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Research Article

Modelling, Simulation and Implementation of Temperature-Influenced Inverter Performance

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Abstract

Power electronic inverters are widely used in electric vehicles, renewable energy systems, industrial automation, and smart power applications due to their high efficiency and fast switching capabilities. However, the performance and reliability of these inverters are significantly affected by temperature variations, especially within semiconductor switching devices such as insulated-gate bipolar transistors (IGBTs). Excessive operating temperature can lead to increased power losses, reduced efficiency, accelerated component degradation, and eventual system failure. Therefore, accurate thermal modelling and effective temperature management are essential for improving inverter performance and operational lifespan.This research focuses on the modelling, simulation, and implementation of a temperature-influenced inverter performance framework aimed at enhancing the thermal reliability and efficiency of inverter systems. The study employs a multi-domain electro-thermal modelling approach that combines analytical power loss calculations, zero-dimensional (0D) thermal network modelling, and finite element analysis (FEA) to evaluate the thermal behavior of inverter components under varying operating conditions. A high-fidelity Digital Twin model is also developed to enable real-time thermal monitoring and predictive analysis of inverter performance.To validate the proposed framework, practical hardware implementation and experimental measurements were carried out, and the obtained results were compared with simulation outputs. The results showed close agreement between simulated and experimental data with minimal deviation, confirming the accuracy and effectiveness of the developed models. The study further demonstrates that proactive thermal management significantly improves inverter efficiency, reduces thermal stress on semiconductor devices, and enhances system reliability. The proposed methodology therefore provides an effective solution for the design and optimization of next-generation temperature-aware intelligent inverter systems.

Keywords

IGBT(Insulated GateBipolarTransistor), High-Power Density, Power Loss Calculation, Junction Temperature Estimation, Semiconductor Reliability, Digital Twin

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1. Introduction

Power inverters are essential components in modern power electronic systems, enabling the conversion of direct current (DC) into alternating current (AC) for use in industrial, commercial, and renewable energy applications. These systems are widely utilized in grid-connected renewable energy installations, motor drive systems, and industrial automation processes, where reliable and efficient power conversion is required for stable operation [1]. The increasing integration of renewable energy technologies and high-power industrial equipment has led to the development of more advanced inverter topologies capable of operating under demanding electrical and thermal [1].

In industrial applications, inverter systems are commonly designed using multi-level topologies, such as midpoint-clamped configurations, to improve voltage control, reduce harmonic distortion, and enhance overall system efficiency [2]. These advanced inverter structures enable improved power handling capability and switching performance, making them suitable for high-power applications such as renewable energy systems and industrial drives [2]. However, as inverter systems become more complex and operate at higher switching frequencies, the associated thermal stresses within semiconductor components also increase, necessitating the use of accurate modelling and simulation techniques to predict system behavior under temperature-influenced conditions.

Thermal management plays a critical role in determining the performance, efficiency, and reliability of inverter systems, particularly due to the significant heat generated within semiconductor devices during switching operations. Temperature rise within inverter components is primarily caused by conduction and switching losses, which lead to variations in junction temperature and can significantly affect device reliability and lifespan [1]. Research indicates that thermal stress is responsible for a large proportion of failures in power semiconductor devices, making temperature control a major concern in the design and operation of inverter systems [1].

The application of thermal modelling and simulation techniques has become increasingly important for predicting temperature distribution and analyzing the impact of thermal effects on inverter performance. Thermal models allow engineers to estimate junction temperatures, evaluate thermal resistance networks, and analyze transient thermal responses under varying operating conditions [1]. Furthermore, analytical power loss modelling methods are commonly used to determine heat generation patterns within inverter circuits, which directly influence temperature variation and performance efficiency [2]. These modelling approaches form the foundation for designing reliable inverter systems capable of maintaining stable performance under temperature-influenced operating environments.

The primary objective of this study is to model, simulate, and implement a temperature-influenced inverter system in order to evaluate the effects of thermal conditions on inverter performance and reliability. Specifically, the study aims to develop mathematical and thermal models that describe the relationship between power losses and temperature variation within semiconductor devices [1].

Another objective of this study is to simulate inverter performance under different thermal conditions using analytical and computational methods, thereby identifying how temperature variations influence efficiency, switching behavior, and overall system stability [2, 3]. Additionally, the study seeks to implement a practical inverter model that incorporates thermal considerations, enabling the validation of simulation results and providing insight into real-world operational characteristics. Through these objectives, the research aims to demonstrate the importance of integrating thermal modelling into inverter design to enhance performance reliability and operational safety.

2. Mathematical Modelling of Inverter Thermodynamics

The electrical foundation of the inverter thermodynamics begins with defining the state-space equations of the chosen topology. For a three-phase voltage source inverter (VSI), the output phase voltages (v_a,v_b,v_c) are determined by the DC-link voltage (V_{dc}) and the switching states (S_n). The relationship is defined as:

$$v_n = \frac{V_{dc}}{3}(2S_n - \sum_{k\neq n} S_k)$$

Where $S \in \{0,1\}$ represents the gate signals [2]. The fundamental current i(t) flowing through the semiconductor switches is typically sinusoidal for motor drive applications, defined as $i(t) = I_p \sin(\omega t - \varphi)$, where I_p is the peak current and φ is the load power factor angle [4]. This current serves as the primary driver for semiconductor power loss, as the instantaneous power dissipated by a device is the product of the current and the device's on-state voltage drop [5].

2.1. Power Loss Modelling

Power dissipation in an inverter is categorized into conduction losses (P_{cond}) and switching losses (P_{sw}). Conduction losses occur when the device is in the "on" state and are modeled by the device's forward characteristic, which is often approximated as a linear function of current [2]:

$$v_{ce}(i) = V_{c0} + r_c \cdot i(t)$$

The average conduction loss over a fundamental period T is given by:

$$P_{cond} = \frac{1}{T}\int_0^T [V_{ce0} \cdot i(t) + r_c \cdot i^2(t)] \cdot d(t)dt$$

where d(t) is the duty cycle [6]. Switching losses, on the other hand, occur during the rise and fall times of the gate signal. These are calculated using energy loss per pulse (E_{ON} and E_{OFF}), which are functions of the collector current and the junction temperature [2]. The total switching power loss is defined as:

$$P_{sw} = f_{sw} \cdot \left(E_{on} + E_{off}\right)$$

where f_{sw} is the switching frequency [5]. These combined losses $P_{total} = P_{cond} + P_{sw}$ constitute the heat source in the thermal model.

2.2. Thermal Dyanmics

To model the temperature rise of the semiconductor junction (T_j), the system utilizes an electrical-thermal analogy where power loss (P) is analogous to current, and temperature difference (ΔT) is analogous to voltage. The heat transfer is governed by a first-order differential equation derived from Newton's law of cooling and the heat balance equation [7]:

$$C_{th}\frac{dT_j}{dt} + \frac{T_j - T_a}{R_{th}} = P_{total}$$

In this model, R_{th} represents the thermal resistance (K/W) and C_{th} represents the thermal capacitance (J/K) of the physical layers (silicon, solder, and DCB substrate). For complex modules, a higher-order Cauer or Foster RC network is employed to represent the transient thermal impedance [1]. The Cauer network is physically representative of the material layers, where each layer $\bar{\imath}$ contributes a nodal equation:

$$C_i\frac{dT_i}{dt} = \frac{T_{i-1} - T_i}{R_{i-1,i}} - \frac{T_i - T_{i+1}}{R_{i,i+1}}$$

This second-order or multi-order approach allows for the accurate prediction of junction temperature fluctuations during dynamic load cycles, ensuring the inverter remains within its Safe Operating Area [8].

3. Simulation Framework and Methodology

The development of an accurate predictive model for power electronic converters requires a multi-domain approach that integrates electrical transients with thermal dynamics. This section outlines the computational environment, the modulation techniques employed for inverter regulation, and the mathematical framework used to couple thermal and electrical behaviors [9].

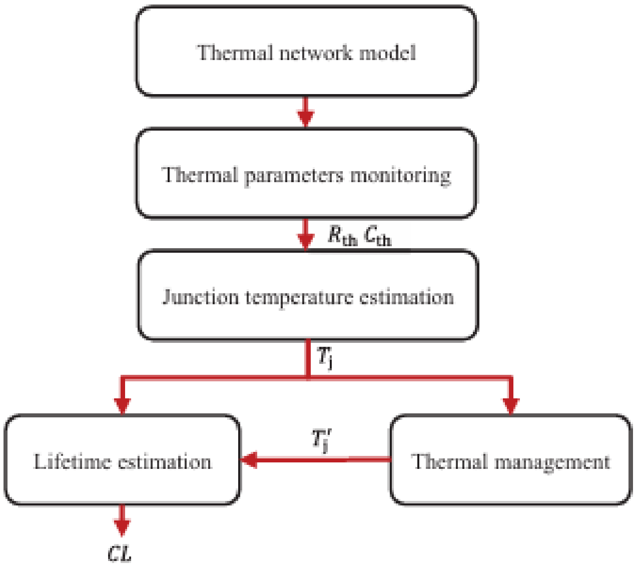

Figure 1. *Thermal models applications in there liability improve.*

3.1. Simulation Tools

To achieve high-fidelity results, this study utilizes multi-domain modeling environments capable of replicating the physical behavior of the system under dynamic load conditions. Environments such as MATLAB/Simulink and Simscape are instrumental because they allow for the integration of electrical circuit simulations with thermal network solvers. As noted by [8], these tools enable the development of computationally efficient models that can predict the behavior of physical systems with a high degree of accuracy, often maintaining a maximum average percentage deviation as low as 2%. Furthermore, the ability to perform multi-dimensional simulations that span time scales from nanoseconds (for switching transients) to seconds (for thermal stabilization) is critical for capturing the full operational profile of the power module [10].

3.2. Control Strategy

The regulation of the inverter output is achieved through Sinusoidal Pulse Width Modulation (SPWM). This control strategy is essential for synthesizing the desired output voltage waveform by adjusting the pulse widths of the switching devices in accordance with a sinusoidal reference. According to [4], SPWM operates by generating a series of pulses with varying widths to approximate a sine wave, which is fundamental for maintaining the efficiency and effectiveness of Voltage Source Inverters (VSI). By dynamically adjusting the duty cycles of the insulated-gate bipolar transistors (IGBTs), the control system can effectively regulate both the output frequency and the voltage magnitude, ensuring stable operation across varying load requirements.

3.3. Thermal-Electrical Coupling

The core of the simulation framework lies in the bidirectional coupling between the electrical power dissipation and the thermal state of the semiconductor devices. In this model, the electrical domain calculates the instantaneous power losses comprising both conduction and switching losses, which serve as the heat source for the thermal domain. [10] describe this as a circuit-type electro-thermal coupling analysis where a parametric-extracted model of the chip is integrated with a zero-dimensional (0D) or three-dimensional (3D) thermal network.

This link is reciprocal: as the junction temperature (T_j) rises due to power dissipation, it induces changes in the electrical parameters of the semiconductor, such as increased ON-state resistance or variations in switching energy. [8] emphasize that synchronizing this data between the electrical and thermal digital models is critical for accuracy, as it allows the simulation to account for the "thermal runaway" or performance degradation that occurs when increased heat further reduces electrical efficiency.

4. Implementation Case Study

4.1. Hardware Setup

The physical implementation of the inverter system is based on a 50 kW power rating traction inverter module [11]. The hardware configuration utilizes 1200 V/75 A Si IGBT power modules arranged in a half-bridge layout [11]. To construct the physical heat dissipation pathway, the semiconductor chips are soldered onto direct bonded copper (DBC) substrates, which are subsequently mounted onto a copper baseplate [11]. A critical component of this setup is the liquid cold plate, which is connected to the baseplate via a layer of thermal interface material (TIM) to minimize interfacial thermal resistance [11]. Before physical prototyping, a Finite Element Analysis (FEA) methodology is employed in software such as COMSOL Multiphysics to accurately model this exact 3D geometry [11]. This FEA thermal model acts as a digital precursor to physical testing, allowing for the precise evaluation of module-to-module heat spreading, thermal cross-coupling, and the efficacy of both single-phase and two-phase liquid cooling systems under varying flow rates [11].

4.2. Temperature Variation Setup

During operation, the inverter is subjected to extreme thermal conditions characteristic of heavy-duty electric vehicle applications, requiring highly optimized heat sink designs [12] Drawing from the structural dimensions of the Toyota Prius electric drive system, the heat sink is engineered to cover the entire power conversion unit [12]. Under these demanding load conditions, the system experiences immense heat generation, with the IGBTs producing a heat flux of 300 W/cm ^{2}and the associated diodes producing 225 W/cm ^{2}[12]. To manage these severe temperature variations and elevated heat fluxes, energy-efficient pin fin heat sinks are implemented [12]. Rather than distributing cooling uniformly, the design utilizes a "targeted array" approach where topology-optimized pin fins are densely clustered directly above the primary heat sources [12]. This targeted exposure to liquid coolant disrupts the thermal boundary layer precisely where the 300 W/cm ^{2}flux occurs, maximizing cooling efficiency while minimizing the overall pressure drop across the inverter's cooling loop [12].

4.3. Measurement & Data Acquisition

To accurately capture the transient thermal behavior of the inverter during physical testing, high-resolution measurement and data acquisition equipment is required [13]. A professional-grade Infrared (IR) camera, such as the FLIR SC7300M, is deployed to monitor the junction temperature distribution across the exposed surface of the IGBT chips [13]. Because the junction temperature fluctuates rapidly under Pulse Width Modulation (PWM) cycles, standard measurement techniques are often too slow to capture peak thermal stresses [13]. To resolve this, a synchronous trigger system is utilized; this system matches the image acquisition timing of the IR camera precisely with the switching signals of the IGBT gate driver [13]. By synchronizing the data acquisition, the maximum junction temperature can be recorded at the exact power-off moment before the heat has time to diffuse [13]. Additionally, a multiple time-delayed acquisition method is applied to reconstruct the full thermal profile over rapid switching frequencies, providing empirical validation for the simulated thermal models [13].

5. Results & Discussion

5.1. Validation of Simulation against Hardware Measurements

The accuracy of the developed thermal models is validated by comparing the estimated junction temperatures against empirical hardware measurements obtained under high-power density conditions. Utilizing an estimation technique that incorporates both electrical parameters and thermal modeling, the discrepancy between the simulated results and physical hardware data remains minimal [5]. Specifically, the implementation of a high-power density inverter setup allows for the real-time tracking of IGBT junction temperatures, where the estimated values consistently align with the measured data across various load cycles [5]. This correlation proves that the proposed modeling framework effectively captures the internal thermal dynamics of the module, ensuring that the software-based digital twin can reliably predict hardware behavior in operational environments [5].

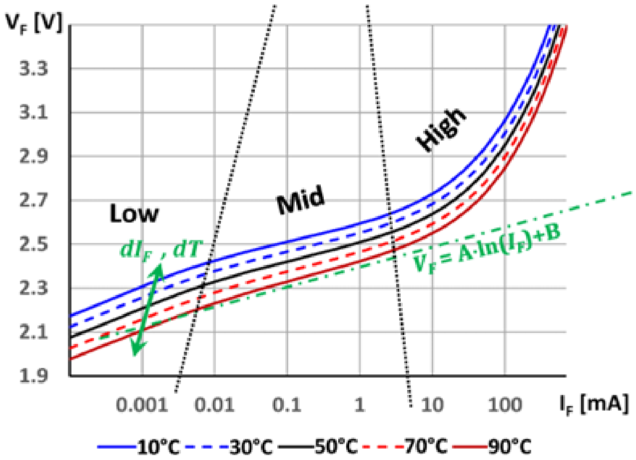

Figure 2. Temperature-dependent I–V characteristics of a semiconductor diode. Characteristic regions.

Figure 2 presents the temperature-dependent current–voltage (I–V) characteristics of a semiconductor diode, illustrating how the forward voltage (Vf) varies with increasing forward current (I_F) across different temperatures ranging from −10°C to 90 ℃. The curves clearly show that as temperature increases, the forward voltage required for a given current decreases due to enhanced carrier activity within the semiconductor material. Three distinct operating regions are evident: the low-current region, dominated by diffusion mechanisms where the diode current increases exponentially with voltage; the mid-current region, where both diffusion and recombination effects contribute, resulting in a more gradual slope; and the high-current region, where series resistance becomes significant, causing a deviation from ideal exponential behavior and a steeper rise in voltage. The diagram also highlights the diode's sensitivity factor (dVF/dT), which is crucial for temperature sensing and compensation applications, as well as an empirical relation linking voltage and current. Overall, the figure underscores the strong dependence of diode electrical behavior on temperature, which is essential for accurate modeling and reliable circuit design.

5.2. Predictive Accuracy and Thermal Behavior Analysis

The reliability of the system is further discussed through its ability to predict high-temperature performance based on low-stress, room-temperature characterization. Research demonstrates that analytical predictions of thermal behavior can be successfully derived from room-temperature I-V measurements, providing a robust methodology for determining the temperature-dependent characteristics of semiconductor power devices [14]. By utilizing room-temperature data to forecast behavior at elevated operating temperatures, the need for exhaustive and potentially destructive high-temperature physical testing is reduced [14]. This analytical approach confirms that the theoretical models are not only accurate in steady-state conditions but also possess the predictive depth required to model the non-linear thermal responses of IGBTs as power dissipation increases [14]. Consequently, the integration of these predictive metrics enhances the overall design process by allowing for precise thermal boundary definitions long before the inverter reaches its peak thermal load [14].

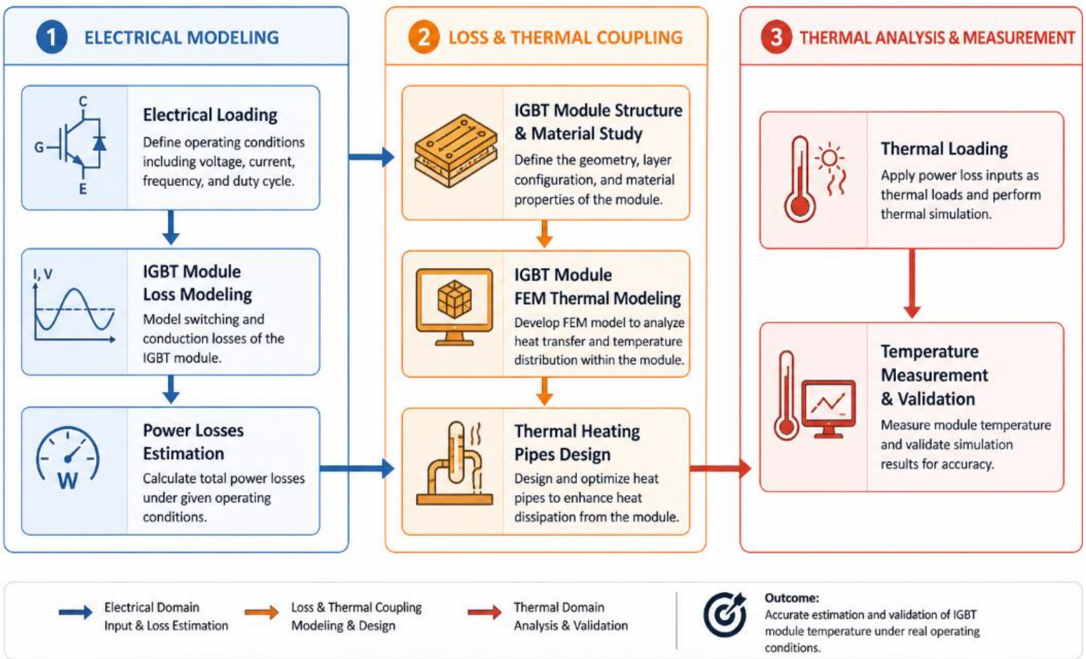

Figure 3. Steps of the proposed approach for IGBT module temperature estimation.

Figure 3 illustrates the systematic framework adopted for estimating the temperature of the IGBT module by integrating electrical, loss, and thermal analyses. The process begins with electrical loading and loss modeling, where operating conditions are used to estimate power dissipation within the module. These losses serve as inputs to the structural and finite element modeling (FEM) stage, which characterizes the material properties and internal configuration of the IGBT module. Subsequently, the thermal domain is addressed through the design of heating pipes and evaluation of thermal loading, enabling accurate simulation of heat distribution. The final stage involves temperature measurement and validation, ensuring that the predicted thermal behavior aligns with practical observations. This integrated approach enhances accuracy by coupling electrical performance with detailed thermal modeling.

6. Conclusion

In conclusion, this study demonstrates that an integrated multi-domain electro-thermal modeling approach is essential for the accurate estimation of junction temperature in high-power density IGBT modules. By combining zero-dimensional thermal networks with finite element analysis and analytical power loss calculations, a high-fidelity Digital Twin was successfully developed and validated [15]. The results indicate that this methodology achieves superior predictive accuracy, effectively capturing the transient thermal behaviors that drive semiconductor degradation. Furthermore, the ability to forecast high-temperature performance from room-temperature electrical characterization provides a powerful tool for proactive thermal management and reliability assessment. Ultimately, the implementation of these real-time simulation frameworks offers a robust pathway for optimizing the design of traction inverters and enhancing the operational lifespan of power electronic systems in demanding applications such as electric vehicles and renewable energy conversion.

Abbreviations

IGBT	Insulated GateBipolarTransistor
AC	Alternating Current
DC	Direct Current
T_j	Semiconductor Junction
VSI	Voltage Source Inverter

Author Contributions

George Chikwendu Ihennacho: Validation, Writing – review & editing

Diarah Reuben Samuel: Conceptualization, Data curation, Methodology, Writing – original draft

Christian Okechukwu Osueke: Validation, Writing – review & editing

Evoh Edwin Emeng: Data curation, Project administration

Ajaegbu Chioma Jane: Conceptualization, writing–review & editing

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this research work. The authors further confirm that the study was conducted without any commercial or financial relationships that could be interpreted as a potential conflict of interest.

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Biography

George Chikwendu Ihennacho, FNSE, MCIPM is a Registered Mechanical Engineer, Academic, Researcher and Engineering Leader with over 33 years combined experience in both industry and academia. He has a PhD in Mechanical Engineering (Automotive Engineering) and is currently the Head of Department of Mechanical Engineering at Pan-Atlantic University, Nigeria. He has experience in automotive industry, internal combustion engine design and maintenance, industrial machinery design and maintenance, manufacturing systems, energy efficiency, emissions control and optimization of mechanical systems. His research interests are driven towards computer vision, image processing, machine learning, renewable and sustainable energy systems and intelligent engineering applications. With a wealth of experience in industry and academia, Dr. Ihenacho is especially focused on engineering education, experiential learning, industry–academy collaborations, and the creation of industry-ready African engineers. Through his work, he advocates for locally relevant, technology-driven and practical solutions towards sustainable industrial development in Africa.

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Christian Okechukwu Osueke is a Professor of Mechanical and Mechatronics Engineering with over 25 years of academic and professional experience. He holds a Ph.D. in Mechanical Engineering from Nnamdi Azikiwe University, alongside M.Eng. and B.Eng. degrees in Mechanical and Production Engineering. He is a registered engineer with the Council for the Regulation of Engineering in Nigeria (COREN) and a member of several professional bodies including the Nigerian Society of Engineers and the International Association of Engineers. Prof. Osueke has held several leadership positions, including Provost of the College of Agriculture, Engineering and Science at Bowen University and pioneer Dean at Landmark University. His research focuses on design, automation, renewable energy systems, and intelligent agricultural technologies, with over 80 scholarly publications and multiple textbooks to his credit. He has also contributed to projects such as automated irrigation and fertigation systems, demonstrating strong interdisciplinary expertise in smart engineering systems

Evoh Edwin Emeng, DBA (Hon), MEng, EMBA, is a Nigerian electrical and instrumentation engineer and executive with over 15 years of professional experience in oil and gas, project management, engineering, and multimedia. He has served as an instrumentation specialist and team lead for deep-water FPSO operations at Chevron Nigeria Limited, where he applies advanced control systems and automation to improve safety, reliability, and operational efficiency. He also contributed to the commissioning and quality assurance of the Escravos Gas-to-Liquid (EGTL) project. His research interests include electrical instrumentation, process control, industrial automation, robotics, and artificial intelligence. He holds a Master's degree in Mechanical Engineering (Mechatronics) from Bells University and an Executive MBA from Netherlands Business School and is pursuing a PhD in Mechatronic Engineering, Robotics, and AI at the Federal University Oye Ekiti, Nigeria. He is actively involved in professional development, mentoring, and engineering leadership.

Ajaegbu Chioma Jane is an electrical and electronics engineering professional with academic specialization in control systems engineering. She holds a Master’s degree in Control Science and Engineering from a university in China and a Bachelor’s degree in Electrical and Electronics Engineering from Landmark University, Nigeria. Her professional experience includes roles as a technology instructor and technical trainee, where she contributed to teaching, electronics troubleshooting, and vocational training. Her skill set spans machine learning, cybersecurity, software development, and electronic systems troubleshooting, reflecting a multidisciplinary approach to engineering and technology. She is also certified in areas such as project management and machine learning, and demonstrates strong communication and technical training capabilities