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Comparative analysis of inverter topologies for 400Hz Ground Power Unit

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Abstract

This paper presents a survey research, analysis, and comparison of the performance of three three-phase inverter circuit topologies applied to GPU ground power supplies in the aviation industry. One of the prominent characteristics of aircraft load systems is their unbalance; therefore, evaluating the operational performance and output voltage quality of the power supply under unbalanced load conditions for these three inverter circuit topologies is the main focus of this research. Additionally, several other parameters such as DC voltage and the input DC filter capacitance utilization are also analyzed and compared. The simulation results using Matlab software demonstrate that the three-single-phase H-bridge topology provides the highest efficiency, maintaining the best output voltage quality, especially under conditions of unbalanced load, thus opening up a new design direction for GPU power supplies for aircraft.

Keywords: *Ground Power Unit, Airplane load distribution, Three-phase inverter topology, Inverter Topology Comparison, Unbalanced Load Condition*

Symbols

Symbols	Units	Description
A, **B**, **C**, N		Phases and Neutral
I_N	A	Neutral current RMS value
C_{dc}	F	DC-link capacitance
ΔV_{dc}	V	Mid-point voltage fluctuation
ω	rad/s	Fundamental frequency

Abbreviations

GPU	Ground Power Unit
SDP	Switching device power

Tóm tắt

Bài báo này trình bày một nghiên cứu khảo sát, phân tích và so sánh hiệu quả của ba cấu trúc mạch nghịch lưu ba pha được áp dụng cho bộ nguồn mặt đất GPU trong ngành công nghiệp hàng không. Một trong những đặc điểm nổi bật của hệ thống phụ tải máy bay là tính không đối xứng, do đó, việc đánh giá hiệu suất hoạt động và chất lượng điện áp đầu ra của bộ nguồn trong điều kiện làm việc với phụ tải không đối xứng của ba cấu trúc mạch nghịch lưu là trọng tâm chính của nghiên cứu này. Thêm vào đó, một số thông số khác như khả năng tận dụng điện áp DC và dung kháng của tụ lọc DC đầu vào cũng được phân tích và so sánh. Kết quả mô phỏng trên phần mềm Matlab cho thấy cấu trúc ba cầu H đơn mang lại hiệu suất cao nhất, duy trì chất lượng điện áp đầu ra tốt nhất, đặc biệt trong điều kiện làm việc với phụ tải không đối xứng, mở ra hướng thiết kế mới cho bộ nguồn GPU cung cấp cho máy bay.

1. Introduction

The load system in airplanes has significantly increased recently in complexity due to advancements in technology and the growing demand for more electrical systems [1-3]. Modern aircraft now incorporate a wide array of electronic devices, from three-phase loads including motors, generators, air conditioning systems, etc., to single-phase loads, such as avionic equipment and fly-by-wire controls, or in-flight entertainment systems. The simple representation of airplane power system is expressed in Fig. 1 [4].

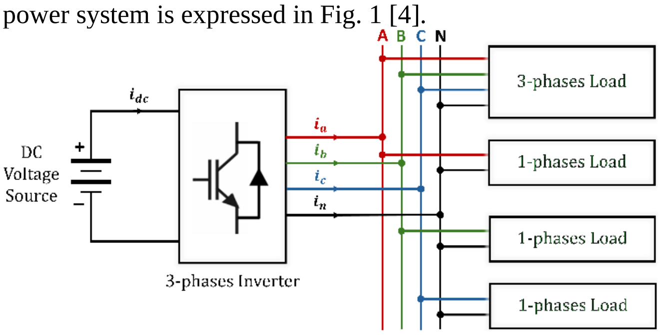

Figure 1: Representation of Airplane power system.

As expressed in Fig.1, the load distribution system in an airplane operates as an unbalanced system, necessitating inverter topologies specifically designed to manage this imbalance effectively. Given the diverse range of single-phase and three-phase loads, the inverter must ensure that power is distributed evenly across all systems, mitigating issues related to voltage fluctuations and maintaining operational efficiency. Advanced inverter designs can dynamically adjust to varying load conditions, providing reliable voltage management while enhancing the overall performance and safety of the aircraft. This raising the requirement to the implementation of the control system which can guarantee the system performance in the unbalanced load condition.

To overcome these challenges, a three-single-phase H-bridge topology has been proposed for the inverter in this research, ensuring high reliability, particularly under unbalanced load conditions. The single loop voltage control scheme has also been designed to evaluate the compatibility of inverter topology with single-phase independent control strategy, which is essential for controlling unbalanced loads. Furthermore, a comparison with classical three-phase three-

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wire and three-phase four-wire topologies has been conducted to verify the advantages of the proposed topology for GPU design.

2. Comparative analysis of topologies

2.1. Three-phase three-wire topology

Three-phase three-wire is one of the most popular topologies, which has been applied for inverter in many publication [5-8], due to its straightforward design. This topology does not provide inherently a neutral point, so the virtual neutral point normally is created at the mid-point of split DC link capacitors [9].

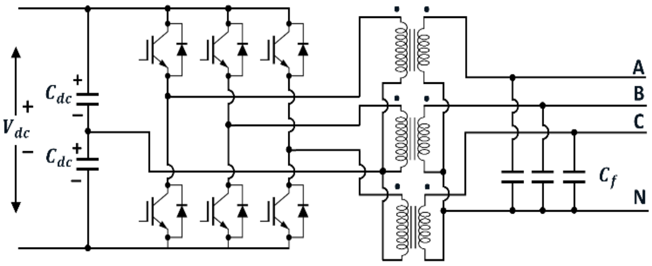


Figure 2: Three-phase three-wire inverter system

A balancing mechanism to regulate the voltage of the mid-point is required for this configuration. Normally, the control design for just mid-point voltage creates the complexity for the overall control system design.
The neutral current can be expressed as [10]:

$$i_n = I_N \sin(\omega t) \tag{2.1}$$

The capacitance can be found as:

$$C_{dc} = \frac{I_N}{\Delta V_{dc} \omega} \tag{2.2}$$

It can be seen in the Eq. (2.2) that, higher voltage value (leading to higher I_N) requires the larger size of mid-point capacitors, causing very low dc link utilization.
High performance is not provided by this inverter structure when faced with unbalanced loads. Unbalanced loads can lead to voltage imbalances across the phases, hence, poor current sharing among the inverter legs, which can overload certain phases.
Even though a smaller number of switches required, the total peak switching device power (SDP) is high [10].

2.2. Three-phase four-wire topology

In a three-phase four-wire inverter, the addition of a fourth leg significantly improves performance when handling unbalanced loads, compared to the traditional three-phase three-wire topology. This extra leg provides an additional degree of freedom in the control system, which, while beneficial, also complicates the control system design. Although this configuration can lead to a 15% improvement in DC link utilization and allows for the use of lower-rated DC link capacitors, it introduces challenges as well [11-13].
Specifically, the increased complexity arises from the unequal current stresses experienced by the neutral leg compared to the other three-phase legs. This disparity can lead to a rise in the SDP relative to the three-phase three-leg inverter [11]. Consequently, engineers must navigate both the intricacies of control design and the hardware implementation challenges that stem from these unequal current distributions. Balancing these factors is essential for optimizing the performance and reliability of the inverter in practical applications.

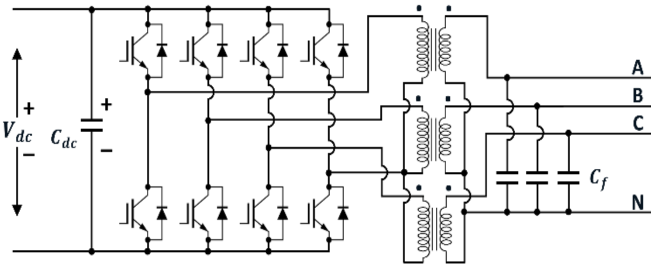


Figure 3: Three-phase four-wire inverter system

2.3. Three-single-phase H-bridge inverter

The three-single-phase H-bridge inverter topology is a versatile and efficient solution for generating three-phase AC power from a DC source [15-18]. The structure consists of three separate H-bridge circuits, each dedicated to producing one phase of a three-phase AC output, as depicted in Fig. 4.

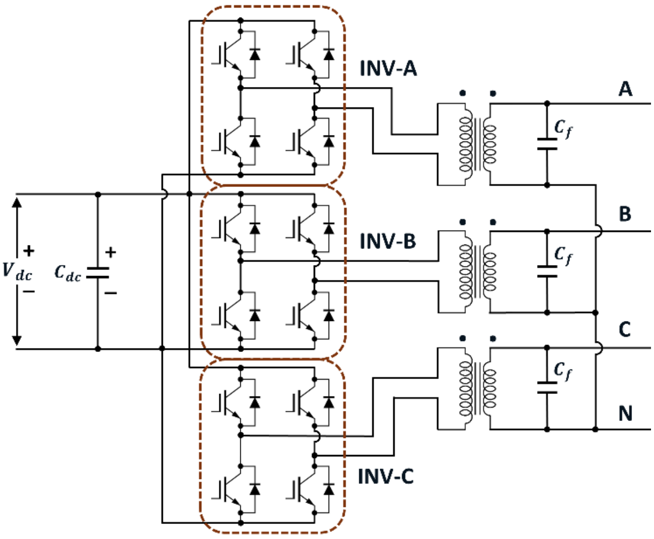


Figure 4: Three-single-phase H-bridge topology.

This inverter topology offers numerous advantages that make it a preferred choice in GPU application. Unlike topologies like three-phase three-wire and three-phase four-wire where switches are rated unequally, this topology allows for all switches to have uniform ratings. Although higher number of devices are required, the total peak SDP is still lower or of the same order, in this converter. Consequently, high efficiency due to lower switching losses, is its primary benefits compared to previous topologies.
Three-single-phase H-bridge topology provides flexibility in modulation and control, allowing each H-bridge to be modulated and controlled independently, inherently producing a balanced three-phase output, crucial for the efficient operation of unbalanced load while reducing harmonic distortion. Besides, the simplicity of the design facilitates easier implementation of control algorithms, troubleshooting, and maintenance.

3. Control system design

3.1. Proposed control scheme

For the three-single-phase H-bridge inverter, each phase can be controlled independently, based on SPWM modulation [16]. Alternatively, 3D-SVM in combination with dual loop control, designed in dq0 coordinator frame, enables a more unified control strategy that can improve overall system efficiency and reduce harmonic distortion. Both methods have their advantages and can be chosen based on the specific requirements of the application.

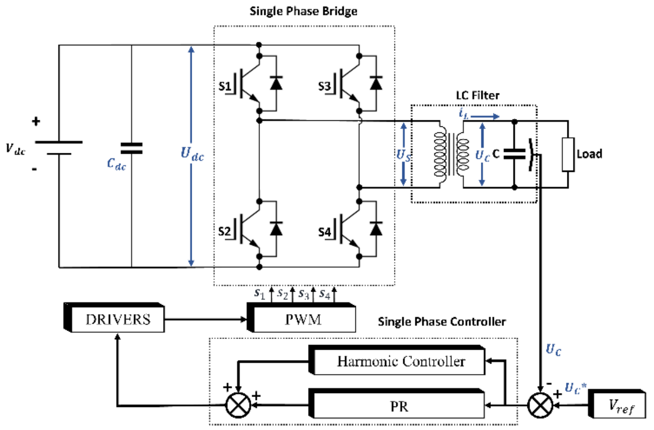


Figure 4: Single-phase independent control system based on SPWM for Three-single-phase H-bridge GPU.

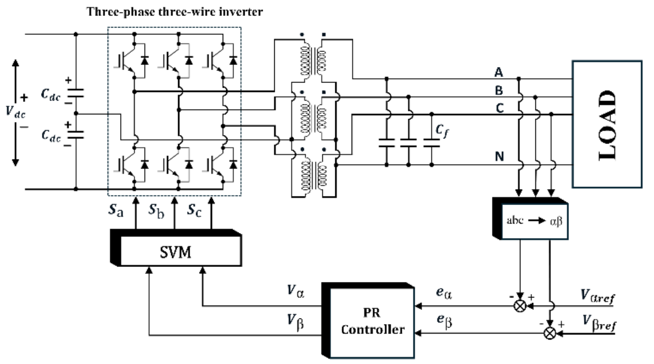


Figure 5: 3-phase 3-wire GPU voltage source overall control system.

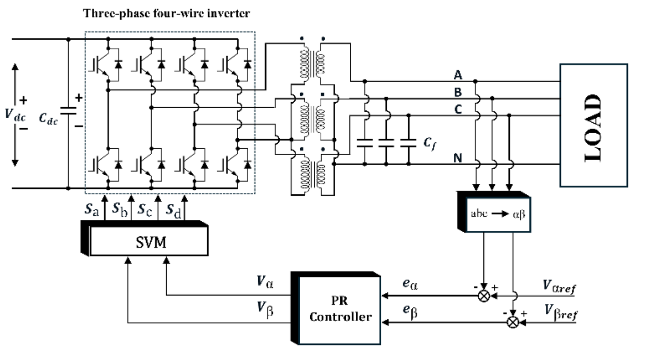


Figure 6: 3-phase 4-wire GPU voltage source overall control system.

To compare to the two topologies mentioned above, independent control in a three-single-phase H-bridge inverter is a significant advantage, as it allows for precise modulation of each phase's voltage and current individually. This capability enables optimal performance in applications of unbalanced load, which is the popular working condition with airplane load fault tolerance; if one H-bridge experiences issues, the others can continue to operate normally, maintaining overall system functionality. Besides, in high-power 400Hz inverters, the switching frequency is limited by the capabilities of high-power switches, often not exceeding 20kHz. This restriction leads to a low ratio between the converter's switching and fundamental frequency, which limits the control bandwidth. As a result, implementing inner current loop control becomes infeasible. For this reason, a three-phase independent single-loop control system is developed for the three single-phase H-bridge GPU. The simulation results have been analyzed in contracted to two previous topologies, with the same single-loop control scheme, to highlight the efficiency of driving individual phase in three H-bridge system.

The independent control system for a single-phase H-bridge is illustrated in Fig. 4. This can be extended to a three-phase system, where three single-phase Proportional Resonant (PR) controllers are used to regulate the output voltage. The three reference signals are set 120 degrees apart to create a balanced three-phase output.

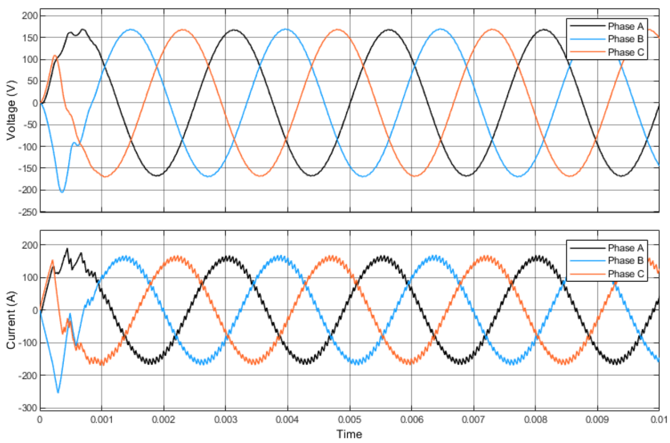
3.2. A case study

A simulation on the MATLAB platform is performed to verify the dynamic response of the three proposed configurations in single-loop voltage control mode. The system parameters are listed in Table 1, which are common across all three cases. The PR controller for the converter topologies is designed using the same method in the frequency domain. Furthermore, the comparison results are analyzed when the system operates in steady-state, where the controller parameters have minimal impact on the comparison outcomes between the three converter topologies. All of these ensure that any performance differences observed are attributable to the topology itself rather than external factors.

Table 1: System parameter

Parameter	Value
Filter inductance (L_f)	200μH
Filter capacitance (C_f)	25μF
PWM frequency (f_{PWM})	18kHz
Transformer ratio (r)	5/3
Output voltage (v_o)	170V (RMS)
Fundamental frequency (f_0)	400Hz

First, the simulation in the case of three-phase rated resistive-inductive (RL) load is shown in Fig. 7a, 7b, 7c.



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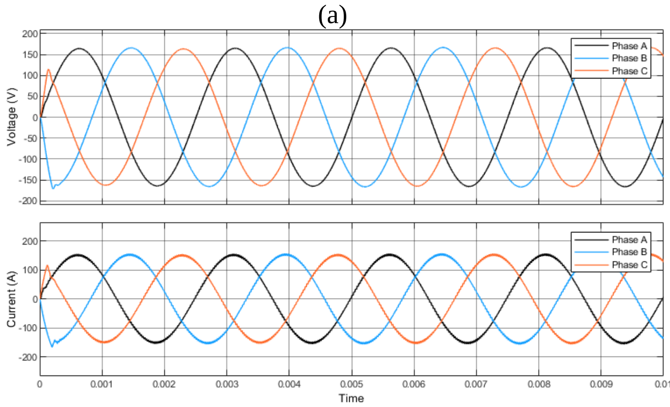

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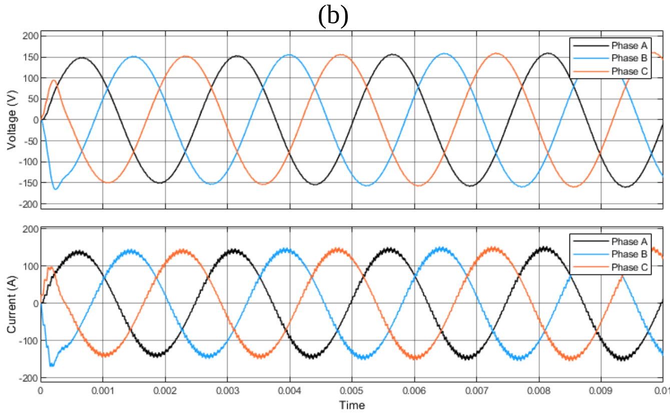
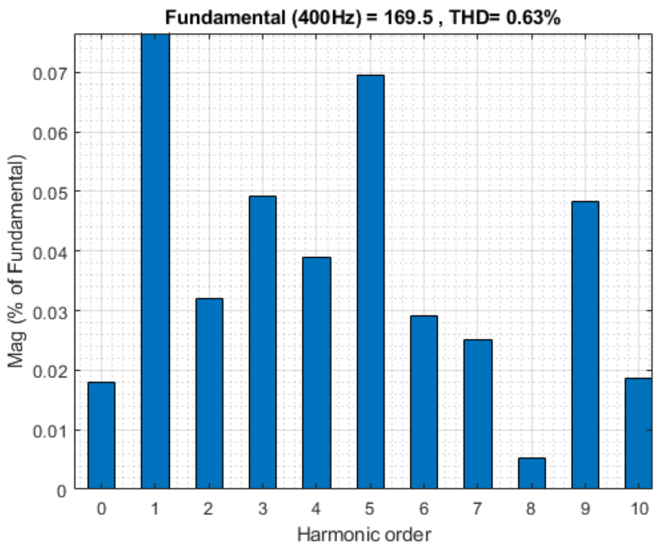


(b)

Figure 7: Three-phase voltages and inductor currents under balanced load condition a) 3-phase 3-wire, b) 3-phase 4-wire c) Three H bridge topology.

It can be observed from the results in Figure 7 that the three-single-phase topology voltage source with an independent phase control structure provides a faster response, with the output voltage maintained at the reference value within approximately 1/4 of a cycle. At the same time, providing the highest voltage quality, as evidenced by the THD value being the smallest, just 0.39% in Figure 8.

This is evident because the output voltage of a single-phase H-bridge inverter typically has a lower amplitude (due to a lower DC-link voltage) and exhibits lower voltage fluctuations compared to the other two topologies. Therefore, under the same transformer and filter circuit parameters, the output voltage will have the smallest THD.



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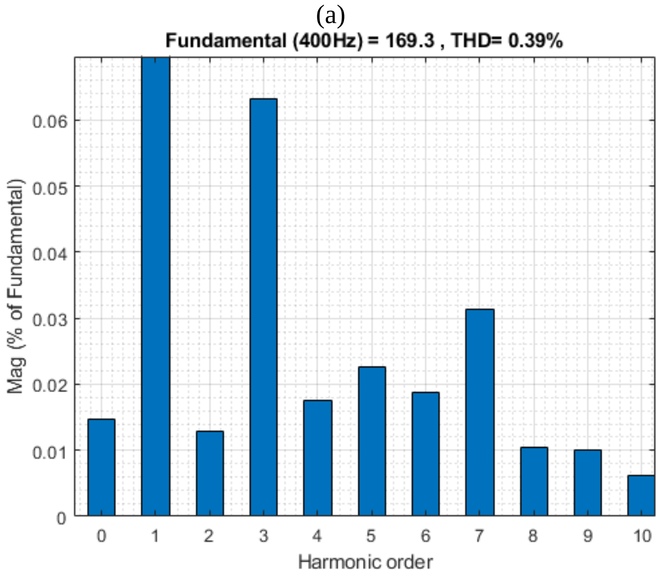

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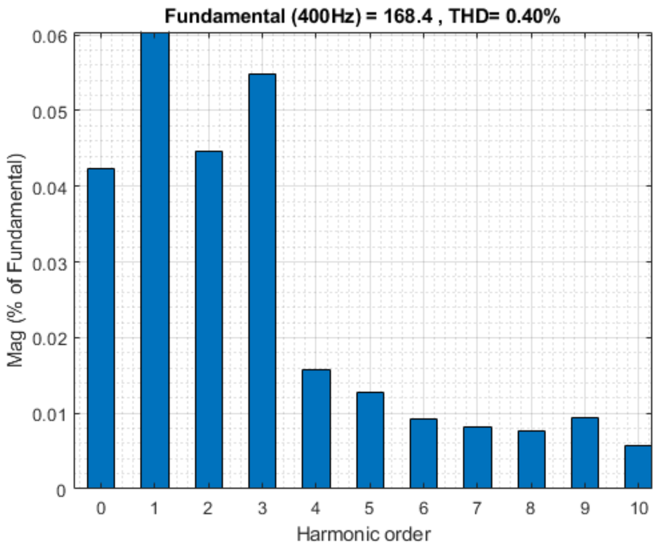
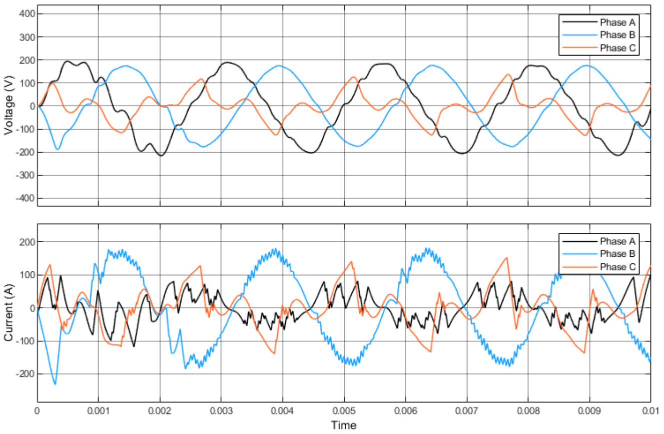


(c)

Figure 8: THD content of output voltage Phase A under the balanced load condition a) 3-phase 3-wire, b) 3-phase 4-wire c) Three H-bridge topology.

The verification simulation continues with the case of an unbalanced load. First, the dynamic response of three inverter sources is analyzed for an RL unbalanced three-phase load, where there is no load on phase A, corresponding to 100% unbalance, while phases B and C are at full load.

Simulation results in Figure 9 and the THD in Figure 11 show that, with a 3-phase 3-wire structure, the output voltage is significantly distorted, with the THD of phase A at 16.72% and phase C reaching as high as 55.98%. Only the voltage of phase B is less distorted, but the THD is still relatively high at 3.91%. This demonstrates a significant disadvantage of this structure in cases of unbalanced loads. The 3-phase 4-wire and single-phase H-bridge still maintain very good voltage responses. In particular, the single-phase H-bridge structure provides an output voltage with low THD for all three phases, and the voltage difference among the three phases is also maintained at less than 1%.



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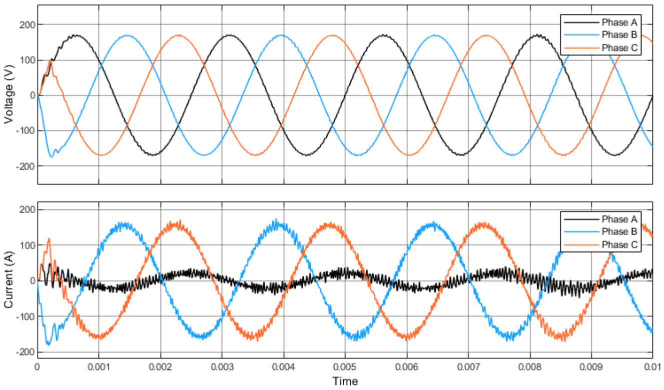

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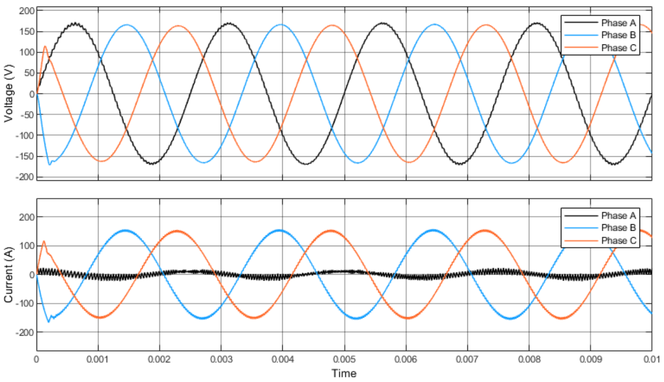
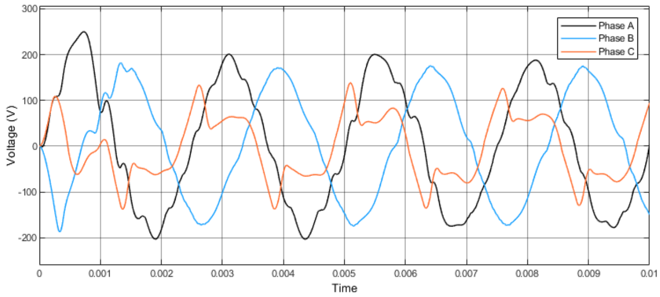


(c)

Figure 9: Three-phase voltages and inductor currents under RL unbalanced load condition a) 3-phase 3-wire, b) 3-phase 4-wire c) Three H-bridge topology.

The investigation continues with the case of unbalanced nonlinear loads. Specifically, phase A is set to no load, phase B is at full load, and phase C is connected to a nonlinear load. The nonlinear load used in this case includes a diode rectifier, combined with a 50µF filter capacitor, and a 1.09Ω load. To compensate the harmonic distortions caused by nonlinear load, the 3rd order harmonic compensators are added to PR controllers. The output voltages in the three cases are shown in Figure 10, and the THD is presented in the chart in Figure 11. Similar to the previous case, the power supply using the 3-phase 3-wire structure cannot maintain the stability of the 3-phase voltage in this case, leading to very high THD, with output voltages of phases A and C being unstable, and phase B exhibiting very poor quality. Meanwhile, the power supplies using the 3-phase 4-wire and combined single-phase structures still maintain a good response, with the output voltage adhering to the reference, and the THD of all three phases being kept low. Notably, the three-single-phase GPU shows superiority in both the maximum voltage difference of the three phases, being less than 1% compared to 1.4% for the 3-phase 4-wire case, and the THD of the 3-phase voltage is also better, with values of 1.12%, 0.37%, and 0.91%, respectively. This demonstrates the superior advantages of the combined single-phase structure when operating under different cases of load imbalance.



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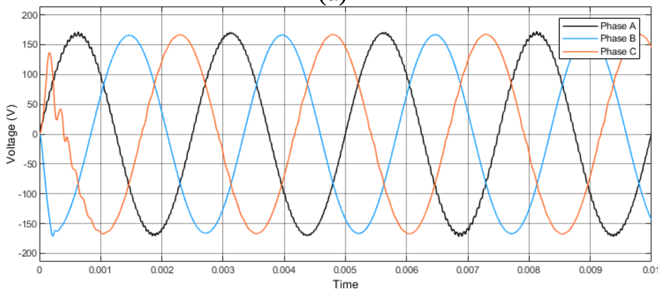

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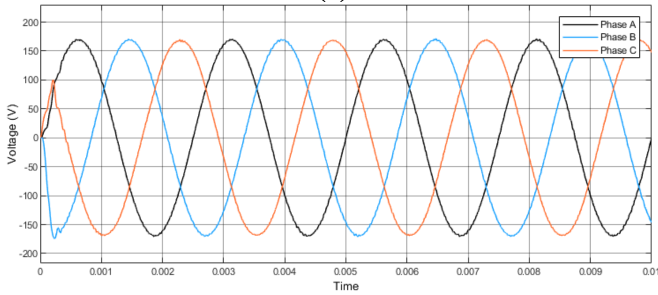

(c)

Figure 10: Three-phase voltages under nonlinear unbalanced load condition a) 3-phase 3-wire, b) 3-phase 4-wire c) Three H-bridge topology.

The investigation continues with the case of unbalanced nonlinear loads. Specifically, phase A is set to no load, phase B is at full load, and phase C is connected to a nonlinear load.

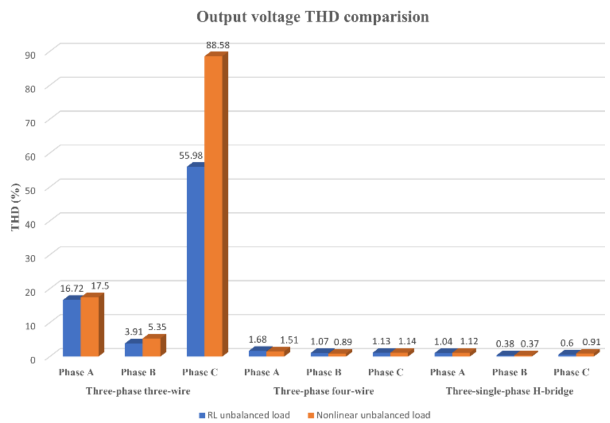

Figure 11: Comparison of output voltage THD as unbalance increased.

To validate the comparative analysis of the inverter topologies, MATLAB simulations are performed under various working conditions. The general system specifications listed in Table 2 are used for the simulations. The DC link voltage utilization and capacitance, as well as the SDP, are determined using analytical calculations.

The efficiency is defined as the ratio of the output power (P_{out}) to the input power (P_{in}). In which, P_{out} is the total power delivered to the load, which is computed based on the measuring the RMS values of voltage and current on the resistive component of load, using the tool available in Matlab. P_{in} is the power drawn from the DC power supply.

Table 2: Comparison result of 3 inverter topologies

Parameter	3-phase 3-wire	3-phase 4-wire	3-phase H-bridge
Min input DC voltage	336V	288V	168V
Min DC Capacitor	2*48.6mF	3.3mF	3.3mF
Capacitor Peak Current	178.5A	11.9A	24.5A
Capacitor RMS Current	28.5A	6.45A	79.5A
Capacitor Energy storage	1.371kJ	136.86J	46.6J
Total peak SDP in kVA	864kVA	920kVA	768kVA
Control/Modulation	SVM	SVM	SPWM
Efficiency	98.30%	96.70%	97.80%
Efficiency (unbalanced Load)	-	95.90%	97.80%

According to the statistical results in Table 2, the GPU with three-single-phase H-bridge inverter topology provides better parameters than the other two topologies in many aspects. In particular, the efficiency is able to maintain stable and significantly better efficiency in both balanced and unbalanced load conditions, demonstrating the suitability of this topology for application in GPU voltage sources.

4. Conclusion

The three most commonly used topologies applied for the industrial inverter voltage source have been analyzed and compared to select the most suitable structure for the aircraft GPU power supply. Simulation results using Matlab software have demonstrated that three-single-phase H-bridge topology provides the best efficiency, also output voltage quality, particularly under unbalanced load conditions, which are one of the key aspects of aircraft load systems. Survey data have shown that as the load unbalance level increases, three H-bridge inverters, combined with a three-phase independent control system, exhibits superior output voltage quality. Additionally, three-single-phase H-bridge inverter shows advantages in various other parameters, including input DC voltage, DC capacitor. All of these results indicate the suitability of selecting three-single-phase H-bridge inverter for the GPU power supply for aircraft.

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