國立清華大學 電機工程學系
實作專題研究成果報告

Development of Si-IGBT/SiC-MOSFET Hybrid Switch Power Module for DC-DC Converter for Wind Power Generation

Si-IGBT/SiC-MOSFET 混合開關功率模組於風力發電之直流轉換器研製

專題領域：電力領域

組　別：A534

指導教授：張淵智副教授

組員姓名：吳威翰

研究期間：113 年 9 月 17 日至 114 年 5 月 1 日

ABSTRACT

This project aims to establish a platform for its application in renewable energy systems. The platform consists of the power generation and a hybrid switch power module for converters. Wind generation was adopted in this experiment for evaluation and proposal thus, the initial step involves constructing the electricity-generating portion of the wind-based power system. Given that actual wind turbines are difficult to acquire, a DC motor substitutes as the primary driver, powering the self-excited induction generator to simulate wind electricity production. A suitably capacitated delta-wired capacitor is connected to the output to facilitate self-excitation. Then, DC power is generated through the rectifier and stored in the DC bus for the subsequent converter. A buck converter utilising a hybrid switch module was implemented, and to evaluate the converter's performance with HSPM, a control strategy ensuring uniform current sharing among its modules was implemented. Simulation results obtained using MATLAB validated both the switching characteristics and the effectiveness of the current sharing mechanism. This evaluation was primarily conducted using the double pulse test (DPT), which is a technique used to analyse the dynamic switching behaviour of power semiconductor devices like MOSFETs and IGBTs.Next, two separate synchronous buck converters were tested and evaluated. The first converter utilised SiC-MOSFETs for both the high-side and low-side switches. The second converter employed Si-IGBTs for both switching positions. The primary objective of these evaluations was to ensure each converter independently achieved a stable step-down voltage from the generator. Finally, a hybrid switch power module converter was designed and tested to step down the voltage of the DC bus used for battery storage in greenhouse energy.

Keyword: Silicon Carbide (SiC), Silicon (Si), Double Pulse Test (DPT), DSP, Hybrid Switch Power Module (HSPM), Switching loss, Efficiency.

摘要

該專題旨在建立一個可再生能源系統之應用平台，此平台由發電機與使用混合開關功率模組之轉換器所組成，此專題中選擇風力發電作為實驗與評估之能源系統，第一步為建造風力發電系統中的發電部分。鑑於實際的風力渦輪機難以獲得，因此採用直流電動機作為原動機取代風機，帶動自激式感應發電機轉動，以此模擬實際風力發電之過程。一組適當容量的三角接電容被連接到輸出端作為自激電容器。發電機產生之 AC 電壓通過整流器被轉換為 DC 電壓儲存在 DC link 中，以便後續進行電壓轉換。第二步為設計一個使用混合開關功率模組之轉換器之降壓轉換器負責 dc link 到實際應用之電壓轉換，並且評估其實際表現，在設計時使用了確保混合開關功率模組之間均流分配的控制策略。使用 MATLAB 之模擬結果驗證開關特性和電流分流機制的有效性。此評估主要使用雙脈衝測試（DPT）進行，該技術常被用於分析 MOSFET 和 IGBT 等功率半導體的動態開關表現。 接著對兩個獨立的同步降壓轉換器進行了測試和評估。第一個轉換器採用 SiC-MOSFET 作為上下臂開關。第二個轉換器則採用了 Si-IGBT 作為上下臂開關，主要目標是確保每個轉換器獨立地從發電機獲得穩定的降壓電壓。最後，完成對於適用於綠能屋與充電樁等低電壓應用場景的混合開關功率轉換器之設計與測試。

關鍵字：碳化矽（SiC）、矽（Si）、雙脈衝測試（DPT）、DSP、混合開關功率模組、開關損耗、效率。

I INTRODUCTION

Wind power, as a key form of renewable energy, is highly beneficial because it harnesses an abundant and inexhaustible natural resource, and therefore, it is essential to take advantage of and fully utilize this clean energy potential.

Silicon has been widely used in power applications due to its abundance, well-established fabrication technology, and good current handling capability. However, due to the inherent limitations of Si material, it is challenging for Si-based power devices to meet the requirements of next-generation power electronic applications, but in recent years, SiC power devices have attracted attention due to their superior properties. SiC offers a wider bandgap, which allows devices to operate at higher voltages and temperatures with lower leakage currents. Additionally, SiC has much higher thermal conductivity and higher power density. These advantages make SiC power devices more efficient and suitable for demanding applications such as, renewable energy.

Traditional buck converters with IGBT devices have high voltage and current handling capabilities. However, it has high switching losses and a limited switching frequency. The goal is to address this issue and develop a converter that expands the application range. The hybrid switch power module addresses these limitations by going beyond what a single transistor can achieve. In the HSPM with the addition of a transistor, SiC-MOSFET parallel with Si-IGBT in a 1:1 configuration offers a promising solution for high-power applications that require both high efficiency and cost-effectiveness. By combining the strengths of both devices, these HSPM can achieve superior performance.

II RESEARCH METHODOLOGY

1 SYSTEM CONFIGURUATION

The main goal in the end is to establish a platform where one can unterlize this hybrid buck converter in green energy. Thus, the wind power system was used, as seen in Figure 1. The induction wind power generator is built to convert the three-phase alternating current generated by the generator into direct current through a rectifier circuit consisting of diodes and parallel currents. To support the system and keep the output voltage steady, we connected a delta-configured bank of self-excitation capacitors (totalling 68 uF) in parallel with the generator's output, providing the necessary reactive power.

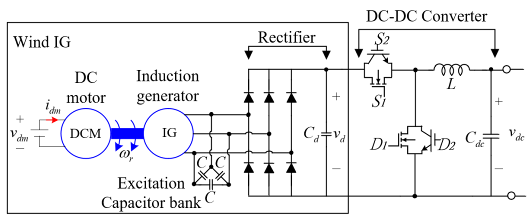
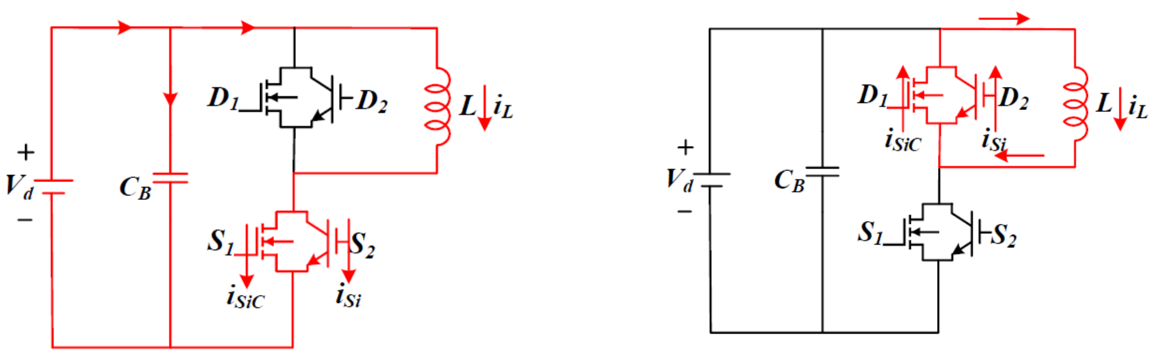


Figure 1: Wind power system

2 DOUBLE PULSE TEST

Figure 2 illustrates the simplified double pulse circuit employed in this experiment to evaluate switching characteristics. The test starts with a First Pulse that turns on the DUT, causing current to build in the inductor until the desired test current is reached. This current level is set by the length of the pulse, along with the inductor's value and the supply voltage. Next, the DUT turns off, and the current flows freely through the body diode or a parallel diode. This allows observation of the diode's reverse recovery current and a slight decrease in current due to circuit resistances. Finally, a Second Pulse turns the DUT on again, further increasing the current. This second switching event includes the effects of the diode's reverse recovery current, making it useful for measuring turn-on losses and the impact of reverse recovery.



(a) DPT circuit during turn-on

(b) DPT circuit during turn-off

Figure 2: DPT Switching Characteristics: (a) ON and (b) OFF

3 HYBRID SWITCH

In the experiment, the two switches are connected in parallel, as shown in Figure 3. This hybrid configuration is designed to capitalise on the strengths of each component for optimised performance. Specifically, it combines the high switching speed and low switching losses of SiC-MOSFETs with the high current-handling capability, low conduction losses(at high currents) and robustness of Si-IGBTs. In the typical HSPM, under the condition when the two transistors have the same gate pattern, the SiC-MOSFET handles the initial current during switching, and the Si-IGBT handles the final current during turn-off. This behaviour is consistent with the theoretical understanding of the inherent characteristics of the individual devices and was previously observed in both the double-pulse testing and the prototype hybrid converter, as shown below in Figures 4(a) and (b).

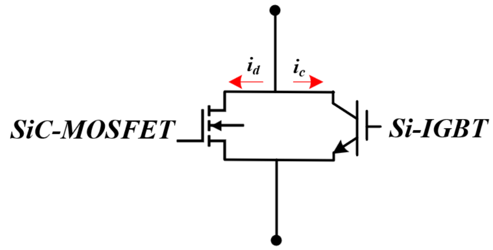
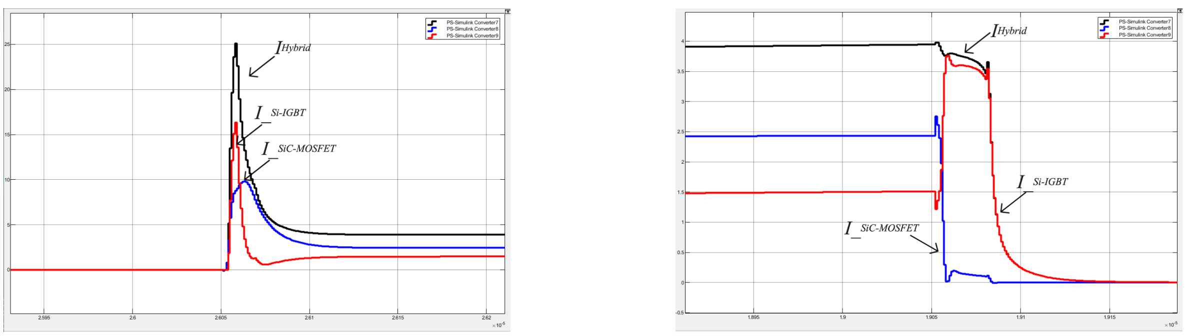


Figure 3: SiC-MOSFET/Si-IGBT Hybrid Switch



(a) Turn ON at 48V/4.3A

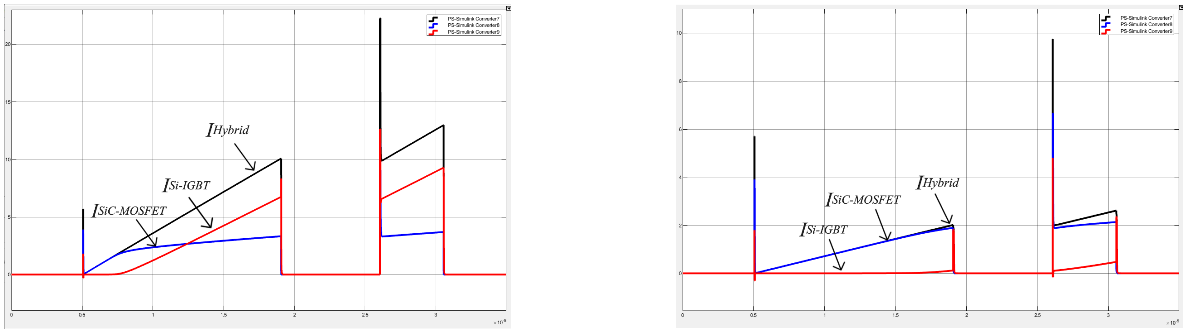
(b) Turn OFF at 48V/4.3A

Figure 4: Switching Characteristics: (a) Turn-on and (b) Turn-off waveforms

3.1 Hybrid switch current sharing

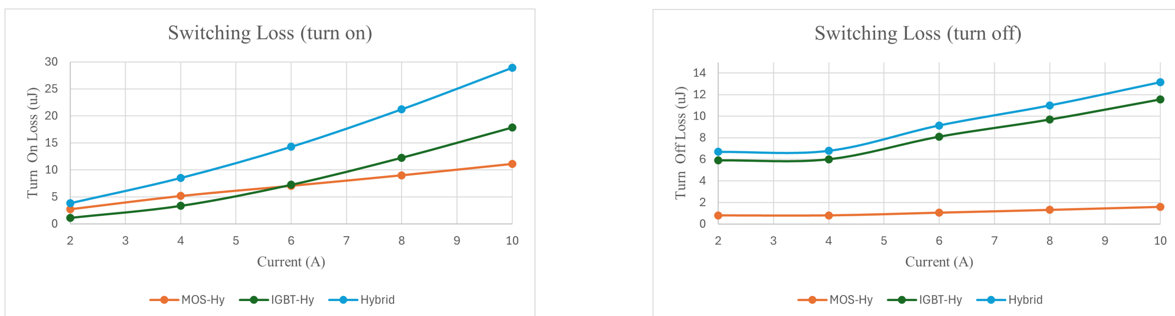
With a hybrid converter, the complexity increases. Two current paths must be monitored, and understanding their interaction and how current is shared between them. At low currents, SiC-MOSFETs exhibit lower conduction losses due to their reduced on-state resistance $R_{\text{DS(on)}}$ compared to Si-IGBTs, which have a higher forward voltage drop and thus higher losses in low current conditions. As a result, SiC-MOSFETs are more efficient for small currents, with most of the current flowing through them. However, at high currents, Si-IGBTs become more advantageous due to their ability to handle large power loads efficiently, as their fixed voltage drop characteristic allows them to manage significant currents better than SiC-MOSFETs, whose on-state resistance increases with voltage rating, making Si-IGBTs more suitable for high-power applications.

The results, as depicted in the figures below, demonstrate a current-dependent sharing behaviour. At a higher current of 10A, both the SiC-MOSFET and Si-IGBT contribute significantly to the total current. Conversely, at a lower current of 2A, the MOSFET dominates conduction, with the Si-IGBT carrying a negligible current.



(a) 48V/10A DPT (b) 48V/2A DPT

Figure 5: Double Pulse Test Configurations: (a) 10A and (b) 2A,



(a) Hybrid Turn on loss (b) Hybrid Turn off loss

Figure 6: Switching loss comparison : (a) Turn ON and (b) Turn OFF

4 HYBRID SWITCH BUCK CONVERTER

Table 1: Component Specifications

Specs	Value	Unit
Input voltage	48	V
Output power	100	W
Output voltage	24	V
Output current	4.3	A
Switching frequency	20	kHz
Inductor current	4.3	A

A hybrid buck converter, also known as a step-down converter, is a type of DC-DC converter that efficiently reduces a higher input voltage to a lower output voltage. This buck converter is designed to step down a 48V input to a 24V output at a switching frequency of 20kHz, delivering an output power of 100W and an output current of 4.3A.

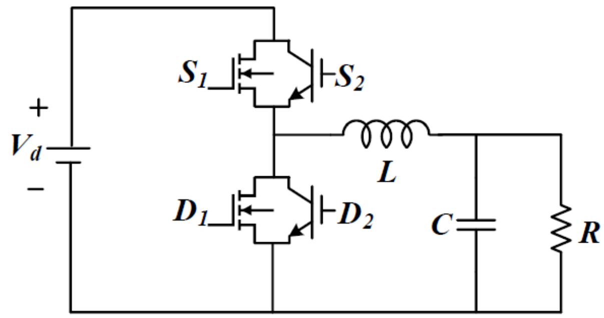


Figure 7: Hybrid Buck Converter Topology

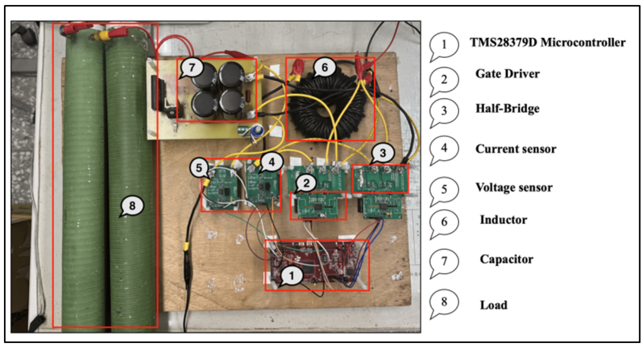


Figure 8: Physical circuit

III EXPERIMENT RESULTS

1 OPEN LOOP Experiment

The buck converter implementation followed a two-step process. It began with a conventional single-switch buck converter (using a SiC-MOSFET only and an Si-IGBT only) to confirm that the hardware operated within the specifications and that the DSP accurately read the measured voltage and current. This step made it possible to confidently implement the hybrid-switch buck converter.

The steady-state analysis results support the theoretical predictions, calculations, and simulation outcomes.

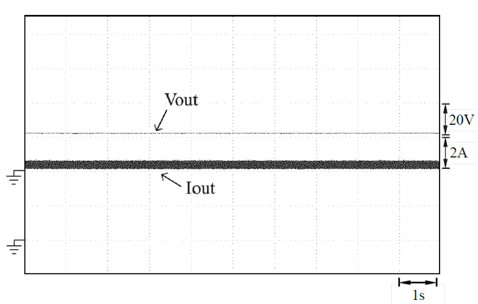


Figure 9: V_{out} 24V and I_{out} 4.3A Steady State

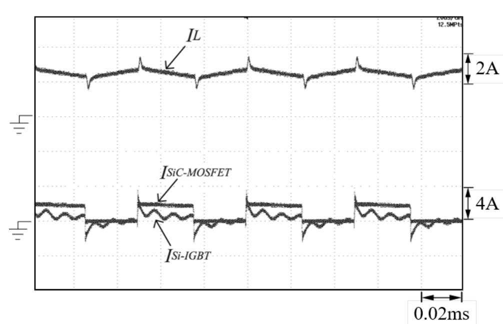
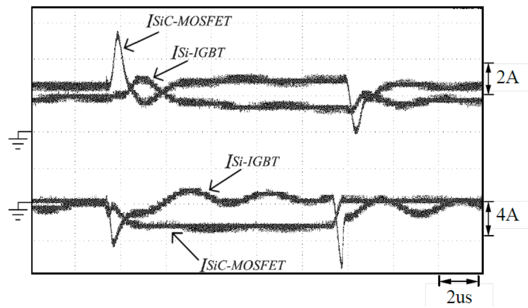
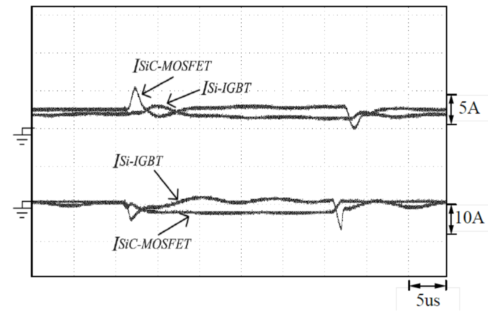


Figure 10: I_{L} I_{Sic} and I_{Si} respectfully



(a) I_{Sic} and I_{Si} during one cycle



(b) I_{Sic} and I_{Si} during one cycle

Figure 11: Switching Characteristics: (a) Current sharing 2A/4A scale and (b) Current sharing 5A/10A scale

2 CLOSED LOOP EXPERIMENT

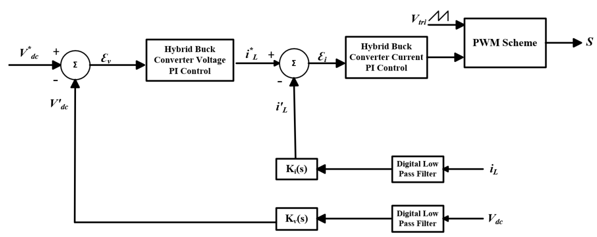


Figure 12: Hybrid Buck Converter Closed Loop Control

This was done by applying a step load step load $10\,\Omega \rightarrow 15\,\Omega \rightarrow 10\,\Omega$. The test is to ensure that the buck converter maintains a stable voltage despite abrupt current demands. Figure 13 illustrates the stable output voltage and current, respectively, successfully reduced from an input of 48V to a regulated 24V output at a current of 2.4A. Figure 14 depicts the inductor current waveform, exhibiting a characteristic triangular shape that signifies the charging and discharging of the inductor. Figures 15 and 16 demonstrate the system's response to step load changes at different scales. The results indicate robust stability, with both the output voltage and current returning to their steady-state values within a short recovery period following the load transient.

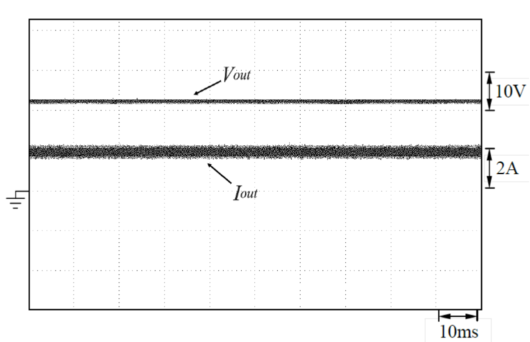


Figure 13: V_{out} and I_{out} Steady State

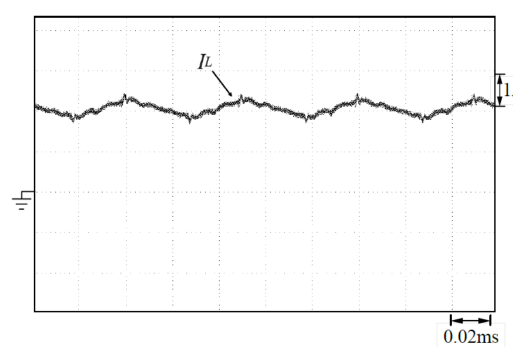


Figure 14: Inductor current I_{L}

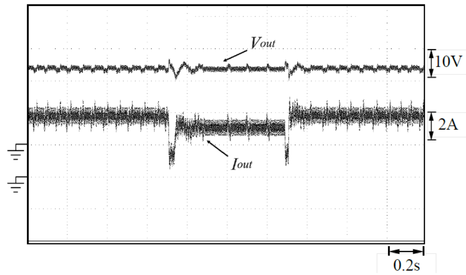


Figure 15: Step load change 10Ω → 15Ω → 10Ω

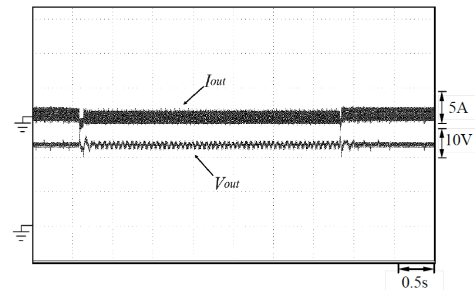


Figure 16: Step load change 10Ω → 15Ω → 10Ω

3 MOTOR CONTROL EXPERIMENT

Table 2: Switching Loss Analysis (All Load Conditions)

	NO-Load		100 Ω		200 Ω		400 Ω		800 Ω		1000 Ω	
Vdm	**Vd**	**RPM**	**Vd**	**RPM**	**Vd**	**RPM**	**Vd**	**RPM**	**Vd**	**RPM**	**Vd**	**RPM**
200	212	2091	180	2001	194	2043	202	2076	207	2094	206	2083
190	199	2026	165	1899	181	1962	188	1985	191	1995	192	1992
180	187	1934	156	1827	169	1881	174	1895	178	1904	179	1907
170	173	1814	143	1736	157	1795	162	1804	164	1815	165	1811
160	159	1723	132	1659	143	1695	148	1716	150	1717	152	1716
150	143	1617	118	1559	128	1594	136	1629	136	1618	137	1617
140	128	1526	105	1476	117	1516	119	1519	121	1520	122	1521
130	113	1421	90	1393	101	1408	104	1420	107	1426	106	1417
120	96	1316	66	1313	80	1322	85	1325	85	1315	86	1318
110	58	1220	24	1236	32	1224	41	1229	47	1228	43	1234
100	2	1113	0	1130	0	1116	0	1115	0	1110	0	1120

Various load conditions were tested to mimic a wind turbine's behaviour under varying wind speeds. We swapped the wind turbine for a 220V, 4A DC motor. By adjusting the motor's supply voltage, we simulated different rotational speeds. This DC motor then drove a 120V, 5.4A induction generator with a rated speed of 2000 rpm and a 0.8 kW output. With lighter loads (higher load resistance), the generator requires less current to maintain operation. This makes self-excitation easier as there is minimal opposition to the buildup of magnetic flux. Conversely, heavier loads (lower load resistance) draw more current, which can suppress self-excitation due to increased electrical resistance and losses. As shown in Figure 18.

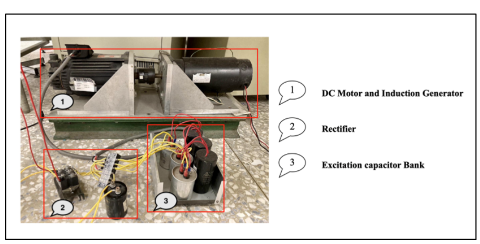


Figure 17: Wind generation setup

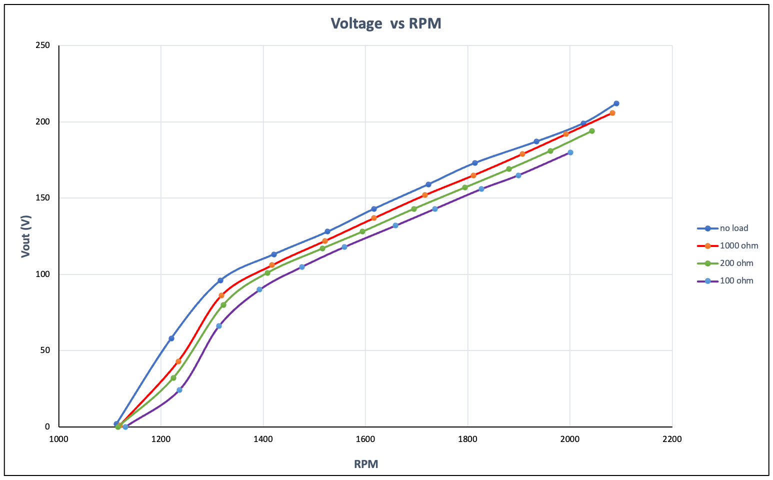


Figure 18: Motor speed and Output Voltage of generator with different load.

IV CONCLUSION

Innovating within familiar concepts, this project explored new areas in power electronics, successfully demonstrating a hybrid SiC-MOSFET/Si-IGBT switch. This configuration enables converters to achieve higher efficiency and load capability by leveraging the complementary strengths of each device. A key to this success is the balanced current sharing, where the analysis revealed the SiC-MOSFET's natural handling of transient currents (due to its low on-resistance) and the Si-IGBT's robust, sustained current delivery at high loads. The project's findings, combining theoretical analysis with practical validation, highlight the significant advantages of this hybrid switch approach in power electronics applications.

While the results are promising, several challenges remain before hybrid switches can achieve widespread adoption. Future work could explore control, such as adaptive gate timing based on load conditions, or optimisation to further refine current sharing and loss distribution.

V Feedback and Thoughts

What set this project apart was the opportunity to implement it from scratch, a hands-on experience unmatched by other courses. The constant discussions and exposure to real, non-ideal situations, often absent in typical classroom settings, provided invaluable learning. I gained first-hand experience from soldering circuits to writing DSP code. The process of soldering circuits and writing DSP code certainly presented its share of headaches, but the immense satisfaction of seeing the final project made every bit of effort worthwhile. My seniors were instrumental in this period, and I deeply appreciate their insightful guidance and unwavering support.