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Design and Implementation of Three Phase Frequency Converter for Aircraft Ground Stations Using Higher Switching Speeds Switches

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ABSTRACT

The silicon insulated gate bipolar devices (silicon IGBTs) are typically employed in construction of Traditional High frequency converter cabinet (THFCC), which are used to integrate utility grid with aircraft ground stations. Due to the physical limitations of silicon switches, the efficiency of THFCC can be enhanced by substituting silicon carbide IGBT for the existing silicon IGBTs devices. The main goal of this study was to demonstrate that the use of silicon carbide IGBTs in THFCC might result in increased efficiency because of their higher switching speeds and power density. This was demonstrated through actual experimental investigations. This work investigated two experimental configurations, the single pulse test (SPT), which uses silicon IGBT and silicon carbide IGBT. The THFCC with only silicon IGBT is implemented and tested to investigate the features of the silicon IGBT. The potential gain in efficiency if silicon carbide IGBTs are used in THFCC in the next study. The test findings yielded a number of interesting observations. At a switching frequency of 20 kilohertz, THFCC with silicon carbide IGBTs efficiency of 85% is achievable. Investigations were conducted into the on/off processes. Experimental silicon IGBT efficiency in SPT was 77%, whereas silicon carbide IGBTs efficiency was 95%. Furthermore, an examination of further aircraft ground stations has been conducted, focusing on semiconductor devices, field applications, and output filters.

1. Introduction

Traditional High-frequency Converter Cabinets (THFCC) are becoming essential components of energy technology for integrating ground power stations for planes with the general electrical grid. A suitable transistor for THFCC is the silicon IGBT, which combines high current density of a bipolar Junction transistor with high impedance of a metal oxide-semiconductor field-effect transistor [1-2]. The main disadvantage of silicon switches is their lower switching frequency which results in an increase in the weight, and passive components [3].

THFCC is composed of two components, three phase inverter (TPI), and six pulse rectifier bridge. This article presents the implementation of THFCC utilizing inverter based silicon IGBT , while silicon carbide IGBT will be used in the following article. Silicon carbide IGBT has lately been able to surpass silicon carbide IGBT as the most used transistor technology because of its better operational characteristics, which include higher voltage blocking, reduced voltage loss, and faster switching speeds [4],[5]. This work aims to design and construct a THFCC using silicon IGBT switches and compare it to the silicon carbide IGBT module under RL loads, fixed gate resistor (10Ω), and constant DC bus voltages, to demonstrate that the implementation of silicon carbide IGBTs in THFCC could result in an increase in efficiency through actual experimental investigations. Several papers compare silicon carbide switches' flipping performance with silicon equivalents. For example, silicon carbide MOSFET (1700V/325A) with silicon IGBT (1700V/310A) were compared in [6]. Due to their lower losses, silicon carbide IGBT devices have a significant impact on power utility applications and can achieve higher breakdown electric field strengths than silicon IGBT switches [7]. silicon carbide IGBTs are a better fit for applications requiring high voltage and high current than silicon carbide MOSFETs. [8-9] . An examination of the literature revealed that silicon carbide IGBT was not utilized in THFCC.

Two experimental systems were presented and evaluated in this study. An SPT system based on silicon IGBT and silicon carbide IGBT was developed for the initial experiment. THFCC with silicon IGBT will investigated in the second experiment while THFCC with silicon carbide IGBT will investigated in the next article to assess the switching performance. THFCC is a laboratory circuit that is constructed, and its switching times (rise and fall times) as well as its positive and negative overshoot are measured. Experimentally, the silicon IGBT based on SPT had an efficiency of 77%, whereas the silicon carbide IGBT enhanced the SPT's efficiency to 95%. The silicon IGBT system based on THFCC technology has an 85% efficiency. According to the studies, the silicon carbide IGBT outperformed the silicon IGBT in terms of switching speed and loss.

The remaining sections of the article are arranged as follows: Design and implementations are covered in Section 2. Section 3: Results and Experimental Setup. The subject is discussed in Section 4. The article's conclusion is given in Section 5.

2. Power Inverter Design and Considerations

This chapter discusses design and concerns for THFCC. In the study, there were two different experiments. In the first experimental, the characteristics of the THFCC system with silcon IGBTs devices were investigated and the efficiency was determined. The design and issues for THFCC are covered in this chapter. There were two distinct experiments conducted for the study. The first experiment examined the characteristics of the THFCC system using silicon IGBT transistors and determine its efficiency. In the second experiment, the switching performance and operational parameters were examined using a SPT with silicon IGBT and silicon carbide IGBT. It was discovered through experimental research that utilizing silicon carbide IGBTs in THFCC could result in an efficiency gain.

A. Traditional Frequency Converter Cabinet Construction with Si-IGBT Switches

The THFCC was made up of the TPI, output filter capacitor, , six

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pulse rectifier thyristor bridge and input filter inductor (10kW). Four silicon IGBTs (CM150DY-24A 1200V Dual IGBTMODTM) switches made up the TPI. There was a reverse recovery free-wheel diode in every transistor. In order to prevent excessive voltage drop and the free-wheel diode effect caused by the IGBT inside the module, the IGBT body diodes (D1 and D2) were connected in parallel with it. The output filter, DC bus, and gate driver were the main parts. The system diagram of the THFCC is shown in Figure 1. The THFCC was divided into two stages. The TPI was utilized in the second stage, while a rectifier was employed in the first stage as an AC/DC converter to provide the required DC power. It converted power at 380 volts with 50 hertz to 209 volts with 400 hertz constant frequency. The TPI served as an interface between grid and the aircraft ground stations, and it was the key component of the THFCC. In this investigation, THFCC-based TPI with silicon IGBT devices were installed. Table 1 displays the specifications of the THFCC. Figure 2 shows the THFCC.

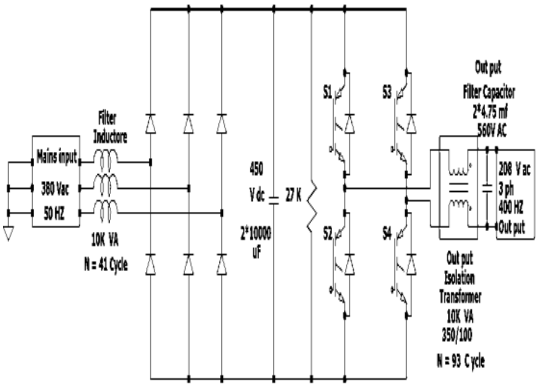

Fig. 1: System diagram of single-phase for THFCC

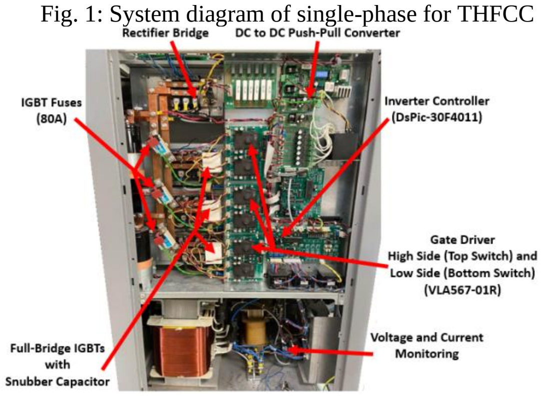

Fig. 2: Traditional Frequency Converter Cabinet

Table 1: Traditional Frequency Converter Details.

Parameters	values
Voltage of output	209 Volt
Maximum power output	10kVA
Incoming voltage	380VAC (3- phase)
DC bus	450VDC
Microcontroller	Microprocessor (dsPIC30F4011)
Frequency of output	400Hz
Frequency of input	Fifty hertz
DC current input	85A

B. Topology of three-phase inverter

The topology of three-phase inverter (TPI) is the main component of THFCC. For aircraft ground stations, TPI transforms direct current (DC) power produced by six-pulse rectifier into alternating current. This work used an extremely efficient microcontroller control circuit to create the PWM signals. These signals will regulate IGBTs' switching behavior during the conversion from DC to AC at 400 Hz and 208 V. The TPI is seen in Figure 3.

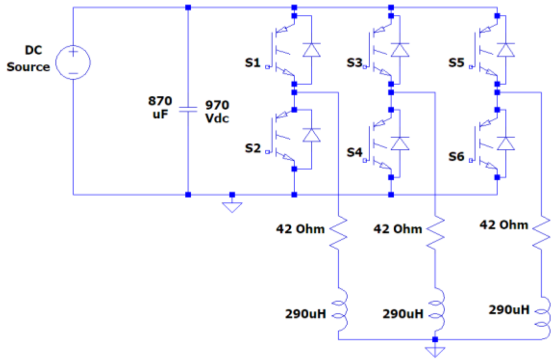

Fig. 3: Topology of three-phase inverter

C. Testing a Single Pulse with SiC and Si-IGBT Switches

In the second experiment, RL loads (42 Ω, 290uH) were used to evaluate an SPT that was built utilizing a silicon IGBT (CM150DY-24A) and a silicon carbide IGBT (APT60GF120JRDQ3) switch. The SPT experiment aimed to gather and analyze the switching properties of silicon IGBTs and silicon carbide IGBTs.

The two sections of the SPT were the power circuit and the control circuit, respectively. While the power circuit provided -5V and +15V, the control circuit generated the appropriate gate signal to operate silicon IGBTs and silicon carbide IGBTs. The SPT activated the IGBT and supplied current to charge the RL load. The SPT should provide a broad pulse that charges the load current to the appropriate measurement magnitude. Studying the rising and falling edges of an IGBT hard-switching transient at the necessary current could be done with SPT. Furthermore, the pulse width of the SPT could be adjusted by varying the amplitude of the IGBT current. Figure 4 displays the SPT circuit for the silicon IGBTs.

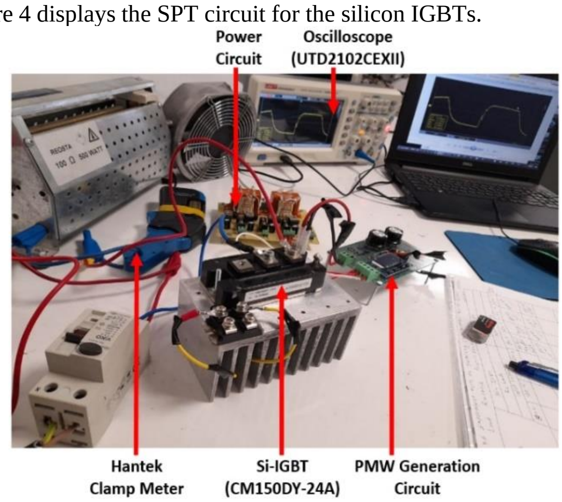

Fig. 4: Single pulse test in the lab utilizing the Si-IGBT (CM150DY-24A) switch

D. Examination of Driver Circuits

The TPI employed VLA567-01R integrated circuit as the IGBT driver. Two half-bridge gate drivers are included on the circuit board of the gate driver, which enables it to operate lower and upper silicon IGBTs and silicon carbide concurrently. Every half-bridge is made up of two independent power sources and two gate drivers. The top switch is controlled by one gate driver, while the bottom switch is controlled by the other.

In the microcontroller circuit, IGBT drivers are needed to buffer the generated PWM signals. A study that discusses the design considerations for gate drives may be found in [10]. The schematic for the gate driver is shown in Figure 5.

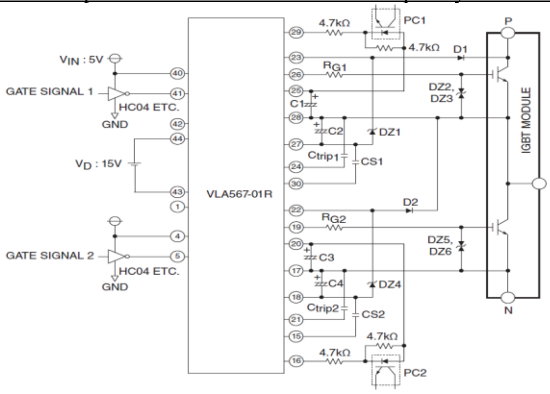

Fig. 5: Diagram of the VLA567-01R gate driver circuit

E. Gate Driver Requirements

To switch quickly, the silicon carbide IGBT Gate To Emitter Voltage needs to increase rapidly. For a fast transient turn-off, silicon carbide IGBT needs a negative voltage like silicon IGBT do. When the IGBT is turned off, the same current capability is needed. Reducing the external gate resistors for turn off and turn on can enhance the gate current capabilities.

In order to switch on by +20 v and turn off by -5 v, a silicon carbide IGBT driver normally delivers both positive + 20 v and negative - 5 v. The silicon carbide IGBTs are more efficient than silicon IGBTs because they are faster.

In order to prevent unwanted ground current from entering the power circuit. Every signal in the driving circuit needs to be galvanically isolated [11].

a) IGBT Snubber Circuit

Transistors can generate dangerously high over voltages and over currents during switching, which can damage power equipment.

Turn-off snubbers minimize the rise in voltage across IGBTs during the transient turn-off, allowing the voltage across the IGBT to stay low until the collector current transfers to the diode. This reduces switching losses during turn-off. The snubber capacitor C_s will charge when the collector current decreases, assisting in limiting the rising voltage across the IGBT.

To decrease voltage overshoot and ringing, the capacitance C_s of the turnoff snubber could be increased. IGBT transistor switching stresses can be decreased using snubber circuits [12]. Figure 6 displays the configuration of the turnoff snubber.

To reduce transient voltage, a snubber capacitor should be placed as close to the IGBT terminals as feasible. When a device fails, the peak current needed to turn it off may be six to ten times higher than its current rating. Peak current will cause the overshoot voltage to rise proportionately in a fault state[13].

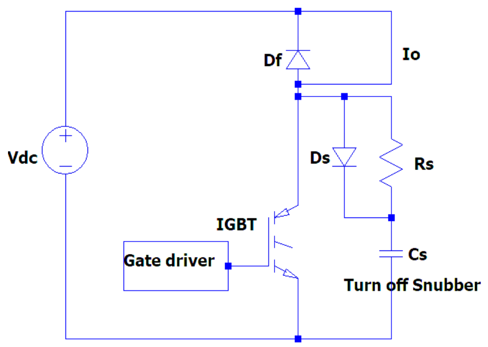

Fig. 6: Turn-off snubber Capacitor

b) Optocoupler Module

An optocoupler is a device that combines a photodetector and a light-emitting diode (LED). The optical detector can be a diode with a binary output when linked to the base of a transistor. Internal LEDs turn on and send IR beams and active phototransistors when the correct input current is applied across the positive and negative terminals. The 6N136 caused the input pulse to have reversed polarity. If the input logic is high, the output will be low; conversely, if the input logic is low, the output will be high. When choosing an optocoupler, consider its speed, delay times for turning on and off, and capacity to reduce output ringing [14].” The 6N136 optocoupler is shown in Figure 7.

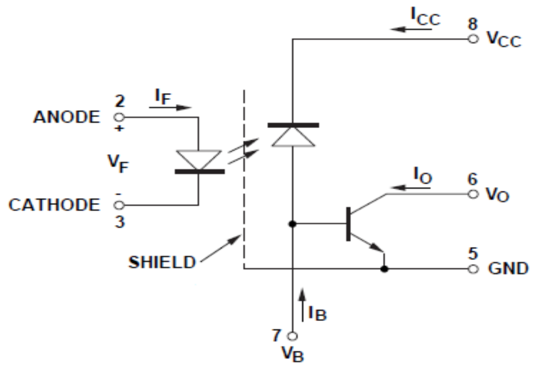

Fig. 7: Optocoupler 6N136

c) Protective Short Circuit

In order to safeguard the circuit, gate drivers are in charge of operating silicon IGBTs and silicon carbide IGBTs.

The gate driver circuit of a transistor should always include the protective circuit [15]. Transistor protection circuits are made to turn off the transistors when their current exceeds a a certain limit. When failures occur and excessive current flows through the transistors, the Short-Circuit Protection system would be shielded. The protective circuit needs to be built with quick and the ability to turn off a switch without damaging the IGBT.

3. Experimental Setup and Results

In this chapter, the specifics of the laboratory setup and measuring devices utilized in the investigations are explained. This section goes over the characteristics of THFCC based on silicon IGBTs and SPT based on silicon carbide IGBT switches, including efficiency and total power losses. Two experiments were performed in this section. In the first experiment, traditional silicon IGBTs were used to study the THFCC, and in the second, silicon IGBTs and silicon carbide IGBT were used to build and implement the SPT. Experiments were used to evaluate the switching characteristics of silicon IGBTs and silicon carbide IGBT and to determine the system's efficiency.

A. Experiments and measurements on the THFCC using silicon IGBTs switches

In this work, measurements for THFCC based Si-IGBT power modules (CM150DY-24A) are analyzed. [16]. Module voltage (Si-IGBT) was 1200V, and current ratings were 150A. The characteristics were measured using a bus voltage of 360V DC, gate resistances of 10Ω, and an RL load of 42 Ω and 290 uH. The advantages of the silicon IGBTs in terms of their high frequency and efficiency were evaluated. To evaluate the voltage and current, we used the Fluke, MICsig oscilloscope, and UT201 clamp multimeter. In this experiment, the transient turn off and turn on waveforms of the silcon IGBTs were examined, together with the switching timings (rise and fall times) under a 2.7A load current situation.

The rise time of the silicon IGBTs module was 297 nanoseconds, and the fall time was 658 nanoseconds. Figure 6 shows that at 2.1A load, positive overshoot contributed 2% and negative overshoot 11% to the overall switching losses for silicon IGBTs.

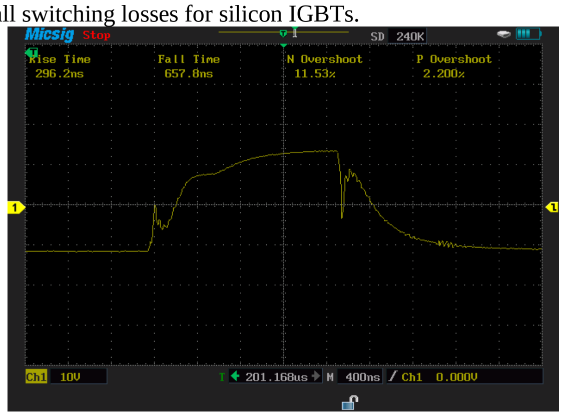

Fig. 8: Switching silicon IGBT waveforms for THFCC

B. Experiments of the SPT using silicon IGBT and silicon carbide IGBT

This study used silicon carbide IGBTs (APT60GF120JRDQ3) and silicon IGBTs (CM150DY-24A) to assess SPT. and SK25GH063 was the other. The module had a 1200V voltage rating and a 150A current rating. At 100 volts DC, with an RL load of 42 Ω and 290 uH, the turn on characteristics of silicon IGBT and silicon carbide IGBT were investigated. The gate resistances turned on were 10Ω and turned off were 11Ω.

The SPT experiment was conducted under the same conditions in order to collect and evaluate the switching characteristics as well as evaluate the advantages of both devices in terms of efficiency and high frequency. The integration feature of the oscilloscope can be used to determine the switching losses of switches. In this experiment, SPT was used to analyze the transient turn off and turn on waveforms of silicon IGBTs and silicon carbide IGBTs in the same way. In the case of a 2.1A load current, the devices' hard switching transient's rising and falling edges may be examined.

Turn on and off characteristics of the silicon IGBT experiment at 100 V voltage rise time, 262 nanoseconds, and voltage fall time, 617 nanoseconds, are shown in Figure 9, and the characteristics of the silicon carbide IGBT experiment at 100 V voltage rise time, 85 nanoseconds, and voltage fall time, 161 nanoseconds, are shown in Figure 10. The on and off switching of silicon IGBTs and silicon carbide IGBTs with RL loads is shown in Table 2.

The switch off transient was quite quick in the test circuit due to stray inductance, which resulted in a significant voltage overshoot and long ringing. Furthermore, it was clear that the voltage overshoot and ringing was the result of an increase in collector current. This allowed the switching durations of the silicon carbide IGBT at 100V input voltages to be found and compared.

Table 2: Experiment with the characteristics of silicon IGBTand silicon carbide IGBT with RL loads at 100V (42 Ω, 290uH).

Switch both on and off	Silicon IGBT with RL loads 100V (42 Ω, 290uH)	Silicon IGBT with RL loads 100V(42 Ω, 290uH)
Time of voltage rise	262 nanoseconds	85 nanoseconds
Time of voltage fall	617 nanoseconds	161 nanoseconds

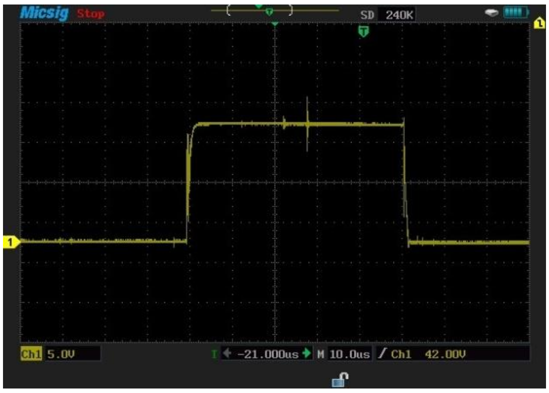

Fig. 9: Test the on/off characteristics of a silicon IGBT at 100 V and 2.1A. The voltage rise and fall times are 262 and 617 nanoseconds, respectively.

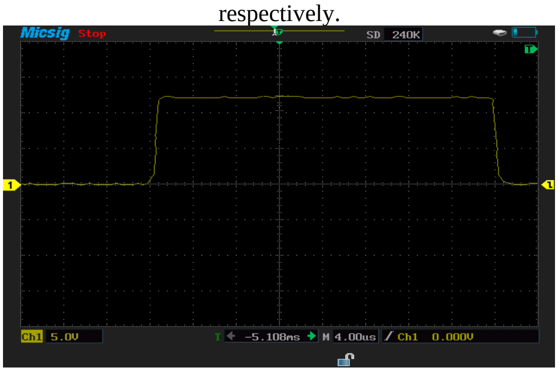

Fig. 9: Test the on/off characteristics of a silicon carbide IGBT at 100 V and 2.1A. The voltage rise and fall times are 85 and 161 nanoseconds, respectively.

4. Discussion

This research first created the THFCC using silicon IGBT, and then examined silicon IGBT properties with RL loads using the experimental THFCC test bench. The goal of the SPT experiment was to examine and assess the switching properties of silicon and silicon carbide IGBTs. They were compared for resistive and RL loads (42 Ω, 290uH).

A comprehensive study of several papers on Aircraft Ground Stations (AGS) is carried out, focusing on semiconductor device (silicon carbide MOSFET), field application, modulation method, control type, and output filter. At the same time, a number of articles on AGS based on silicon IGBTs were examined. It was found that SiC-IGBT had not been used for THFCC (400Hz, 208V) at AGS -based industries. Turn on gate resistance of 10 ohm and turn off gate resistance of 11 ohm, respectively, were used to determine the turn on and turn off switching periods.

Measurements were made of the positive and negative overshoots as well as the on/off switching timings, and information was gathered from the test outcomes. For silicon IGBTs, the sum of the switching losses resulting from positive and negative overshoot was 5% and 16%, respectively. These values were achieved as about % 0 and % 4, respectively, under the same conditions for silicon carbide IGBT. These results demonstrate that silicon carbide IGBTs have lower switching energy losses.

Both silicon IGBT and silicon carbide IGBT modules' turn on speeds were assessed. The silicon carbide IGBT modules reached a steady state value quicker and were able to be turned on almost six times faster than silicon IGBT modules. In contrast, because there was no tail current, the silicon carbide IGBT oscillated more and switched off faster than silicon IGBT modules. As a result, based on the needs of the aircraft application, the appropriate technological foundation was offered for selection.

The waveforms displayed in the earlier figures and tables demonstrated three crucial characteristics: voltage drop, current overlap, and large overshoot current. Table 3 shows the overall power losses and overall efficiency for an experimental with an RL load at a 100V input voltage. The THFCC-based silicon IGBT had an efficiency of 85 percent. SPT-based silicon IGBTs had an efficiency of 86%, whereas silicon carbide IGBTs had a 96% efficiency rate.

Table 3: Overall losses and overall efficiency for Si- IGBT and SiC-IGBT SPT with RL loads (42 Ω, 290uH) at a voltage of 100V supplied.

Category Of circuit	Kind of device	Total Power Losses in Switching $P_{T,loss}(t)$	Conduction Losses Overall $P_{T,Cond}(t)$	Switching Losses Total $P_{T,sw}$	Overall Power Output P_{out}	Overall Power Losses $P_{T,tot}$	Overall Losses P_{loss}	Overall Effectiveness η
SPT	Silicon IGBT CM150DY-24A	5 watt	1 watt	31 watt	222 watt	33 watt	33 watt	86 %
SPT	Silicon Carbide IGBT APT60GF120JRDQ3	6 watt	0.13 watt	32 watt	391 watt	32 watt	32 watt	96 %
THFCC	Silicon IGBT CM150DY-24A	12 watt	8 watt	14 watt	939 watt	23 watt	142 watt	85%

5. Conclusion

In this paper two separate experiments were examined. For the first experimental research, the SPT system was developed and designed. The developed SPT experimental setup was used to compare the silicon IGBTs and silicon carbide IGBT modules' operational performances. Under identical operating conditions, the hard switching behavior of two silicon carbide IGBT modules and one silicon IGBT module was compared.

The THFCC-based silicon IGBT modules were examined in the second experimental study, and the system's efficiency was determined. The reasons for the effects of switching features were given. In addition to the positive and negative overshoots, switching timings (rise and fall times) and collector - emitter voltages and gate - emitter voltages were determined. As can be observed from the previous figures and tables, the silicon carbide IGBT had a faster voltage fall time than the silicon IGBT, which resulted in a shorter total switching time.

The silicon carbide IGBT had a faster switching speed and significantly smaller loss than silicon IGBT. Simultaneously, it was discovered that silicon carbide IGBT could operate at a high power density and efficiency. Then, during the SPT, it was found that silicon carbide IGBTs modules had been more efficiently achieved than silicon IGBTs.

The analysis shows that the THFCC with only silicon IGBT efficiency of 85% may be attained with a switching frequency of 20 kHz. The silicon carbide IGBT efficiency in the SPT was 95%, whereas the experimental silicon IGBT efficiency was 77%. A silicon carbide transistor could be used in place of the old silicon transistor to boost efficiency. Results from the experimental tests have shown that an efficiency boost may be result in the case of employing silicon carbide IGBTs in New High frequency converter cabinet (NHFCC).

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