A 25kW Silicon Carbide 3kV/540V Series-Resonant Converter for Electric Aircraft Systems

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***Abstract*—In this work, a 25 kW all silicon carbide (SiC) series-resonant converter (SRC) design is proposed to enable a single stage dc to dc conversion from 3kV to 540V (±270V) for future electric aircraft applications. The proposed SRC consists of a 3-level neutral-point-clamped (NPC) converter using 3.3kV discrete SiC MOSFETs on the primary side, a H-bridge converter using 900V SiC MOSFET modules on the secondary side and a high frequency (HF) transformer. The detailed design methods for the SRC power stage and the HF transformer are presented. Especially, a tradeoff between the complexity for the cooling system and the need for power density is addressed in the transformer design, leading to a novel multi-layer winding layout. To validate the effectiveness of the proposed SRC design, a converter prototype has been developed and comprehensive experimental studies are performed.**

Keywords—3.3 kV SiC MOSFETs, HF transformer, medium voltage, resonant converter.

I. INTRODUCTION

Thanks to the advancement of the silicon carbide (SiC) technology, compared to their silicon counterparts, the SiC devices can withstand higher voltage and operate at higher switching frequency, which can enable a high efficiency single stage conversion from the medium voltage (MV) dc to several-hundred volts low voltage dc. This can be attractive to various applications, e.g., the data center power supplies and auxiliary power supplies for the railway systems and/or electric aircraft, due to the reduced complexity, higher efficiency and power density [1].

At present, maximum onboard electric power generation capacity in operating commercial airliners is approximately 1 MW on the Boeing 787, which consists of both 235V ac feeder and ±270V dc feeder to support the motors and other type of electric load on the airplane. Recently, Airbus launched a hybrid-electric demonstrator, E-Fan X [2], which features the use of 2MW electric motors and 3kV dc electrical distribution. The use of MV dc distribution on an aircraft system can enable a significantly higher efficiency for electric power distribution.

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In this paper, the design and demonstration of an isolated 3kV to 540V dc/dc converter are presented. This concept can bridge the future 3kV dc distribution system and the state-of-the-art (SOA) electrical equipment using 270V dc. For isolated DC-DC converters, both dual-active bridge (DAB) and series-resonant converters (SRC) are widely used [3]-[5]. The SRCs feature clamped switching voltages, simple operation, and zero-voltage switching (ZVS) for all devices. Therefore, higher efficiency can still be achieved at high switching frequency, which is the key to reduce the volume of the passives and the magnetics. In this design, the latest 3.3kV SiC MOSFETs are used to design an SRC operated at the resonant frequency. To accommodate the 3kV dc voltage, a neutral-point-clamped (NPC) half-bridge converter [4] is used on the primary side.

The high operating frequency and the high terminal voltage pose several challenges for the design of high frequency (HF) MV transformer. Especially the use of thicker insulation layers and the needs to achieve high power density make the thermal management difficult for the transformer. In addition, the partial discharge (PD) could be a potential issue for the HF transformer designed to operate in the thin air of 20,000-25,000ft. Therefore, the additive manufacturing was used to prototype the bobbins with multi-layer configuration to ensure sufficient insulation between the winding layers. The overall transformer design is presented in detail in this paper.

II. MV SRC CONVERTER DESIGN

The circuit diagram of the proposed SRC is shown in Fig. 1. Since the dc link voltage is 3 kV on the primary side, an NPC half-bridge using 3.3 kV 80 mΩ discrete SiC MOSFETs

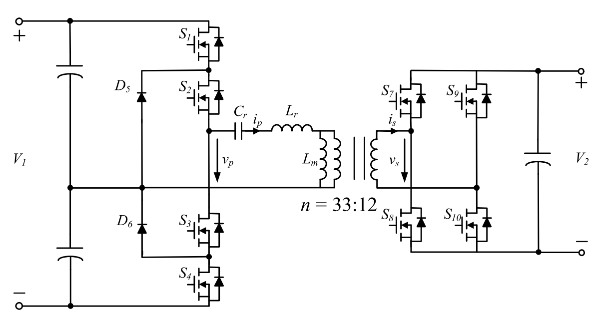

Fig. 1. Circuit diagram of the proposed SRC converter.

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in TO-247 package is selected. Due to the use of half bridge on the primary side, the MV terminal voltage for the transformer is ±1500V. The resonant tank consists of the leakage inductor L_r, the resonant capacitor C_r and the magnetizing inductor L_m. There parameters are summarized in Table I. On the secondary side, since the output nominal voltage is 540 V, custom 900V SiC modules with forced air cooling are used. The resonant frequency of the proposed SRC is 48 kHz.

Due to the high switching frequency, the SiC MOSFETs should operate under ZVS conditions to ensure high efficiency. Fig. 2 shows the waveforms of the converter when it operates at the resonant frequency. The converter has six operating modes in a period with details described as follows.

Mode 1 (t_0 to t_1): This mode starts when the resonant inductor current i_p becomes positive. S_1 and S_2 are both turned on at t_0 and i_p flows through S_1 and S_2 during this mode. S_7 and S_{10} on the secondary side are turned on. The L_m is linearly charged by the terminal voltage and the output current i_o is proportional to the difference between i_p and the magnetizing current i_m.

TABLE I

KEY PARAMETERS OF THE PROPOSED SRC CONVERTER

Parameter	Specification
Nominal power	25 kW
Operating frequency	48 kHz
Input voltage	3 kV
Output voltage	540 V
Resonant capacitance	54.9 nF
Leakage inductance	200 µH
Magnetizing inductance	5.2 mH
Transformer turns ratio	33:12

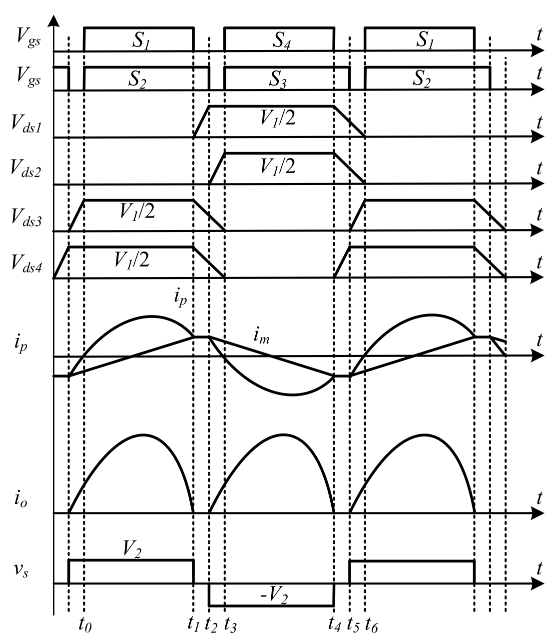


Fig. 2. Theoretical waveforms of the proposed SRC converter.

Mode 2 (t_1 to t_2): At the time instant t_2, i_p and i_m are equal. Meanwhile, i_o decreases to zero and S_7 and S_{10} are turned off. In this mode, the output is disconnected from the transformer, thus L_m becomes a free inductor, which is in series with L_r resonating with C_r. S_1 is turned off, while S_2 is still ON. The drain-to-source voltages of S_3 and S_4 start to decrease and the drain-to-source voltage of S_1 starts to increase. The primary resonant current i_p freewheels through D_5 and S_1.

Mode 3 (t_2 to t_3): S_2 is turned off at t_3 and i_p flows through the body diodes of S_3 and S_4, which leads to ZVS for S_3 and S_4. In this operating mode, i_p starts to drop. S_8 and S_9 are turned on and i_o begins to rise.

The operation modes 4-6 are similar to mode 1-3 and are not discussed in details here. The analysis shows that ZVS conditions can be achieved for S_1 ~ S_4 and ZCS can be achieved for S_7 ~ S_{10}. In addition, the voltage of the primary MOSFETs are the half of the input dc link voltage V_1.

III. THE HF MV TRANSFORMER DESIGN

HF transformer is one of the most critical components of the proposed converter, since it provides the galvanic isolation between the primary side and the secondary side. Though numerous HF or MV transformer designs can be found in the existing literature, it is still challenging to design the HF MV transformers, especially for the high power applications. The insulation layer of the MV transformer is usually designed to be relatively thick, in order to meet the insulation requirement. Meanwhile, the surface area of the transformer is much smaller due to high power density of HF transformer, which poses significant challenges to the thermal management. Therefore, high efficiency and high-performance insulation design are critical to the HF MV transformer.

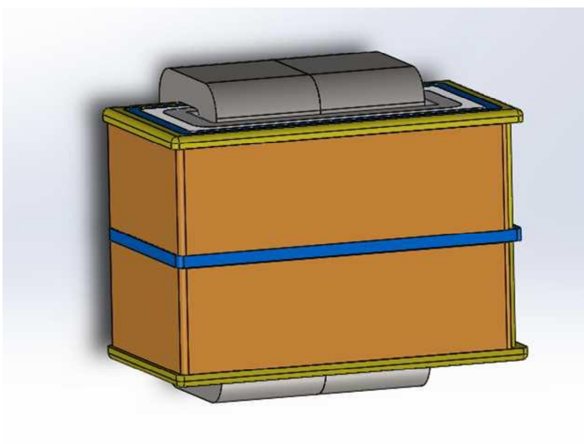
Although the use of higher operating frequency, e.g., 50-100 kHz, may increase the power density, it could also result in much higher core and winding losses. In this work, considering the requirements of high power density, the resonant frequency of the SRC is selected as 48 kHz. In this case, nanocrystalline core is selected due to its low core loss in the 10~50 kHz range and high operation flux density. The C cores are used in this transformer. Compared with E cores, C cores have a larger exposed area of the winding package for the forced convective cooling and an easier construction of the litz wire terminations [5]. The parameters of the transformer are listed in Table II.

To achieve ZVS condition in the proposed SRC, an air gap of 3 mm is chosen without using a long dead time and to mitigate the large winding loss caused by fringing field. In addition, the flux density of the transformer is critical to the core loss. Although the saturation flux density, B_{max}, of the nanocrystalline can be larger than 1 T, the core loss could be unacceptable when the operating frequency is up to 48 kHz. In this design, the peak flux density of 0.3 T is selected for both low core loss and high power density. With the optimized turns ratio, litz wire and winding structure, the total loss of the core and windings are 117.5 W, which leads to a peak efficiency of 99.53%.

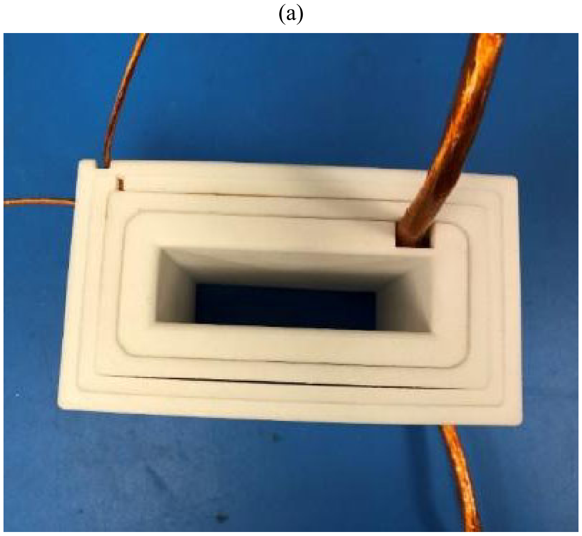
TABLE II

KEY PARAMETERS OF THE HF TRASNFORMER

Parameter	Specification
Nominal power	25 kW
Operating frequency	48 kHz
Terminal voltages	±1.5 kV/ ±540 V
Turns-ratio	33:12
Primary winding	0.1mm (AWG38) × 900
Secondary winding	0.1mm (AWG38) × 3600
Winding type	Shell-type
Core type	F3CC0125 nanocrystalline FT-3M
Volume	69.9 in^3
Efficiency	99.53%



(a)



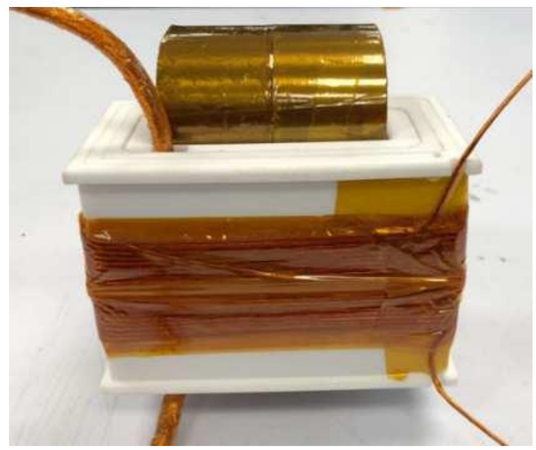
(b)

Fig. 3. The proposed HF transformer: (a) 3D rendering and (b) the cross-sectional view of the multi-layer bobbin.

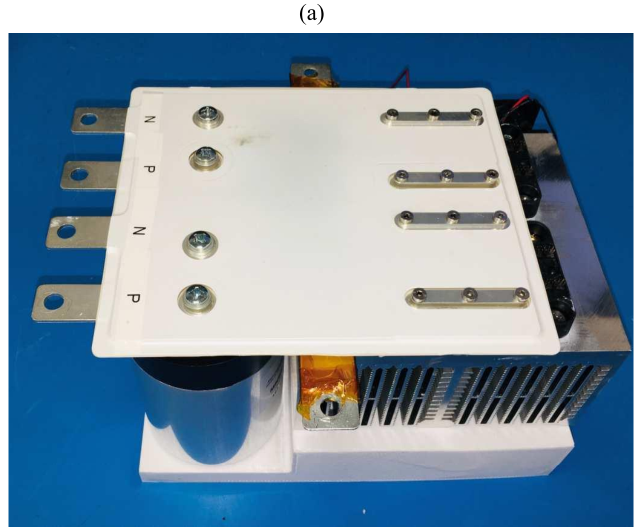
Due to the high electric potential difference between primary side and secondary side, proper electric insulation material should be placed between these two sets of windings for isolation purpose. The Kapton film has a high insulation performance. However, it is difficult to remove the air from multiple tape layers, thus the partial discharge is inevitable. Using the Nomex insulation paper can mitigate this issue. However, wrapping the core or windings with thick insulation paper is not easy. In the proposed design, as shown in Fig. 3(a), 2 mm-thick 3D-printed bobbins are used to enhance the insulation capability and also the mechanical robustness. The dielectric strength of the 3D-printing material (Polyamide 11) can be 30.2 kV/mm. The solid fulfill of 3D-printed bobbins also mitigate the risk of partial discharge. As shown in Fig. 3(b), each layer of the primary and secondary windings is wound on individual 3D-printed bobbins and assembled concentrically. The secondary winding is arranged between the primary winding and the magnetic core.

IV. PROTOTYPING AND EXPERIMENTAL STUDIES

In addition to the HF transformer prototype, as shown in



(a)



(b)

Fig. 4. Picture of (a) HF transformer and (b) the H-bridge converter on the secondary side.

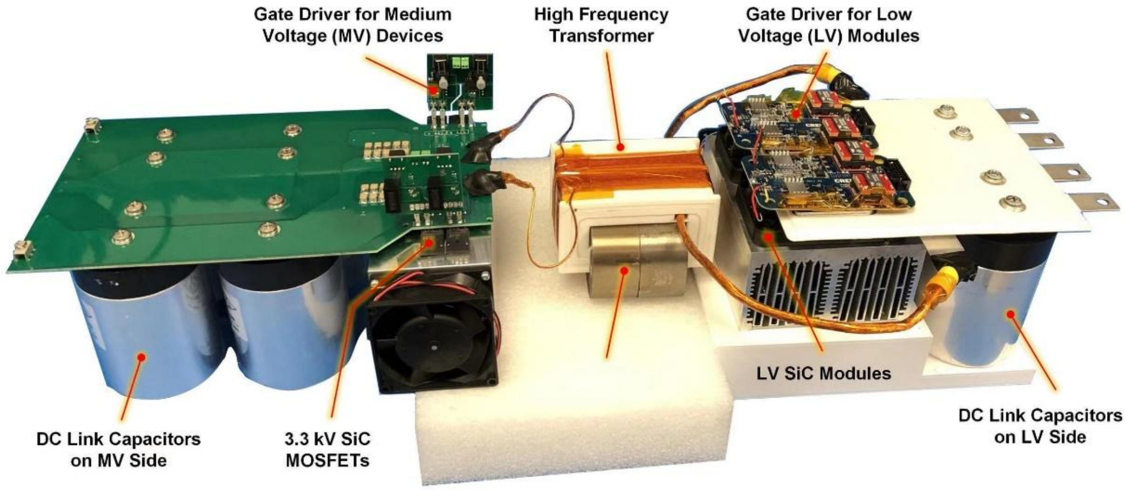


Fig. 5. Prototype of the proposed SRC converter.

Fig. 4(a), other power converter stages have been prototyped as well. On the low voltage side, i.e., the secondary side, the H-bridge converter [6] is shown in Fig. 4(b), which consists of two 900V half bridge SiC modules, a laminated busbar and dc link capacitors. Fig. 5 shows the overall prototype of the proposed converter for the experimental verification. The primary converter includes four discrete 3.3kV SiC MOSFETs and two diodes. Two dual-chancel gate drivers are place on top of the main power board to drive the SiC MOSFETs. A 0-4 kV power supply is connected to the MV side of the converter. The overall test setup is shown in Fig. 6.

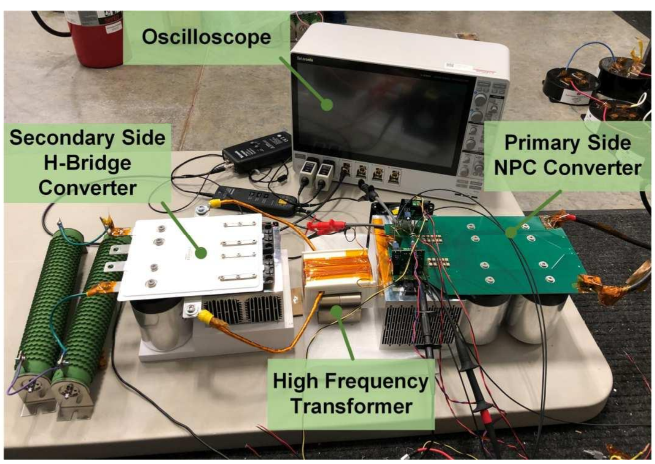
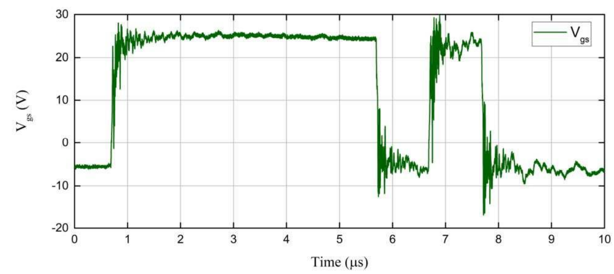


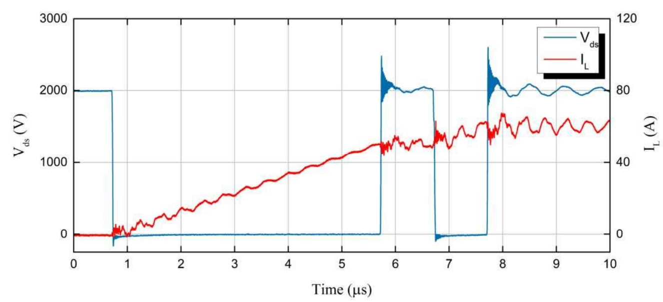
Fig. 6. The experimental test setup.

A. Device Testing Results

The double pulse test (DPT) and multi-pulse test have been performed to validate the circuit and gate driver design. The results of the DPT using the D_6 and S_4 shown in Fig. 1 are shown in Fig. 7. The DC bus voltage is 2000V and the peak inductor current I_L is around 60 A. It can be seen that the measured maximum drain to source voltage is 2604V. This relatively high voltage overshoot mainly caused by the intrinsic high stray inductance of the TO-247 package.



(a)



(b)

Fig. 7. The DPT results (a) the gate to source voltage and (b) the drain to source voltage and the load current.

B. Converter Testing Waveforms

To verify whether the proposed converter can achieve ZVS conditions, the voltage of the primary side devices and the primary resonant current are measured. The prototype is operated at the resonant frequency $f_0 = 48$ kHz and a duty cycle of 0.5. The dead time is set to 800 ns to make sure ZVS can be achieved for the primary side devices. The DC bus voltage of 3 kV is applied. The primary side NPC is controlled by the dSPACE MicroLabBox. A Tektronix oscilloscope with two 6 kV differential voltage probes and a Rogowski coil are used for the measurement. The measured voltage waveforms of the MV MOSFETs S_1 and S_4 are shown in the upper plot of Fig. 8. It can be seen that ZVS can be achieved on the primary side

MOSFETs. The lower plot of Fig. 8 shows the measured waveform of the primary resonant current. The waveforms are smooth to validate the proper design of the converter. The results illustrate that the resonant frequency is equal to the switching frequency, which means that soft-switching is achieved over the entire load range.

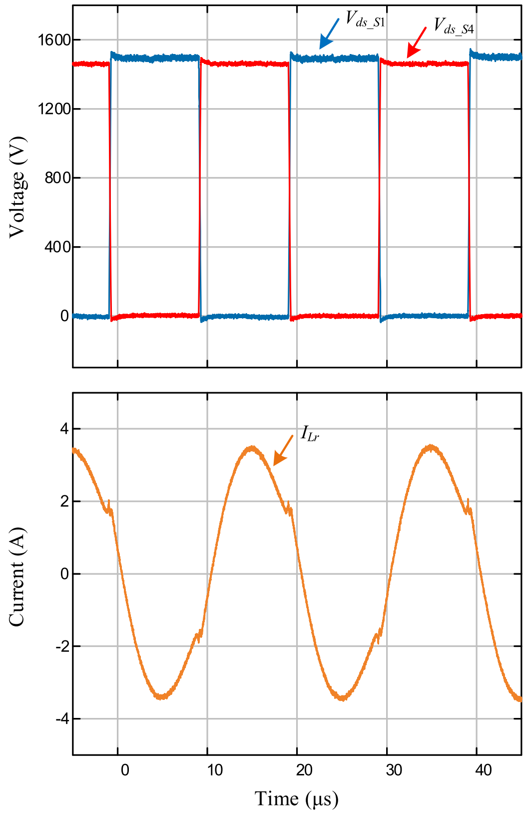


Fig. 8. Measured waveforms of primary side devices voltages and resonant current.

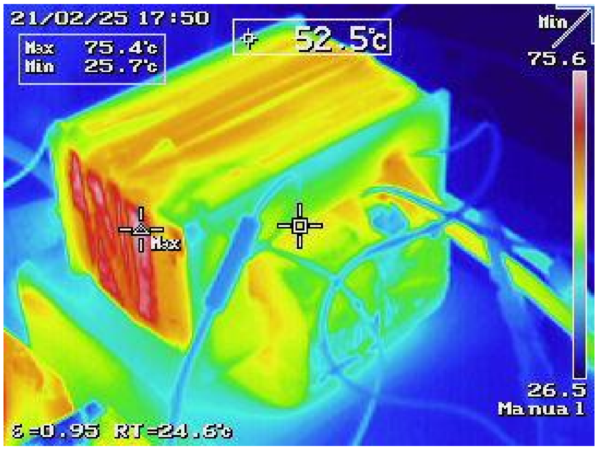


Fig. 9. Thermal image of the HF transformer in the short circuit test.

C. *Thermal Test and Efficiency Measurement*

A thermal test has been performed to verify the thermal performance of the HF transformer. In this test, the secondary terminal of the HF transformer is shorted and the primary RMS current is equal to current in the full-load condition. Therefore, only the winding losses reach to their maximum value in this operation mode. The system is continuously operated for over an hour until it reaches the thermal equilibrium. The thermal image at the steady state is presented in Fig. 9. It can be seen that the temperature of the winding is much higher than that of the core during the test. The hot-spot on the winding of the HF transformer is 75.4 °C. In addition, the efficiencies of the SRC converter with different loads are measured and the efficiency curve is shown in Fig. 10. It can be observed is that the system efficiency can go beyond 99.0% in the medium to heavy load range, e.g., 50% ~ 100%, with a peak efficiency of 99.08%.

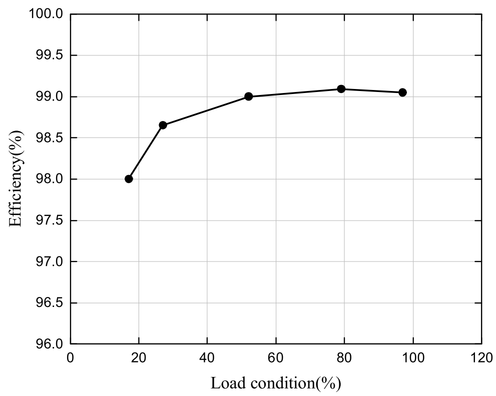


Fig. 10. Measured efficiencies of the SRC prototype.

V. Conclusions

In this work, a 25 kW, 48 kHz all SiC SRC design is presented to enable a single stage dc to dc conversion from 3kV to 540V (±270V) for future electric aircraft applications. The design of the converter power stage and HF transformer were presented. 3-D printed bobbins are used to enhance the insulation capability and also the mechanical robustness, which eliminates the risk of partial discharge. The prototype of the proposed SRC is built. The experimental waveforms show that the SRC can achieve ZVS for all switches. The experimental results also proved that the SRC can achieve an overall efficiency around 99%.

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