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Comprehensive Analysis of Optimal Phasor Measurement Unit Placement for Enhanced Power System Observability and State Perception

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Abstract: This paper offers a detailed overview of the best strategies for placing Phasor Measurement Units (PMUs) in modern power systems. As smart grids become more complex, with the integration of renewable energy and the need for real-time monitoring, effective PMU placement is now a vital area of research. The main goal in existing studies is to achieve full system observability while using fewer PMUs. This approach also aims to lower installation costs, improve reliability, and enhance the accuracy of state estimation.

Several methods have been examined. These include traditional mathematical approaches like Integer Linear Programming and Nonlinear Programming. They also feature newer techniques such as heuristic optimization, multi-stage algorithms, artificial intelligence models, and frameworks that consider cyber security. Recent research also addresses practical issues like zero injection buses, communication limits, data integrity attacks, the reliability of measurement systems, and the incorporation of renewable energy.

This review shows the shift from basic observability-focused techniques to more advanced multi-objective optimization methods that tackle real-world problems. It also points out current research trends and gaps, especially in merging reliability, security, and computational efficiency into a single PMU placement framework. The insights from this study can help in creating stronger and more cost-effective PMU placement strategies for future smart grid systems.

Keywords-Phasor Measurement Unit (PMU), Optimal PMU Placement (OPP), Power System Observability, State Estimation, Smart Grid .

I. INTRODUCTION

Modern power systems are becoming more complex due to the integration of renewable energy, smart grid technologies, and increasing demand for reliable operation. In such systems, Phasor Measurement Units (PMUs) play an important role by providing accurate and synchronized measurements, which help in monitoring, state estimation, and fault detection.

However, installing PMUs at every bus is not practical because of their high cost. Therefore, the Optimal PMU Placement (OPP) problem focuses on placing a minimum number of PMUs in such a way that the entire system remains observable.

Earlier approaches mainly used mathematical techniques like Integer Linear Programming and topological methods to solve this problem. While these methods are effective, they often ignore real-world factors. Recent research has moved towards advanced techniques such as heuristic algorithms, multi-stage optimization, and AI-based methods, which consider practical issues like system reliability, communication constraints, and cyber-security.

This paper presents a review of various PMU placement methods, highlighting their objectives and key differences. It also identifies recent trends and challenges, which can help in developing more efficient and reliable PMU placement strategies for modern power systems.

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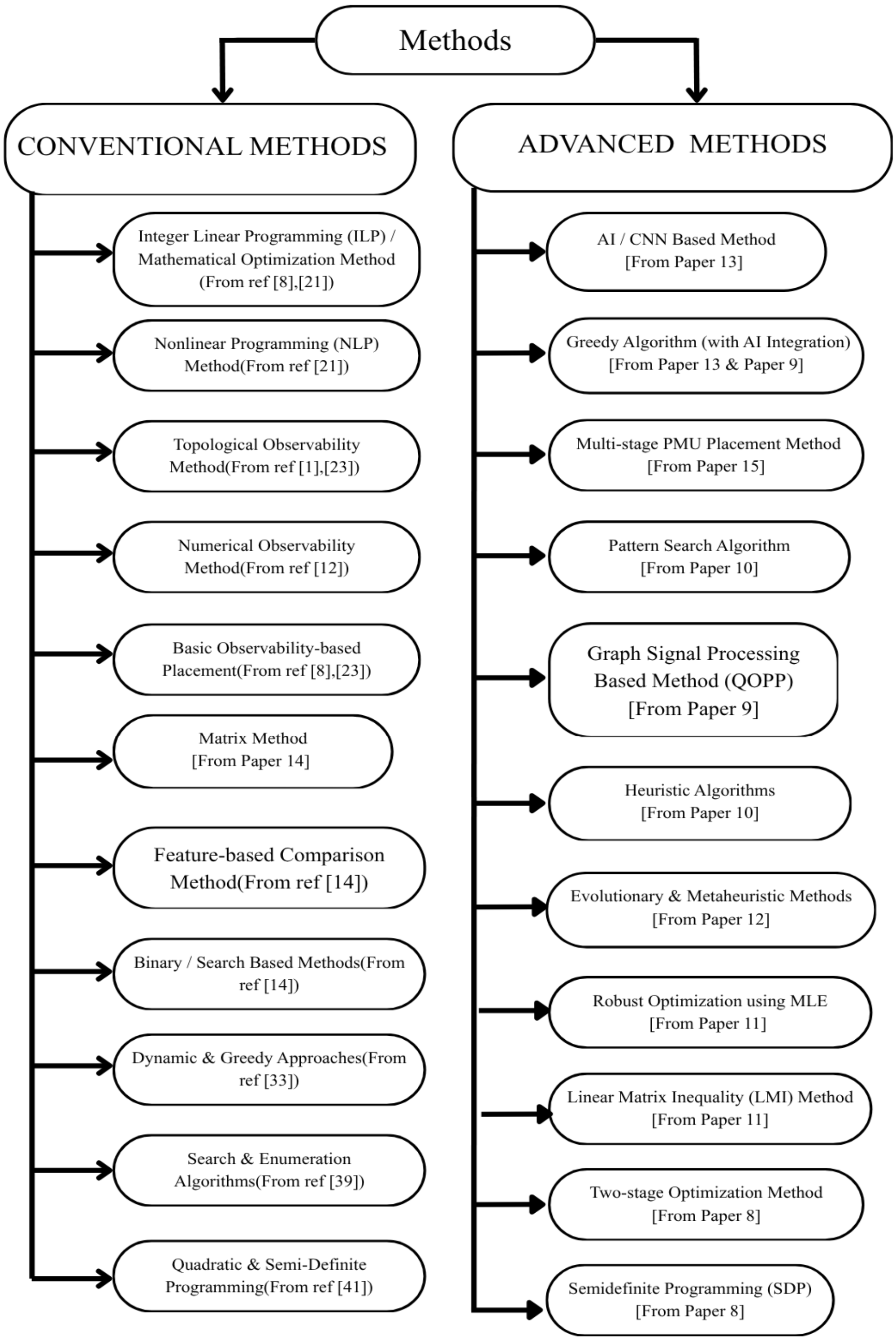

SRNO	NAME OF AUTHOR	YEAR	OBJECTIVE OF AUTHOR
1.	Maveeya Baba, Nursyarizal B.M. Nor, M. Aman Sheikh, A. Momin Baba, Masood Rehman, Syed Hamid Ali Shah	2021	The goal is to minimize the number of PMUs while ensuring full system observability, improving computational efficiency compared to conventional methods. [1]
2.	Batool Al-Khraisat, Ali S. Al-Dmour, Khaled Al-Maitah	2021	The focus is on minimizing both the number of PMUs and the total installation cost (including PMU, PDC, and communication infrastructure).[2]
3.	Nitish Arora, S.T. Nagarajan	2021	To design a two-stage topological algorithm for PMU placement. Stage 1 adds PMUs starting from buses with maximum valency, while Stage 2 eliminates redundant PMUs. []
4.	Sandeep Kumar Mishra, Kunja Bihari Swain, Murthy Cherukuri	2021	The objective is to reduce the number of PMUs required while maintaining full observability, and compare results with other optimization techniques.[3]
5.	Mantra Patel, Shefali Talati	2021	The goal is to ensure full observability of IEEE test systems while reducing computation time and improving efficiency compared to standard methods.[4]
6.	Suresh Babu Palepu, M. Damodar Reddy	2021	The objective is to minimize the number of PMUs while ensuring complete observability and robustness in state estimation.[5]
7.	Yang Peng, Zhi Wu, Chen Fang, Shu Zheng, Jingtao Zhao	2021	To propose a greedy algorithm-based PMU placement method that improves both state estimation accuracy (via information entropy) and fault observability (via Monte Carlo simulation and interval algorithms) in distribution networks with high penetration of distributed generation.[6]
8.	Subhranshu Sekhar Puhan, Renu Sharma, Saumya Ranjan Lenka	2021	To develop a fuzzy logic-based PMU placement framework integrated with Wide Area Monitoring Systems (WAMS). The aim is to identify faulted backup protection zones (BPZs) and faulted lines using PMU data, ensuring adaptive backup protection in stressed grid conditions.[7]
9.	Mohd. Navaid Ansari, Rishi Kumar Singh, Ankur Kumar Gupta	2021	To study the impact of Zero Injection Buses (ZIBs) on PMU placement and propose deterministic algorithms (Depth First Search, Simulated Annealing, Integer Linear Programming). The goal is

			to minimize PMU count while maintaining full observability and improving state estimation accuracy.[8]
10.	Yuanbing Ye ,Nan Liu Zhiwen Pan	2022	To develop an optimal PMU placement and bandwidth allocation method that maintains power system observability under communication constraints while minimizing overall cost and communication delay.
11.	Sravan Kumar Kotha, Bhooshan Rajpathak,Bhuvanagiri Ramesh, M. K. Khedkar	2022	To determine optimal placement of micro-PMUs in interconnected radial distribution networks ensuring full observability, minimum deployment cost, and improved redundancy for real-time monitoring.[24]
12.	Bishal Rimal, Nirmal Paudel, Aayush Bhattarai	2022	To propose an optimal PMU placement strategy using modified simulated annealing that ensures full system observability with minimum PMUs while improving redundancy and handling contingencies like PMU outage and ZIB.[23]
13.	Ali Selim, Salah Kamel, Mohamed Abdelkader, and Francisco Jurado	2022	To solve the optimal PMU placement problem using Henry Gas Solubility Optimization (HGSO) for achieving full observability with minimum PMUs and reducing state estimation error.[17]
14.	Sudipta Ghosh, Younes J. Isbeih Mohamed Shawky El Moursi,SyafiqKamarulAzman Ehab El-Saadany	2022	To develop a multi-objective optimal PMU placement strategy that ensures complete observability while minimizing cost, maximizing redundancy, and enhancing transient stability of the power system. [21]
15.	Mohammad Shahraeini, Shahla Khormali, Ahad Alvandi	2022	To propose an optimal PMU placement method that maximizes reliability of the measurement system while ensuring full observability with minimum number of PMUs using weighted adjacency matrix.[19]
16.	Ziqin Gao, Jianing Li	2022	To design an optimal PMU placement method considering data integrity attacks, ensuring system observability and minimizing installation cost while protecting against cyber-attacks.[20]
17.	Zhenglong Sun,Xiaoya Wang,Yoash Levron	2023	To develop a detailed learning (CNN-based) model for classification of frequency disturbance events and integrate optimal PMU placement using a greedy algorithm for exact and rapid detection under partial observability. [13]

18.	Xin Huang,Li Gu,Ding Xu,Yining Yuan	2023	To present an optimal FTU/PMU placement method for precise fault section localization in distribution networks by minimizing line section length and improving fault detection efficiency at low cost. [14]
19.	Haoyu Chen,Junjie Lin, Mingquan Tu	2023	To design a multi-stage optimal PMU placement method based on node measurement index for improving system observability considering topology, parameters, and operational characteristics.[15]
20.	Wei Xia , Deming He, and Junbin Chen	2023	To optimize PMU placement for improving detection of false data injection attacks (FDIA) using graph signal processing and subspace-based projection detection methods[9].
21.	Ravindra Manama*, Ramesh Adireddyb, Lakshmi Kambampatic, Manoz Kumar Reddy Karri d, Tata Rao Donepudie, Srinivasa Rao Rayapudi	2023	To determine optimal placement of micro-PMUs in distribution networks using pattern search algorithms guaranteeing complete observability with a minimum number of devices. [10]
22.	Tengpeng Chen, He Ren, Yuhao Sun, Markus Kraft, and Gehan A. J. Amaratunga	2023	To develop an optimal PMU placement method considering multiple practical parameters like zero-injection buses, PMU loss, channel limits, and minimizing state estimation error using robust statistical models. [11]
23.	Feng Hua, Wengen Gao,Pengfei Hu, Lina Qiao	2023	To propose an improved nonlinear programming method for optimal PMU placement under single PMU failure while assuring system observability and redundancy.[12]
24.	Yong Li, Xiuru Wang, Taibao Xia, Wangqing Mao	2023	To develop a two-stage optimal PMU placement method that ensures minimum PMU installation while maintaining system observability, specifically focusing on renewable hosting nodes and N-1 contingency conditions, so that the power system remains observable even under PMU failure and high renewable penetration.
25.	Jaydeep Parmar, Chiragkumar Parekh, Pramod Patel	2024	It focuses on minimizing the number of PMUs required while ensuring complete topological observability of the power system, and validates the approach using standard IEEE bus systems

26.	Anand K, Tapan Prakash	2024	The objective is to minimize the number of PMUs while maximizing measurement redundancy, thereby improving system reliability and robustness under measurement loss conditions.
27.	Jiacheng Ge, Yijun Xu, Zaijun Wu, Lamine Mili, Shuai Lu, Qinran Hu, Wei Gu (2024)	2024	It aims to maximize the degree of observability and eliminate dependency on accurate system models, thereby improving robustness and computational efficiency.
28.	Xu Zhou, Yuhong Wang, Yunxiang Shi, Qiliang Jiang, Chenyu Zhou, Zongsheng Zheng	2024	It incorporates quantitative observability indices and captures system topology and operational conditions to enhance placement decisions and improve state estimation accuracy.
29.	Akash Kumar Mandal, Swades De, Bijaya Ketan Panigrahi (2024)	2024	It accounts for practical constraints such as limited input current channels and formulates a cost-constrained optimization model for accurate state estimation.
30.	Rajendra Shrestha, Larissa Souto, Pedro Eisenkraemer, Rabindra Bhatta, Konrad Schmitt, Manohar Chamana, Stephen Bayne, Argenis Bilbao	2024	This paper applies machine learning techniques, including Random Forest models, for optimal PMU placement. It uses real-time simulation data to detect anomalies and improve system observability, offering a data-driven alternative to traditional optimization methods.
31.	Priya Venugopal, D. Devaraj, Johney Isaac (2024)	2024	This study formulates the PMU placement problem as a constrained optimization problem solved using a Genetic Algorithm. It aims to minimize the number of PMUs while ensuring complete system observability and validates the approach using IEEE test systems.
32.	Tejaswi Algam, Anandita Chowdhury, Prasanta Kundu (2024)	2024	This research develops a PMU placement model considering variable installation costs for different buses and applies the Binary Arithmetic Optimization Algorithm. It determines optimal PMU locations while reflecting realistic economic constraints.
33.	Boya Sneha, Rohit Babu, Sheila Mahapatra	2024	This paper presents an Integer Linear Programming-based PMU placement approach that minimizes both

			the number of PMUs and measurement redundancy. It introduces the System Observability Redundancy Index to improve system reliability and robustness.
34.	B. Sneha, Rohit Babu, Sheila Mahapatra (2024)	2024	This work proposes a Modified Simulated Annealing algorithm for optimal PMU placement. It improves convergence speed and global search capability while incorporating system constraints and reducing computational complexity.
35.	Sruthi Ankam,Vedik Basetti,Sachidananda Sen	2025	The primary objective of the proposed Binary Artemisinin Optimization (BAO) algorithm is to achieve complete observability of a power grid using the minimum number of Phasor Measurement Units (PMUs). [38]
36.	Satyendra Pratap Singh ,Sonu Kumar Bairwa,Hanuman Bairwa,Rachna Tyagi	2025	The objective of this research is to develop a strategic framework for the Optimal PMU Installation (OPI) in power systems to minimize infrastructure costs while ensuring complete network observability. [28]
37.	Aishwarya Premnath,Divya N A	2025	The objective of this research is to develop a multi-objective optimization framework for the Optimal PMU Placement (OPP) problem using the Binary Arithmetic Optimization Algorithm (BAOA). The goal is to maximize power system monitoring capabilities while minimizing economic and operational overhead.[31]
38.	Nur Shahida Midi* ,Nurhazwani Mohd Hanafi ,Mohd Fahmi Hussin ,Mohd Shahrin Abu Hanifah	2025	The primary objective of this study is to solve the Optimal PMU Placement (OPP) problem by identifying the minimum number of Phasor Measurement Units required to ensure full network observability. [32]
39.	Sruthi Ankam ,Vedik Basetti ,Sachidananda Sen ,Chandan K Shiva	2025	The primary objective of this research is to achieve simultaneous optimal placement of Phasor Measurement Units (PMUs) and Phasor Data Concentrators (PDCs) within a power grid to minimize installation and communication costs.[33]
40.	Milos Katani ,Yi Guo,John Lygeros ,Gabriela Hug	2025	to develop a theoretically grounded methodology for optimal Phasor Measurement Unit (PMU) placement in power systems modeled by differential-algebraic equations (DAE). [34]
41.	Irabiel Romero ,Roummel Marcia ,Ignacio Aravena ,Noemi Petra	2025	To develop an Optimal Experimental Design (OED) framework for the placement of Phasor Measurement Units (PMUs) to enhance power system state

			estimation.[35]
42.	Gabriel D.D.R. Hamacek ,Wilingthon G. Zvietcovich ,Nilberth H. de Souza ,Francisco R.A.C. Baracho	2025	The main objective of the paper is to solve the Optimal PMU Placement (OPP) problem in electric power systems using the Symbiotic Organism Search (SOS) metaheuristic. [36]
43.	Yuqi Jiang ,Yan L ,Zhiding Liang ,Thomas Morstyn	2025	The primary objective of this research is to solve the Optimal PMU Placement (OPMUP) problem using a hybrid quantum-classical approach to ensure full power grid observability at the minimum installation cost.[37]
44.	Sruthi Ankam, Vedik Basetti,Sachidananda Sen	2025	The primary objective is to determine the minimum number of Phasor Measurement Units (PMUs) required to maintain complete power system observability while simultaneously defending against Data Integrity (DI) attacks. [38]

II. INFORMATION

The collective research focuses on optimal placement of Phasor Measurement Units (PMUs) in power systems so that they can see everything with the minimum devices. This central theme is always getting more complicated, which shows how modern power networks are always changing and getting harder to deal with.

A. Methods for Optimization:

Researchers have utilized a diverse array of algorithms and mathematical models. Some classical methods are Integer Linear Programming, Genetic Algorithms, and Simulated Annealing. Some newer metaheuristics are Henry Gas Solubility Optimization, Symbiotic Organism Search, Binary Arithmetic Optimization, and Binary Artemisinin Optimization. These methods try to find a good balance between speed, efficiency, and how hard it is to compute. At the same time, researchers have looked into machine learning models (like CNNs and Random Forests) and even quantum-classical hybrid approaches. This shows a move toward smart and flexible solutions. System Observability and Redundancy: A common goal is to make sure that the entire system can be seen in a variety of situations, such as when a PMU fails, when there are Zero Injection Buses (ZIBs), or when renewable energy sources are used. A lot of studies use redundancy indices or multi-stage frameworks to make sure that the grid can be seen even when it is under stress or has been compromised. This shows that resilience and strength are very important.

B. Economic and Practical Constraints:

Several works highlight installation cost minimization, considering not only PMUs but also Phasor Data Concentrators (PDCs), communication infrastructure, and bandwidth allocation. Some models integrate variable installation costs per bus and limited input channel constraints, making the optimization more realistic for practical deployment.

C. Advanced Functional Objectives:

Beyond observability and cost, research has expanded to include:
Fault detection and localization using PMU/FTU placement strategies.
Transient stability enhancement through multi-objective optimization.
Adaptive backup protection in stressed grid conditions via fuzzy logic frameworks.
State estimation accuracy improvement using entropy measures, Monte Carlo simulations, and robust statistical models.
Cybersecurity resilience is all about protecting systems from sneaky attacks that try to tamper with or inject false data. To stay ahead, researchers are blending traditional security methods with cutting-edge technologies.

Instead of relying only on mathematical models, newer approaches use:

- Real-time simulations to spot problems as they happen.
- Machine learning to detect unusual patterns that could signal an attack.
- Quantum-inspired optimization to strengthen defenses and make systems more adaptive.

This shift marks a big step forward—from rigid, formula-based protection to smarter, flexible, and secure monitoring frameworks that can evolve alongside emerging threats.

III. CONCLUSION

This paper reviewed various approaches for optimal placement of Phasor Measurement Units (PMUs) in power systems. From the study, it is clear that the main goal across all methods is to achieve complete system observability using the minimum number of PMUs while keeping the cost low and improving system performance.

Traditional methods such as mathematical and topological approaches provide simple and effective solutions, but they often do not consider real-world challenges. On the other hand, advanced methods like heuristic algorithms, multi-stage optimization, and AI-based techniques offer better performance by considering practical factors such as reliability, communication constraints, contingency conditions, and cyber-security issues.

It is also observed that recent research is moving towards multi-objective optimization, where multiple factors like cost, accuracy, redundancy, and system stability are handled together. Despite these advancements, there is still a need for more efficient and unified approaches that can balance all these factors effectively in real-time power systems.

Overall, this review highlights the importance of intelligent and practical PMU placement strategies, which are essential for improving monitoring, control, and reliability in modern smart grids. Future work can focus on developing hybrid and adaptive methods that can handle dynamic system conditions more efficiently.

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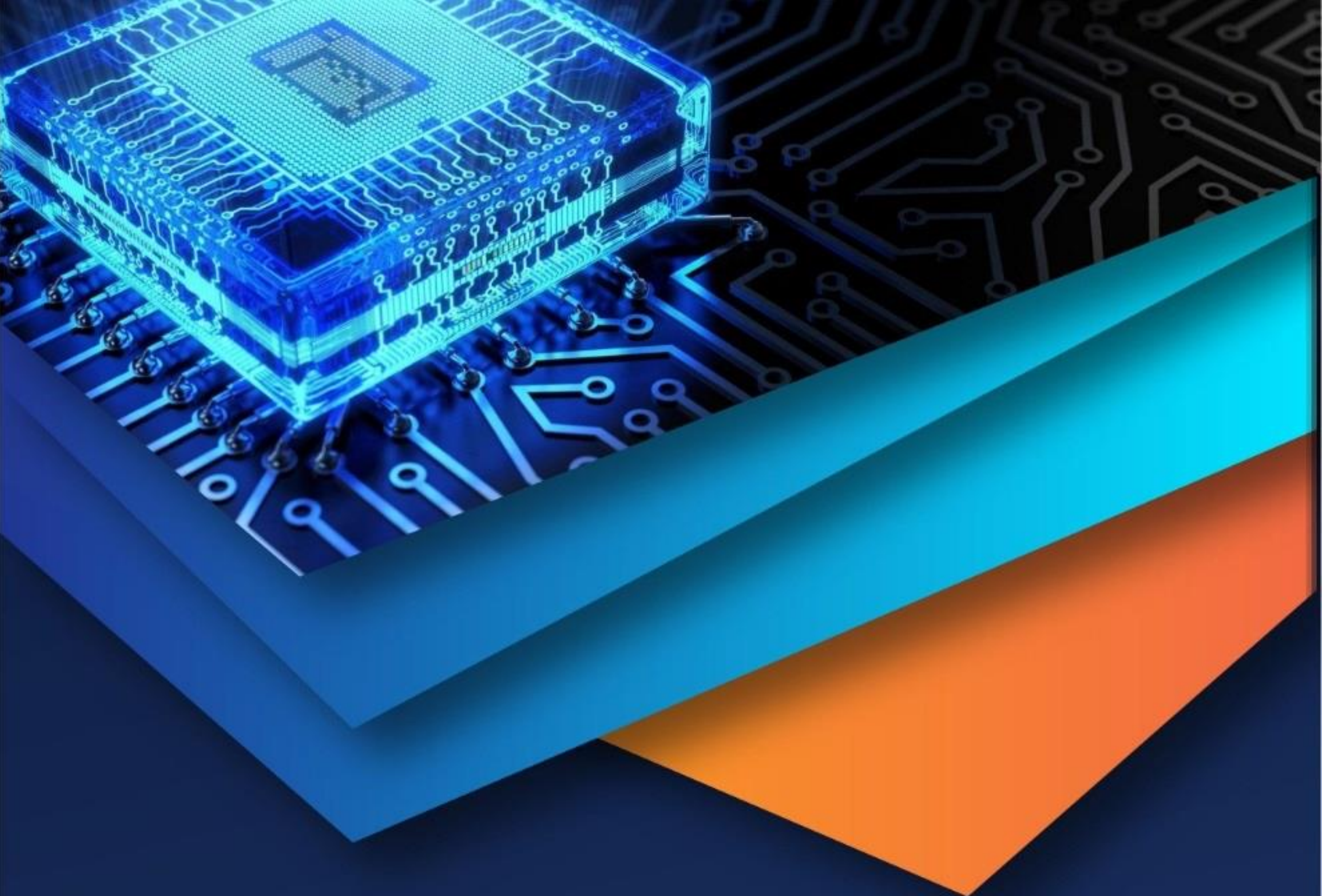

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