미래 전기항공기용 듀얼 4-권선 변압기 기반 비대칭 멀티포트 DC-DC 컨버터

부디위차크사나 루카스, 이동춘
영남대학교 전기공학과

Asymmetric Multiport DC-DC Converter Based on Dual Four-Winding Transformers for Future All-Electric Aircraft

Lukas A. Budiwicaksana and Dong-Choon Lee
Department of Electrical Engineering, Yeungnam University

ABSTRACT

In this paper, a novel multiport DC-DC converter for future all-electric aircraft (AEA) is proposed. The proposed converter topology can integrate both fuel cells and batteries, which are the main power sources of AEA, and isolate the propulsion systems and avionic loads. Furthermore, two four-winding medium-frequency transformers are utilized to avoid insulation issues in high-power and medium-frequency operation. In addition, the proposed topology has lower number of switches, can operate at various voltage gain, and has higher efficiency compared to the existing topologies. The basic operation of the proposed topology is discussed and verified with simulations of a 400 kW system.

1. Introduction

All-Electric Aircraft (AEA) has become a promising technology due to the advanced development of fuel cells and batteries for the past decade[1,2]. To regulate the load buses at a constant value from varying-voltage sources, DC-DC converters have a crucial role. Approximately, the total load of AEA is around 4-12 MW. Medium/high-frequency power conversion is preferred to reduce the total size and weight. However, there is limitation for the realization of high-power and medium-frequency operation due to insulation issues. To address this, one converter unit can be constructed by more than one transformer.

Resonant converters are preferred for this realization due to simple operation and high efficiency. However, their efficiency significantly drops when the voltage gain of the converter is not unity, since they have to operate above the resonance. This paper proposes a novel resonant converter topology that can provide various voltage gain at a constant switching frequency to maintain high efficiency. Furthermore, the number of switches is reduced, making the converter lighter and has higher power density.

2. Proposed Converter and Operating Principle

The proposed converter topology is shown in Fig. 1, which is beneficial to interconnect fuel cells and batteries in

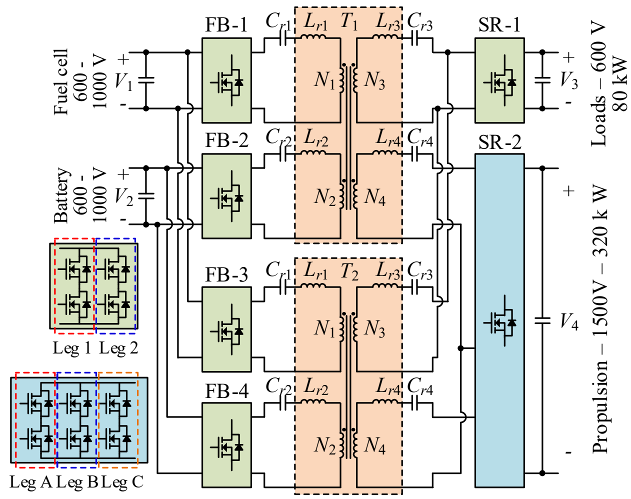

Fig.1. Proposed converter topology.

Port 1 and 2, respectively. For the load side, the avionic loads (Port 3) and propulsion systems (Port 4) are separated. The topology is constructed using two four-winding transformers with leakage inductance L_{rx} and number of turns N_x, where $x = \{1, 2, 3, 4\}$ represents the port number. Each port consists of a resonant capacitor, denoted by C_{rx}. For high-power operation, the full-bridge (FB) configuration is paralleled on the source side. On the load sides, synchronous rectifiers (SRs) are utilized. The SR in Port 4 has three legs that consists of two individual legs (Leg A and B) and a shared leg (Leg C).

The operating principle of the proposed converter is similar to that of resonant converters. To meet the voltage specification in Fig. 1, the number of turns should be $N_1 = N_1 = N_3 \neq N_4$, so that $L_{r1} = L_{r2} \neq L_{r3} \neq L_{r4}$. Therefore, resonant frequency can be expressed as

$$f_0 = 1\big/\left(2\pi\sqrt{L_{rx}C_{rx}}\right) . \quad (1)$$

The aforementioned assumption yields unequal C_{rx} for each port to meet a specific resonant frequency.

Fig. 2 shows the key waveforms of the converter. The FB switches are modulated with a constant frequency at the

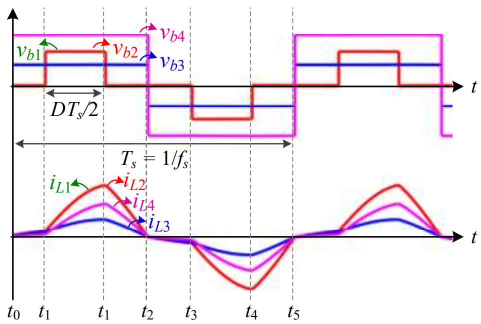

Fig.2. Key waveforms of the proposed converter.

TABLE I. Parameters for simulation

P_{rated}	400 kW	L_{r1}, L_{r3}, L_{r2}, L_{r4},	27 μH, 27 μH, 10 μH, 20 μH
V_1, V_2	600 ~ 1000 V	C_{r1}, C_{r3}, C_{r2}, C_{r4},	4.2 μF, 4.2 μF, 11.26 μF, 5.6 μF
V_3, V_4	600V, 1500 V	L_m	15 mH
N_1: N_2: N_3: N_4	1:1:1.05:2.55	$f_s = f_0$	15 kHz

resonance (f_s = f_0), and the output voltage can be regulated by controlling the width of the input-side bridge voltages D through a phase shift between Leg 1 and 2. Using the same analysis as for conventional resonant converters, the voltage gain can be derived as

$$G(D)\big|_{f_s=f_0} = \left.\frac{V_k}{V_j}\right|_{\substack{k=3,4\\ j=1,2}} = \sin\left(\frac{D}{2}\right) \qquad (2)$$

where k and j represent the port number connected to load and source, respectively. Note that (2) is only valid when f_s = f_0, where the equivalent resonant tank impedance is equal to zero.

3. Performance Verification

The performance of the proposed converter is validated through simulations using the parameters listed in Table I. The transformer parameters are chosen from [3], which has rated power of 200 kW and operating frequency of 15 kHz for one unit.

Fig. 3 shows the simulation results at full load condition. Based on (2), D is 180° and 74° to regulate the output voltage at the rated condition when V_1 is 600 V and 1000V, respectively. Notice that for both conditions, the switching frequency is kept constant at 15 kHz.

The efficiency of the proposed converter is calculated by considering conduction loss, switching loss, transformer winding loss, and core loss. Fig. 4(a) shows the estimated efficiency of the converter under various input voltages. The maximum efficiency at 98.4 % can be achieved. For a fair comparison, the efficiency of conventional input-parallel output-parallel series-resonant converter with two transformers is estimated, which is shown in Fig. 4(b). The efficiency for V_1 = 600 V is similar to the proposed one. However, as V_1 increases, the converter has to operate above the resonant frequency and lose soft switching.

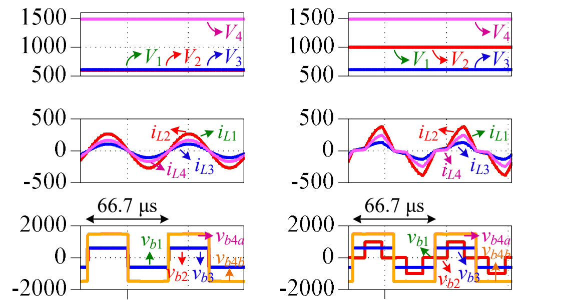

Fig.3. Simulation at full load condition (400 kW). (a) V_1 = 600 V. (b) V_1 = 1000 V.

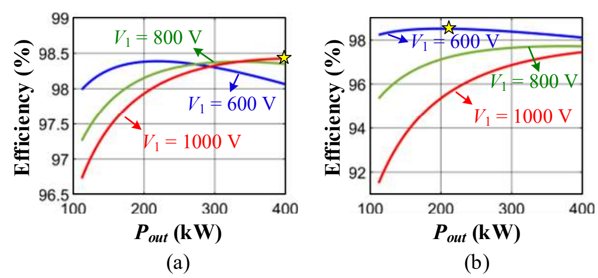

Fig.4. Estimated efficiency. (a) Proposed topology. (b) Frequency-modulated series-resonant converter.

Consequently, the switching loss increases and deteriorate overall efficiency. Moreover, the proposed converter reduces the total switches from 32 to 26, which can increase the power density and simplify the thermal management.

4. Conclusions

In this paper, a novel multiport DC/DC converter topology for AEA based on dual four-winding transformers has been proposed. The working principle of the topology is similar to that of the existing resonant converter. However, it can provide various voltage gains at a constant switching frequency. Consequently, the efficiency is much higher than the conventional topology. The performance of the proposed converter has been verified through simulations of a 400 kW system. A maximum efficiency of 98.4 % can be achieved.

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. RS-2024-00347621).

References

[1] Zeroavia, "Fuel cell superstack." Accessed: Jul. 29, 2024. [Online]. Available: www.zeroavia.com.

[2] Wright Electric, "The world's lightest electric vehicle batteries." Accessed: Jul. 29, 2024. [Online]. Available: https://www.weflywright.com/battery-launch.

[3] Z. Guo, R. Yu, W. Xu, X. Feng and A. Q. Huang, "Design and optimization of a 200-kW medium-frequency transformer for medium-voltage SiC PV inverters," *IEEE Trans. Power Electron.*, vol. 36, no. 9, pp. 10548-10560, Sept. 2021, doi: 10.1109/TPEL.2021.3059879.