–4, Sep. 2011.

[4] Murat Yilmaz, Philop T. Krein, "Review of battery charger topology, charging power levels, and infrastructure for plug-in electric and hybrid vehicles," in *IEEE Transactions on Power Electronics*, vol. 28, no.5, pp.2151-2169, 2013.

[5] Jun Imaoka and Masayoshi Yamamoto, "A novel integrated magnetic structure suitable for transformer-linked interleaved boost chopper circuit" in *Energy Conversion Congress and Exposition (ECCE) 2012 IEEE*, pp.3279-3284, 2012.

[6] Pit-Leong and Wong, Peng Xu "Performance improvements of interleaving VRMs with coupled inductors" in *IEEE Transactions on Power Electronics*, vol.16, no.4, 2011.

[7] H.N "Design principles of a symmetrically coupled inductor strucutre for multiphase synchronous buck converters" in *IEEE Transactions on Power Electronics*, vol.58, no.3, 2011.

[8] D. Yu, Z`. Xiaohu, B. Sanzhong, S. Lukic, and A. Huang, "Review of non-isolated bi-directional DC-DC converters for plug-in hybrid electric vehicle charge station application at municipal parking decks," in *IEEE 2010 Applied Power Electronics Conference and Exposition*, pp. 1145, 2010.

[9] P. Das, S.A. Mousavi, and G. Moschopoulos, "Analysis and design of a nonisolated bidirectional ZVS-PWM dc–dc converter with coupled inductors," in *IEEE Trans.Power Electron.*, vol. 25, pp. 2630-2641, Oct. 2010.