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Digital Controller for Industrial Induction Heating System

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Abstract: This experiment demonstrates the design and im- plementation of a smart control system for an induction casting machine using the dsPIC33CK256MC506-E microcontroller. The system integrates a PFU-400 TAIE PID Temperature Con- troller** to regulate the machine's heating process. The tem- perature inside the heating coil is measured using a sensor and displayed on the PID controller, which also allows manual adjustment of temperature settings. The PID controller outputs a control signal to the microcontroller, which dynamically ad- justs the phase shift of the voltage supplied to the induction coil. This phase-shift regulation ensures precise power delivery, maintaining the desired temperature for the casting process. The closed-loop system effectively combines real-time feedback and advanced phase-shift control to achieve stable and efficient heating. The experiment highlights the synergy between embedded systems and control algorithms in industrial applications.

I. INTRODUCTION

Induction casting machines are widely used in industrial applications for precision heating processes, relying on elec- tromagnetic induction to generate heat. Accurate temperature control in such systems is critical for ensuring product quality and energy efficiency. This experiment focuses on designing a smart control system for an induction casting machine using the dsPIC33CK256MC506-E microcontroller. The system em- ploys a PFU-400 TAIE PID Temperature Controller to monitor and adjust the temperature within the heating coil. The PID controller receives input from a temperature sensor installed in the heating machine, providing real-time feedback on the system's current state. It displays critical parameters such as temperature, voltage, and current, while also allowing manual adjustment of the target temperature. The output signal from the PID controller is processed by the microcontroller, which dynamically regulates the phase shift of the voltage sup- plied to the induction coil. This phase-shift control mechanism ensures precise modulation of power delivered to the heating coil, achieving stable temperature control and optimal energy utilization. This study integrates embedded systems and control strate- gies to enhance the performance of induction casting ma- chines, demonstrating the effectiveness of real-time feedback loops in industrial heating applications.

II. LITERATURE REVIEW

1) Induction Heating Principles: Kothari, D.P., Nagrath, I.J. (2018): "Power System Engineering" Kothari and Nagrath explore the principles of electromagnetic induction and its application in industrial heating systems. The authors empha- size the importance of controlling electrical parameters such as voltage, current, and frequency for achieving efficient and uniform heating. They also introduce phase-shift modulation as an effective method to regulate power delivery in induction systems. This study establishes the theoretical foundation for the heating mechanism used in the induction casting machine. The regulated phase-shift control implemented by the micro- controller directly aligns with the principles outlined, ensuring precise control over power supplied to the heating coil.
2) PID Controllers for Temperature Control: Smith, C., Corripio, A.B. (2016): "Principles and Practices of Automatic Process Control" Smith and Corripio provide an in-depth anal- ysis of PID controllers, which are widely used for temperature regulation in industrial applications. They demonstrate the robustness and effectiveness of PID controllers in maintaining stable operating conditions by dynamically adjusting inputs based on real-time feedback from sensors. The incorporation of the PFU-400 TAIE PID Temperature Controller in this system is supported by this study. The controller serves as a critical component that not only monitors the temperature but also allows user input to define the desired temperature. Its output is crucial for guiding the microcontroller's phase-shift regulation.
3) Microcontroller-Based Control Systems: Chen, W., Yu, C. (2019): "Embedded Systems Design and Applications" This study examines the use of advanced microcontrollers, such as the dsPIC33 series, in industrial control systems. The authors highlight features like integrated PWM (Pulse Width Modulation) modules and ADCs (Analog-to-Digital Converters), which enable precise phase-shift modulation and seamless communication with external devices. The dsPIC33CK256MC506-E

microcontroller utilized in this ex- periment directly benefits from the features discussed by Chen and Yu. Its capability to process the PID output and generate precise PWM signals for phase-shift control makes it an ideal choice for this application.

4) Phase-Shift Control Techniques Tanaka, H., Kobayashi, S. (2020): ”Advanced Power Electronics for Industrial Ap- plications” Tanaka and Kobayashi emphasize the significance of phase-shift modulation in regulating power supplied to induction heating systems. Their experiments reveal that fine- tuning the phase angle can enhance energy efficiency and prevent overheating, both of which are essential for ensuring product quality in casting processes. This research validates the use of phase-shift control in the induction casting machine. The microcontroller’s ability to dynamically adjust the phase shift based on the PID controller’s output ensures optimal energy use and temperature stability, reflecting the findings of this study.
5) Feedback and Safety Mechanisms: Zhao, L., Zhang, Y. (2017): ”Feedback Systems: Design and Analysis” Zhao and Zhang discuss the role of feedback systems in maintaining sta- bility and ensuring safe operation in industrial processes. They recommend integrating real-time feedback with robust control algorithms while also implementing fail-safe mechanisms to handle potential faults such as overcurrent and overvoltage. The feedback loop established in this experiment, where the temperature sensor continuously provides data to the PID controller, aligns with the principles discussed by Zhao and Zhang. Additionally, the system’s reliance on real-time data ensures stability and precise control, while safety measures like current and voltage monitoring are integrated to prevent faults.

III. PROPOSED SYSTEM

The proposed system is designed to regulate the temperature of an induction casting machine using a dsPIC33CK256MC506-E microcontroller in conjunction with a PFU-400 TAIE PID Temperature Controller. The system relies on a temperature sensor to monitor real-time heating, with the sensor data fed to the PID controller. The PID controller displays critical parameters such as temperature, current, and voltage while allowing users to set the desired temperature. The output signal from the PID controller is processed by the microcontroller, which dynamically adjusts the phase shift of the voltage supplied to the induction coil, ensuring precise power delivery. A closed-loop feedback mechanism ensures the system adapts to temperature deviations in real time. This integration of PID control and phase-shift modulation enables stable temperature regulation, improves energy efficiency, and enhances product quality. The system’s design incorporates safety features such as overcurrent and overvoltage protection, ensuring reliable operation. By combining real-time control with user-friendly interaction, the proposed system offers an efficient and robust solution for induction casting applications.

A. System Architecture

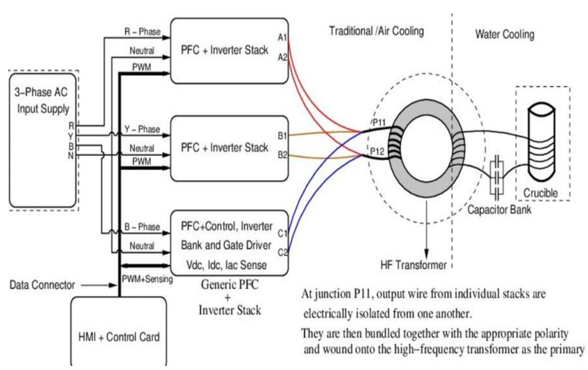

Fig. 1: System Architecture

The system architecture consists of a three-phase AC input supply connected to multiple PFC (Power Factor Correction) + Inverter Stacks, each controlling phase-shifted voltage for efficient power regulation. The outputs are combined at a junction point and wound onto the primary side of an HF (High-Frequency) Transformer, which drives the induction heating system. The transformer is connected to a capacitor bank and crucible, forming the core of the heating process. Temperature regulation is achieved through real-time feedback from sensors to an HMI and Control Card, supported by air and water cooling mechanisms to manage heat dissipation. This architecture ensures precise control, energy efficiency, and system stability for the induction casting machine.

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B. Key Components

1) *dsPIC33CK256MC506-E microcontroller:* The dsPIC33CK256MC506-E microcontroller is used to control the phase shift of a coil in the induction casting machine, adjusting the voltage supplied to the system. It interfaces with the PFU-400 TAIE PID Temperature Controller to regulate temperature in real-time. Its high-speed processing, precise timing, and PWM capabilities make it ideal for managing temperature control and voltage regulation efficiently.

Fig. 2: dsPIC33CK256MC506-E microcontroller

2) *PFU-400 TAIE PID Temperature Controller:* The PFU- 400 TAIE PID Temperature Controller regulates temperature by processing sensor input and using PID logic to adjust heating elements. It displays real-time temperature and volt- age values and allows manual setpoint adjustments, ensuring precise and stable control in the induction casting machine. PFU-400 TAIE PID Temperature Controller monitors the temperature of the induction casting machine via a sensor and sends this data to the microcontroller. It adjusts the heating system by regulating the voltage through phase shift control and provides real-time temperature and voltage readings, ensuring efficient and accurate operation.

Fig. 3: PFU-400 TAIE PID Temperature Controller

3) *Temperature Sensor (Thermocouple):* A Temperature Sensor (Thermocouple) is a device that measures temperature by detecting voltage changes generated by the junction of two dissimilar metals when exposed to heat. The thermocouple senses the temperature of the induction casting machine. It sends the temperature data to the PFU-400 TAIE PID Temperature Controller, enabling precise tempera- ture monitoring and control for efficient operation.

Fig. 4: temperature Sensor(Thermocouple

4) *Power Factor Correction (PFC) Circuit:* A Power Factor Correction (PFC) Circuit improves the power factor of an electrical system by reducing phase differences between voltage and current. It enhances energy efficiency, reduces losses, and complies with power quality standards. PFC circuit ensures efficient power utilization by minimizing reactive power. This improves the system's overall efficiency, stabilizes voltage supply, and reduces heat generation in components, leading to reliable and cost-effective operation.

Fig. 5: Power Factor Correction (PFC) Circuit

5) *Induction Coil:* An Induction Coil is a crucial compo- nent in induction heating systems. It generates a magnetic field when AC current flows through it, inducing eddy currents in the material placed inside the coil. These currents produce heat due to the material's resistance. The induction coil is responsible for heating the material. The dsPIC33CK256MC506-E microcontroller regulates the coil's phase shift to control the voltage and, subsequently, the heat generated, ensuring precise temperature control for the casting process.

Fig. 6: Induction Coil

6) *Crucible:* A Crucible is a heat-resistant container used to hold and melt materials, typically metals, at high temperatures during industrial processes. It is designed to withstand extreme heat without deforming or reacting with the contents. crucible holds the material being melted. The heat generated by the induction coil efficiently melts the material within the crucible, while the system's temperature control ensures consistent and precise heating for optimal casting quality.

Fig. 7: Crucible

C. *Working Mechanism*

The induction casting machine is a carefully designed system that integrates advanced power electronics, precise temperature control, and user-friendly interfaces to achieve efficient and consistent heating. The process seamlessly com- bines hardware components and a microcontroller-based con- trol system to maintain high levels of performance.

1) Power Input and Conversion: The system begins with a three-phase AC input supply, which is fed into three separate Power Factor Correction (PFC) and inverter stacks. Each PFC circuit converts the AC input to DC while improving power factor, ensuring optimal power delivery. The DC output is then passed to inverters that generate high-frequency AC required for induction heating. These inverters utilize pulse-width modulation (PWM) to precisely regulate the output frequency and voltage.
2) High-Frequency Transformer and Induction Coil: The high-frequency AC from the inverters is sent to a transformer that steps up the voltage and provides electrical isolation. This transformed energy is delivered to the induction coil, which is wound around a crucible containing the metal. The alternating magnetic field generated by the induction coil induces eddy currents in the metal, causing it to heat up rapidly due to resistive losses.
3) Temperature Sensing and Feedback: A temperature sensor, such as a thermocouple or RTD, is placed near the crucible to continuously monitor the temperature of the molten metal. The sensor sends real- time temperature readings to the PFU-400 TAIE PID Temperature Controller, which plays a crucial role in maintaining precise control of the heating process by providing feedback to the system.
4) PID-Based Control System: The PFU-400 TAIE PID Temperature Controller re- ceives the temperature data and compares it with the desired setpoint. Based on this comparison, the PID controller generates an output signal to correct any devi- ations. This signal is sent to the dsPIC33CK256MC506- E microcontroller, which adjusts the phase shift of the inverter's output. By controlling the phase shift, the sys- tem regulates the power supplied to the induction coil, ensuring consistent heating at the desired temperature.
5) Energy Efficiency and Stability: To enhance energy efficiency, a capacitor bank is placed near the induction coil. This bank ensures proper impedance matching between the induction coil and the high-frequency transformer, minimizing power losses and stabilizing the system. Additionally, the PFC cir- cuits in the inverter stacks reduce reactive power and maximize efficiency.

6) Cooling System for Heat Management: The system includes a cooling mechanism to prevent overheating of critical components, such as the induction coil and inverters. Depending on the design, the machine may use air cooling with fans or water cooling with a closed-loop system to maintain the desired operational temperatures.

By combining high-performance hardware and intelligent con- trol algorithms, the induction casting machine delivers precise and efficient heating. Its robust design ensures stability, while the intuitive HMI provides users with easy access to critical controls and real-time data, making it a highly effective tool for casting applications.

IV. TECHNICAL IMPLEMENTATION

The induction casting machine's implementation is divided into three primary sections: hardware setup, software design, and system workflow. Each component plays a crucial role in ensuring the system's reliability, efficiency, and user- friendliness.

A. Hardware Setup

The hardware of the induction casting machine is built around the dsPIC33CK256MC506-E microcontroller, which acts as the central control unit. It manages the interaction between the components and ensures smooth regulation of the induction heating process. The system includes a PFU- 400 TAIE PID temperature controller, which maintains precise temperature levels by processing inputs from a temperature sensor (such as a thermocouple or RTD). The temperature data is also sent to the microcontroller for monitoring and regulation. The PFC (Power Factor Correction) circuit converts the three-phase AC input into DC, ensuring efficient energy usage, while the inverter stack generates the high-frequency AC voltage necessary for induction heating. A high-frequency transformer isolates and transmits the energy to the induction coil, which produces a magnetic field to heat the crucible con- taining the metal. To ensure optimal performance, a capacitor bank is used to stabilize the energy transfer by matching the impedance between the coil and the transformer. The system also incorporates a cooling mechanism—either air cooling or water cooling—to prevent overheating of critical components during operation.

B. Software Design

The software forms the backbone of the system, enabling seamless communication between the hardware components and the user interface. The dsPIC33CK256MC506-E mi- crocontroller is programmed using MPLAB X IDE and is configured to control the phase shift of the inverter. This phase shift regulates the voltage supplied to the induction coil and ensures precise temperature control. The microcontroller communicates with the PID temperature controller to receive feedback from the temperature sensor and adjust the heating process accordingly. Custom algorithms for voltage regulation, phase control, and error detection are embedded into the microcontroller's firmware.

C. System Workflow

The operation of the induction casting machine begins with the user setting the desired temperature on the PID temperature controller. The temperature controller receives input from the temperature sensor and sends the actual temperature reading to the microcontroller. The microcontroller compares the actual temperature with the setpoint and adjusts the phase shift of the inverter stack accordingly. This adjustment regulates the voltage supplied to the induction coil, ensuring precise control of the heating process. The PFC circuit converts the incoming three-phase AC to DC, while the inverter stack generates high-frequency AC voltage. The energy is transferred through the high-frequency transformer to the induction coil, which heats the crucible via electromagnetic induction. As the system operates, the temperature, voltage, and current data are contin- uously monitored and displayed on the HMI. If any anomalies, such as overheating or power surges, are detected, the system triggers safety mechanisms to prevent damage to the machine or the workpiece. Once the desired temperature is achieved, the operator can proceed with the casting process. The sys- tem ensures that all parameters remain stable throughout the operation, providing a reliable and efficient solution for metal casting. By combining advanced hardware components with intelligent software algorithms, the induction casting machine delivers a powerful and user-friendly solution for industrial applications. Its precise temperature control, energy efficiency, and safety features make it an indispensable tool for modern metalworking industries.

The figures demonstrate the hardware setup of the induction casting machine, highlighting its ability to achieve precise and efficient metal casting. This setup is designed to ensure accuracy in temperature regulation and heating, providing a reliable and user-friendly experience for operators. The front side of the machine features an intuitive HMI interface, enabling easy operation and control of system parameters. Testing confirmed the functionality, safety, and efficiency of the system, proving its capability to enhance the metal casting process significantly.

The hardware setup integrates various components seamlessly. The HMI display guides operators through each stage of the casting process. For instance, it displays prompts such as ”Set Desired Temperature” and ”Heating in Progress,” along with real-time data on temperature, current, and voltage. After the casting operation is complete, the system provides notifications like ”Process Complete” or ”Cooling Engaged,” ensuring smooth workflow and operator awareness.

The dashboard of the induction casting machine’s HMI is user-friendly and designed to manage the casting process efficiently. The main screen presents critical features such as Temperature Control, System Diagnostics, Current and Voltage Monitoring, and Error Logs. These features are organized into interactive sections, allowing operators to navigate and configure the system easily. Additionally, the dashboard offers real-time monitoring of operational parameters. A ”Current Readings” section provides live updates on temperature, current, and voltage, ensuring transparency and enabling opera- tors to maintain the desired conditions for efficient casting. The design follows a minimalist approach with clear visual indicators for critical states like “Overload Alert” or “Cooling Required,” enhancing usability and focus.

Testing results validated the integration of both hardware and software components, showcasing their synergy in main- taining accurate temperature control and stable energy de- livery. The feedback mechanisms ensured seamless inter- action between components like the PID controller, dsPIC microcontroller, and induction coil. The system performed reliably under different operating conditions, demonstrating its capability to meet the stringent demands of industrial casting applications.

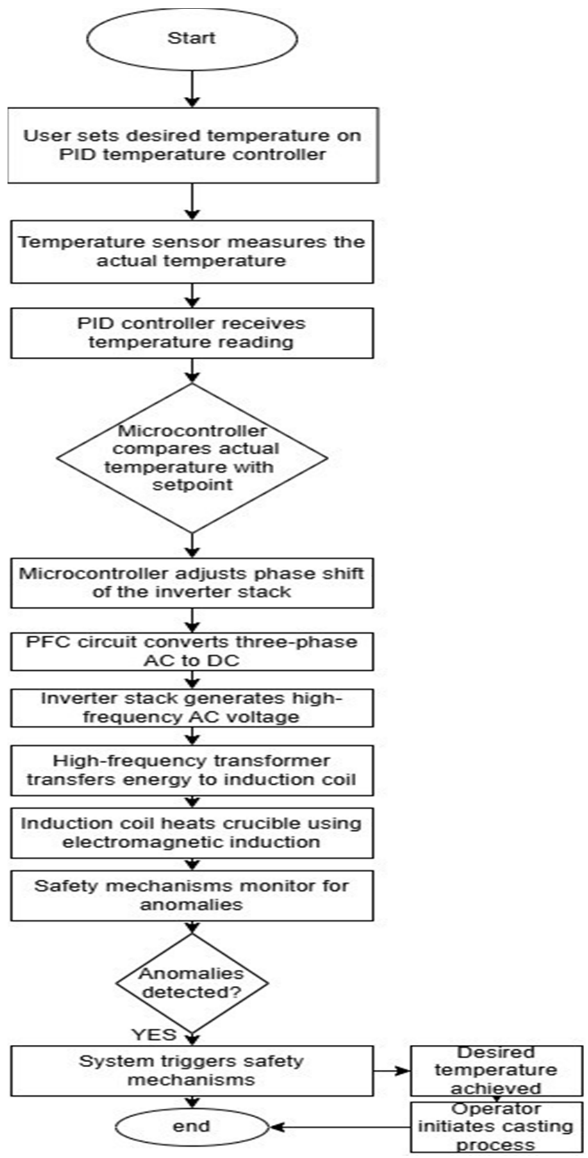

Fig. 8: Workflow

V. ADVANTAGES AND LIMITATIONS

A. Advantages

1) Accurate Temperature Control: The system ensures pre- cise temperature regulation through the integration of the PID controller and dsPIC microcontroller, leading to consistent casting quality.
2) Energy Efficiency: The phase-shift control mechanism optimizes power delivery to the induction coil, reducing energy waste and operating costs.
3) User-Friendly Operation: The HMI interface simpli- fies the control and monitoring of critical parameters, making the system accessible even for operators with minimal technical training.
4) Improved Safety: Automated monitoring and alert mech- anisms for overloads, voltage fluctuations, and overheat- ing enhance safety during operation.
5) Real-Time Monitoring: Live data on temperature, cur- rent, and voltage allows operators to make immediate adjustments, minimizing errors and improving produc- tivity.
6) Data Logging and Traceability: The system records operational data, enabling detailed analysis for process optimization and maintenance planning.

B. Limitations

1) Dependency on Hardware Reliability: The system heav- ily relies on the stable functioning of components such as the PID controller, microcontroller, and induction coil. Any failure in these critical parts could disrupt operations.
2) High Initial Costs: The advanced components and inte- gration required for the system may lead to significant initial investment, making it less accessible for smaller- scale operations.
3) Complex Maintenance Requirements: The system in- volves multiple high-precision components, which may require specialized expertise for troubleshooting and repairs.
4) Environmental Sensitivity: Factors such as power supply fluctuations and external temperature conditions may affect the system’s performance, requiring additional safeguards for consistent operation.

VI. CONCLUSION

The proposed induction casting machine demonstrates a robust and efficient system for precise metal heating, lever- aging advanced microcontroller technology, PID tempera- ture control, and user-friendly interfaces. By integrating the DSPIC33CK256MC506 microcontroller with the PFU-400 TAIE PID Temperature Controller, the system achieves real- time phase-shift regulation, ensuring accurate temperature control and energy efficiency. The inclusion of an HMI provides operators with seamless interaction and monitoring capabilities, while safety mechanisms enhance operational reliability. This design not only improves process accuracy and productivity but also reduces manual intervention, making it a significant advancement in industrial casting applications. Although the system’s complexity and initial costs present challenges, its long-term benefits in terms of precision, ef- ficiency, and traceability outweigh these limitations. Future developments could include remote monitoring via IoT in- tegration and enhanced fault-tolerant mechanisms to further optimize its industrial application potential.

VII. ACKNOWLEDGMENT

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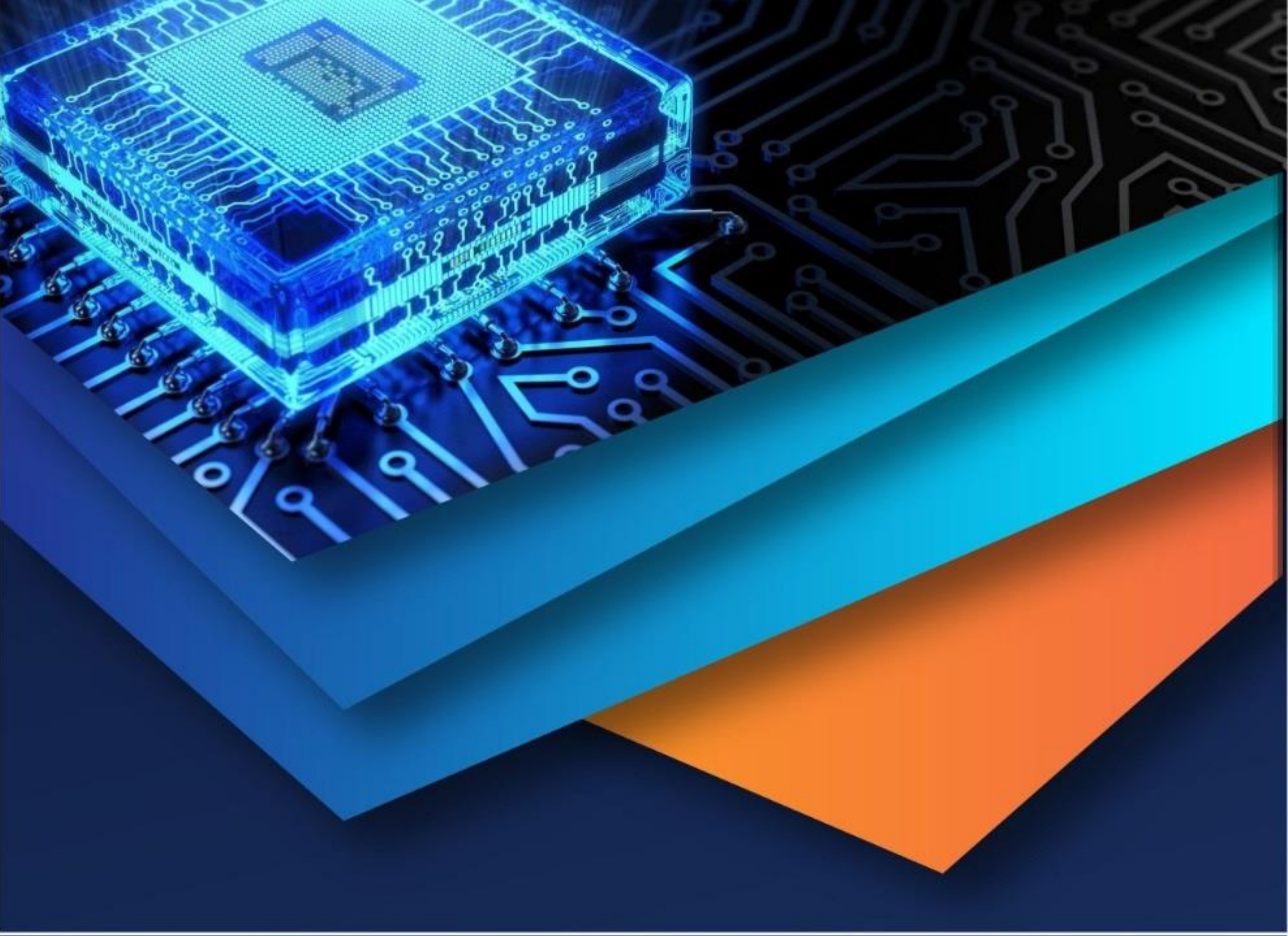

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