

Araştırma Makalesi – Research Article

Uçaklarda Kullanım Amaçlı Interleaved Süper Lift Luo Dönüştürücü Tasarımı

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ÖZ

Bu çalışmanın temel amacı, havacılık sistemleri için mevcut topolojilere kıyasla daha düşük kayıplar elde etmek için 28V batarya ile çalışan 1,2kW interleaved super lift Luo dönüştürücü tasarlamaktır. Uygulanan devrenin basit yapısı nedeniyle kayıplarda azalma amaçlanmaktadır. F-22 gibi askeri uçaklar ve Boeing 787 gibi sivil uçaklar batarya sistemleri için 270V DC kullanılmaktadırlar. Bu nedenle, 270V DC standardının uygun olduğu yeni hava araçları eski gerilim standartlarıyla çalışmayabilir. 28'den 270 volta yükseltme hem eski hem de yeni sistemler için iyi bir çözüm olarak düşünülmektedir. Bu nedenle, eski havacılık teknolojisini yeni sistemlere uyarlamak için 28 voltu 270 volta yükselten bir interleaved süper lift Luo dönüştürücü tasarımı önerilmiştir. Silisyum karbür MOSFET tabanlı interleaved süper lift Luo dönüştürücünün çift döngü PI kontrolör tasarımı gerçekleştirilmiştir. Bu makale, alanındaki gelişmelere uyum sağlamak amacıyla uçaklarda kullanım için interleaved süper lift Luo dönüştürücü tasarımının prensiplerini göstermektedir ve konsept simülasyonlar kullanılarak doğrulanmıştır.

Anahtar Kelimeler- Uçak, DA-DA güç dönüşümü, Darbe genişlik modülasyonu

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An Interleaved Super Lift Luo Converter Design for Aircraft Applications

ABSTRACT

The main purpose of this study is to adapt a 28V battery powered super Lift Luo converter topology to the aircraft systems by adding the interleaving feature. It is aimed to have better efficiency compared to conventional designs. F-22 military aircraft and civil aircraft such as Boeing 787 use 270V DC for battery systems. New standards for the avionics using 270V DC may not apply to older avionics. Therefore, conversion from 28V to 270V can be an advantageous application for both new and old systems. As a result, an interleaved super lift Luo converter has been designed to increase the voltage from 28V to 270V with a quite high conversion ratio so existing old systems stay up-to-date due to developments. Analysis of this new interleaved super lift Luo converter was carried out with a double loop PI controller. The topology uses silicon carbide MOSFETs as high-frequency switches. This paper shows the design philosophy of the converter and proves the system with simulations.

Keywords- Aircraft, DC-DC power converters, Pulse width modulation

I. INTRODUCTION

Developments in the aviation industry show that pneumatic and hydraulic applications are replaced by electrical equivalents [1-2]. Avionic systems using 270V DC have many advantages over 115V AC bus. Examples include reducing transmission losses and reducing energy storage element volumes and weight. The required power is obtained by the avionics conveniently due to 270V DC. Also, it can provide 115V AC voltage without any difficulty owing to its simple inverter concept. However, aircrafts that have older technology, may not be compatible with 270V DC bus (see Figure 1).

After the Second World War, DC generators were replaced with constant frequency (CF) generators. Then, turbojet fighter jets were supported with constant speed drives (CSD) to reduce engine speed to a value which can be used in CF generators. Following the development of solid-state switching technology, unreliable CSD systems were removed and generators were replaced with variable speed / constant frequency (VSCF) systems which are commonly used in F-18 fighter jets and Boeing 737-500 airliners [2]. The electrical architecture of a conventional aircraft (left) and a more electric aircraft (right) systems are shown in Figure1.

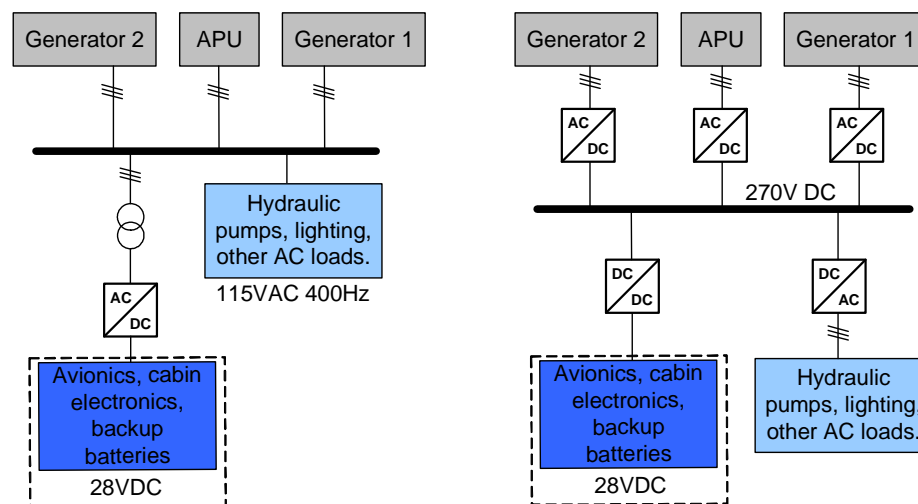


Figure 1. The power system architecture of a generic aircraft (left) and a more electric aircraft system (right)

Parallel to the ongoing developments, 270V DC standard was proposed for aviation usage (MIL-STD-704B [3]). The main aim of this voltage level was to obtain higher power density for new aircrafts. Therefore, it was foreseen that replacing 115V AC voltage with 270V DC voltage can increase stealth ability and enable design changes for future aircrafts. It was well known that DC is less detectable than AC as 270V DC systems have been employed in submarines since the beginning of the 20th century. Following the stealth and design concerns in military aircraft production, 270V DC system started to take place in F-22 stealth aircraft followed by F-35 JSF project [4]. In the meantime, more electric aircraft (MEA) started to take place in the aircraft industry [5-6] as it has cost benefits and allows integration of key subsystems. The developments cause the design of avionic systems which require 270V DC to operate. To offer some potential benefits avionics need MEA hence 270V DC especially for manned and large aircraft.

A boost converter is a good candidate to enable the technology to convert the aircraft which is produced with the previous 115V AC bus technology. There are applications at the same voltage level in the market despite their low power capability [3-6]. This situation reveals the need for high power applications. Some researchers are studied non-isolated boost converter for aircraft applications [7]. The design uses six interleaved boost converter with 97% efficiency for 20kW output. However, using a boost converter with a high conversion rate can increase stress in semiconductors and make it difficult to control. A half-bridge DC-DC converter is considered for MEA applications [8]. This topology could cause over-voltage issues at the output and complex

control. A bi-directional 28V-270V buck-boost converter is proposed as low side voltage 28V and high side voltage 270V [9] for high power. The system uses some buck-boost power modules to obtain 12kW output power. This increases modularity and makes the system reliable. There are interesting converter studies such as dual active bridge topology (DAB) [10] to reach 270V DC voltage. This design uses wide-bandgap silicon carbide (SiC) semiconductors to increase efficiency and robustness [11]. Since these semiconductors also have higher switching capabilities, they allow reducing the size of passive elements such as inductors and capacitors and the weight of the system to be reduced in general. Another version of the dual active bridge uses LLC resonant converter for 270V-28V conversion [12]. This topology did not employ SiC semiconductors however obtained 96% efficiency. Utilising wide-bandgap semiconductors is not the only option to improve efficiency however the designed interleaved super lift topology uses SiC MOSFETs to provide a more compact and lightweight solution. To meet the high-power density target of power converters, SiC MOSFET is better choice for its silicone (Si) counterpart to be considered for such applications as they operate at much higher voltages, frequencies and temperatures. Requirements for both 28V and 270V DC systems are given in Table 1. Limits for transient voltage are available in the MIL-STD- 704 w / CHANGE 1 [13] standards document.

Table 1. Standards for various voltages [13]

	Limits	
	28V DC System	270V DC System
Steady State	22.0 to 29.0V	250.0 to 280.0V
Distortion Factor	0.035 max.	0.015 max.
Ripple Amplitude	1.5V max.	6.0V max.

In order to cope with the increase in electrical energy requirement, the super lift Luo converter has been designed to support new high voltage distribution systems applications and to keep the old aircraft system active.

II. METHODS

A. Super Lift Luo Converter

The main purpose of this converters is providing a higher output voltage than the input voltage. This voltage gain can also be achieved using a transformer. However, to fulfil certain requirements of aircraft applications, transformers are avoided as they are bulky and they reduce the efficiency significantly. Main requirements for a converter which will be applied on aircraft are must-have abilities as lightweight, simple circuitry, simplicity and robustness. Therefore, application of a super lift Luo converter is selected as voltage lifting topology. This voltage boosting technique, in other words, increasing the voltage with a high conversion rate, has been successfully applied in DC-DC converters. The output voltage of the converter generally increases arithmetically. However, the super lift Luo converter has a unique approach. Super lift technique allows a geometric increase of voltage. This increases the voltage transfer gain tremendously [14]. As a result, this feature allows for lifting the voltage significantly compared to other DC-DC converters.

Some different super lift Luo converters are introduced in the literature [15]. The converter will be used in this study is the super lift Luo converter with positive output. Each circuit in the basic series has a switch SW , an inductor L_1 , two capacitors as C_1 , C_2 and two diodes as D_1 , D_2 as seen in Figure 2. Continuous conduction mode is utilized for this converter. The main super lift converter circuit and its equivalents during turn-on and turn-off are shown in Figure 2 below.

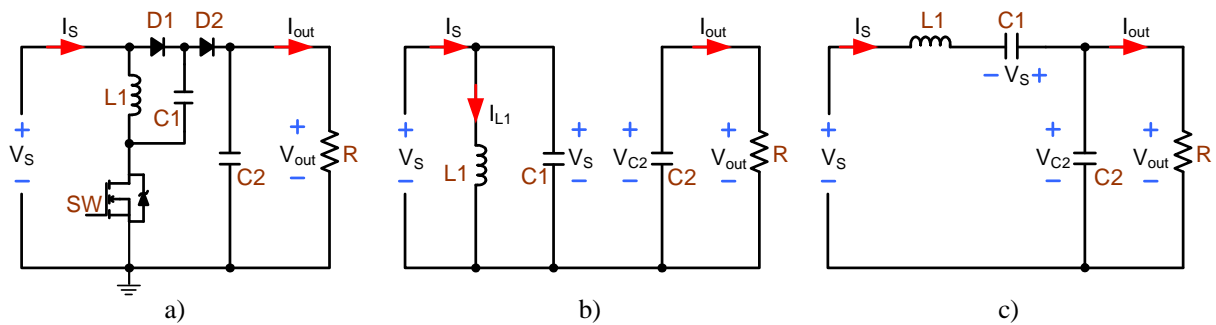


Figure 2. a) Circuit schematic, b) turn-on and c) turn-off equivalent schematics

During the switch-on period dT , input voltage (V_s) charges the capacitor C_1 and increases the inductor current i_{L1} . During the turn-off period $(1-d)T$ the current i_{L1} decreases with voltage $-(V_{out} - 2V_s)$. Then, the inductor current ripple (Δi_{L1}) is calculated as follows.

$$\Delta i_{L1} = \frac{V_s}{L_1} dT = \frac{V_{out} - 2V_s}{L_1} (1-d)T \quad (1)$$

$$V_{out} = \frac{2-d}{1-d} V_s \quad (2)$$

where V_s is the converter input voltage, d is the duty cycle and T is the period. Figure 3 shows the gain (G) as a function of the duty cycle. Assuming an ideal system with no power loss, power and the transfer gain can be calculated as;

$$V_s \times I_s = V_{out} \times I_{out}, \quad G = \frac{V_{out}}{V_s} = \frac{2-d}{1-d} \quad (3)$$

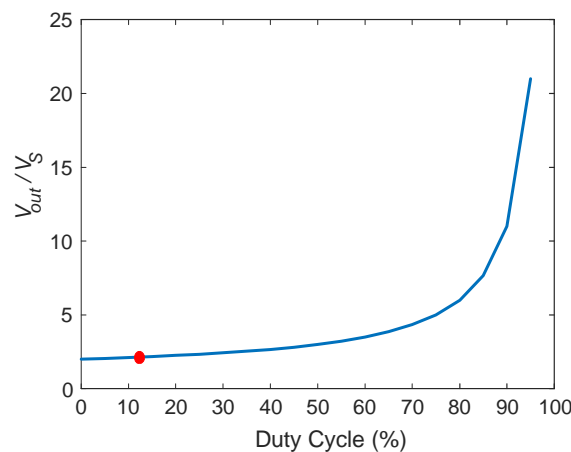


Figure 3. Gain variation as a function of the duty cycle for the proposed converter

During switch on-time, input current i_s is equal to $(i_{L1} + i_{C1})$, at switch-off time i_s , i_{L1} and i_{C1} have the same current value. The average charge at C_1 should remain the same in steady-state. The relationships are as follows.

$$i_{S_OFF} = i_{L1_OFF} = i_{C1_OFF} \quad i_{S_ON} = i_{L1_ON} + i_{C1_ON} \quad dTi_{C1_ON} = (1-d)Ti_{C1_OFF} \quad (4)$$

B. Interleaved Super Lift Luo Converter

Interleaved converter design is mainly based on the idea of dividing the current drawn from the source to n lines. By splitting the branch current, peak current values can be reduced as shown in Figure 7. The stress on the DC grid or battery caused by the drawn current peaks can be reduced using this method [16]. As a result, the lifetime of the battery can be extended, and grid quality can have a less negative effect. Figure 4 illustrates the block diagram of the interleaved converter. Here, two super lift Luo converters are used as interleaved topology.

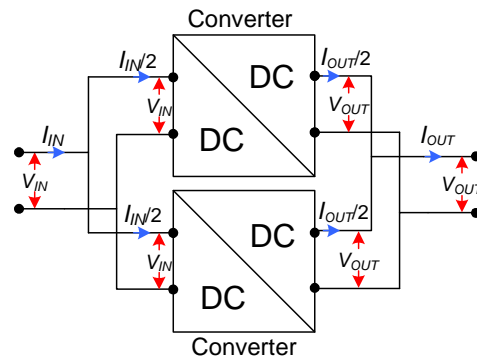


Figure 4. Block diagram of super lift Luo converter

The required current can be simply increased and output voltage ripple can be reduced by increasing the number of branches. Current stress in the semiconductors and other components can be distributed evenly by using a modulation with a shift between branches, and the ripple frequency of output current value is multiplied with the number of branches. The increment at the frequency will provide a smaller output capacitor choice as can be calculated using Equation 5.

$$C = \frac{I_{out} \times d}{\Delta V_C \times f_{sw}} \quad (5)$$

where C is capacitor value, d is the duty cycle, ΔV_C is allowable voltage ripple and f_{sw} is switching frequency. If all variables remain constant and f_{sw} increases, the capacitor value can be smaller.

As efficiency is a critical point for converters, interleaved converters improve system efficiency by reducing ripple voltage and allowing higher switching frequency [17]. If switching frequency is selected for an interleaved system as f_{sw} , for a non-interleaved system with the double branch, the switching frequency must be $2f_{sw}$. Efficiency improvements can be done using wide-bandgap semiconductors. Therefore, SiC MOSFETs are a suitable selection for this topology. They allow higher switching frequencies and reduce the size of components, i.e., capacitors, inductors, transformers and filters. The proposed topology voltage level enables to use of MOSFETs instead of IGBTs which have higher switching losses.

III. SIMULATION

The simulation of the interleaved super lift Luo converter is done using PSIM and the power circuit is represented below in Figure 5. PSIM is a power electronics simulation software which allows rapid modelling and simulation. Simulation and circuit parameters are tried to be selected in a realistic way based on calculations that comply with MIL-STD-704 standards [13] while ignoring switching losses. Voltage tolerances and ripple agree with the standards. A closed-loop control approach with the PI controller is simulated in this paper. The

Ziegler-Nichols method is employed to determine initial PI values. Then fine-tuning is accomplished for the PI values after adding current feedback.

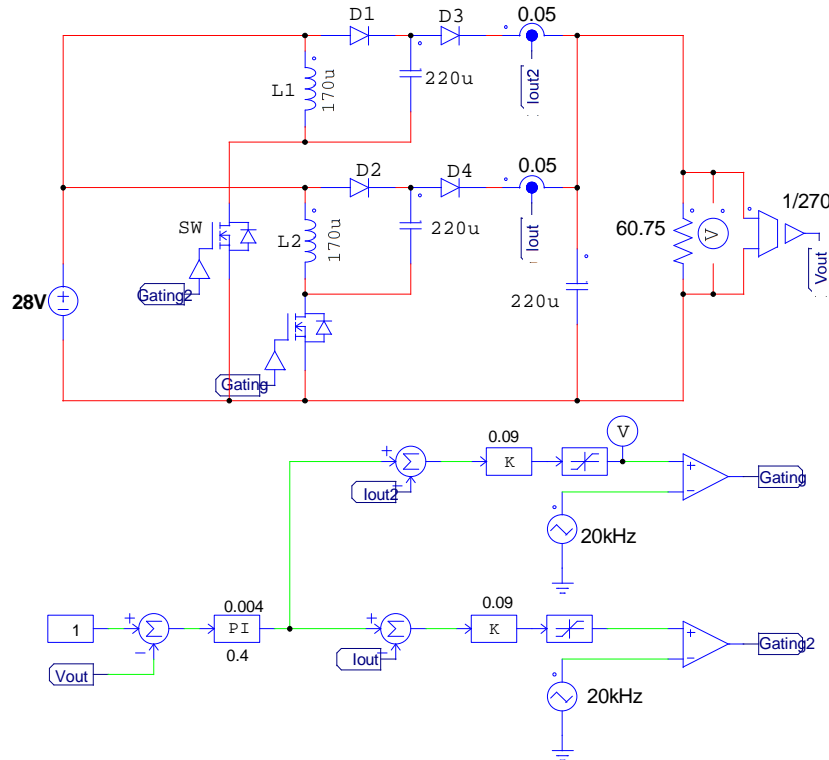


Figure 5. Circuit schematic and control system of the proposed converter

Each DC link inductor in the proposed topology is determined to operate in continuous conduction mode (CCM) according to the 7A peak-to-peak ripple (ΔI) calculation. The output capacitor is also determined to give a maximum voltage ripple of 1%. In order to stay on the safe side in terms of electromagnetic interference (EMI) and audible noise issues, 20kHz switching frequency was determined for each super lift branch. This topology can also be operated in discontinuous conduction mode (DCM) using a smaller inductor value. This operation will require a more complex control system. In this case, the study is only focused on CCM.

Avionics require waveforms with high-quality and extremely stable output voltage. Different approaches regarding control systems can be found in the literature. Applications for the feedback voltage control are split into two categories. One is control of single loop voltage [18-19] and the other is control of double loop voltage [20-21].

Pulse width modulation (PWM) method with hard switching has been used to control the high-frequency SiC MOSFETs. Each signal comes from the controller has a 180-degree difference. At the control system design level, a PI (Proportional-Integrator) controller with current input from the closed loops is used. PI controller system uses proportional and integrator methods to compare a reference signal with the output. In this controller, K values are determined as 0.09, P value as 0.4 and I value as 0.004. The voltage feedback value is divided into 270 and the current feedback value is divided into 500. Since both current and voltage loops are used, the control method is called double-loops. The voltage feedback is taken directly from the load at the output of the converter and the current feedback is directly from the inductor of each interleaved converter. The positive input of the comparator is the control signals of the switches. Negative inputs are 20kHz triangular carrier signals.

Figure 6 shows the output voltage (V_{out}), current (I_{out}) and power (P_{out}) values of the converter. The model complies with the standards by showing good agreement with the values set out in MIL-STD-704 [13]. The system output value settles within 0.2 s to the required value. Also, at the output, current ripples and output ripples are negligibly small. While 28V DC to 270V DC conversion, 4.5A output current is obtained with a total power of 1.2kW.

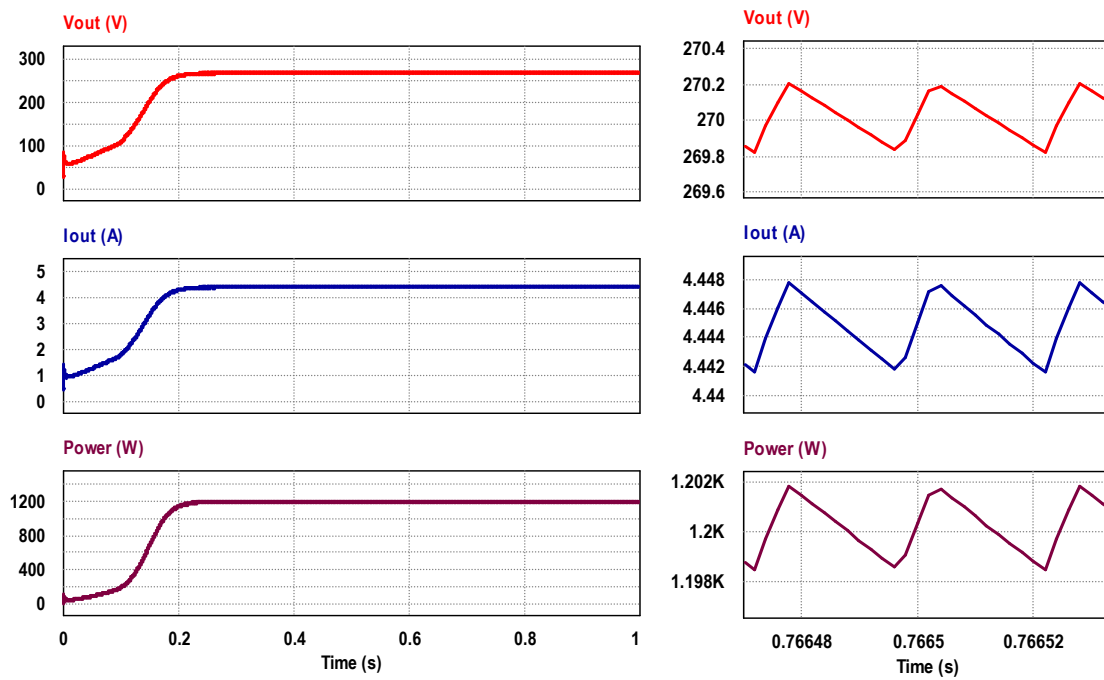


Figure 6. Circuit voltage, current and power output with ripples

The advantages of interleaved architecture were discussed before as high-frequency ripple, low peak to peak ripple and high current capacity due to the divided structure. In Figure 7, the inductor current ripple of each branch is $\sim 7A$. Each inductor current has 32% ripple. These fluctuations are halved due to interleaved topology. If the interleaved branches are increased there will be less ripple. It is also important to optimize passive elements in this circuit. Please note that currently all the components are assumed ideal.

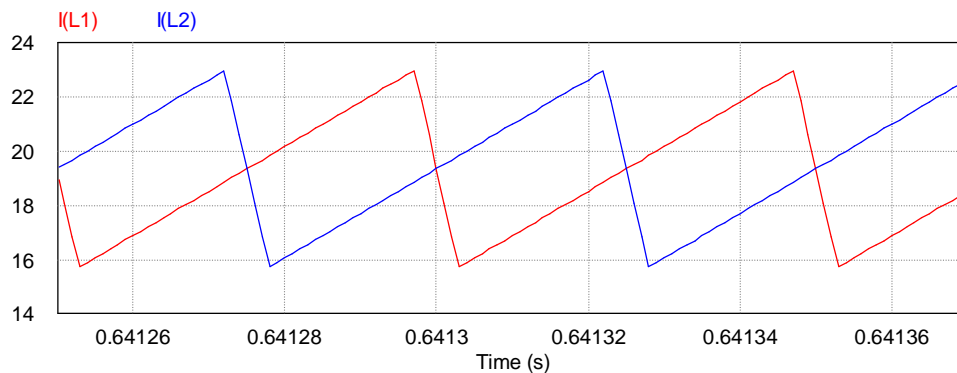


Figure 7. Input inductor current ripples

IV. CONCLUSION

In this study, a 1.2kW interleaved super lift Luo converter for aircraft applications is designed and simulated for retrofit and new avionics applications. The system is designed to have higher power density, better reliability, efficiency and robustness while considering standards.

The designed interleaved topology is an alternative for a different type of topologies for aircraft applications, especially for retrofit applications. The super lift function allows having higher conversion ratio with safer operation. It is also extendible due to its interleaved nature for higher power levels. The interleaved scheme is adapted to super lift Luo converter which has a very high voltage lifting capability. The interleaved approach reduces ripple voltage hence reduces losses. It also reduces the high current stress across the single switch. Additionally, interleaved topology gives a faster transient response when the load changes. These important features are so critical for aircraft applications. This modular approach is good for high power applications.

As wide-bandgap semiconductors are becoming less expensive it is also important to use SiC MOSFETs for this topology to have much higher efficiency, higher power density and better thermal management. SiC MOSFETs permit higher voltage margins as well.

As a result, 270V DC output is observed with promising current and voltage ripple values. Double-loop PI controller works well and modulates the converter to lift the voltage conveniently despite high conversion ratio. Therefore, this design and its variations for different power levels can be good candidates for the retrofit and MEA applications.

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