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Determination of Bus Strength and Stability by using Voltage Stability Indexes for Transmission Expansion Planning

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Abstract: In this paper, Determination of bus strength and stability by using the voltage stability indexes for transmission expansion planning. The voltage stability indexes represent the change in voltage at a particular due to reactive power variation to the corresponding bus and it gives the strength and stability of a particular bus. In this paper, eigenvalues show the strength and stability of a bus. If the eigenvalue is more the corresponding bus is more stable and less sensitive other words if the eigenvalue is less the corresponding bus is less stable and high sensitive due to reactive power variation at a particular bus. A different connection between the buses in a transmission network gives the different eigenvalues. In this paper carryout work on IEEE 30 bus and IEEE 57 bus system to determine the strength and stability of the buses in both original case and base case and also applied PSO optimization technique to find better stability and strength of the buses.
Keywords: Load flows, Jacobin matrix, voltage stability analysis, transmission expansion planning, Eigenvalues.

I. INTRODUCTION

In transmission system planning, when demand for electricity from the distribution system is expected to grow, to ensure that the demand will be served in the future, the transmission system must be expanded in advance. Therefore, the Transmission Expansion Planning (TEP) is one of the vital processes to guarantee the reliability and also security of the power system. TEP is the process of selection of construction plan to meet the demand in the future. The selected construction plan must have the lowest total cost while maintaining the ability of the transmission system to transfer power securely. Mathematically, TEP is classified as a Mixed Integer Nonlinear Programming problem. This problem combines difficulties of both nonlinear programming and integer programming together. Currently, there is no standard method that can be used to solve this problem efficiently. There are many literatures that proposed methods to solve for the TEP. However, most of those methods simplified the problem by using the DC model. Some of them considered the construction of transmission lines problem and reactive power compensation problem, separately. Moreover, nearly all of them neglect the voltage stability problem which is one of the most critical problems at present.

The modern power system requires the network configurations from transmission expansion planning outcome to also consider reliability and stability. In conventional power system planning, reliability is typically considered independently from stability as part of an overall analysis. However, a power system with high voltage stability will naturally have improved reliability with respect to load variations and single contingencies. In addition, a network with high voltage stability can reduce the power losses on transmission lines. Therefore, the motivation in this paper is to determine all the network configurations for the TEP problem with the principal criteria of voltage stability. This approach is based on the modal analysis technique to find the voltage stability indexes. The proposed approach is intended to be used along with other approaches or as an additional evaluation tool in expansion planning process. It only considers expansion planning from stability standpoint, without considering the economics of the expansion. A typical application of this method is in planning power systems where reliability and stability are set as the main priority, such as the power network of a ship or a military microgrid.

This paper begins in Section II by first introducing the modal analysis method that is used to find the voltage stability indexes, i.e. eigenvalues. The theoretical foundation of this method is presented in order to clarify the stability of a specific bus and a power system in general.

This method determines the all the eigenvalues of a particular network and it gives the stability and sensitivity of the buses. In Section III is about Particle Swarm Optimization for optimizing the Eigenvalues of the corresponding bus. Section IV delivers conclusions about results and our future work.

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II. VOLTAGE STABILITY ANALYSIS

For going to voltage stability analysis need to about bus classification and modal analysis.

A. Bus Classification

A bus is nothing but a point or node which is an interconnection of one or many transmission lines, loads and generators. In a power system each bus is associated with 4 quantities, such as magnitude of voltage (|V|), phase angle of voltage (δ), active power (P) and reactive power (Q). In a load flow solution, two quantities are specified and the remaining two are required to be determined through the solution of the equation. The buses are classified depending on the two known quantities that have been specified [9]. Buses are divided into three categories as shown in below

1) *Slack Bus:* This is used as a reference bus in order to satisfy or meet the power balance condition. A slack bus is usually a generating unit. There is a possibility to adjust the power generation to meet the power balance condition. The effective generator at this bus supplies the losses to the network, this is necessary because the magnitude of the losses will not be known until the calculation of the current is complete. Slack bus is usually identified as bus 1. The known variable on this bus is |V| and δ and the unknown is P and Q. The slack bus will give as an angular reference for all remaining buses in the system, which phase angle is set to 0°. The voltage magnitude is also assumed to be 1 p.u. at the slack bus.
2) *Generator Bus:* This is a voltage control bus. The bus is connected to a generator unit in which output power generated by this bus can be controlled by adjusting the prime mover and the voltage can be controlled by adjusting the excitation of the generator. Often, limits are given to the values of the reactive power depending upon the characteristics of individual machine. The known variable in this bus is P and |V| and the unknown variables are Q and δ.
3) *Load Bus:* This is a non-generator bus. The real and reactive power supply to a power system are defined to be positive, while the power consumed in a power system are defined to be negative. The consumer power is met at this bus. The known variable for this bus is P and Q and the unknown variable is |V| and δ.

B. Voltage Stability Based on Modal Analysis

In a power transmission network, the voltage stability is represented by the stability indexes, i.e. each bus Eigenvalues. These eigenvalues represents the voltage changes due to reactive power variations, and gives the information about system stability, such as when the power system experiences, or comes close to experiencing, voltage instability, or where weak voltage points exist. The eigenvalues can be determined directly via the method of modal analysis, a numerical approach that is Newton-Raphson method.

Newton-Raphson method is an iterative method which approximates a set of non-linear simultaneous equations to a set of linear simultaneous equations using Taylor's series expansion and the terms are limited to the first approximation. It is the most frequently used iterative method for the load flow because its convergence characteristics are relatively more powerful compared to other alternative processes and the reliability of Newton-Raphson approach is comparatively good since it can solve cases that lead to divergence with other popular processes. If the assumed value is near the solution then the method takes less time to converge and the results obtained very quickly, but if the assumed value is farther away from the solution then the method may takes more time to converge and it takes more time to obtain results. This is another iterative load flow method which is widely used for solving a nonlinear equation.

The real and reactive power at i^{th} bus is

$$P_i - jQ_i = V_i^* I_i \qquad (1)$$

The nodal equation can be written in a generalized form for an n bus system

$$I_i = \sum_{j=1}^{n} Y_{ij} V_i \qquad (\text{ i=1, 2, 3…… n}).$$

By solving equations eq 1 & 2, We get real and reactive power.

In a power system, the net real and reactive power delivered to the i^{th} bus can be computed from bus voltage and Y -bus matrix

$$P_i = \sum_{j=1}^{n} V_i V_j Y_{ij} \cos(\delta_i - \delta_j - \theta_{ij})$$

$$Q_i = \sum_{j=1}^{n} V_i V_j Y_{ij} \sin(\delta_i - \delta_j - \theta_{ij}) \qquad (3)$$

For a change in P_i, Q_i or both, the system behavior can be studied using linearized equations at the steady-state operating point as follows,

$$\begin{bmatrix}\Delta P \\ \Delta Q\end{bmatrix} = \begin{bmatrix} J_{P\delta} & J_{PV} \\ J_{Q\delta} & J_{QV}\end{bmatrix}\begin{bmatrix}\Delta\delta \\ \Delta V\end{bmatrix} = \left[J_{AC}\right]\begin{bmatrix}\Delta\delta \\ \Delta V\end{bmatrix} \quad (4)$$

Where ΔP, ΔQ are incremental changes in real and reactive power, and Δδ, ΔV are incremental changes in voltage angle and magnitude respectively. The Jacobin matrix in the linearized equation, J_{AC} is same as the Jacobian matrix from the load flow solved by Newton-Raphson method. Since the voltage magnitude depends mainly on reactive power, to investigate the system stability, let ΔP be 0 then

$$\Delta Q = [J_{QV} - J_{Q\delta} J_{P\delta}^{-1} J_{PV}]\Delta V$$

$$\Delta Q = [J_R]\Delta V \quad (5)$$

or the voltage increment can be expressed in terms of reactive power increment

$$\Delta V = J_R^{-1}\Delta Q = \xi\Lambda^{-1}\eta\Delta Q$$

$$\Delta V = \sum_i^n \frac{\xi_i \eta_i}{\lambda_i}\Delta Q \quad (6)$$

Where $J_R = \xi\Lambda\eta$ is decomposed into a diagonal eigenvalue matrix by right and left eigenvector matrices, and (ξ_i, η_i) are the i^{th} column right and row left eigenvectors of J_R.

Manipulating (3) and (4), the voltage increment associated with i^{th} mode is given by

$$\Delta V_{mi} = \frac{1}{\lambda_i}\Delta Q_{mi} \quad (7)$$

The increment in voltage at each bus represents on the reactive power variation via the eigenvalue. If λ_i is small, the voltage variation caused by a reactive power increment is large. In other words, a small eigenvalue means a weak bus voltage. If λ_i is zero, the system voltage collapses regardless of any reactive power variation. Note that the eigenvalues are determined by the network configuration and the load conditions, and thus by investigating eigenvalues, a power system robustness to be estimated.

III.PARTICLE SWARM OPTIMIZATION

PSO based operators are explore the search space. In 1995, Kennedy and Eberhart first introduced the particle swarm optimization method, it is a population based meta-heuristic that simulates social behaviour of organisms such as fish schooling and bird flocking. PSO, as an optimization tool, provides a population-based search procedure in which individuals called particles change their positions with time. In a PSO system, particles fly around in a multi dimensional search space. During the process, each particle adjusts its position according to its own experience, and the experience of neighbouring particles, making use of the best position encountered by itself and its neighbours. The swarm direction of a particle is defined by the set of particles neighbouring the particle and its historical experience. To get optimal solution, each particle adjusts their positions by using the following updating equations.

$$V_{id}^{(t+1)} = w \times V_{id}^{(t)} + C_1 \times r_1 \times (pbest_{id} - X_{id}^{(t)}) + C_2 \times r_2 \times (pbest_d - X_d^{(t)}) \quad (9)$$

$$X_{id}^{(t+1)} = X_{id}^{(t)} + V_{id}^{(t+1)} \quad (10)$$

Where C_1, C_2 are acceleration coefficients, w is inertia weight, r_1 and r_2 are random numbers in the range of [0,1]. $V_{id}^{(t)}$ and $X_{id}^{(t)}$ denote the velocity and position of the particle in d^{th} dimension at t^{th} iteration. $pbest_{id}$ is the value in dimension d of the best parameters combination (a particle) found so far by particle *i*. $pbest_{id} = (pbest_{i1}$………..$pbest_{id})$ is called personal best. $gbest_d$ is the value in dimension d of the best parameters combination (a particle) found so far in the swarm. $gbest_d = (gbest_i$……… $gbest_d)$ is represented as the global best. In the search space, particles track the individual's best values and the best global values. The process is terminated if the number of iteration reaches the pre-determined maximum number of iteration.

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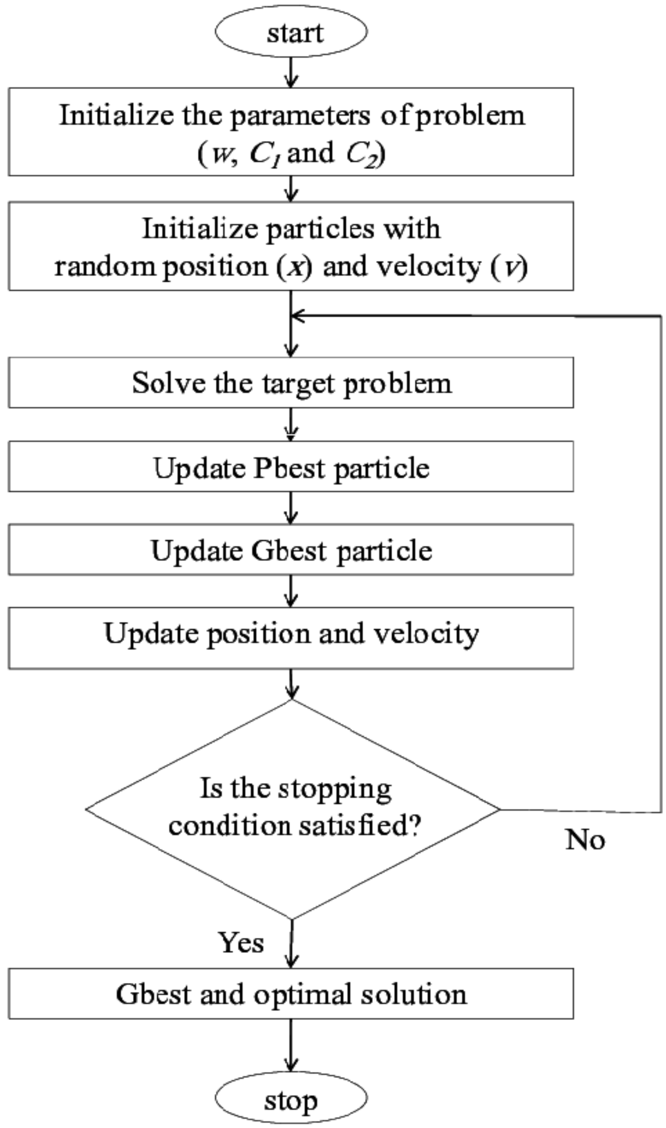

Fig. 2 Flow chart for PSO

IV. RESULTS AND CONCLUSION

In this paper contains mainly two network systems that are IEEE30 bus and IEEE57 bus systems, each system will be taken into two cases i.e. base case and original case.

The bus robustness and sensitivity is find outs by using eq. (7). If the λ_i value is high, the voltage variation due to reactive power increment is less and if the λ_i value is less, the voltage variation due to reactive power increment is high.

A. Results of IEEE 30 bus System

If an IEEE 30 bus system contains 41 transmission lines, 6 generator buses and 24 load buses. The standard IEEE 30 bus system is treated as original case. The base case contains extra three lines added to the original system. The base case contains 44 transmission lines.

The bus Eigen value is more; the corresponding bus is high robustness and less sensitivity. The bus Eigen value is less; corresponding bus is less robustness and high sensitivity.

The results for top 5 strongest buses and top 5 weakest buses of the IEEE 30 bus for both Original case and Base case are shown in below tables.

TABLE I
TOP 5 STRONGEST BUSES OF IEEE 30 BUS SYSTEM

Original case				Base case			
Conventional		PSO		Conventional		PSO	
λ_3	94.2657	λ_3	97.1837	λ_3	96.6551	λ_3	98.1875
λ_4	55.6849	λ_4	56.6749	λ_4	60.3061	λ_4	60.5961
λ_6	35.0182	λ_6	35.4781	λ_6	54.8119	λ_6	56.1576
λ_7	33.4009	λ_7	33.6051	λ_7	52.1834	λ_7	55.0186
λ_9	31.5612	λ_9	33.0605	λ_9	49.0325	λ_9	47.3555
V_3	0.9961	V_3	1.0003	V_3	0.9961	V_3	1.0202
V_4	0.9855	V_4	1.0238	V_4	0.9876	V_4	1.0132
V_6	0.9757	V_6	1.0074	V_6	1.0034	V_6	1.0108
V_7	0.9725	V_7	1.0010	V_7	0.9970	V_7	1.0107
V_9	0.9757	V_9	1.0074	V_9	1.0406	V_9	1.0191

TABLE III
TOP 5 WEAKEST BUSES OF IEEE 30 BUS SYSTEM

Original case				Base case			
Conventional		PSO		Conventional		PSO	
λ_{21}	0.4093	λ_{20}	0.4160	λ_{21}	0.4724	λ_{21}	0.4738
λ_{22}	0.7454	λ_{21}	0.7629	λ_{22}	0.8035	λ_{22}	0.8072
λ_{23}	1.6994	λ_{22}	1.7322	λ_{23}	1.7287	λ_{23}	1.7191
λ_{24}	2.3229	λ_{23}	2.3658	λ_{24}	3.3085	λ_{24}	3.3432
λ_{26}	3.0054	λ_{24}	3.0372	λ_{25}	4.1046	λ_{25}	4.1616
V_{21}	0.9599	V_{20}	0.9743	V_{21}	0.9844	V_{21}	0.9987
V_{22}	0.9607	V_{21}	0.9885	V_{22}	0.9850	V_{22}	0.9995
V_{23}	0.9442	V_{22}	0.9893	V_{23}	0.9668	V_{23}	0.9832
V_{24}	0.9517	V_{23}	0.9656	V_{24}	0.9736	V_{24}	0.9902
V_{26}	0.9541	V_{24}	0.9795	V_{25}	0.9891	V_{25}	1.0088

Where λ_i represent the eigenvalue to the corresponding bus and V_i represents the corresponding bus voltage.

From the results of table III and Table II, Base case gets high values when compared to original case. It means by adding some extra lines to the already existing system it improves the voltage stability and strength of the buses. By comparing the results of conventional method and PSO method, PSO gets the better results (high values) it means the stability and strength of the buses is improved by using PSO method.

B. Results of IEEE 57 bus System

If an IEEE 57 bus system contains 80 transmission lines, 7 generator buses and 50 load buses. The standard IEEE 30 bus system is treated as original case. The base case contains extra three lines added to the original system. The base case contains 83 transmission lines.

The bus robustness and sensitivity is find outs by using eq. (7). If the Eigen value is more, the corresponding bus is high robustness and less sensitivity. If the Eigen value is less, the corresponding bus is less robustness and high sensitivity.

The results for top 5 strongest buses and top 5 weakest buses of the IEEE 57 bus for both original case and base case are shown in below tables.

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TABLE IVII
TOP 5 STRONGEST BUSES OF IEEE 57 BUS SYSTEM

Original case				Base case			
Conventional		PSO		Conventional		PSO	
λ_4	170.7350	λ_4	173.6507	λ_4	175.7057	λ_4	178.1681
λ_5	119.6551	λ_5	121.4307	λ_5	122.1074	λ_5	123.7410
λ_7	102.4507	λ_7	102.9920	λ_7	106.5489	λ_7	108.2169
λ_{10}	94.3423	λ_{10}	94.3958	λ_{10}	105.9623	λ_{10}	107.5597
λ_{11}	82.4916	λ_{11}	86.5518	λ_{11}	94.9058	λ_{11}	96.0724
V_4	0.9821	V_4	1.0180	V_4	0.9838	V_4	0.9721
V_5	0.9777	V_5	0.9932	V_5	0.9783	V_5	0.9968
V_7	0.9884	V_7	0.9856	V_7	0.9907	V_7	0.9987
V_{10}	0.9766	V_{10}	0.9735	V_{10}	0.9829	V_{10}	0.9862
V_{11}	0.9854	V_{11}	1.0011	V_{11}	0.9905	V_{11}	1.0093

TABLE VV
TOP 5 WEAKEST BUSES OF IEEE 57 BUS SYSTEM

Original case				Base case			
Conventional		PSO		Conventional		PSO	
λ_{35}	0.2388	λ_{41}	0.2381	λ_{36}	0.2574	λ_{37}	0.2636
λ_{36}	0.6231	λ_{42}	0.6234	λ_{37}	0.7941	λ_{38}	0.8082
λ_{37}	0.8757	λ_{43}	0.8601	λ_{38}	1.1029	λ_{39}	1.1234
λ_{39}	1.0528	λ_{44}	1.0537	λ_{39}	1.6086	λ_{40}	1.6352
λ_{40}	1.2333	λ_{45}	1.2337	λ_{40}	1.7245	λ_{41}	1.7567
V_{35}	0.9712	V_{41}	1.0403	V_{36}	1.0176	V_{37}	1.0372
V_{36}	0.9805	V_{42}	0.9612	V_{37}	1.0246	V_{38}	1.0389
V_{37}	0.9894	V_{43}	0.9557	V_{38}	1.0413	V_{39}	1.0034
V_{39}	0.9874	V_{44}	1.0025	V_{39}	1.0246	V_{40}	0.9852
V_{40}	0.9775	V_{45}	1.0484	V_{40}	1.0162	V_{41}	0.9969

Where λ_i represent the eigenvalue to the corresponding bus and V_i represents the corresponding bus voltage.

From the results of table III and Table IV, Base case gets high values when compared to original case. It means by adding some extra lines to the already existing system it improves the voltage stability and strength of the buses. By comparing the results of conventional method and PSO method, PSO gets the better results (high values) it means the stability and strength of the buses is improved by using PSO method.

Finally, the results of PSO method are better than the conventional method. The strongest buses have high voltage stability whenever reactive power variation is more; these buses are high robustness and low sensitivity. The weakest buses have low voltage stability when reactive power variation is less; these buses are low robustness and high sensitivity.

V. CONCLUSIONS

In this paper mainly focused on sensitivity, robustness and stable configuration for an IEEE 30 bus and IEEE 57 bus system. This method is mainly based on load flow analysis method to get voltage stability indexes i.e. Eigenvalues. The PSO method is gets more robustness and less sensitivity of the buses when compared to conventional case. The simulation results are shows the strong and weak buses configuration for an IEEE 30 bus and IEEE 57 bus system. By using these results easily identifies the bus robustness and sensitivity. It is helpful to the power transmission system expansion and planning to get the best configuration network.

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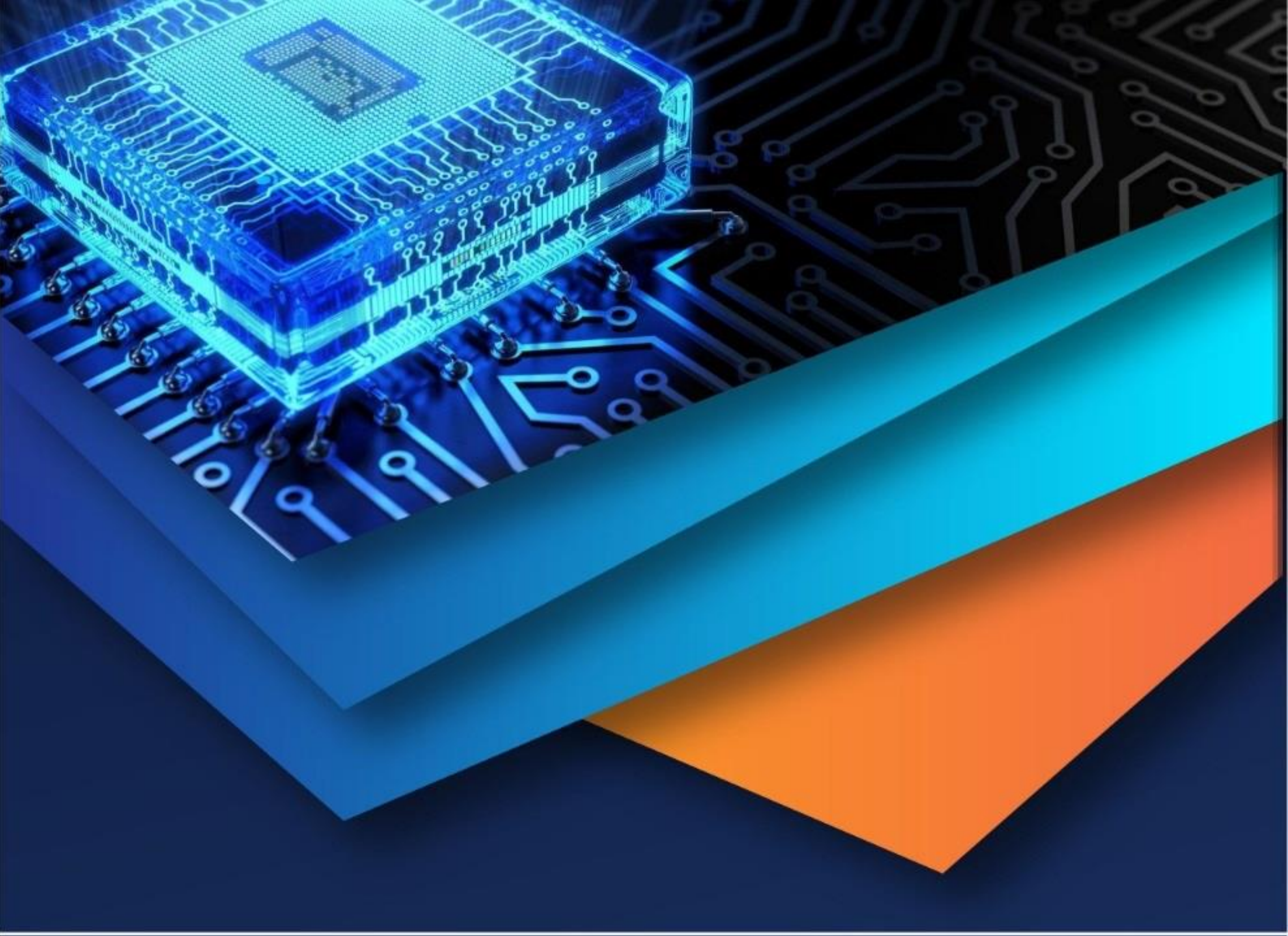

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