MATEC Web of Conferences **314**, 02005 (2020) https://doi.org/10.1051/matecconf/202031402005
ICSC-ISATECH 2019

1.2kW Interleaved synchronous buck converter design for aviation systems

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Abstract. The principal aim of this work is to design a battery-operated 1.2kW interleaved synchronous buck converter for aviation systems to obtain lower losses compared to the existing topologies. It is desired to achieve at least a 5% loss reduction. Military aircrafts such as F-22 and civil aircraft as Boeing 787 are using the 270V DC for their battery systems. Although 270V DC system has some advantages such as reducing loses and the passive element sizes, old avionics that have been designed, produced and used since the second world war may not be compatible with the 270V DC system. Conversion from 270V to 28V appears to be quite promising for both old and new systems. Therefore, a buck converter design for 270 to 28V conversion is proposed in this study to adapt older avionics technology to accommodate new achievements. The analysis of the SiC MOSFET based interleaved synchronous buck converter with a double loop PI controller is presented. The paper demonstrates the principles of the design and discusses possible future developments. The concept is verified using simulations.

1 Introduction

The recent developments in aircraft applications are mainly replacing pneumatic and hydraulic applications with electrical equivalents [1-2]. 270V DC system which is recently employed in aircraft has many benefits. For instance, loss reduction in transmission and energy storage element sizing. It makes easier to supply the required power to the avionics with lower losses using 270V DC. It also makes easier to supply 115V AC to the system with smaller and less complicated inverters. However, the avionics have been designed, produced and used since the second world war may not be compatible with the 270V DC system. A buck converter can be used to adapt previous voltage levels and standards to enable the usage of those avionics. There are circuits in the market for the same voltage range but low power applications in general [3-6]. This reveals a requirement for circuit design with high power capability.

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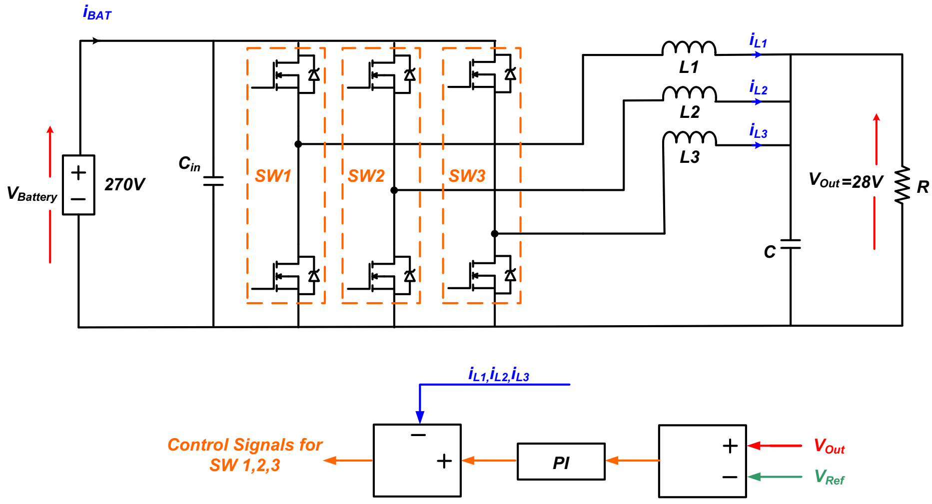

Figure. 1. The proposed interleaved synchronous buck converter

In this study, an interleaved synchronous buck converter topology is proposed for aircraft systems. Figure 1 shows this topology and its control block diagram.

1.1 Theoretical background

The weight and size of the power electronic elements can be quite critical while making a design for aircraft application. Interleaved systems cause smaller ripples at both input and the output of the circuit. So they use smaller energy storage elements compared to single buck converter's larger inductors or capacitors. They also provide higher reliability due to switch fault tolerance [7]. The output current is N times greater when each converter gives the same current as of the non-interleaved converter. The proposed interleaved topology is suitable due to the requirements for high current and low voltage output [7-9]. In addition, synchronous converter have many advantages compared to simple buck topology which has a diode instead of a high-frequency switch. Synchronous converters have higher efficiency compared to nonsynchronous converters with no forward voltage drop and they are better suited for high-frequency applications [10]. There are different topology approaches such as dual active bridge topology [11]. This topology is using wide-bandgap SiC semiconductors to increase the converter efficiency. Using GaN or SiC transistor switches for the design will result in substantial loss reduction in the converter system [12]. Therefore the designed topology employs SiC MOSFETs. Design requirements are defined by MIL-STD-704. The requirements for DC systems for both 28V DC and 270V DC are shown in Table 1. Transient voltage limits can be found in MIL-STD- 704 [13] specification.

Table 1. Voltage Standards [13].

	Limits	
	28 V DC System	**270 V DC System**
Steady State	22.0 To 29.0 Volts	250.0 To 280.0 Volts
Distortion Factor	0.035 Maximum	0.015 Maximum
Ripple Amplitude	1.5 Volts Maximum	6.0 Volts Maximum

1.2 Proposed topology

The study recommends 3 interleaved buck converter stages. All stages employ 2 switches for buck switching. Each switch couple (SW1, SW2, SW3) is driven by a double loop feedback controller. Each control signal acquires current data from IL1, IL2, IL3 and modulates SW1, SW2 and SW3 respectively. Utilizing the three-level interleaved stage, 100kHz switching frequency causes 300kHz ripples at the output waveforms of the system. This high-frequency ripple is easy to filter so it requires a smaller output capacitor. In addition, the output filter of the converter could be downsized if the driving signals of N converters have 2π/N phase-shift each [13]. The reason is due to including each converter's output current, and its frequency is greater than the non-interleaved converter frequency. Also, if a switch malfunctions, the remaining two stages of the interleaved system can continue operating within the MIL-STD-704 DC voltage standards [14].

2 Simulation

The interleaved synchronous buck converter is simulated using PSIM simulation software and is shown below in Figure 2. In the simulation, the switching losses are neglected. Circuit and simulation parameters are selected realistically to comply with MIL-STD-704 [14] standards. Ripple levels and voltage tolerances comply with the standards. Optimal working conditions are considered for element sizing and one switch fail scenario. In this paper, the optimal working scenario with the PI controller is simulated.

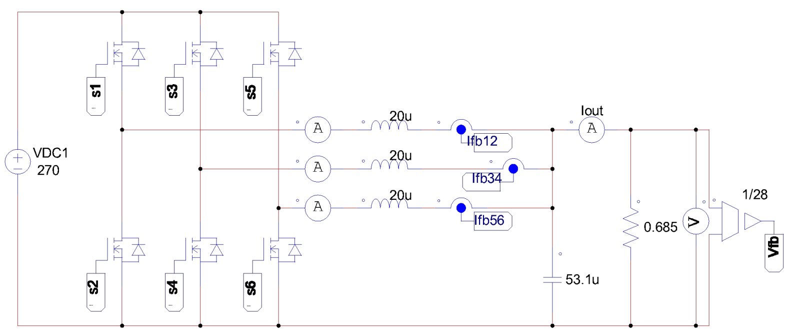

Figure. 2. The proposed circuit simulation model

The power stage of the circuit is shown in Figure 2. Inductors are selected for continuous conduction mode (CCM) with maximum 12A DC peak-to-peak ripple (ΔI) on each one of them. Also, an output capacitor is selected to have a maximum of 3% voltage ripple. 100kHz switching frequency is determined to use smaller passive components. As can be seen in Figure 2, the low-pass output filter consists of an inductor and a capacitor and provides decent filtering (see Figure 4). Discontinuous conduction mode (DCM) can also be employed with this topology using substantially smaller inductor value. This requires further investigation.

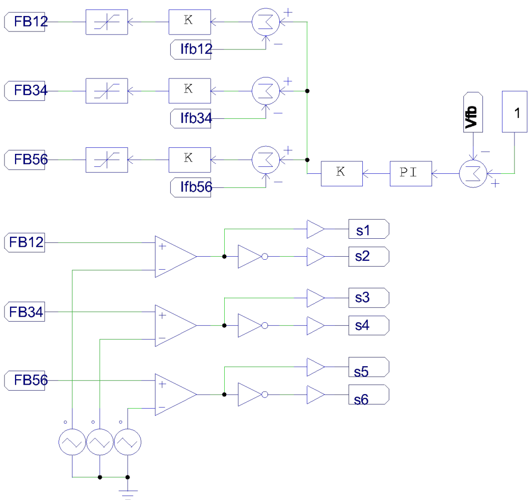

Figure. 3. Proposed circuit control and modulation scheme

Avionic systems require high-quality waveform and very stable voltage output. The converter literature suggests different methods for control systems. Voltage control applications are divided into two groups. One is the single loop voltage control [15-16] and the other is the double loop voltage control [17-18].

At the design stage of the control system, all interleaved systems considered as one system to protect the failure of the one from the other. Therefore, the control system uses three closed-loop PI control with current feedback as seen in Figure 3. Proportional-Integrator controller system is a control method which uses a reference signal to compare with the output using proportional and integrator calculations. In this controller, all K values are selected as 1, P is selected as 2 and I is selected as 0.004. Voltage feedback is divided by 28 and current feedback is divided by 100. If both voltage and current feedback loops are used, it is called double-loop control system. Voltage feedback is obtained from the output of the system which is directly connected to the load and current feedbacks for each interleaved stage is acquired directly from inductors. Positive inputs of the comparators are control signals of switches 1-2, 3-4 and 5-6 respectively. Negative inputs are 100kHz triangular carrier signals with $2\pi/3$ phase difference. It is important to note that if a failure occurs in a single interleaved stage, it is still possible to obtain the desired output voltage with this control approach.

3 Results

Figure 4 shows the converter output voltage (V_{out}) and current (I_{out}) waveforms. The topology and performed simulations comply with the standards at MIL-STD-704 [14]. System output value settles at the required value in 0.02 seconds. Also, 0.1A of current ripple (I_{ripple}) and 0.07V of voltage ripple (V_{ripple}) is obtained at the output. The conversion from 270V to 28V took place with an output current of about 41A and a power output of 1150W. Table 2 provides the parameters based on the simulations.

Table 2. Simulation Results.

Parameters	**Values**
V_{IN}	270V
I_{IN}	4.25A
V_{OUT}	28V
I_{OUT}	40.9A
V_{RIPPLE}	0.07V
I_{RIPPLE}	0.1A
Power	1145W

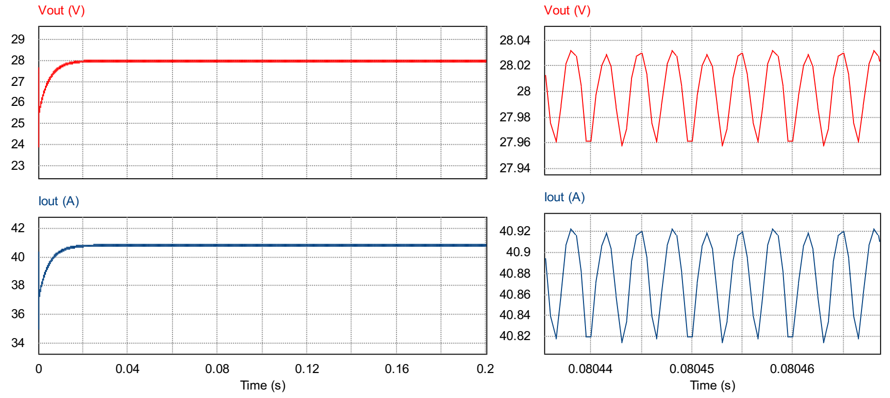

Figure. 4. Converter output voltage and current waveforms including ripples

Although the converter system demonstrates very high efficiency and almost no losses, all the passive elements and semiconductors are assumed to be ideal in the simulations. Future work requires loss calculations including thermal management and test results.

4 Conclusions

A 1.2kW synchronous interleaved buck converter designed and simulated for retrofit purposes. System design is based on reliability, better efficiency and standards which were determined by MIL-STD-704F [14].

A high-frequency switch is used for the low side switch instead of a diode to make the system interleaved. This permits optimal timing control and reduces the passive element sizes by allowing higher switching frequency so the losses can be reduced significantly. As a result, the proposed topology has reduced losses and fluctuations by employing synchronous and interleaved approaches whilst employing SiC MOSFETs. This also minimizes thermal management needs. Besides, it is still possible to obtain the required power output if there is a failure at one of the interleaved stages.

This topology and its variations for different power levels can be good candidates for the aviation industry. Although the proposed converter offers the desired loss reduction, further work is required to perform more detailed simulation and test results.

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