3-port LDC 비교 분석 : 제안하는 DABSRC vs. Toyota DAB

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Comparative Analysis of 3-port LDC: Proposed DABSRC vs. Toyota DAB

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ABSTRACT

This article proposes a new isolated, three-port, bidirectional DC-DC converter for EV LDC. By controlling duties and phase shift of LV and HV sides, the proposed topology achieves DCX at bridges 1 and 3, and near DCX at bridge 2, resulting in significantly reduced switching losses. Further, controlling phase shift between bridges 1 and 2 greatly reduces the circulating current by half. A theoretical comparison analysis between Toyota's 3-port DAB converter and the proposed converter that has been implemented indicates an overall 2% improvement in efficiency and a 33% reduction in volume, due to the enhanced capability to increase switching frequency. A 3-port LDC 7.5kW/L prototype with 200kHz, 48V/4kW and 12V/2.1kW outputs has been built in the laboratory to validate the theory.

1. Introduction

In electric vehicles, HV lithium-ion batteries serve as the primary power source for the LV auxiliary loads [2]. Due to the increasing demand for entertainment and safety features in vehicles, the standard LV network simultaneously utilizes two types of power source, 12V and 48V. The 12V power source supplies electricity to critical sensors, the 48V power provides power for propulsive electrical loads. Toyota's converter [1] is a combination of Dual Active Bridge (DAB) and interleaved Buck/Boost as shown in Fig 1a. This converter offers the advantage of achieving Zero Voltage Switching (ZVS) for all switches. However, it has the drawback of *high turn-off* current at LV side, which leads to increased switching loss. On the other hand, operating at a duty cycle of $D_L=0.25$ is necessary to realize voltage conversion 12V/48V, which impairs the transformer utilization rate in DAB converter [3], resulting in increased transformer's effective current and conduction losses. These drawbacks lead to increasing switching frequency to improve power density which is not feasible. This article proposes a new topology using dual transformers in combination with a series resonant circuit (SRC) to solve the high turn-off current problem. Moreover, the circulating current can be reduced when operating with a wide input voltage range. Therefore, efficiency and power density can be improved.

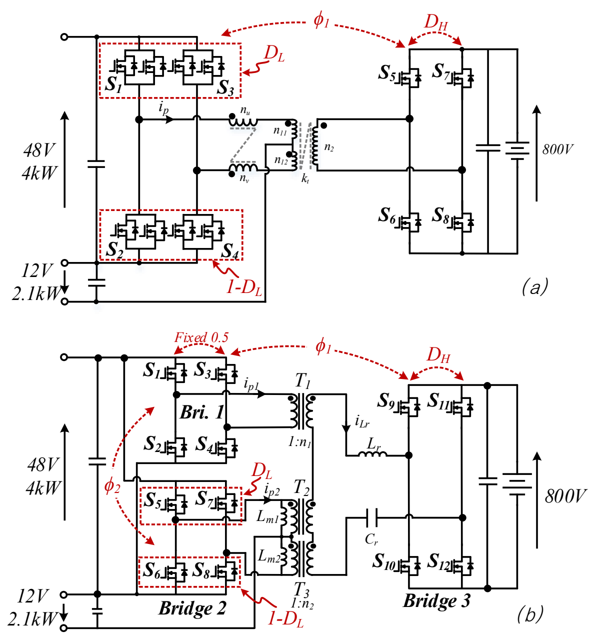

Fig.1 Topology comparison of 3-port LDC converter (Po = 6.1kW). Both topologies have same number and same ratings of switches. (a) Toyota Topology [1]; (b) Proposed Topology

2. Comparison: Proposed vs. Toyota topology

Fig.1b illustrates the proposed topology with voltage of the HV side ranging from 400V to 840V, and the LV voltage comprising 48V/4kW and 12V/2.1kW. It utilizes four control variables: D_L, D_H, ϕ_1 and ϕ_2. Bridge 2's MOSFETs function asymmetrically with duty ratio (D_L) acting as an interleaved buck/boost converter. D_H is the phase shift ratio between the two legs of bridge 3, ensuring that the rms voltage of v_{ab} and v_{cd} are matched. ϕ_1 represent the phase shift ratio ensuring energy transfer between the HV and LV sides. ϕ_2 is the phase shift ratio between bridge 1 and bridge 2. A comparison between the proposed topology and Toyota's topology is presented in Table 1. Under the same power 6.1kW, with an equal number of MOSFETs and kVA of transformer, both topologies achieve ZVS turn-on. Due to the large turn-off current, Toyota's converter operates at a switching frequency of 100kHz. Meanwhile, the switching frequency of the proposed converter is 200kHz.

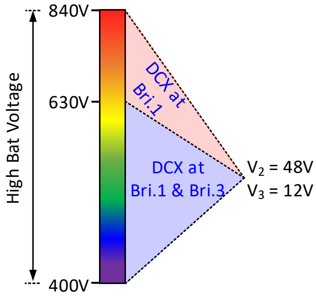

Fig.2 DCX region of the proposed topology, showing low turn-off current and ZVS turn-on.

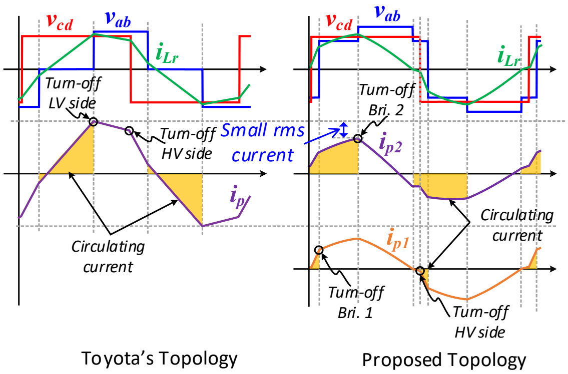

Fig. 3 Comparison of circulating current of Toyota and proposed topology at optimal point. The proposed topology has significantly smaller circulating and turn-off currents, allowing for an increase in switching frequency up to 200kHz, while Toyota's topology only reaches 100kHz due to high turn-off and circulating currents.

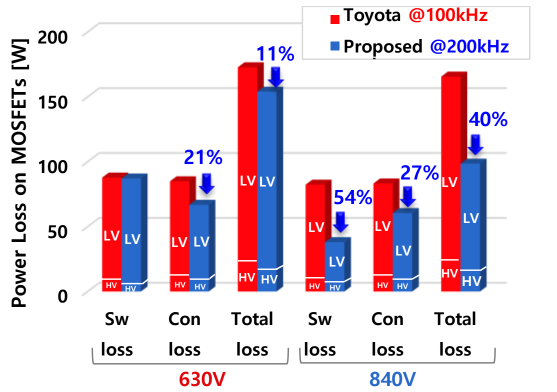

Fig. 4 Comparison of total switch losses between Toyota and Proposed converter at 630V/48V/12V, 840V/48V/12V, power rating 6.1kW

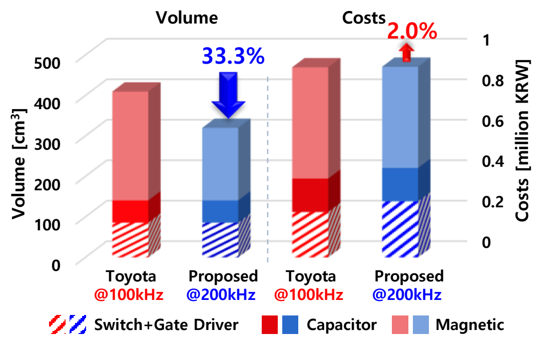

Fig. 5 Comparison of Volume and Costs between Toyota and Proposed Converter with power rating 6.1kW

The highlight of the proposed topology is additional phase shift control variable (ϕ_2) between bridge 1 and 2. This variable has the capability to adjust the voltage v_{t2}, bridge 1 and 3 achieve DCX within the range of 400V to 630V (shown in Fig 2). The turn-off current in the proposed topology (92A) is lower than conventional topology (257A). In contrast, the conventional topology lacks this variable, making it unable to control the turn-off current. As a result, the switching loss of the proposed topology is reduced by 54% at 840V (shown in Fig 3).

Furthermore, to ensure all MOSFETs achieve ZVS turn-on, the rms voltage of v_{ab} and v_{cd} must be matched. In the Toyota's topology, only D_H and D_L are used, D_L is fixed by the voltage conversion ratio of 12V/48V, which means the phase shift between the legs in the bridge 3 will be smaller (D_H<0.5) when increasing HV, leading to an increase in circulating current and, consequently, conduction losses in increased. For the proposed topology, the phase shift of bridge 1 is consistently at 0.5, which significantly reduces the circulating current on LV side. By incorporating an additional secondary transformer, the v_{ab} is further controlled by v_{t2} (as shown in Fig 3), resulting in D_H is higher than conventional converter. As a result, circulating current is reduced, leading to an improvement in conduction loss as shown in Fig 4. Fig 5 illustrates the volume and costs of the two converter types. Due to Toyota converter's switching frequency being less than half that of the proposed structure, the volume is improved by 33%. The volume of the magnetic component

Table 1 Overall Comparison between the Toyota's and Proposed Topology for 3-port LDC with power rating of 48V/4kW and 12V/2.1kW

		Toyota converter [1]	Proposed converter
Number of switches		12	12
Switching characteristic (at 630V)		Bridge 1: S1, S3: Small turn off current S1, S4: ZVS turn on, High turn off current Bridge 2: S5, S6: Small turn off current S7, S8 ZVS turn on, High turn off current	Bridge 1, Bridge 3: DCX Bridge 2: S6, S8: DCX S5, S7: ZVS turn on, Hard turn off
kVA of transformer		8kVA	T1: 6.7kVA, T2&T3: 2.4kVA
Turn off current	400V/48V/12V	257A (LV side)	92A (LV side)
	630V/48V/12V	306A (LV side)	56A (LV side)
	840V/48V/12V	400A (LV side)	94A (LV side)
Switching frequency		100kHz	200kHz
Peak Efficiency with 12V output		95.9%	97.3%

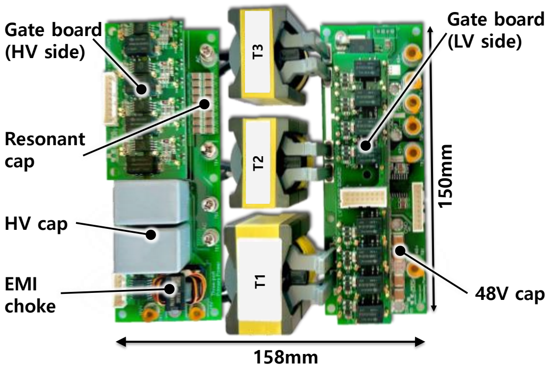

Fig.6 800V/48V/12V 6.1kW prototype

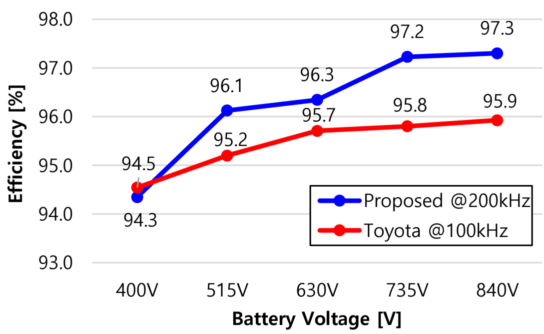

Fig. 7 Comparison of computational efficiency between Toyota and proposed topology with 6.1kW, 48V/12V low side

predominates, while the volumes of other components remain the same.

3.Experiment Results

Fig. 6,8,9 and 10 illustrates the prototype of the 3-port LDC topology with an experimental power rating of 6.1kW (4kW of 48V and 2.1kW of 12V), a 22μH resonant inductance, a 64.14nF resonant capacitance. For the cases of 400V and 630V, thanks to the resonant circuit and D_H=0.5, the inductor current takes on a sinusoidal shape, thereby minimizing high-order harmonic components. All MOSFETs at LV side and HV side achieve ZVS turn-on with different high voltage. The experimental results have successfully validated the operational capability of the proposed topology.

4. Conclusion

Through comparative analysis of efficiency, volume, and costs, it has been demonstrated that the proposed topology offers improvements over Toyota's topology for the 3-port LDC 6.1kW application. Experimental results have validated these analyses.

Reference

[1] K. Itoh, S. Inoue, T. Sugiyama and M. Sugai, "Design and modulation method of Multi-port DC/DC converter for next generation HV sub system," IECON 2016 - 42nd Annual Conference of the IEEE Industrial Electronics Society, Florence, Italy, 2016, pp. 1318-1323.

[2] H. -P. Kieu, D. B. -H. Nguyen, D. Lee and S. Choi, "All-in-one Magnetic Structure for PSFB converter with

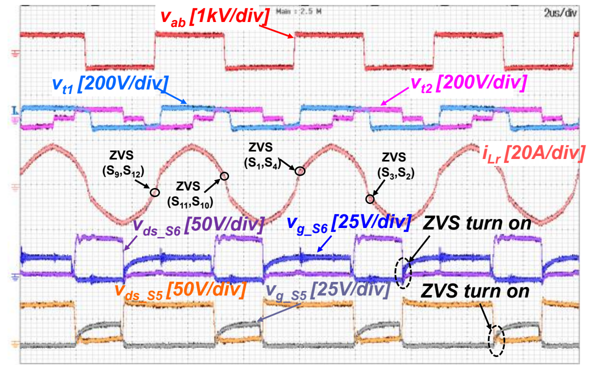

Fig.8 Experimental results at 400V/48V/12V 6.1kW

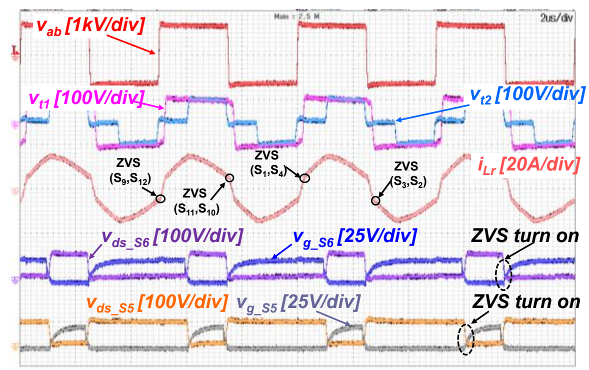

Fig. 9 Experimental results at 630/48V/12V 6.1kW

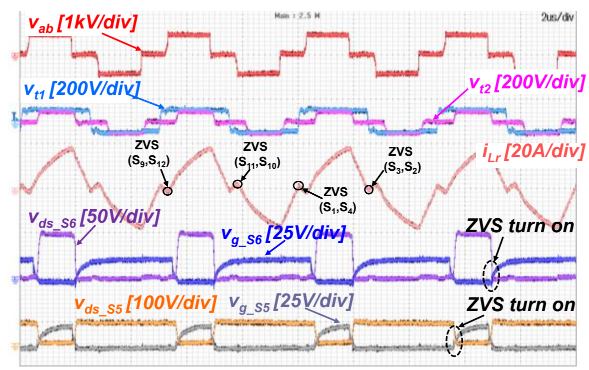

Fig. 10 Experimental results at 840V/48V/12V 6.1kW

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Current Doubler Rectifier," 2024 IEEE Applied Power Electronics Conference and Exposition (APEC), Long Beach, CA, USA, 2024, pp. 875-880,

[3] Sato, Motoki & Uno, Masatoshi & Tada, Yoshiya. (2022). Multiport converter integrating automatic current balancing interleaved PWM converter and DAB converter with improved transformer utilization for electric vehicles. Electrical Engineering in Japan. 215. 10.1002/eej.23375.