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Estimation of Damping Torque for Small-Signal Stability of Single Machine Infinite Bus System

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***Abstract—* This paper discusses the Estimation of damping torque coefficient for Small-signal stability of infinite bus system. This damping torque coefficient is used to identify the angle stability of a system. Initially a mat lab coding was utilized to generate the time domain responses of rotor angle, rotor speed and electromagnetic torque under various loading conditions. The particle swarm optimization (PSO) technique is then used for accurate estimation of damping torque coefficient. The mat lab coding results using PSO, under various loading conditions shows the effectiveness of the proposed control strategy.**

***Index terms* – Damping torque coefficient, Particle swarm optimization, Small-signal stability, and Synchronizing torque coefficient.**

I. INTRODUCTION

The power system instability can be demonstrated in many different ways depending on the system configuration and working mode. Since power system works on synchronous generators, an essential condition for system operation is that all synchronous machines remain in synchronism [1-3]. The small signal stability is the ability of the power system to maintain synchronism when subjected to a small disturbance [1]. The operating condition of the power system changes with respect to time because of the dynamic nature of the system. The rotor angle stability can be analyzed from the Synchronizing torque coefficient K_S and Damping torque coefficient K_D. For stable operation of the system, both synchronizing and damping torque coefficients must be positive.

The electromagnetic torque deviation is split into Synchronizing torque and Damping torques. The Synchronizing torque is responsible for restoring the rotor angle excursion and the Damping torque damps out the speed deviations [4, 5]. In general the synchronizing and damping torques are expressed in terms of Synchronizing torque coefficient K_S and Damping torque coefficient K_D. These K_S, K_D can be calculated frequently for stability assessments. Various computational techniques like Simulation Annealing (SA) algorithm, Evolutionary programming (EP), Genetic Algorithm (GA) and Differential Evolution (DE) are employed for optimization problem [7, 8]. These techniques need more parameters, high calculation time and not easy to implement when compared to particle swarm optimization. Particle swarm optimization (PSO) was developed by Kennedy and Eberhart. This has appeared as a promising algorithm for handling the optimization problems [20]. PSO is a robust, non-linear and population based stochastic optimal technique which can generate high quality solutions within shorter calculation time. The single-machine power system modeling and small-signal stability studies are carried out using Eigen analysis based technique With PSO (particle swarm optimization) optimal strategy. The suggested control technique is based on estimation of damping torque coefficient K_D of a synchronous machine from the time responses of the rotor angle $\Delta\omega_r(t)$, rotor speed $\Delta\delta(t)$ and electromagnetic torque $\Delta T_e(t)$. Thus PSO has been chosen to coordinate the operation in estimating Damping torque coefficient K_D for stability analysis [17-19].

II. POWER SYSTEM MODEL

A simplified block diagram model of the small signal performance is shown in fig1 [1]. In this work, the proposed method has been tested on a system comprising a single machine connected to infinite bus system through a transmission line. Normally, for small signal stability study a second-order model is considered for the synchronous generator. The single machine infinite bus system model is linearized at a particular operating point to obtain the linearized power system model. This model is represented with some variables, such as electrical torque, mechanical torque, and rotor speed and rotor angle.

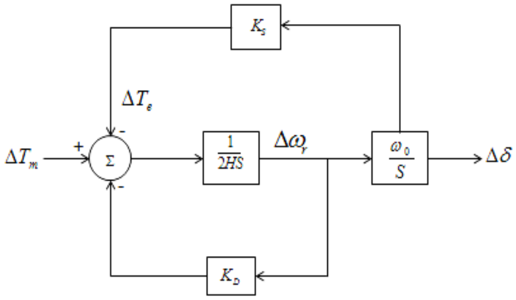

Figure1. Block diagram model of small signal performance.

In the classical generator model, the acceleration circuit dynamic equations are:

$$\frac{\Delta\omega_r}{\Delta t} = \frac{1}{2H}(T_m - T_e - K_D\Delta\omega_r) \qquad (1)$$

$$\frac{\Delta\delta}{\Delta t} = \omega_0\Delta\omega_r \qquad (2)$$

Where T_m, T_e are mechanical torque, electromagnetic torque and $\omega_0 = 2\pi f_0$. From the block diagram, the following state-space form is developed.

$$X = AX + BU$$

$$\frac{d}{dt}\begin{bmatrix}\Delta\omega_r \\ \Delta\delta\end{bmatrix} = \begin{bmatrix} -\frac{K_D}{2H} & \frac{-K_s}{2H} \\ \omega_0 & 0 \end{bmatrix}\begin{bmatrix}\Delta\omega_r \\ \Delta\delta\end{bmatrix} + \begin{bmatrix}\frac{1}{2H} \\ 0\end{bmatrix}\Delta T_m$$

The elements of the system matrix A are function of K_D, H, X_T and the initial operating conditions.

The perturbation matrix B depends on the system parameters only. From the block diagram of figure1, we have

$$\Delta\delta = \frac{\omega_0}{S}\left[\frac{1}{2HS}\left(-K_S\Delta\delta - K_D\Delta\omega_r + \Delta T_m\right)\right] \qquad (3)$$

And the characteristic equation is

$$S^2 + \frac{K_D}{2H}S + \frac{K_S\omega_0}{2H} = 0 \qquad (4)$$

Therefore, the damping ratio is

$$\xi = \frac{1}{2}\frac{K_D}{\sqrt{K_S\,2H\omega_0}}$$

(5)

$$I_t = \frac{E' - E_B(\cos\delta - j\sin\delta)}{jX_T} \tag{6}$$

$$X_T = X_d' + X_E \tag{7}$$

$$K_S = \frac{E' E_B}{X_T}\cos\delta_0 \tag{8}$$

III. SMALL SIGNAL STABILITY ASSESSMENT USING MODAL MATRICES

The power system experiences small disturbances by small changes in loads. Then the system will be driven to an infinite state $X(t_0) = X_0$ at time t_0 =0. The system responds according to the state equations. The linearized state equations can be used to find the Eigen values λ_i of the system matrix A, where $\lambda_i = \sigma_i \pm j\omega_i$ are the distinct eigenvalues corresponding to a set of right and left eigenvectors. Here σ_i is a damping factor and ω_i is Damped angular frequency. The right and left Eigen vectors are orthogonal and are usually scaled to be orthogonal. Real eigenvalues indicates modes which are aperiodic and complex eigenvalues indicates modes which are oscillatory. The uses of right and left eigenvectors are for identifying the relationshipbetween the states and the modes is that the elements of the eigenvectors are dependent on units and scaling associated with the state variables. To overcome this participation matrix which combines the right and left eigenvectors are used. The participation factor provides a measure of association between the state variables and the oscillatory modes.

IV. SMALL-SIGNALSTABILITY ASSESSMENT USING SYNCHRONISING AND DAMPING TORQUES.

The electromagnetic torque (T_e) deviation of a machine can be expressed as its speed (ω) and angle (δ) deviations, which are called damping and synchronizing torques. The synchronizing and damping torques are expressed in terms of its synchronizing torque coefficient (K_S) and damping torque coefficient (K_D). Then the electromagnetic torque deviation will be expressed as:

$$\Delta T_e(t) = K_D\omega_0\Delta\omega(t) + K_S\Delta\delta(t) \tag{9}$$

Where $\Delta\omega_r(t)$ = change in rotor speed

$\Delta\delta(t)$ = change in rotor angle

V. OVER VIEW OF PARTICLE SWARM OPTIMIZATION

PSO is one of the evolutionary based optimization techniques [Fukuyama, 1999; Kennedy and Eberhart, 1995]. This method is introduced based on the research of bird and fish flock movements behavior. Due to its many advantages like its simplicity and easy implementation, the algorithm can be widely used in function optimization.

A. PSO Algorithm:

The particle swarm optimization consists of ‘n’ particles and the particles position stands for the potential solution in D-dimensional space. Each particle can be shown by its current speed and position. Particles change its position according to it’s:

1. Current position
2. Current velocity
3. Distance between its current position and $pbest$
4. Distance between its current position and $gbest$

Velocity of each particle can be modified based on the following equation.

$$v_{id}^{k+1} = w v_{id}^{k} + c_1 r_1^{k} (pbest_{id}^{k} - x_{id}^{k}) + c_2 r_2^{k} (gbest_{id}^{k} - x_{id}^{k})$$

By using velocity equation, a certain velocity which gradually gets close local best and global best can be calculated. The current position of the particle can be modified by the following equation.

$$x_{id}^{k+1} = x_{id}^{k} + v_{id}^{k+1}$$

Where, $pbest$ represents the D-dimension quantity of the individual “i” at its most optimist position at its “k” times and $gbest$ represents the D-dimension quantity of the individual “i” at its most optimist position at its “k” times. The speed of the particle at its each direction is confined in between –vdmix and +vdmax. If vdmax is too big, solution is far from the best and if vdmax is too low, it means that the solution will be local optimism. C1, C2 represents speeding figures which lies between 0 to 2. r1, r2 represents random fiction, and 0-1 is a random number.

VI. ESTIMATION OF LOWER AND UPPER LIMITS OF DAMPING TORQUE COEFFICIENT.

For the linearized system model presented in figure1, the eigenvalues of the local system can be evaluated. The proposed method is aiming to search for the optimal damping torque coefficient, such that the damping ratio can be maximized.

$$\xi = \frac{1}{2} \frac{K_D}{\sqrt{K_S 2H\omega_0}}$$

Where ξ =damping ratio.

For stable operating condition of the system the Damping ratio must be in [0.4, 0.7]. Hence the Corresponding values of K_D will be [35.712, 63.125]. The control parameters can be tuned through the optimization algorithm. The proposed algorithm will be as follows.

VII. IMPLEMENTATION OF PSO FOR OPTIMAL ESTIMATION OF DAMPING TORQUE

Step1. Read the system input data, PSO parameters.

Step2. Initialize population of particle (K_D) with random velocities and positions.

Step3. Evaluate fitness values using the objective function.

$$\xi = \frac{1}{2} \frac{K_D}{\sqrt{K_S 2H\omega_0}}$$

Step4. Each particle has its own best position called local best and the best position among all the particles is called global best.

Step5. Update the velocity of particle using

$$v_{id}^{k+1} = v_{id}^{k} + c_1 r_1^{k} (pbest_{id}^{k} - x_{id}^{k}) + c_2 r_2^{k} (gbest_{id}^{k} - x_{id}^{k})$$

Check the updated velocity, within the limits or not

$$v_i^{\min} \le v_i \le v_i^{\max}$$

Step6. Update the position of particle using

$$x_{id}^{k+1} = x_{id}^{k} + v_{id}^{k+1}$$

Step7. Evaluate fitness values of the new particles. Update the local best values as current fitness values if these values are better than previous values, update it. Then find new global best values.

Step8. Repeat the procedure until the stopping criteria is reached.

VIII. RESULTS AND DISCUSSIONS

In this work the optimal values of K_D are obtained using PSO and the rotor speed, rotor angle and electromagnetic torque responses are generated and are compared with those obtained in [1]. In which the damping torque coefficient is chosen randomly [-10, 0, 10]. In addition the same responses are generated for different loading conditions using mat lab coding. It is observed that the steady state stability of the system is improved. These responses are shown in figure2-a to figure4-c. The rotor responses are obtained for various conditions:

1. Nominal operating condition (P=0.9, Q=0.3).
2. Light operating condition (20% of the nominal values).
3. Heavy operating condition (50% higher than the nominal operating condition).

The following responses show the rotor characteristics under various loading conditions.

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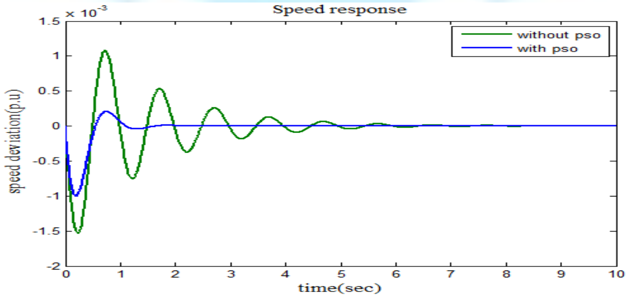

Figure 2-a. Rotor speed response for P=0.9,Q=0.3.

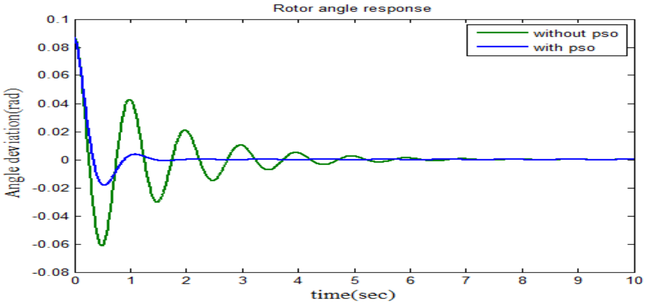

Figure 2-b. Rotor Angle response for P=0.9, Q=0.3.

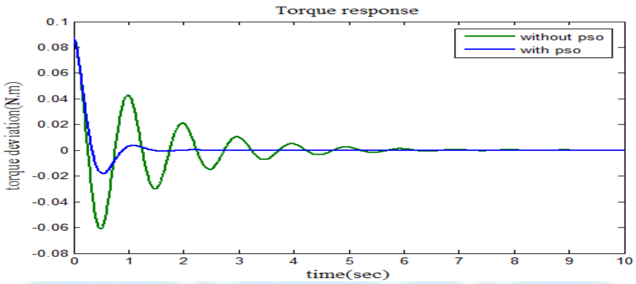

Figure 2-c. Torque response for P=0.9, Q=0.3.

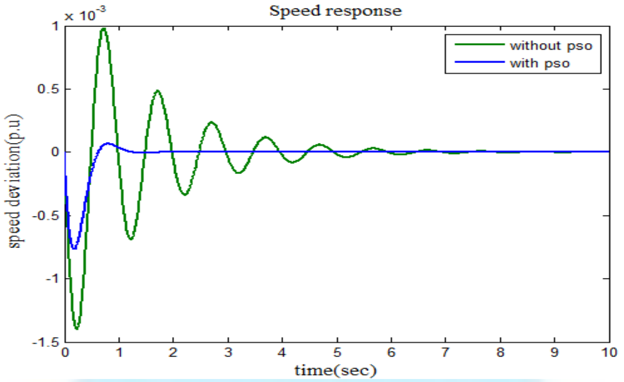

Figure 3-a. Rotor speed response for P=1.35, Q=0.45.

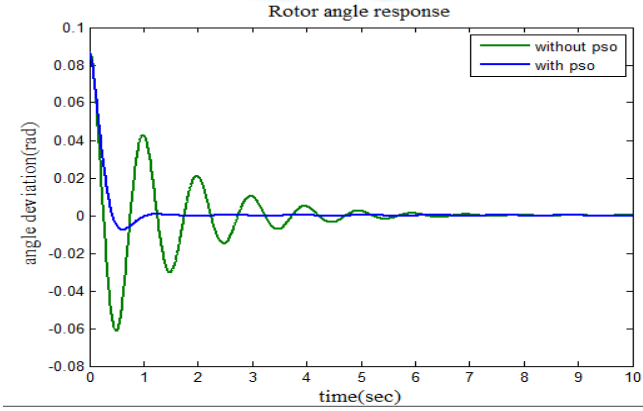

Figure 3-b. Rotor Angle response for P=1.35, Q=0.45

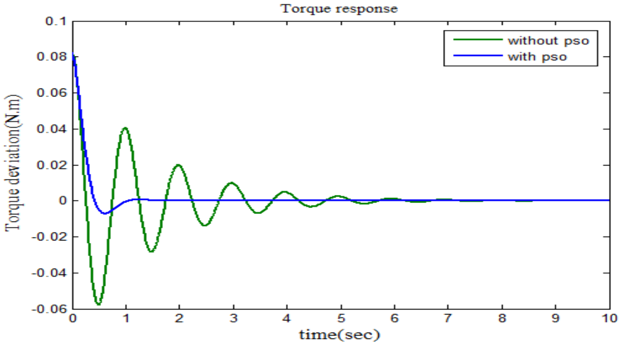

Figure 3-c. Torque response for P=1.35, Q=0.45.

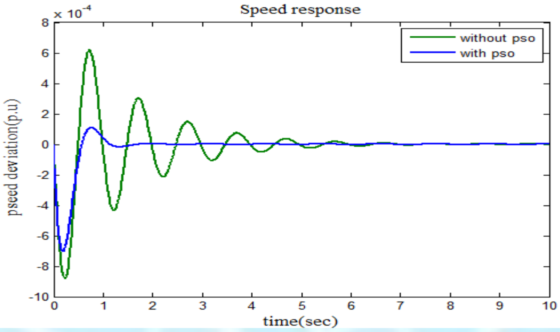

Figure 4-a. Rotor speed response for P=0.72, Q=0.24

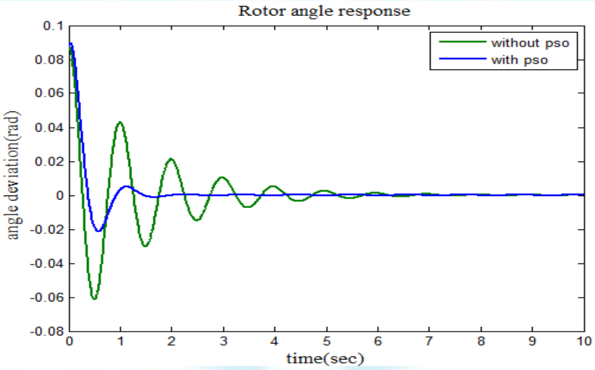

Figure 4-b. angle response for P=0.72, Q=0.24.

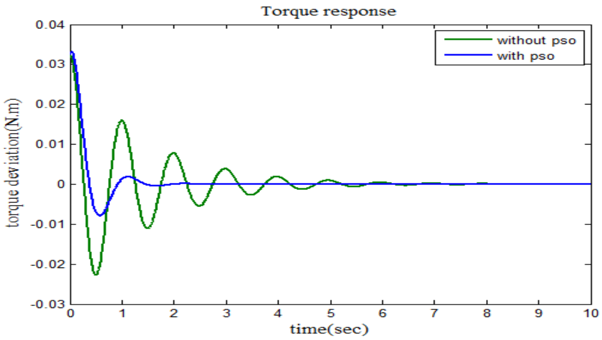

Figure 4-c. Torque response for P=0.72, Q=0.24.

IX. CONCLUSION

In this project the steady state performance improvement is obtained by the accurate estimation of damping torque coefficient using particle swarm optimization technique. The matlab programming results using PSO under various loading conditions shows the effectiveness of the proposed technique. Compared to normal operating conditions under heavy and light operating conditions the peak over shoots are very high which are reduced using PSO technique. The effectiveness of the proposed controller is to provide good damping of low frequency oscillations. It can be concluded that the proposed PSO controller extends the power system stability limit by enhancing the system damping.

APPENDIX

Input data:

1. Generator parameters:

$$H = 3.5, T'_{d0} = 8, X_d = 1.81, X_q = 1.76,$$

$$X'_d = 0.3, R_a = 0.003, K_{sd} = K_{sq} = 0.85$$

2. Transmission line parameters:

$$R_e = 0, X_e = 0.65, X_L = 0.15.$$

Table1. (Lower, Upper limits of control parameter):

PARAMETER	K_D
Lower limit	35.712
Upper limit	63.125

Table2.PSO Parameters

Population size	10
Maximum number of generations	50
Acceleration coefficients(C1,C2)	1.4
Inertia weight	1

Table3 (Loading conditions):

S.no	Cases	P(p.u)	Q(p.u)
1	Nominal operating condition	0.9	0.3
2	Heavy operating condition (50% higher than the nominal load)	1.35	0.45
3	Light operating condition(20% of the nominal operating condition)	0.72	0.24

Table4. (Optimal value of control parameter)

K_D	57.8

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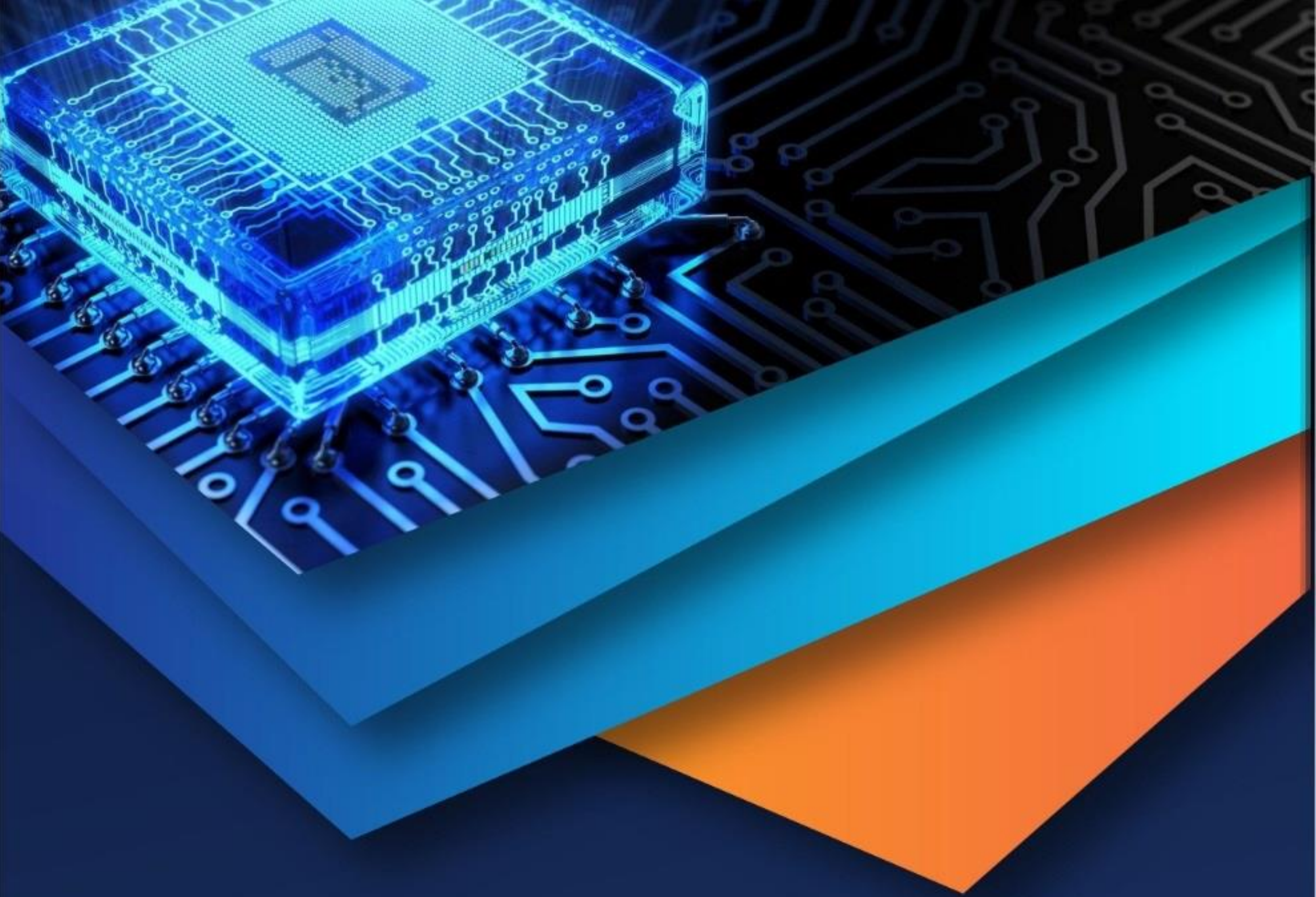

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