OPTIMAL DESIGN OF SILICON CARBIDE MOSFET HALF BRIDGE POWER MODULE FOR 200A CURRENT RATING BASED ON ELECTROTHERMAL SIMULATION

Genesis M. Cruz
Christian Rocky D. Linatoc
Gio Paolo C. Pascual

Power Module Technology Development
Integrated Micro-electronics Inc, Binan, Laguna
genesis.cruz@global-imi.com
christian.linatoc@global-imi.com
gio.pascual@global-imi.com

ABSTRACT

This research paper delves into optimizing a power module to handle 200A, stemming from a recognized market gap in the limitations faced by 39mm×32.4mm modules concerning higher currents. This optimization seeks to bridge this gap by enhancing the performance of compact modules, catering to applications that demand robust output within space constraints. By achieving the 200A target, this study addresses substantial market demand and advances the efficiency of power modules. By skillfully navigating through material choices and design methods, this study employs multidisciplinary tools to predict and analyze module performance accurately. Through evaluations of current distribution, thermal resistance, and heat capacity, the study culminates in the optimal design of a silicon carbide MOSFET-based half-bridge power module, offering the potential to revolutionize power electronics with enhanced capabilities and performance.

1.0 INTRODUCTION

In recent years, there has been a significant increase in the demand for high-power electronics applications in various fields, including electric vehicles, renewable energy systems, data centers, and industrial automation systems. Power module, a highly advanced engineering product that contains a single or several components combined into a functional and isolated unit, is the foundation of these applications[1].

Power modules are high-power devices that provide electrical connections, thermal conduction, electrical insulation, and mechanical support. They provide efficient, reliable, high-performance power management solutions for modern electronic subsystems. By incorporating multiple devices into a single package, power modules streamline the design process and reduce the amount of board space needed. They come in various configurations, each tailored to specific applications, such as single-switch, half-bridge, full-bridge, and three-phase modules[1].

The core building blocks of power electronics systems are semiconductor devices, which are visualized in Figure 1. Proper packaging design is necessary to construct a device from bare semiconductor chips. The SiC MOSFET half-bridge power module is an exceptional example of power module technology that employs the latest advances in silicon carbide MOSFETs. These MOSFETs provide numerous advantages, such as lower on-resistance, higher switching speeds, and higher operating temperatures, making them ideal for high-power and high-frequency applications[1].

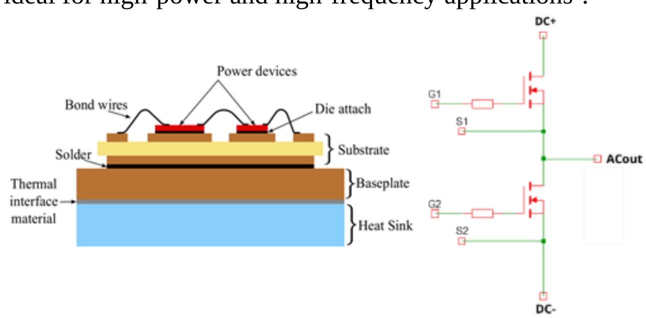

Figure 1. Half Bridge Power Module[1] Package (left) and Schematic (right)

The half bridge configuration of the power module, as shown in Figure 1, comprises two switches that work in tandem to regulate the current delivered to the load, allowing efficient control over the output while minimizing power losses. In high side switching, the switch, particularly MOSFET, is placed between the load and the positive supply voltage (DC+). When the high side switch is closed or turned on, it connects the load to the positive supply, allowing current to flow from DC+ to the load, and, consequently, to ACout. ACout represents the processed and manipulated output signal that results from this switching. Conversely, the switch is placed between the load and the ground (DC-) in low side switching. When the low side switch is closed, it provides a path for current to flow from the ACout signal through the load and into the ground. The researchers used a half bridge configuration for this study with two paralleled dice per switch.

Every power module requires current limits to protect its components, such as power MOSFETs, pins, and bondwires, which all have inherent maximum current ratings. The device area usually determines the current rating of one device. In addition to current limits, the packaging of power modules must provide effective thermal management[2].

Optimizing power modules for a high current rating is a critical aspect of power electronics design, as these modules have a specific operating range that must be carefully considered. High-current power modules can face several challenges impacting their performance. One of the main issues with high-current power modules is heat dissipation. As the current flow through the module increases, it generates more heat, which can cause thermal stress and lead to device failure. Inadequate thermal management can also cause hotspots, resulting in uneven temperature distribution across the module and reducing its overall efficiency[3].

Another problem with high-current power modules is the risk of electrical breakdown. These modules operate at high voltages and currents, which can cause insulation failures if the module's design is not optimized for electrical performance. An electrical breakdown can lead to short circuits, device damage, and fire hazards. Moreover, power modules designed to handle elevated currents often exhibit larger dimensions and higher costs compared to smaller modules intended for lower currents. As a result, it is crucial to design these modules to be as compact and cost-effective as possible while maintaining high performance. This poses a significant technical challenge in meeting the demands of high-power applications requiring higher current handling capabilities[2].

This study delves into the motivation behind optimizing the SiC MOSFET half-bridge power module to accommodate a specific current rating of 200A, driven by a market gap within modules of 39mm×32.4mm size. This optimization targets enhancing compact module performance to address this gap. Power modules with 200A current rating are highly versatile and frequently apply to high-power electronic systems like motor drives, power converters, and inverters. They are often employed in energy-critical applications like electric vehicles, renewable energy systems, data centers, and industrial automation systems.

To achieve this goal, the researchers investigate the various design parameters that affect the electrothermal performance of the power module. They aim to identify suitable materials and design methods to achieve desired electrical characteristics and thermal response. They use multidisciplinary toolsets to predict the module's performance and conduct an electrothermal analysis to accurately capture the constraints' influences. Finally, they evaluate the module's current and temperature distribution, thermal resistance, and heat capacity to determine the optimal SiC MOSFET-based half-bridge power module design capable of handling 200A.

The study focuses solely on optimizing the design of the SiC MOSFET half-bridge power module for a specific current rating of 200A. Other current ratings and power module configurations may require different design considerations. The study does not take into account the effects of external factors, such as environmental conditions and system-level interactions, that may impact the performance of the power module. It does not explore the long-term reliability and durability of the optimized design, which may only become apparent after extensive use and testing. Despite these limitations, the study provides valuable insights into the design considerations and optimization techniques for SiC MOSFET half-bridge power modules. It offers a foundation for future research in this field.

2.0 REVIEW OF RELATED WORK

Refer to 1.0 Introduction.

3.0 METHODOLOGY

This chapter outlines the methodology for optimizing the SiC MOSFET-based half-bridge power module for high current capability.

The study uses a quantitative research design that involves simulations to investigate the electrothermal performance of the power module under different design parameters. The research design includes the following.

3.1 Material Selection

Based on the literature review, the researchers identify suitable materials for the power module components, including the substrate, die, and interconnection materials. Notably, this study employs three distinct substrates, namely Aluminum Nitride (AlN), Alumina (Al_2O_3), and Silicon Nitride (Si_3N_4), as part of its experimental framework.
The selection is based on properties such as thermal conductivity, density, specific heat, and electrical resistivity, which play a significant role in the overall efficiency and performance of the module.

3.2 Design Simulation

Power modules involve multiple physical phenomena, such as electrical and thermal behaviors. Multiphysics simulation tools allow researchers to analyze these interactions simultaneously, providing a more accurate representation of real-world behavior. The simulation was conducted using Finite Element Analysis and Computational Fluid Dynamics software.

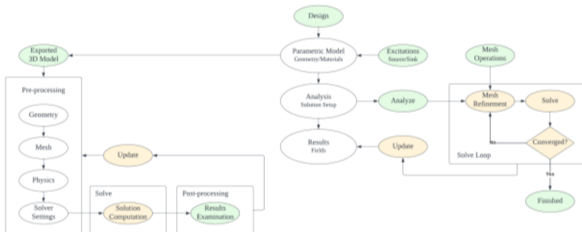

Figure 2. Simulation Environment.

In the pursuit of enhancing the design and performance of power modules, shown in Figure 2, is the simulation methodology that integrates current density field plots, thermal resistance analysis, and Joule heating analysis as a comprehensive framework. This methodology operates at the intersection of electrical and thermal behaviors, encompassing a multifaceted approach to achieve optimal module functionality.

3.2.1 Current Density Field Plot Analysis

Current density field plots visually represent how electric current flows through the module's components, such as bondwires pins and copper traces. These plots reveal high and low current density areas, helping identify potential congestion points or uneven distribution. Understanding current paths aids in optimizing the design to ensure uniform current distribution, which is essential for preventing hotspots.

In this simulation, current density field plots encompass the analysis of electric current flow through module components corresponding to two distinct pin positions, as shown in Figure 3. This evaluation offers valuable insights into the distribution of current paths and the identification of potential congested regions for each pin position configuration.

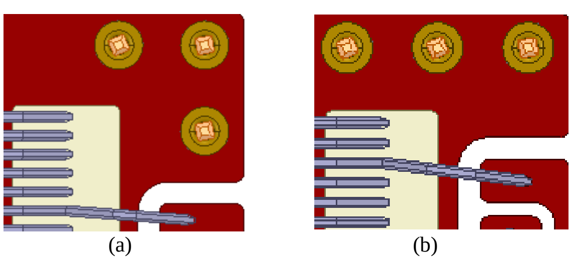

Figure 3. Pin Layout 1 (a) and Pin Layout 2 (b)

The current path is then determined, and the input current of 200A is defined. A field plot calculator was used to analyze the current distribution in the conducting paths. The formula used by the solver for the computation is indicated below:

$$I = \int J_{DC} SA_{Qn}$$

wherein,
J_{DC} = current density
SA_{Qn} = section area

To verify the bondwires' capacity to accommodate the simulation's extracted current, the researchers assessed the maximum permissible current for the bondwire material. Utilizing the equation:

$$I = kd^{\frac{3}{2}}$$

wherein
k = constant corresponding to wire composition and length
d = diameter of wire (in)

3.2.2 Thermal Resistance Analysis

Thermal resistance analysis is vital to understanding how efficiently heat is conducted and dissipated within the module. Researchers can identify potential bottlenecks in heat dissipation pathways by evaluating thermal resistance between components such as semiconductor devices, copper traces, and substrates. This information guides the design of effective thermal management strategies to prevent overheating.

In the context of thermal resistance analysis, three different substrates were considered. This analysis involves assessing the heat transfer characteristics and thermal behavior of the power module when utilizing each of these distinct substrate materials: Al_2O_3 (Alumina), Si_3N_4 (Silicon Nitride), and AlN (Aluminum Nitride).

To closely mimic real-world operational conditions, the simulation established a steady baseplate temperature of 60°C for the power module. All module components adhered to this temperature boundary, creating a uniform thermal environment. Additionally, each die was subjected to a controlled heating load of 180 W.

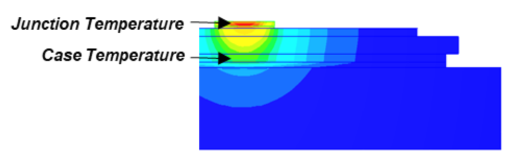

Figure 4. Power Module Stack-up.

To evaluate the junction to case thermal resistance of the module, the researchers plug in the extracted temperatures from the power module stack-up, as illustrated in Figure 4, into the following equation:

$$R_{Thjc} = \frac{T_j - T_C}{P_d}$$

wherein,

T_j= maximum junction temperature

T_C= maximum case temperature

P_d= power dissipated

Comparison and validation were done to align computed thermal resistance obtained through simulation with the thermal resistance value specified in the die datasheet.

3.2.3 Maximum Current and Power Computation

With the results obtained from the thermal resistance analysis, the maximum power can be calculated using the following formula:

$$P = \frac{T_j - T_c}{R_{Thjc}}$$

wherein,

T_j = maximum allowable junction temperature

T_c = derated case temperature

R_{Thjc} = junction to case thermal resistance

Plugging in the results obtained from the above computation, the maximum current can be determined using the following equation:

$$I = \sqrt{\frac{P}{R}}$$

P = maximum power

R = drain to source ON resistance

3.2.4 Joule Heating Analysis

Joule heating analysis focuses on understanding the heat generated due to the resistance of the materials to the electric current passing through them. By quantifying Joule heating, researchers can identify areas where excessive heat is generated, potentially leading to high temperatures and material degradation. This analysis is essential for optimizing material choices, current paths, and heat dissipation solutions to minimize losses due to Joule heating.

The baseplate surface temperature was defined at a boundary condition of 60°C, and this temperature was initially applied to all components. For the simulation, significant inputs include a current magnitude of 200A and a voltage level of 0V.

Based on the extracted temperatures, the researchers evaluate the heat capacity of the power module, which measures the amount of heat energy the module can store.

3.3 Data Analysis

The collected data is analyzed statistically. These visual representations help reveal the influence of different design factors on the electrothermal performance of the power module. This connects to the study's goal of finding the best design for a SiC MOSFET-based half-bridge power module handling 200A.

4.0 RESULTS AND DISCUSSION

This chapter presents the results and analysis of the study, including the identification of design parameters affecting electrothermal performance, optimization of design parameters, and evaluation of the optimized design using electrothermal analysis.

4.1 Current Density Field Plot Analysis

Figures 5 and 6 showcase visual representations of how electric currents move through the power module. These visuals highlight strong and weak current flow areas, offering insights into how design changes affect current distribution.

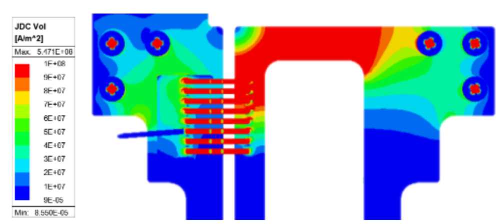

Figure 5. Current Distribution in High Side Switch.

These variations in color intensity across the plot provide visual insights into the distribution and magnitude of current within different components and pathways of the module.

In Figure 7, the current distribution results for bondwires visualized through box plots entail a comparative analysis of two distinct pin position configurations. These provide a concise visual overview of how electric current is distributed across the bondwires under each pin arrangement.

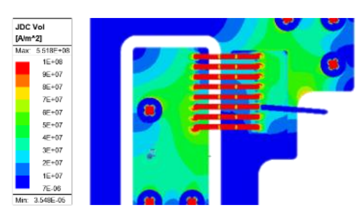

Figure 6. Current Distribution in Low Side Switch.

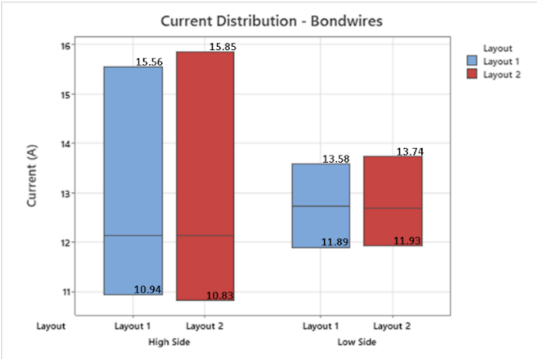

Figure 7. Current Distribution in Bondwires.

As observed, the current distribution among the bondwires within each layout exhibits a notable level of consistency, indicating a balanced sharing of current across the bondwires.

However, pin layout 1 exhibits lower variability and more favorable current behavior. In pin layout 1, the bondwire current spans a range of 4.62 on the high side and 1.69 on the low side. In pin layout 2, the bondwire current covers a range of 5.02 on the high side and 1.81 on the low side.

It was also noted that the maximum bondwire current extracted was 15.56A for Layout 1 and 15.85A for Layout 2. The calculated maximum permissible current for the aluminum wire was determined to be 19.98A.

In Figure 8, Pin Layout 2 showcases a slightly higher maximum current of 35.62A for a single pin, compared to Pin Layout 1 with a maximum of 34.79A. In terms of overall minimum pin current, pin layout 1 records 30.85A, while pin layout 2 exhibits a slightly lower value of 29.35A. Notably, the computed range of pin currents for layout 1 spans 2.69 at the high side switch and 3.94 at the low side switch, while for layout 2, it spans 6.27 at the high side switch and 4.64 at the low side switch. This indicates that pin layout 1 has less variability in the current distribution among pins. This observation implies that pin layout 1 demonstrates a more refined and precise design approach, resulting in a more consistent and uniform current distribution across the power module's pins.

It was also observed in both layouts that the pin closest to the copper edge tends to carry the highest current due to its proximity to the edge's electrical pathways and conductive elements. This positioning creates a more direct and low-resistance path for current flow. This phenomenon leads to an uneven current distribution among the pins, with the one closest to the copper edge bearing the highest load.

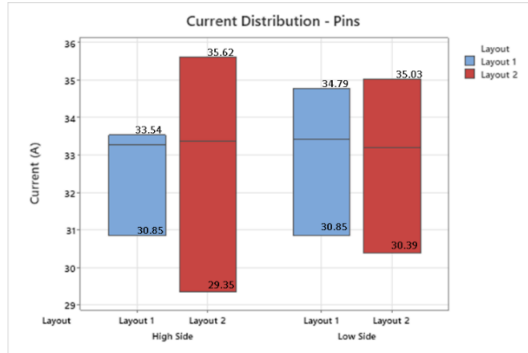

Figure 8. Current Distribution in Pins.

4.2 Thermal Resistance Analysis

In this part are the analysis outcomes aimed at understanding how heat propagates within the power module.

Based on the provided thermal resistance values in Figure 9, when the high side is switched on, AlN has the lowest thermal resistance at 0.1233°C/W. Si_3N_4 has a slightly higher thermal resistance at 0.1342°C/W. Al_2O_3 has the highest thermal resistance at 0.2793. The percentage increase in thermal resistance from AlN to Si_3N_4 is approximately 8.84%, indicating Si_3N_4's higher resistance to heat flow. Similarly, the percentage increase in thermal resistance from AlN to Al_2O_3 is about 126.90%, highlighting Al_2O_3's comparatively poorer heat conduction characteristics.

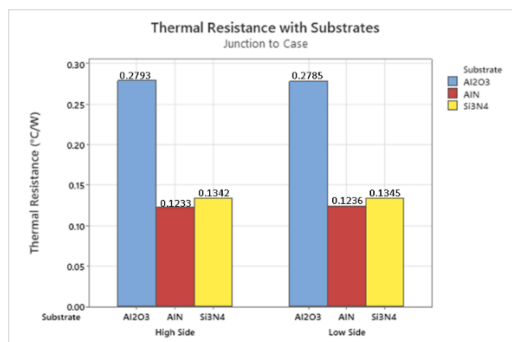

Figure 9. Thermal Resistance with Different Substrates.

The results when the low side is switched on give the same comparison. AlN exhibits a thermal resistance of 0.1236°C/W. Al_2O_3 has a thermal resistance of 0.2785°C/W, and Si_3N_4 records a thermal resistance of 0.1345°C/W. Al_2O_3 demonstrates a substantial percentage increase of approximately 106.68% compared to AlN. Si_3N_4 exhibits a more modest percentage increase of about 8.27%, indicating a slight elevation in resistance compared to AlN.

These values suggest that AlN has the best thermal conductivity among the considered substrate materials, as indicated by its lower thermal resistance value. On the other hand, Al_2O_3 exhibits the highest thermal resistance, indicating comparatively the lowest thermal conductivity. Si_3N_4 falls in between the other two materials in terms of thermal resistance. These observations provide insights into how the different substrate materials could affect heat dissipation within the power module.

4.3 Maximum Current and Power Computation

Based on Table 1, a lower thermal resistance value enhances heat dissipation and reduces the temperature difference between the junction and case. It allows higher power dissipation while maintaining acceptable ΔT.

Table 1. Computed Current and Power Values

Substrate	Max Power (W	Max Current (A)	Case Temp (°C)	Junction Temp (°C)
Si3N4	855.97	308.40	60	175
	707.11	280.30	80	175
Al2O3	412.33	214.04	60	175
	340.62	194.54	80	175
AlN	931.55	321.72	60	175
	769.54	292.41	80	175

It can be seen that higher power and lower R_{DSon} result in higher current levels. Conversely, lower power and higher RDSon values lead to lower current flow.

AlN exhibits the highest maximum power handling capacity among the substrates, followed by Si_3N_4 and Al_2O_3. This suggests that AlN has superior heat dissipation capabilities, allowing it to handle higher power levels.

AlN exhibits the highest maximum current handling capacity among the substrates, reaching 321.72A at 60°C case temperature. This suggests that AlN can handle currents close to the 200A target under specific conditions. Similarly, Si_3N_4 also demonstrates substantial current handling capabilities, indicating potential suitability for meeting the target. Based on the computation, Al_2O_3 can also meet the current requirement with a case temperature derated to 60°C.

4.4 Joule Heating Analysis

The following results provide insight into how different substrate materials respond under joule heating conditions.

As plotted in Figure 10, the pins' maximum temperatures during joule heating differ across the substrate materials. Si_3N_4 reaches 125.08°C, AlN shows 124.33°C, and Al_2O_3 records the highest at 128.13°C. This indicates that Al_2O_3 experiences more significant heating, likely due to its thermal characteristics. Si_3N_4 and AlN exhibit comparatively better thermal performance with lower maximum temperatures.

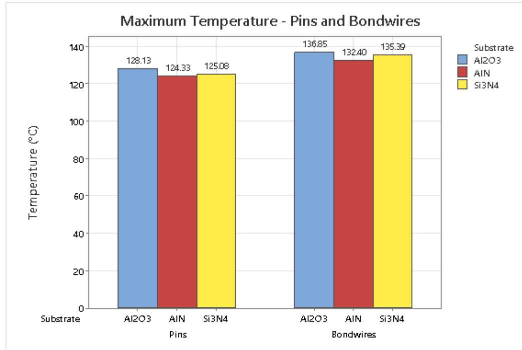

Figure 10. Joule Heating in Pins and Bondwires

The outcomes of the joule heating analysis focused on bondwires yield several key conclusions. Al2O3 demonstrates the highest maximum temperature among the substrate materials studied, reaching 136.85°C. This suggests that Al_2O_3 may be more susceptible to heat buildup and less effective in dissipating heat under joule heating conditions. In contrast, Si_3N_4 records a slightly lower maximum temperature of 135.39°C, indicating relatively better thermal performance. Notably, AlN exhibits the lowest maximum temperature at 132.40°C, underscoring its favorable heat dissipation capabilities.

5.0 CONCLUSION

Based on Current Density Field Plot Analysis, the closer the pins are to the copper edge, the more they exhibit a high current-carrying tendency. Consequently, this results in an unequal current distribution across the pins, with the pin nearest to the copper edge carrying the greatest current load. Conversely, pins positioned farther away from the copper edge demonstrate a more even and distributed current flow. Achieving uniform current distribution relies on optimizing pin positions. This approach ensures a more even current flow across all pins by strategically arranging pin layout, adjusting spacing, and accounting for proximity to the copper edge.

Based on Thermal Resistance Analysis, AlN is the most efficient at conducting and dissipating heat compared to Si_3N_4 and Al_2O_3. The lower thermal resistance of AlN indicates its superior thermal conductivity, which enables it to effectively transfer heat away from the junctions within the power module. AlN is the most suitable substrate for applications requiring efficient heat management and thermal performance.

Based on Maximum Current and Power Computation, lower thermal resistance values enhance heat dissipation and support higher power dissipation with acceptable temperature differences; a relationship exists between power, R_{DSon}, and current levels.

In terms of power capability, AlN exhibits superior maximum power handling capabilities compared to Si_3N_4 and Al_2O_3, highlighting its effective heat dissipation properties. In terms of current capability, AlN demonstrates the highest maximum current handling capacity, reaching levels above the targeted 200A, with Si_3N_4 also displaying substantial current handling potential, and Al_2O_3 can meet the current requirement with a derated case temperature of 60°C.

These findings underscore the interplay of junction temperature, case temperature, and substrate choice in influencing the power module's heat dissipation and current handling capabilities.

Based on Joule Heating Analysis, AlN has efficient heat dissipation capabilities compared to Si3N4 and especially Al2O3. This characteristic is critical for electrical applications as it helps prevent excessive temperature rise and thermal stress, reducing the likelihood of electrical failure.

6.0 RECOMMENDATIONS

It is strongly recommended to conduct actual testing to ensure accuracy by accounting for complexities and unforeseen challenges not explored in the simulation. The combination of simulation and actual testing builds confidence, validates results, and provides empirical data, ultimately enhancing the research's credibility and practical applicability. It is also recommended to expand the research scope beyond electrical aspects. This extension should encompass a thorough exploration of the power module's mechanical and process considerations. This comprehensive method delves deeply into the module's mechanical resilience, manufacturing intricacies, and possible vulnerabilities. By adopting such a holistic research endeavor, substantial contributions can be made to bolster the power module's overall performance, reliability, and durability. This, in turn, ensures the module's optimal functionality and resilience across a wide array of research and practical applications.

7.0 ACKNOWLEDGEMENT

The researchers extend their heartfelt gratitude to the Power Module Technology Development Team for their invaluable contributions to their study. They are particularly thankful to Sir Leomar, Sir Ronald, and Sir Paulo for their guidance, insights, and support throughout this project. This research would not have been possible without their encouragement and assistance.

8.0 REFERENCES

1. Y. Yang, L. Dorn-Gomba, R. Rodriguez, C. Mak and A. Emadi, "Automotive Power Module Packaging: Current Status and Future Trends" in IEEE Access Vol. 8, 2020, pp 160126- 160129.

2. C. Bailey, H. Lu, T. Tilford, J. Rizvi, and C. Yin, "Co-design and multi-physics analysis for power electronic modules" in International Conference on Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems, 2009, pp 1-4.

3. Pang, Y. F., Scott, E. P., Chen, J. Z., and Thole, K. A., "Thermal Design and Optimization Methodology for Integrated Power Electronics Modules" in ASME, 2005, pp. 59–66.

9.0 ABOUT THE AUTHORS

Genesis M. Cruz is a Bachelor of Science in Electronics Engineering graduate specialized in Industrial Automation and Control from Mapua University in Manila. Currently, she is an Electrical Simulation Design Engineer in Power Module Technology Development at IMI.

Christian Rocky D. Linatoc is a graduate of Bachelor of Science in Electronics Engineering major in Microelectronics from First Asia Institute of Technology and Humanities in Tanauan City, Batangas. He passed the Electronics Engineering board examinations in April 2018. Currently, he is an Electrical Simulation Design Engineer in Power Module Technology Development at IMI.

Gio Paolo C. Pascual is a Bachelor of Science in Electronics Engineering graduate from University of Perpetual System Dalta – Las Piñas. He passed the Electronics Engineering board examinations in October 2018. Currently, he is a Product Characterization Engineer in Power Module Technology Development of IMI.