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Original Article

Modified Active Bridge Converter for Voltage Control of Electronic Load in More Electric Aircraft

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Abstract *- This paper proposes and implements a modified bridge converter to feed various AC and DC electronic loads in an aircraft. The emerging More Electric Aircraft and All Electric Aircraft trend have given rise to the need for novel power electronic circuits which should be capable of handling multiple avionic system loads- both AC as well as DC and also should be versatile and flexible enough to provide output voltage control to facilitate the desired operation of the connected loads. In this paper, a simplified active bridge converter circuit is proposed, simulated and implemented, which can be used to feed the electric power to the electronic systems inside an aircraft at variable voltage. The circuit uses a PWM inverter in conjunction with a rectifier and is capable of feeding power to AC and DC loads at various stages of the circuit. The prototype of the proposed circuit is also implemented. It is tested by connecting one AC and one DC load, and the output voltages are varied by changing the modulation index of the PWM inverter control circuit. The implementation is Hardware In Loop type, where the control circuit is implemented in MATLAB/Simulink, and PICCOLO Launchpad provides the interface between MATLAB and the hardware of the power circuit. The simulation and hardware results are compared for various values of modulation indices, and the future scope to modify this circuit into a bidirectional converter to improve the system efficiency is discussed.*

Keywords *- More Electric Aircraft, Dual active bridge converter, PWM inverter, Rectifier.*

1. Introduction

The aircraft industry's demands to optimize aircraft performance, decrease operating and maintenance costs, increase reliability, and reduce co2 emissions- have given rise to the concept of more electric aircraft (MEA) and, ultimately, All Electric Aircraft. Traditionally almost all the major load on the aircraft is driven by various secondary power sources, including mechanical, hydraulic, electrical, and pneumatic. The era of more electric aircraft has arrived thanks to recent developments in power electronics, fault-tolerant design, flight control systems, electro-hydrostatic actuators, high-density electric motors, and power generation and conversion systems. This tendency is accelerating as aircraft OEMs collaborate with their suppliers to develop new systems and adopt more electrically demanding systems. The aircraft industry is expected to make major advancements in terms of aircraft weight, total life cycle costs, fuel consumption, simplicity of maintenance, and dependability through adopting the MEA concept.

The weight of aircraft is one of the biggest problems the aviation industry has to deal with. Numerous studies have demonstrated that MEA can significantly lower fuel and hardware weight, resulting in a much smaller aircraft. However, even with our modern technologies, MEA is still often heavier. This is partially caused by the larger-than-expected power electronics box, where the EMI filters weigh a staggering 25% and 40% (B. Touré *et al*. 2012).

Since MEA replace hydraulic and/or pneumatic components with their electric equivalents, the electric power needed is substantially larger for MEA than for traditional aircraft (Nagel 2017). A significantly increased need for electricity creates difficulties with cooling and dynamic regulation of power generation and conversion. It should be noted that the weight of these electrical components can be reduced significantly by the continual development of power electronics and their related cooling and control techniques.

This paper proposes a novel topology for generating a variable dc voltage from a fixed dc voltage. The novelty of the proposed topology is the ability to feed an AC load in the aircraft, if any, in the intermediate stage of the conversion.

2. Review of Literature

Very extensive and rigorous study is being carried out in the field of More, Hybrid and All Electric Aircraft technology in terms of the electric machines, powertrains (Rajashekara 2014), power converters (Mohan 2003), EPS architectures and control strategies for power distribution to the avionic loads (Sayed *et al*. 2021; Buticchi *et al*. 2022; Benzaquen *et al*. 2021; Naik and Mehta 2017).

An aircraft's distribution system can be considered an onboard microgrid because the aircraft is an isolated system with generators and loads. Various paradigms are available depending on the quantity of power electronics placed and the actuator's characteristics. These have been specified in the Department of Defense Interface Standard: Aircraft Electrical Power Characteristics. MIL-STD-704F defines aircraft electric power characteristics as constant voltage/constant frequency, constant voltage/variable frequency, and dc distribution.

A constant speed gearbox powers the generator in the case of constant voltage/constant frequency, and power is distributed via a three-phase 115 V, 400 Hz system. Because the constant speed gearbox utilized to provide the constant speed shaft is complex and bulky, this solution will not be widely used. Electrical generators with controllable excitations are connected to variable-speed shafts supplied by the main engines in the case of constant voltage/variable frequency (Wang *et al.* 2016). However, frequency converters are required to create variable frequency systems, which increase the aircraft's weight. Furthermore, the challenge of synchronization of several generators coupled on the main shaft complicates the system (Gao *et al.* 2017). Finally, an AC-to-DC converter turns generator power into a high-voltage (HV) dc supply in a dc distribution. All auxiliary equipment is intended to function on dc voltage. DC-to-DC converters are needed to be created for the LV side. Still, nonetheless, this technique simplifies the actuation system since standard voltage source inverters can be adopted instead of back-to-back or matrix-based converters.

Much research is being done about what type of architecture should be used for the power system to be employed in a more electric aircraft (Chen *et al.* 2018; Maldonado and Korba 1999). As previously stated, the options are constant voltage/constant frequency, constant voltage/variable frequency, or direct current distribution. Furthermore, a combination of these options can be used to benefit from the favorable characteristics of any of these topologies.

A great deal of research has already been done on various potential power system architectures that could be employed in more electric aircraft. Diverse power electronic converters, such as inverters, matrix converters, DC to DC converters, and so on, are required for various power system topologies. References (Yin *et al.* 2017; Mathew *et al.* 2014) show the incorporation of inverters in the electric power system structure of a more electric aircraft.

The authors of the paper (Yin *et al.* 2017) created a 50-kW SiC two-level three-phase voltage source inverter prototype with a gravimetric power density of 26 kW/kg. The converter has a switching frequency of up to 100 kHz and a dead band of 250 ns.

A three-phase three-level diode clamped inverter running at 400Hz frequency has been devised and developed in the reference article (Mathew *et al.* 2014), with a lower distortion factor. However, using inverters and rectifiers raises the issue of harmonics mitigation and power quality enhancement. As a result, a great deal of thorough research has been conducted on these challenges, and all viable solutions are studied in publications (Chen *et al.* 2011; Biagini *et al.* 2013; Guerreiro *et al.* 2013; Nademi and Soghomonian 2016).

In the paper (Chen *et al.* 2011), a load current feedforward compensation approach is proposed based on the analysis and modelling of the shunt APF with closed-loop control. The authors claim that it increases the APF's dynamic performance. As previously stated, the increased use of power electronic subsystems in more-electrical aircraft (MEA) poses significant problems to aircraft power distribution in terms of power quality on board.

This issue is addressed in the paper (Biagini *et al.* 2013), which proposes a five-level active shunt filter topology with an upgraded deadbeat current controller for a fixed frequency 400 Hz aircraft power grid. The suggested controller has a large bandwidth current control loop that can compensate for high-frequency harmonics while using a lower device switching frequency. The proposed topology is evaluated for an aeroplane electric power system with variable speed and constant frequency (VSCF).

The design, simulation, and implementation of a Multilevel Aeronautical Active Power Filter (AAPF) for a Variable Speed Variable Frequency (VSVF) advanced aviation electric power system are presented in the reference paper (Guerreiro *et al.* 2013). Most often, AAPFs are used to reduce current harmonics, enhance the source power factor, and alleviate the impacts of unbalanced loads. The Aircraft Electrical Power System (AEPS) differs greatly from residential and industrial power systems because the frequency can range between 360 Hz and 900 Hz, and the load dynamics are frequently altered. As a result, an improved filtering technique is necessary for aircraft applications, particularly if an AC power supply design is used.

A Shunt Active Filter (SAF) based on modular multilevel converter (MMC) architecture is proposed in the paper (Nademi and Soghomonian 2016), which may be utilised to track and adjust the harmonic contents of load currents in an aeroplane power distribution system. The SAF is implemented using the current control scheme and the finite control set-model predictive control (FCSMPC) method. The authors focused on system transients and steady-state behaviours by varying loads, supply impedances, and operating frequencies.

The use of semiconductor devices, such as SiC or GaN, is a part of the answer to overcoming the weight issue as they have some intrinsic qualities, such as high power density, minimal internal losses, ability to function at the high switching frequency, and high operating temperature (Luckett *et al*. 2020). For MEA to be efficient, EMI filters must be made lighter and smaller. Common and differential mode filter design improvements might not take us very far from our current situation. To make aircraft lighter, new power electronics topologies might be required.

System integrations and multi-physics discipline integrations are the answers in situations where electric systems have little chance of competing with pneumatic and hydraulic systems (Warncke *et al.* 2017). Numerous studies have demonstrated that the MEA will be significantly more appealing than alternative techniques in terms of weight, size, fuel efficiency, clean air and noise reduction with aircraft level modifications. Dual active bridge converters are a particularly common option if a bidirectional power flow is necessary for the aircraft EPS due to its inherent soft switching, high power density, high efficiency, galvanic isolation, and the minimal number of passive components (Jiang and Liu 2021; Fernandez-Hernandez *et al.* 2020; Guan *et al.* 2020). But in addition to these operating issues, DAB converters also experience greater current stress, increased switching loss of the switch tube, and increased power loss in the magnetic components like inductors and transformers (Coppola *et al.* 2020; Rahrovi *et al.* 2021; Fan *et al.* 2019). In order to address the issues with the use of DAB converters, novel PWM techniques are being researched and put into practice for aircraft applications (Barzkar and Ghassemi 2020; Mendes *et al.* 2021).

3. Proposed Topology

Figure 1 shows the simulation diagram of the proposed topology. It is a simplified version of a two-stage dc to dc converter where the fixed dc voltage is converted into a variable ac voltage in the first conversion stage by using a high-frequency full bridge converter. Any AC load in the aircraft can be fed from these terminals in the proposed circuit. In the second stage of the conversion, the variable ac from the first stage is converted into variable dc by using a diode bridge. Any dc load, like a DC motor or rechargeable battery, can be connected on the output side. The load parameters like dc motor speed or battery terminal voltage can be adjusted as per the requirement with the help of the full bridge inverter in the first stage. PWM control strategy is used to control the output voltage level of the full bridge (Kumar et al. 2014).

The gating pulses required for turning ON the IGBT switch are generated by comparing a Sine Wave of 50 Hz with a Triangular wave of 15 kHz. Depending upon the chosen Modulation Index, the pulse width is varied, and accordingly, the output voltage of the PWM inverter will change. Figure 2 shows the generation of switching pulses by the PWM method (Chin *et al.* 1984).

Figure 3 shows the control scheme that generates PWM pulses for switching IGBTs with a variable modulation index.

Figures 4 and 5 show the PWM pulse generation for modulation indices 1 and 0.6, respectively. As the modulation index reduces, i.e. as the amplitude of the modulation wave (sinusoidal wave) reduces, the width of the generated pulses reduces proportionately. However, the scope of this paper is limited to the discussion of simulation results only.

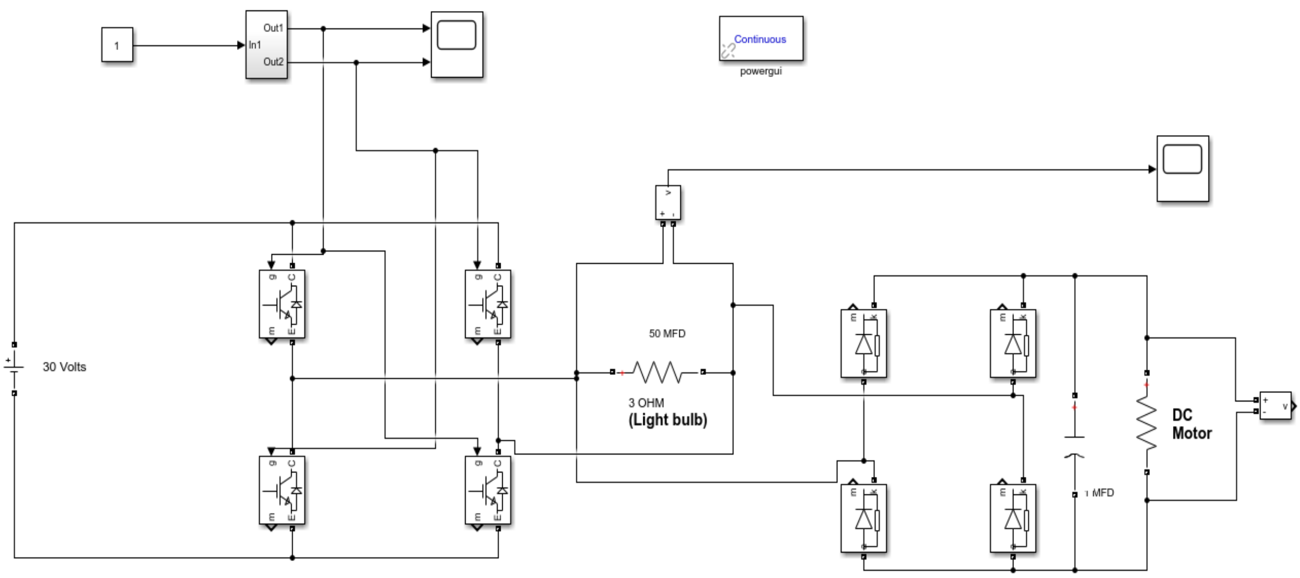

Fig. 1 Proposed topology simulation diagram

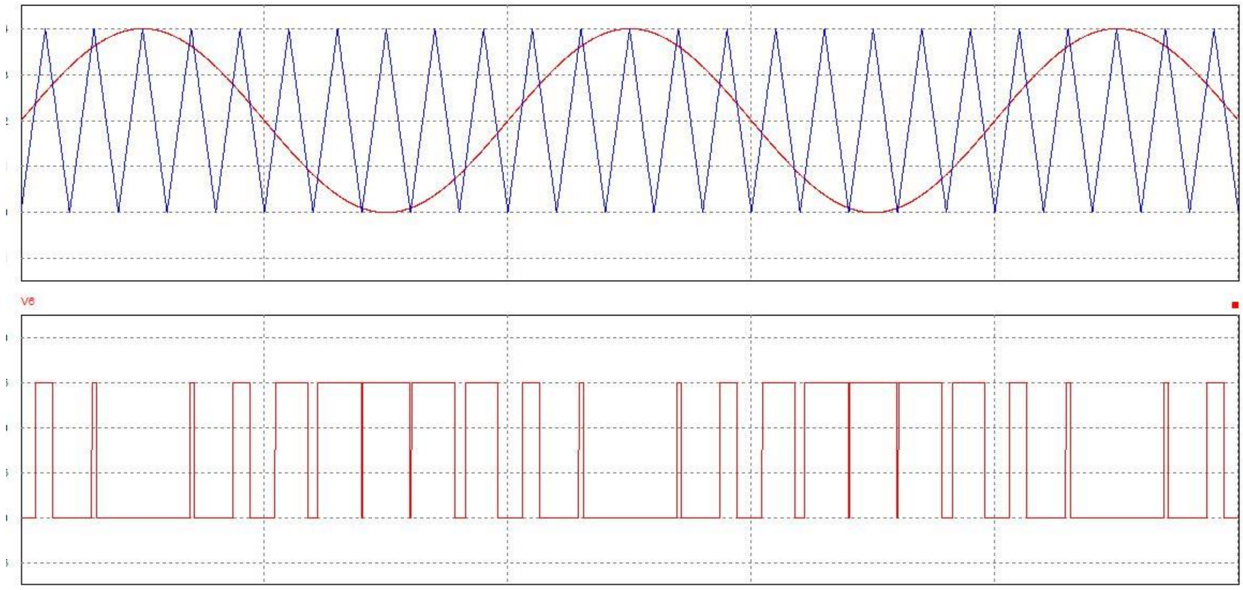

Fig. 2 Generation of switching signal by PWM method

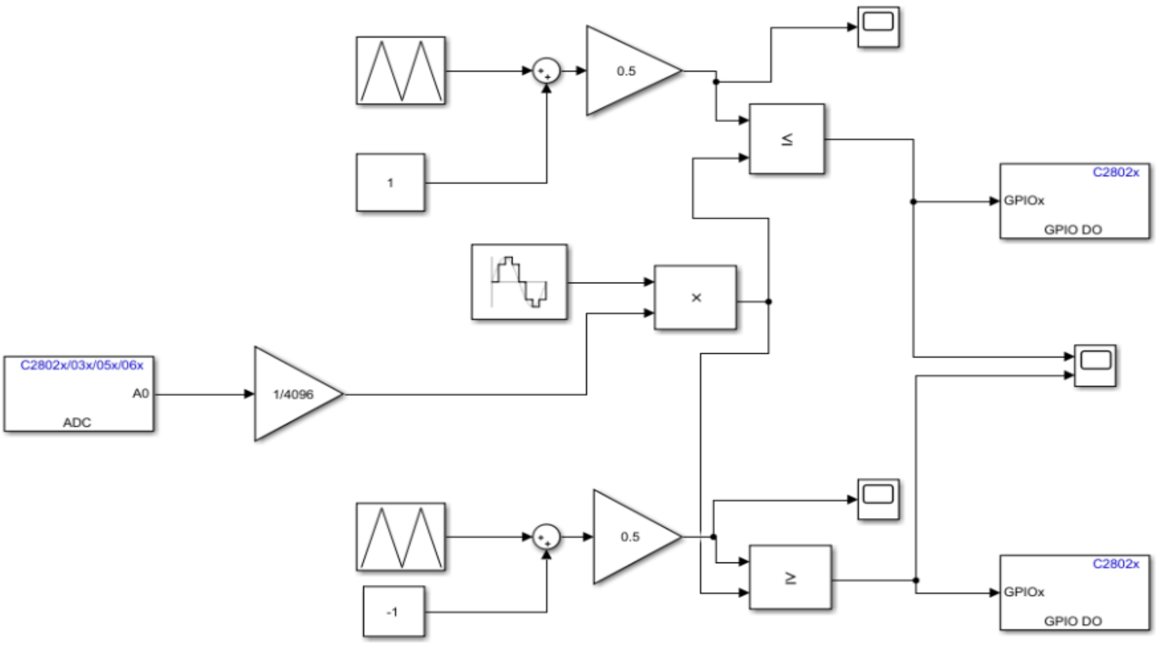

Fig. 3 The control scheme for PWM pulse generation of IGBT full bridge

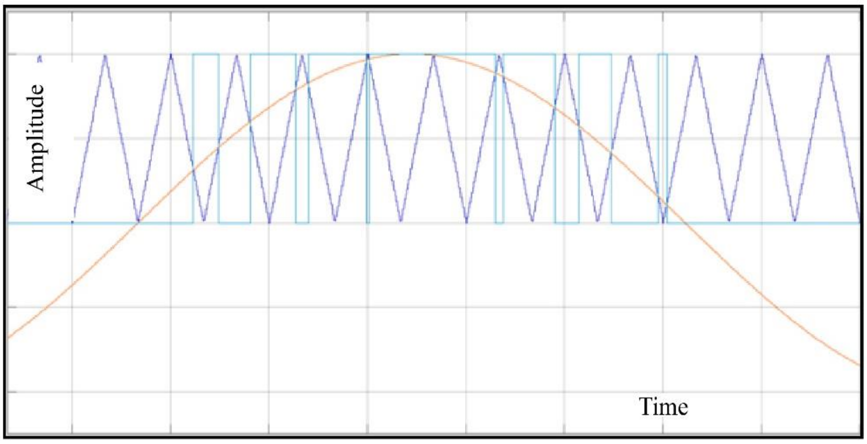

Fig. 4 Generation of PWM pulses for modulation index 1

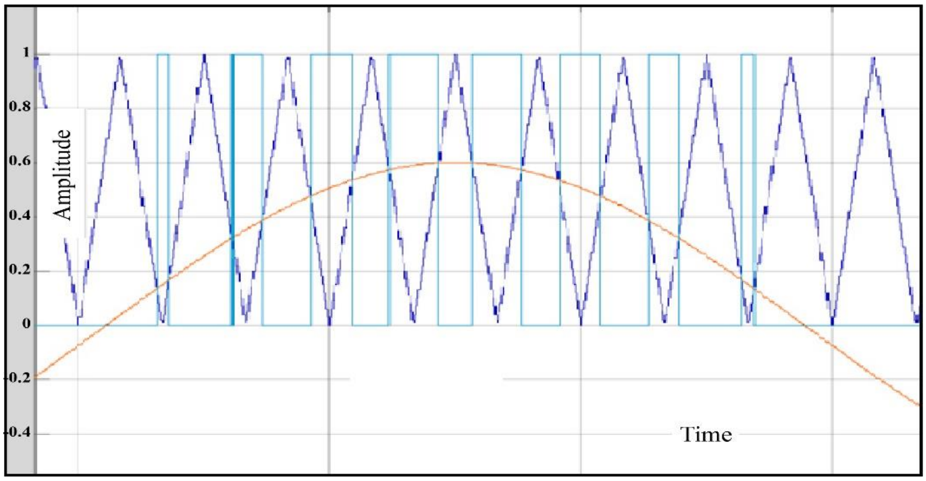

Fig. 5 Generation of PWM pulses for modulation index 0.6

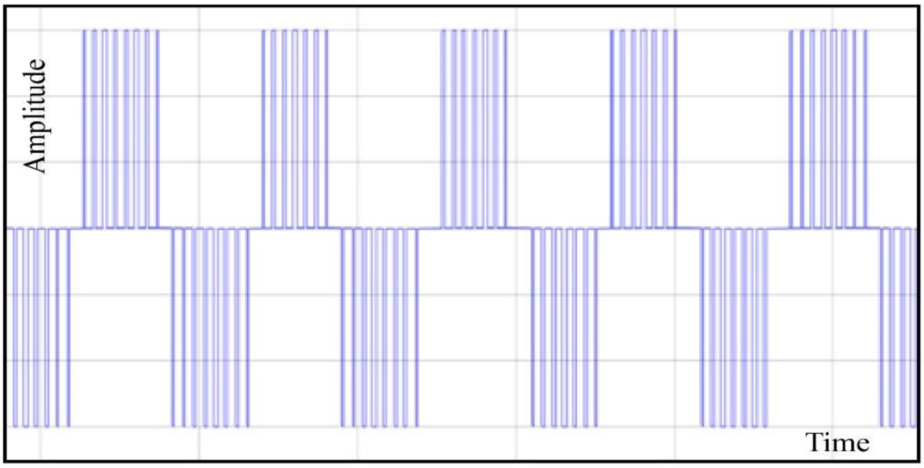

Fig. 6 The output waveform of the PWM inverter before filtering

Fig. 7 The output waveform of the PWM inverter after filtering

4. Simulation Results

Figure 6 shows the unfiltered output of the PWM inverter. This output waveform clearly contains a large amount of high-frequency harmonics, which can be easily filtered with the help of a capacitor of appropriate ratings. Figure 7 shows the output of the PWM inverter after filtering.

Table I shows the PWM inverter output voltage, i.e. AC output voltage, and the rectifier output voltage, i.e. DC output voltage, for various modulation index values from 0.1 to 1. It is clear from this table that the DC voltage levels can be adjusted between 5 V to 13.6 V, and AC voltage levels can be adjusted from 6.6 V to 16.8 V depending upon the load requirements.

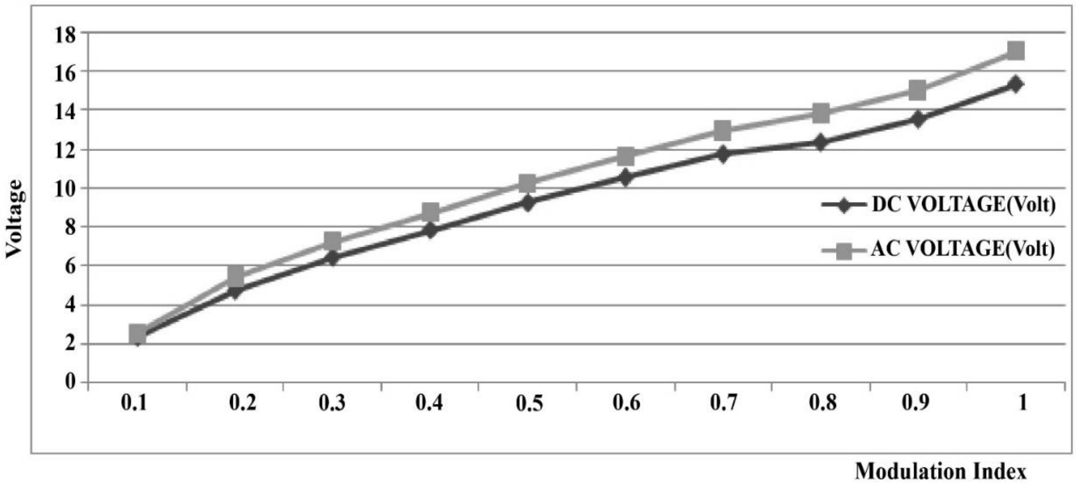

Fig. 8 AC and DC output voltages of the proposed topology for modulation indices from 0.1 to 1

Table 1. Output Voltages for the proposed topology for various Modulation Indices

Modulation Index	Output Voltage Reading	
	DC Voltage (Volt) (Rectifier Output)	AC Voltage (Volt) (PWM Inverter Output)
0.1	5	6.6
0.2	6.6	8.6
0.3	7.8	10
0.4	8.7	11.1
0.5	9.7	12.3
0.6	10.5	13.2
0.7	11.6	14.3
0.8	12.5	15.6
0.9	13.6	16.7
1.0	13.6	16.8

Figure 8 shows the graph of output AC and DC voltages plotted against modulation indices ranging from 0.1 to 1.

5. Hardware Implementation

The simulation implemented is provided with hardware in the Loop facility, which enables the use of MATLAB for implementing the control circuit part and generating the control signals for the IGBTs in the proposed topology and a C2000 F28027 PICCOLO Launchpad, which enables the user to change the modulation index in real-time and provide the PWM gate signal generated according to the modulation index to the IGBTs in the hardware circuit.

In order to take command from the user regarding the modulation index, a potentiometer is used to create a voltage divider circuit. The potentiometer output voltage is fed to an ADC on the PICCOLO launchpad, whose output can be used in the control circuit simulation built on MATLAB/Simulink platform. Depending upon the ADC output, the modulation index of the PWM signal is decided in the simulation, and the gate signals for the IGBTs are generated. These gate pulses are received on the PICCOLO Launchpad with the help of the Digital Output block available in the MATLAB package for external Launchpads like PICCOLO, DELFINO etc. The gate signal is received on the external PICCOLO platform. It is conditioned appropriately so the gate signals can be recognized by the IGBT bridge implemented in the hardware circuit. An opto-isolator and gate driver IC TLP 250 is also used at every gate output signal to isolate the control circuit and power circuit and thereby protect the control circuit from any high voltage or current surges which can not be sustained by the control circuit, which is designed to work at a low voltage and current levels. It also steps up the output of the PICCOLO Launchpad to a suitable value that the IGBT gate terminals can recognize. Using TLP 250 isolation and driver circuit, 5 V voltage levels are stepped up to 15 V and fed to the gate terminals of IGBTs. Table II gives the specifications of IC TLP 250.

Figure 9 shows the circuit diagram of IC TLP 250 used as an optoisolator and driver circuit. Figure 10 shows the hardware of the driver circuit implemented using IC TLP 250. The power supply of 15 V required by IC TLP 250 is generated using a step-down transformer of 230 V/15 V and then converting the 15 V AC voltage to the corresponding DC using a rectifier IC. The rectified output is filtered by using a capacitor.

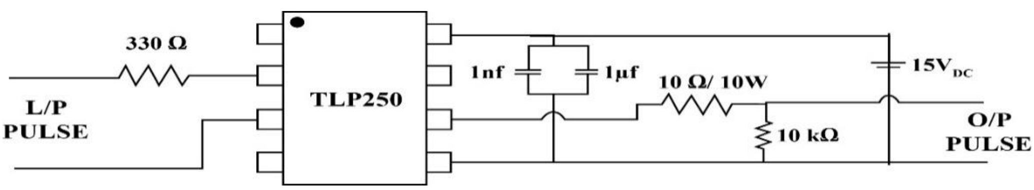

Fig. 9 Circuit diagram of TLP 250

Table 2. IC TLP 250Specifications

Sr. No.	Parameter	Values
1	Input Threshold Current	5 MA
2	Supply Current	11 MA
3	Supply Voltage	10-35 V
4	Output Current	$\pm 1.5\ A$
5	Switching Time	1.5 μS
6	Isolation Voltage	2500 V RMS

The IGBTs used to build the PWM inverter circuit are IGBT (FGA25N120ANTD) (Rice and Mookken 2015). The specifications of the same are given in Table III.

Table 3. IGBT FGA25N120ANTD Specifications

Sr. No.	Parameter	Values
1	Collector-Emitter Voltage	1200 V
2	Gate Emitter Voltage	$\pm 20\ V$
3	Pulsed Collector Current	45 A
4	Diode Continuous Forward Current	25 A
5	Collector Current (at 100°)	25 A
6	Max Power Dissipation (At 100°)	74 W

Figure 10 shows the hardware implementation of the proposed topology. The comparative results of the simulation and hardware implementation are given in Table IV.

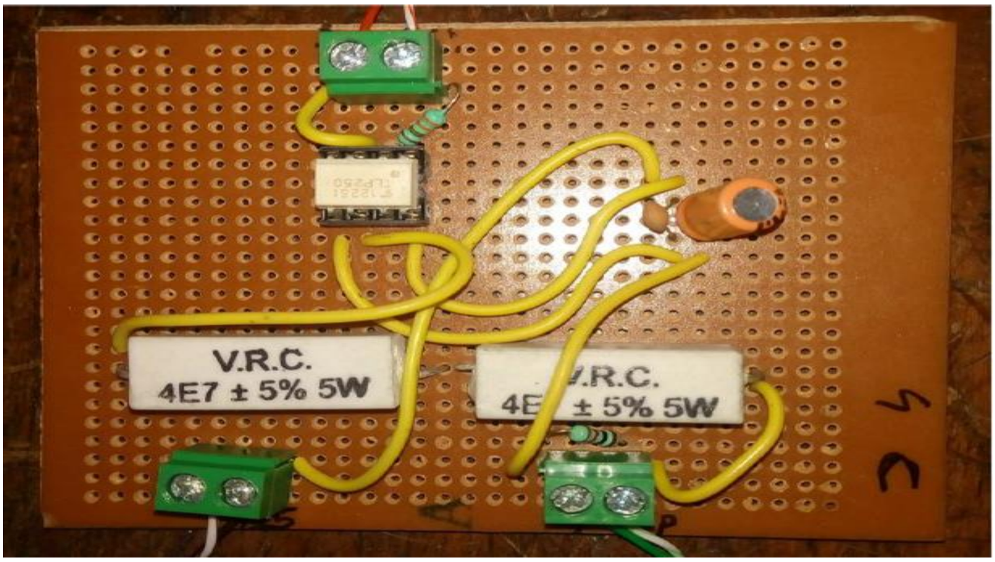

Fig. 10 The hardware of the driver circuit using IC TLP 250

Table 4. Comparative Analysis of Simulation and Hardware Results

Sr. No.	Modulation Index	Simulation Results		Hardware Results	
		DC Voltage (Volt)	AC Voltage (Volt)	DC Voltage (Volt)	AC Voltage (Volt)
1	0.1	2.54	2.82	2.3	2.5
2	0.2	5.73	6.36	4.7	5.4
3	0.3	8.27	9.19	6.4	7.2
4	0.4	10.18	11.31	7.8	8.7
5	0.5	12.09	13.43	9.2	10.2
6	0.6	13.37	14.84	10.5	11.6
7	0.7	14.64	16.26	11.7	12.9
8	0.8	15.91	17.68	12.3	13.8
9	0.9	16.55	18.38	13.5	15
10	1.0	17.19	19.09	15.3	17

6. Conclusion

Modern aircraft have been increasingly electrified in recent years due to the advantages of system efficiency. With the increased number of appliances connected to aircraft distribution, the need for electric power at different voltage levels and smooth voltage control has come into the picture. The proposed topology has made it possible to generate a controllable voltage DC power and AC power which can be used for various electronic applications like aviation signalling systems, illumination systems in the aircraft, fans and air conditioning systems, audio and video systems for the passengers etc. Both AC and DC loads can be fed from the same system and the same topology and be implemented at a much larger power level depending upon the requirements of the aircraft.

The simulation and the hardware implementation of the proposed topology show promising results in smooth voltage control and the power quality being fed to the loads all over the range of operation. Suppose the proposed prototype is scaled up to meet the requirements of the aircraft. In that case, it can replace many hydraulic and pneumatic systems currently being used, which will ultimately lead to reduced weight, higher efficiency, reduced fuel consumption and a much more eco-friendly aircraft system.

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