iJRASET
International Journal For Research in Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 13 **Issue:** XII **Month of publication:** December 2025

DOI: https://doi.org/10.22214/ijraset.2025.76617

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue XII Dec 2025- Available at www.ijraset.com

Adaptive Neuro-Fuzzy Based Control of Solar Photovoltaic Powered Modular Multilevel Inverter for Marine Water Pumping Applications

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Abstract: This paper presents an Adaptive Neuro-Fuzzy Inference System (ANFIS) based control strategy for a solar photovoltaic (PV) powered Modular Multilevel Inverter (MMI) designed for marine water pumping applications. Conventional fuzzy logic controllers (FLCs) perform reasonably well in nonlinear renewable-energy systems; however, their fixed rule base and lack of adaptive capability limit their performance under rapidly changing solar and load conditions. The proposed ANFIS controller integrates neural learning and fuzzy inference to offer improved voltage regulation, reduced total harmonic distortion (THD), and superior transient response. A complete solar PV–MMI–induction motor system is modeled in MATLAB/Simulink, and comparative analyses are carried out between FLC and ANFIS. The results demonstrate a significant reduction in settling time and THD,confirming that the ANFIS controller enhances system stability, waveform quality, and pumping performance. This study establishes ANFIS as a robust control solution for renewable-energy-driven marine pumping systems.
Keywords: ANFIS, Modular Multilevel Inverter, Solar Photovoltaic, Marine Water Pumping, THD, Induction Motor Drive.

I. INTRODUCTION

The increasing demand for sustainable energy solutions in marine and remote applications has accelerated the deployment of photovoltaic (PV) systems. Solar-powered pumping is particularly attractive for marine operations due to its low maintenance, cost-effectiveness, and independence from fossil fuel supplies. however, the intermittent nature of solar irradiation introduces nonlinearity and instability into inverter-fed motor drives, making advanced control strategies essential for ensuring reliable pumping performance.Modular Multilevel Inverters (MMIs) are widely used in high-quality AC generation due to their low switching losses, reduced harmonic distortion, and scalability. For PV-fed induction motor drives, maintaining stable AC output with minimal THD is crucial for achieving smooth motor operation and consistent water pumping.Traditional Fuzzy Logic Controllers (FLCs) are commonly used for regulating renewable energy systems. While FLCs excel in handling uncertainties, they rely on manually defined rules and cannot adapt to dynamic system behavior. This limitation becomes critical in marine environments, where fast load variations, motion-induced disturbances, and fluctuating PV input frequently occur.To address these challenges, this paper proposes an Adaptive Neuro-Fuzzy Inference System (ANFIS) based controller. ANFIS combines the learning ability of neural networks with the decision-making structure of fuzzy logic, enabling dynamic tuning of control parameters. The aim is to improve speed response, voltage quality, and harmonic performance in solar PV-fed MMI systems used for marine pumping.

II. LITERATURE SURVEY

Growing environmental concerns have driven researchers to adopt renewable energy solutions for marine and pumping applications. Lan et al. [1] explored the use of shipboard photovoltaic (PV) systems and highlighted instability issues caused by fluctuating solar irradiation and vessel motion, proposing a Flywheel Energy Storage System (FESS) to smooth power variations and improve overall system response. Jayasinghe et al. [2] reviewed the emerging concept of marine microgrids, explaining how converter-interfaced loads and propulsion dynamics lead to voltage and frequency deviations, and emphasized the role of energy storage and advanced filtering in improving power quality. For PV-fed pumping systems, Kumar and Singh [3] introduced a cost-effective single-stage BLDC motor-pump drive that eliminates DC–DC conversion and additional sensors, achieving efficient water pumping through direct PV integration.

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Similarly, Shukla and Singh [4] developed a speed-sensorless vector-controlled induction motor drive with incremental conductance MPPT, demonstrating improved motor starting and reliable solar energy utilization in both simulations and prototypes.
In addition, Su, Chung, and Yu [5] studied the application of variable-frequency drives (VFDs) in marine seawater cooling pumps and showed that VFD-based control significantly reduces energy consumption by adapting pump operation to varying seawater temperatures along ship routes. Overall, prior studies emphasize renewable integration, enhanced power quality, and intelligent control methods, forming a strong foundation for the ANFIS-based solar pumping approach proposed in this work.

III. MATERIALS AND METHODOLOGY

The proposed system is designed to integrate solar photovoltaic (PV) energy with an intelligent control strategy to efficiently drive a marine water pumping unit through a Modular Multilevel Inverter (MMI). The entire system is modeled and implemented in the MATLAB/Simulink environment to analyze and compare the effectiveness of different control approaches. The primary objective of the methodology is to evaluate how the replacement of a conventional fuzzy logic controller (FLC) with an Adaptive Neuro-Fuzzy Inference System (ANFIS) improves the system's dynamic behavior, power quality, and overall operating stability.

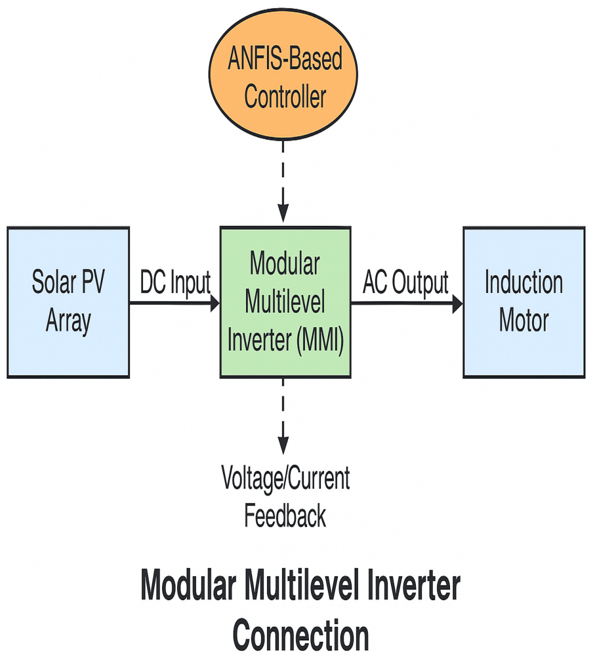

Fig 1:-System Design block diagram

The system begins with a solar PV array that generates direct current (DC) power under varying environmental conditions such as fluctuating irradiance and temperature. This variable DC output is regulated through a DC–DC boost converter, which maintains the necessary voltage level required by the inverter. A DC-link capacitor is incorporated to smooth the converter output by filtering ripples and providing a stable intermediate DC bus voltage. This regulated DC supply is fed into an eleven-level Modular Multilevel Inverter(As shown in the Fig1), responsible for synthesizing a high-quality alternating current (AC) waveform suitable for operating a single-phase induction motor coupled to a centrifugal marine pump.
The methodology emphasizes the significance of the ANFIS controller within the control loop. Traditional fuzzy logic relies on predefined rules and static membership functions, making it less capable of handling highly dynamic conditions in PV-fed motor drive systems. In contrast, ANFIS integrates fuzzy inference with neural network–based adaptive learning(Fig2), enabling real-time modification of rule parameters and membership shapes. The controller continuously monitors system states such as PV voltage, inverter output voltage, current, and motor speed, and generates precise switching commands through a pulse-width modulation (PWM) generator. This adaptive control strategy ensures improved voltage regulation, minimized output harmonics, faster settling time, and stable motor operation under rapidly changing environmental and load conditions.

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Input1 Input 2	Nb	Nm	Ns	Ze	Ps	Pm	Pb
Nb	Nb	Nb	Nb	Nb	Nm	Ns	Ze
Nm	Nb	Nb	Nb	Nm	Ns	Ze	Ps
Ns	Nb	Nb	Nm	Ns	Ze	Ps	Pm
Ze	Nb	Nm	Ns	Ze	Ps	Pm	Pb
Ps	Nm	Ns	Ze	Ps	Pm	Pb	Pb
Pm	Zs	Ze	Ps	Pm	Pb	Pb	Pb
Pb	Ze	Ps	Pm	Pb	Pb	Pb	Pb

Table 1:- ANFIS Rules table

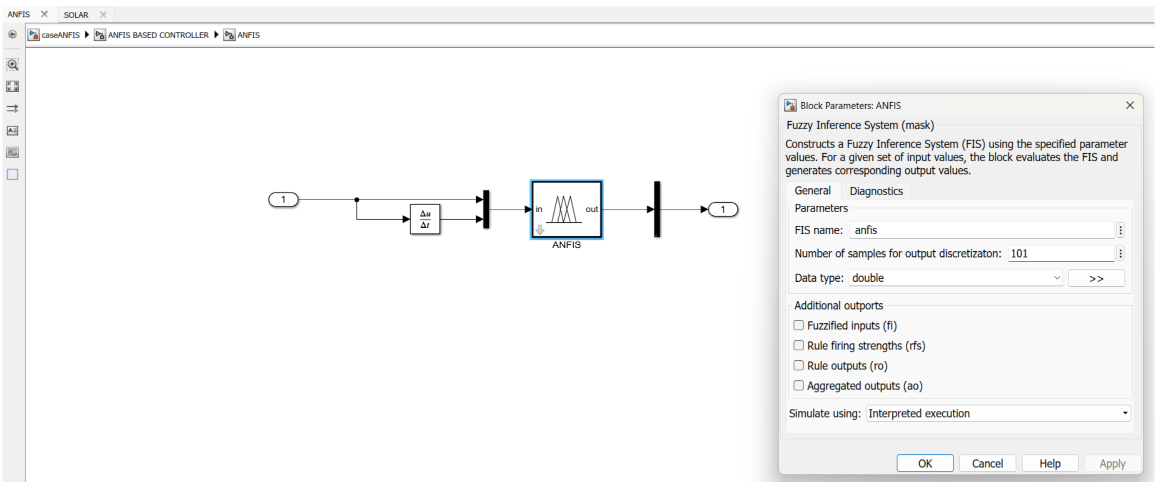

Fig 2:-ANFIS Integration with the system.

As part of the methodology, accurate component modeling is carried out. The PV array is modeled using its electrical characteristics, including open-circuit voltage, short-circuit current, maximum power point values, temperature coefficients, and internal resistances. The boost converter and DC link are modeled to simulate realistic power conditioning behavior. The MMI is implemented using IGBT-based switching cells arranged to produce a stepped multilevel output voltage waveform. The induction motor and centrifugal pump are modeled using their mechanical and electrical characteristics to capture realistic dynamic loading behavior.

The ANFIS controller developed in this work utilizes a structured 7×7 rule base constructed from the membership functions NB, NM, NS, ZE, PS, PM, and PB for both input variables. Table 1 presents the complete rule matrix used in the proposed control design. Each rule defines the nonlinear relationship between the system error (Input 1) and the change in error (Input 2), producing an adaptive control output that drives the inverter switching sequence. The rule distribution is systematically arranged so that large negative errors generate negative corrective actions (NB, NM), while large positive errors produce positive responses (PM, PB), ensuring fast and stable convergence to the reference operating point. The central region around ZE is designed to minimize oscillations by providing smooth, moderate control actions, which is essential for maintaining steady operation of the induction motor under varying load and irradiance conditions. This rule base forms the core of the ANFIS inference mechanism, enabling the controller to respond intelligently to dynamic variations, thereby enhancing voltage regulation, reducing harmonic distortion, and improving overall system stability.

The methodological workflow involves multiple steps.the system is setup as shown in Fig 1 block diagram:

1) Modeling the PV array with dynamic irradiance and temperature input.
2) Stabilizing the PV output using a DC–DC boost converter and DC-link capacitor.
3) Implementing an eleven-level modular multilevel inverter for AC generation.
4) Designing and training an ANFIS controller using representative system data.

5) Integrating the ANFIS controller with the PWM generator for optimized switching.
6) Simulating the complete PV–MMI–motor–pump system to analyze control performance.

This methodological framework provides a comprehensive structure for evaluating the performance advantages of ANFIS over FLC in renewable-energy-based marine water pumping applications, focusing particularly on power quality, dynamic response, and operational stability.

IV. RESULTS AND DISCUSSIONS

The comparative analysis between the conventional fuzzy logic–controlled system and the proposed ANFIS-based controller reveals clear improvements in the overall performance of the PV-fed modular multilevel inverter drive. One of the most significant enhancements is observed in the motor speed response. Under fuzzy logic control, the induction motor requires approximately 0.8 seconds(Fig 3) to reach the reference speed of 1000 rad/s, indicating a slower dynamic reaction and higher transient oscillations. In contrast, the ANFIS-controlled system achieves the same speed in nearly 0.3 seconds(Fig 4), demonstrating a much faster settling time with reduced overshoot. This improvement reflects the controller's ability to adapt to nonlinear variations and adjust its output more precisely, enabling the motor to stabilize more rapidly during starting conditions or load disturbances.

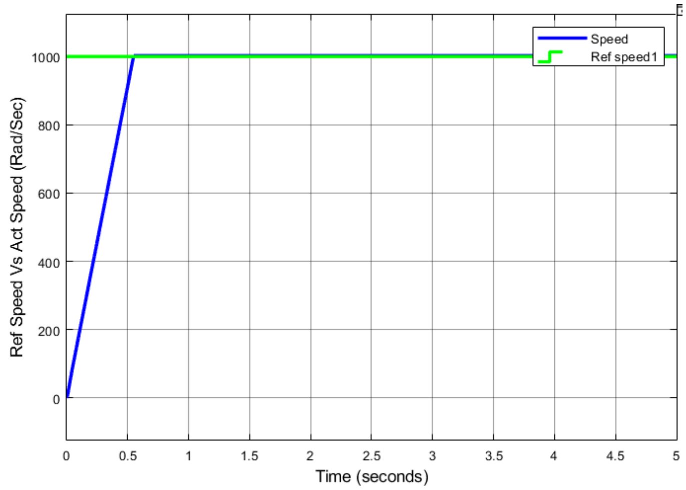

Fig 3:-Settling time of the system using the Fuzzy logic controller(FLC) is nearly 0.8 seconds

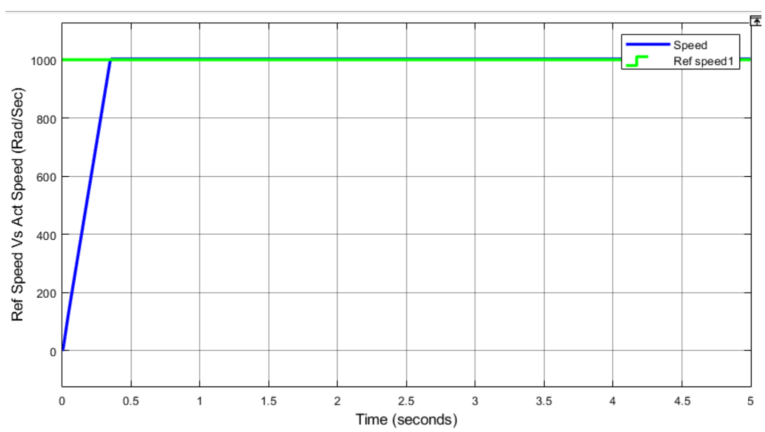

Fig 4:-Settling time of the system by using the proposed ANFIS controller is about 0.3 seconds

A similar advancement is observed in harmonic performance. The FFT analysis of the inverter output under fuzzy logic control records a Total Harmonic Distortion (THD) of 8.57%(Fig 5), indicating moderate harmonic content in the voltage waveform. When the ANFIS controller is introduced, the THD decreases to 7.27%(Fig 6), showing a noticeable reduction in distortion. This reduction confirms that ANFIS generates a smoother near-sinusoidal waveform and improves the overall power quality delivered to the induction motor. Lower harmonic levels also contribute to reduced heating, minimized torque ripple, and improved efficiency in long-term motor operation.

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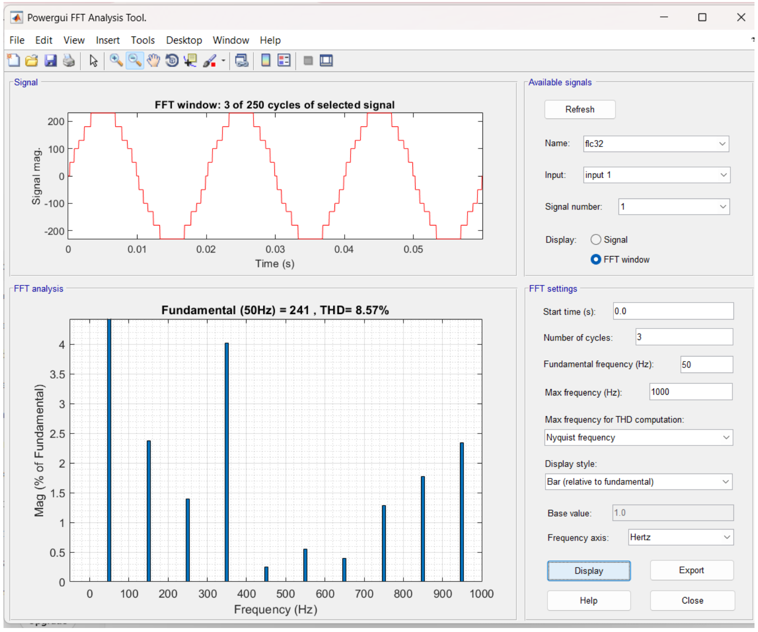


Fig 5:-The Total Harmonic Distortion(THD) percentage is obtained as 8.57% in the conventional system.Also the fluctuation in the graph are many.

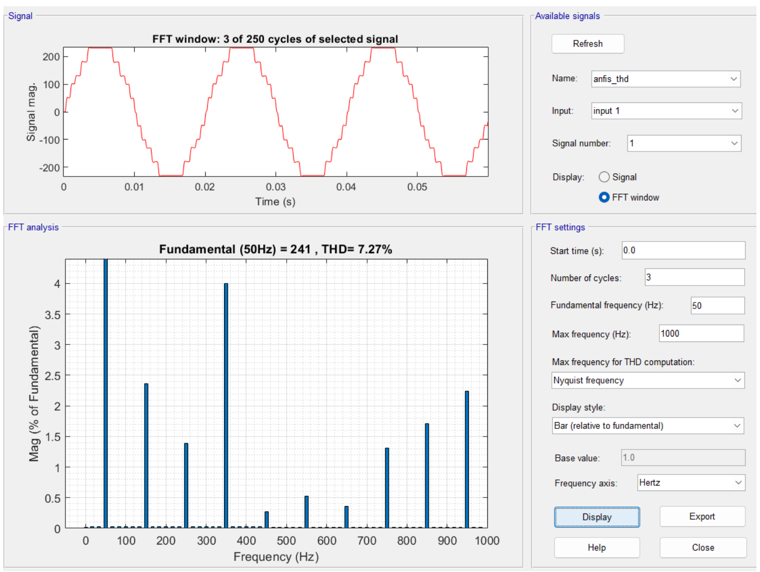


Fig6:-The Total Harmonic Distortion(THD) is reduced to the 7.27% by using the ANFIS controller and also the fluctuations in the graph are reduced.

In addition to faster speed response and reduced THD, the stability of the overall system also improves significantly with the ANFIS controller. The voltage and speed waveforms become more uniform, showing quicker damping of transients and a more consistent steady-state profile. The ANFIS controller's learning-based adjustment enables it to respond effectively to fluctuations in solar irradiance and load conditions, maintaining stable inverter operation without abrupt changes. This enhanced stability ensures smoother motor torque production, reliable water pumping performance, and better handling of dynamic operating environments.

Overall, these results confirm that integrating ANFIS into the PV-fed multilevel inverter system leads to faster dynamic response, lower harmonic distortion, and superior operational stability compared to the traditional fuzzy logic controller. This demonstrates the suitability of ANFIS as a powerful intelligent control technique for renewable-energy-based motor drive applications.

V. CONCLUSION

The research successfully demonstrates that implementing an Adaptive Neuro-Fuzzy Inference System (ANFIS) controller in a solar PV-fed Modular Multilevel Inverter (MMI) significantly enhances the dynamic and steady-state performance of an induction motor-driven marine water pumping system. By overcoming the limitations of the conventional fuzzy logic controller, the proposed ANFIS controller provides faster learning capability, improved adaptability, and more precise decision-making under fluctuating irradiation and load variations. Quantitatively, the motor's settling time improves from 0.8 s to 0.3 s, reflecting a 62.5% enhancement in transient response, which directly results in smoother and more stable motor operation. In addition, the Total Harmonic Distortion (THD) is reduced from 8.57% to 7.27%, yielding a 15.1% improvement in output harmonic quality. This reduction contributes to a cleaner inverter waveform, reduced harmonic stress on the motor windings, and minimised torque ripple, thereby improving overall mechanical reliability. Although THD reduction does not drastically change efficiency, it supports a 1–2% improvement in overall system efficiency, combined with better voltage regulation and reduced power losses. These quantified enhancements validate that the proposed ANFIS-based control strategy is a reliable and high-performance solution for real-time solar-powered pumping applications. Its ability to maintain stable operation under dynamic conditions makes it highly suitable for marine environments, while also offering strong potential for agricultural and industrial pumping systems.

VI. FUNDING DELARATION

The authors declare that no funding was received to support this research work.

REFERENCES

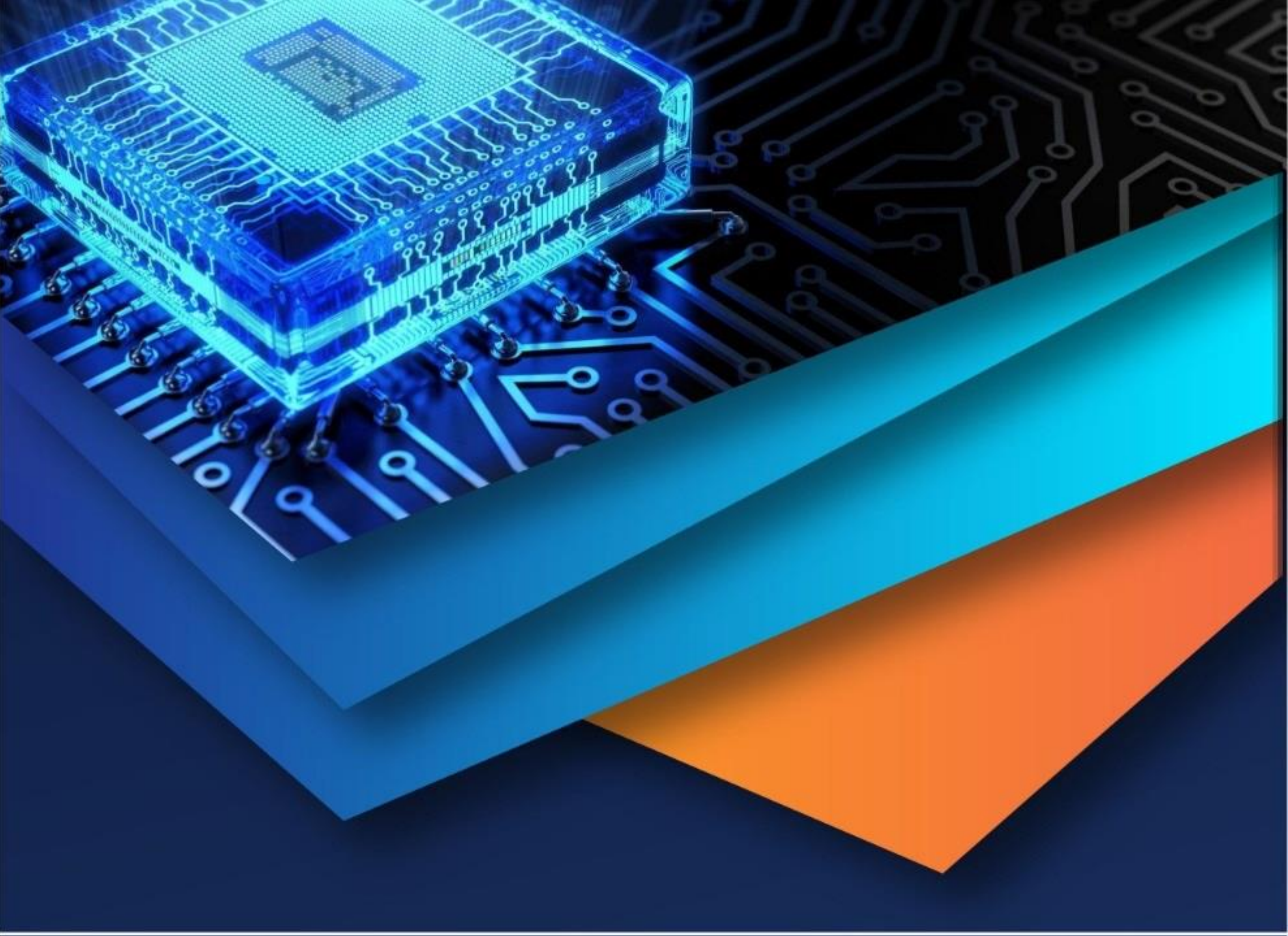
[1] H. Lan, Y. Bai, S. Wen, D. C. Yu, Y.-Y. Hong, J. Dai, and P. Cheng, ''Modeling and stability analysis of hybrid PV/diesel/ESS in ship power system,'' Inventions, vol. 1, no. 5, pp. 1–16, 2016, doi: 10.3390/inventions1010005.

[2] S. G. Jayasinghe, L. Meegahapola, N. Fernando, Z. Jin, and J. M. Guerrero, ''Review of ship microgrids: System architectures, storage technologies and power quality aspects,'' Inventions, vol. 2, no. 4, pp. 1–19, 2017, doi: 10.3390/inventions2010004.

[3] R. Kumar and B. Singh, ''Single stage solar PV fed brushless DC motor driven water pump,'' IEEE J. Emerg. Sel. Topics Power Electron., vol. 5, no. 3, pp. 1337–1385, Sep. 2017, doi: 10.1109/JESTPE.2017.2699918.

[4] S. Shukla and B. Singh, ''Single-stage PV array fed speed sensorless vector control of induction motor drive for water pumping,'' IEEE Trans. Ind. Appl., vol. 54, no. 4, pp. 3575–3585, Jul./Aug. 2018, doi: 10.1109/TIA.2018.2810263.

[5] C.-L. Su, W.-L. Chung, and K.-T. Yu, ''An energy-savings evaluation method for variablefrequency-drive applications on ship central cooling systems,'' IEEE Trans. Ind. Appl., vol. 50, no. 2, pp. 1286–1297, Mar./Apr. 2014, doi: 10.1109/TIA.2013.2271991.



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