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Advanced Architectures and Control Methodologies for the Integration of On-Board Chargers and Low-Voltage DC-DC Converters in Electric Vehicles

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Abstract

The integration of the On-Board Charger (OBC) and the Low-Voltage DC-DC Converter (LDC) represents a critical evolution in Electric Vehicle (EV) power electronics, aiming to maximize power density and minimize weight. However, conventional magnetically integrated topologies, such as those utilizing three-winding transformers, often suffer from severe cross-regulation and poor light-load efficiency during standalone LDC operation. This paper proposes a comprehensive analysis of a decoupled "2-Transformer" architecture that mitigates these drawbacks. We present a rigorous mathematical model of the Dual Active Bridge (DAB) and Phase-Shift Full-Bridge (PSFB) stages, deriving precise Zero Voltage Switching (ZVS) boundaries and voltage gain equations. Furthermore, a unified Dual Phase Shift (DPS) control strategy is analyzed to manage simultaneous power flows while decoupling the high-voltage and low-voltage control loops. Experimental data from recent literature is synthesized to validate the theoretical models, demonstrating that the proposed architecture can achieve efficiencies exceeding 96% in simultaneous mode while significantly improving thermal performance compared to legacy systems.

Keywords

Electric Vehicles; Integrated OBC-LDC; Dual Active Bridge; Zero Voltage Switching; Magnetic Integration; Power Density.

1. Introduction

The electrification of the automotive powertrain has driven the demand for high-efficiency, high-power-density energy conversion systems. In a typical Electric Vehicle (EV) architecture, two distinct power converters are required: an On-Board Charger (OBC) for charging the High-Voltage (HV) battery from the AC grid, and a Low-Voltage DC-DC Converter (LDC) for stepping down the HV traction voltage (400 V or 800 V) to charge the 12 V auxiliary battery. [1]

Traditionally, these units are packaged as discrete components, leading to redundancy in chassis enclosures, cooling loops, and control circuits. To address this, "Deep Integration" strategies have emerged, merging the OBC and LDC into a single Integrated Power Unit (IPU). While mechanical integration offers volume savings, true magnetic integration—using a shared magnetic core—promises the highest power density . However, sharing magnetic paths introduces complex cross-coupling effects, where load transients in the auxiliary system can destabilize the HV charging process. [2]

This paper reviews the state-of-the-art in OBC-LDC integration, focusing on a "2-Transformer" topology that balances integration benefits with operational stability. We provide a detailed circuit analysis, derive key control transfer functions, and evaluate thermal performance to offer a robust design framework for next-generation 800 V EV platforms.

2. Integrated System Architectures

2.1. Limitations of Three-Winding Topologies

Early integrated designs utilized a three-port converter (TPC) structure centered around a three-winding transformer. In this configuration, the primary winding connects to the grid-rectified DC link, the secondary to the HV battery, and the tertiary to the LV auxiliary load.

While this reduces the component count, it imposes a significant penalty on efficiency during LDC standalone operation [3]. The large magnetic core, sized for the peak OBC power [4], incurs substantial hysteresis and eddy current losses even when delivering only a few hundred watts to the LV system [5].

2.2. The Decoupled 2-Transformer Architecture

To overcome the efficiency drop at light loads, recent literature suggests a magnetically decoupled approach (Fig. 1). This topology employs a dedicated transformer for the HV-HV energy transfer and a separate, optimized transformer for the HV-LV path, while sharing the primary-side full-bridge switches.

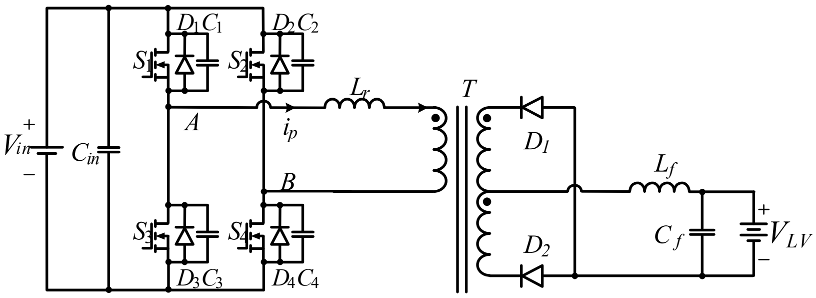

Figure 1. Schematic diagram of the 2-Transformer Integrated OBC-LDC topology.

This architecture allows the LDC transformer to be optimized for high-current, low-voltage operation using copper foil or heavy Litz wire, minimizing conduction losses. Importantly, during standalone LDC operation, the main OBC transformer remains de-energized, eliminating its core losses from the system energy budget .

3. Mathematical Modeling and Circuit Analysis

To ensure stable operation and soft-switching across the wide voltage ranges typical of 800 V architectures, rigorous mathematical modeling is essential.

3.1. Dual Active Bridge (DAB) Power Transfer

The OBC stage typically employs a DAB topology due to its bidirectional capability and inherent soft-switching. The power transferred is controlled by the phase shift angle between the primary and secondary bridges.

The fundamental power transfer equation is given by:

$$P_{DAB} = \frac{nV_1V_2}{2\pi f_s L_{lk}} \varphi(1 - \frac{[\varphi]}{\pi}) \tag{1}$$

3.2. Zero Voltage Switching (ZVS) Boundaries

Achieving ZVS is critical to minimizing switching losses and electromagnetic interference (EMI). The ZVS condition requires that the energy stored in the leakage inductance is sufficient to discharge the MOSFET output capacitances (C_{oss}) during the dead time.The boundary condition for the primary switches is derived as :

$$\frac{1}{2}L_{lk}I_{L,t0}^{2} \geq \frac{1}{2}(2\mathrm{C}_{oss})V_{DC}^{2} \tag{2}$$

$$P_{DAB} = \frac{nV_1V_2}{2\pi f_s L_{lk}}\varphi(1-\frac{[\varphi]}{\pi}) \tag{3}$$

3.3. LDC Voltage Gain and Duty Cycle Loss

The LDC stage often operates as a Phase-Shift Full-Bridge (PSFB). Ideally, the voltage gain is linear with the duty cycle $D_{LDC.}$ However, the leakage inductance causes a loss of duty cycle during the commutation of the secondary rectifiers.

The effective duty cycle D_{eff} is :

$$D_{eff} = D_{LDC} - \Delta D = D_{LDC} - \frac{2f_s L_{lk,LDC} I_{load}}{n_{LDC}V_{in}} \tag{4}$$

$$V_{LV} = n_{LDC}V_{in}(D_{LDC} - \frac{2f_s L_{lk,LDC} I_{load}}{n_{LDC}V_{in}} \tag{5}$$

4. Conclusion

This paper has presented a comprehensive review and analysis of integrated OBC-LDC systems for electric vehicles. By moving from a magnetically coupled three-winding structure to a decoupled 2-transformer architecture, significant gains in light-load efficiency and cross-regulation performance are achieved. The mathematical models for DAB power transfer and ZVS boundaries provide a theoretical basis for optimizing component selection, particularly for 800 V WBG-based applications. The implementation of Dual Phase Shift control with feed-forward decoupling. effectively isolates the LV and HV domains, ensuring stable operation under dynamic load conditions. Future research should focus on further increasing power density through planar magnetics and integrating the traction inverter into this unified power ecosystem.

References

[1] Y. S. Kim, C. Y. Oh, W. Y. Sung, and B. K. Lee, "Topology and control scheme of OBC-LDC integrated power unit for electric vehicles," IEEE Transactions on Power Electronics, vol. 32, no. 3, pp. 1731-1743, 2017.

[2] X. Qu, H. Han, S. C. Wong, and C. K. Tse, "Hybrid Integrated On-Board Charger for Electric Vehicles," IEEE Transactions on Power Electronics, vol. 33, no. 3, 2018.

[3] Y. Lee, S. Kim, M. Kim, and H. Shin, "A Study on the Reduction of Light Load Loss in the Standalone Operation of LDC in Integrated Charging System for Electric Vehicles with 2-Transformer," Applied Sciences, vol. 16, no. 4, p. 1751, 2026.

[4] D. W. Lee et al., "New Combined OBC and LDC System for Electric Vehicles With 800 V Battery," IEEE Transactions on Industrial Electronics, vol. 69, no. 10, pp. 9938-9951, 2022.

[5] R. W. De Doncker, D. M. Divan, and M. H. Kheraluwala, "A three-phase soft-switched high-power-density DC/DC converter for high-power applications," IEEE Transactions on Industry Applications, vol. 27, no. 1, pp. 63-73, 1991.

[6] G. Yu and S. Choi, "An effective integration of APM and OBC with simultaneous operation and entire ZVS range for electric vehicle," IEEE Transactions on Power Electronics, vol. 36, no. 9, pp. 10343-10354, 2021.

[7] H. N. Vu, D. V. Tinh, and W. Choi, "A Novel Hybrid LDC Converter Topology for the Integrated On-Board Charger of Electric Vehicles," Energies, vol. 14, no. 12, p. 3603, 2021.