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Impact of Reactive Power Generation and Absorption on Voltage Regulator: A Case Study in an Industrial Power System

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Abstract: The stability and reliability of any electrical power system, particularly in industrial settings, relies heavily on the meticulous control of reactive power (RP) flow and subsequent voltage regulation. Theoretically, the instantaneous amount of reactive power required is fundamentally dependent upon the prevailing voltage level. Maintaining voltage within acceptable limits is critical, as voltage drops can significantly impact the operational efficiency and life expectancy of connected equipment. Reactive power generation (capacitive) and absorption (inductive) characteristics dictate the voltage profile; voltage rise often requires reactive power absorption, while voltage drop necessitates generation.

The Automatic Voltage Regulator (AVR) serves as the primary voltage control system for synchronous generators. The AVR operates by controlling the generator excitation system to regulate the generator's terminal voltage. When a voltage reduction is detected (such as during heavy industrial load changes), the AVR responds by increasing the generator excitation, which consequently boosts the generator Electro-Motive Force (EMF) and increases the amount of reactive power generated, thereby raising the terminal voltage to the desired set point.

This study analyzes the dynamic performance of the AVR using transfer function models for its core components: the amplifier, exciter, generator, and sensor. While the basic AVR model may exhibit instability, simulation results demonstrate that stabilization techniques improve response. Specifically, the Proportional-Integral-Derivative (PID) controller is highlighted as a highly effective industrial process control method.

The integral component of the PID controller eliminates steady-state error following a step function input, resulting in superior performance (reduced overshoot and faster settling time) compared to the basic AVR or AVRs stabilized using rate feedback. Furthermore, this case study discusses external reactive power compensation, such as FACTS devices, which are essential to mitigate large-scale voltage variations caused by the dynamic reactive power demands associated with varying industrial loads. Effective control ensures system stability is maximized and transmission losses are minimized.

Keywords: Reactive Power Control, Automatic Voltage Regulator (AVR), Voltage Stabilization, PID Controller, Industrial Power System

I. INTRODUCTION

The foundation of secure and reliable power delivery in an industrial setting rests on comprehensive voltage and reactive power control. While active power is crucial for work, reactive power (RP) is indispensable, as it is required to facilitate the movement of active power through the transmission and distribution network to the consumer. Reactive power management is a major concern for power systems, addressing issues of system stability, grid reliability, and security.

A. The Necessity of Voltage and Reactive Power Control

In any electrical system, the instantaneous amount of reactive power necessary is theoretically dependent upon the voltage level. Maintaining acceptable voltage levels is a crucial objective of voltage control. If the available voltage value changes, the efficiency of equipment connected to the system is significantly affected, which can lead to a reduction in life expectancy. Voltage control objectives include maximizing system stability, maintaining voltages at all terminals within acceptable limits, and reducing reactive power flow to minimize the losses. Reactive power is stored in magnetic fields by inductors (including synchronous machines, transformers, and reactors, which absorb RP) and in electric fields by capacitors (which generate RP). Poor reactive power control can lead to serious adverse effects, including damage to equipment, increased losses, and the risk of voltage collapse.

Voltage collapse typically occurs when voltage instability causes a substantial and progressive decline in system voltage, often leading to protective devices tripping and further voltage decrease [1].

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The dynamic requirement for reactive power varies drastically based on the industrial load conditions. Transmission lines exhibit complex reactive power characteristics under light loading conditions; the line itself generates reactive power (known as the Ferranti effect), which must be absorbed by the system. Conversely, under heavy loading, the transmission lines consume reactive power, which leads to voltage degradation. This variability necessitates a responsive and robust voltage control mechanism.

B. The Role of the Automatic Voltage Regulator (AVR)

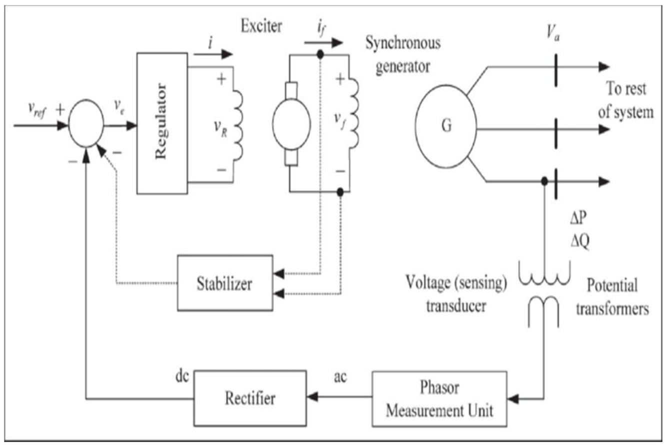

Figure 1: Simple AVR model

The Automatic Voltage Regulator (AVR) is the standard control system used on synchronous generators to maintain system voltage stability. The AVR supplies the field voltage and current to the field winding of the synchronous machine. This mechanism subsequently regulates the generator's terminal voltage. The operational principle involves the AVR measuring the generator's terminal voltage using a potential transformer (PT). The sensed voltage signal is rectified and then compared to a fixed reference point, generating an error signal. This error signal is amplified and controls the field exciter, which supplies current to the generator's field winding [2]. When the terminal voltage drops, the AVR increases the generator excitation. This increased excitation boosts the generator's Electro-Motive Force (EMF), leading to an increase in the generated reactive power and ultimately raising the terminal voltage back to the desired value.

C. AVR Modelling and Stabilization

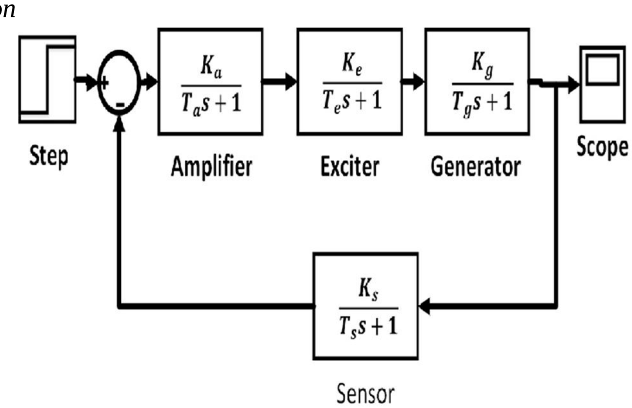

Figure 2: AVR model

For dynamic analysis and simulation, the AVR is commonly modelled as a unity feedback control system. The forward path comprises four main component blocks: the amplifier, the exciter, the generator, and the sensor (or feedback path). Due to the inherent complexity and time constants of the components, the basic AVR model often results in an unstable or oscillatory response. To ensure a satisfactory system response, stabilization techniques are required. Rate Feedback Stabilization: One method to increase relative stability is by introducing rate feedback.

By appropriately adjusting the constants of the feedback loop, a zero can be added to the open-loop transfer function. PID Controller Implementation: A more common and highly effective method used in industrial process control is the PID controller. The PID controller is inserted into the forward path of the AVR system [3]. The derivative component adds a zero to the open-loop transfer function, and the integral component adds a pole at the origin. This configuration is beneficial, as the integral controller is designed to reduce the steady-state error to zero following a step function input, resulting in improved transient response and elimination of residual errors. Simulations comparing these methods show that the PID-compensated AVR offers superior performance characteristics, such as lower peak overshoot and shorter settling time.

II. LITERATURE SURVEY

Automatic Voltage Regulator (AVR) is identified as the basic control system applied to synchronous generators. It is responsible for generator excitation control, regulating the terminal voltage, and controlling reactive power flow by adjusting the exciter's field voltage. This report aims to present a detailed study comparing the basic AVR model with models incorporating a stabilizer and a conventional controller (PID controller) to find the most effective stabilization technique [4]. Shunt Compensators and FACTS Devices For wider system stability and dynamic support, FACTS (Flexible AC Transmission Systems) devices are essential. The Static VAR Compensator (SVC) is highlighted as a modern technology that provides dynamic reactive power support.

Transmission Line Compensation Reactive power management is particularly important in transmission lines where loading conditions relative to the Surge Impedance Loading (SIL) determine reactive power needs. When the load is greater than SIL, the line acts inductively, consuming reactive power. It focuses on analyzing the application of devices like the FCTCR (Fixed Capacitor Thyristor Controlled Reactor) to regulate voltage and enhance power transfer capability in high-voltage long-distance transmission lines. Voltage Dependence and Reactive Power: The instantaneous amount of reactive power at a power grid point depends upon the system frequency and the level of voltage. Deviations in voltage levels, load amount, and equipment efficiency can significantly affect system behavior [5].

Widely to improve both steady-state voltage profile and dynamic stability. STATCOM offers faster response and better low-voltage support than SVC, making it favorable where voltage recovery after disturbances matters.

III. REACTIVE POWER COMPENSATION

Reactive power compensation devices supplement the AVR by generating or absorbing reactive power, ensuring that voltage levels are maintained within permissible limits and system losses are minimized.

A. Sources and Sinks of Reactive Power

Reactive power is generated by shunt capacitors, synchronous generators, synchronous condensers, and PV systems (static and dynamic sources). Reactive power is absorbed by heavily loaded transmission lines, transformers, shunt reactors, inductive loads, and synchronous machines [6].

B. Shunt Compensation

Shunt Capacitors: These are highly effective for voltage control and load stabilization [7]. They are typically installed near load centres to inject reactive power, compensating for heavy load conditions and thereby reducing voltage drops.

C. FACTS Devices

Flexible AC Transmission Systems (FACTS) devices provide highly dynamic reactive power control, which is necessary in industrial systems characterized by rapid load changes.

Static VAR Compensator (SVC): The SVC is a static compensator often composed of a fixed capacitor connected in parallel with a Thyristor Controlled Reactor (TCR). By adjusting the firing angle of the thyristors, the inductive reactive power absorbed by the reactor is controlled [8]. The SVC can dynamically generate (capacitive) or absorb (inductive) reactive power, aiding the AVR in stabilizing voltage.

Static Synchronous Compensator (STATCOM): The STATCOM is a solid-state shunt device that utilizes power electronics to rapidly inject or absorb reactive power. STATCOMs offer superior response speeds and dynamic capabilities compared to synchronous condensers and SVCs, making them highly effective for rapid voltage control.

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IV. CLASSIFICATION OF VOLTAGE REGULATION AND REACTIVE POWER COMPENSATION EQUIPMENT

Managing voltage regulation and reactive power in modern power systems, especially in the presence of large and fluctuating industrial loads, has always been a complex challenge. Over time engineers have developed a wide variety of technologies to handle these issues [9]. Each technology generation was introduced to overcome the shortcomings of its predecessor, and each offers distinct benefits and limitations.

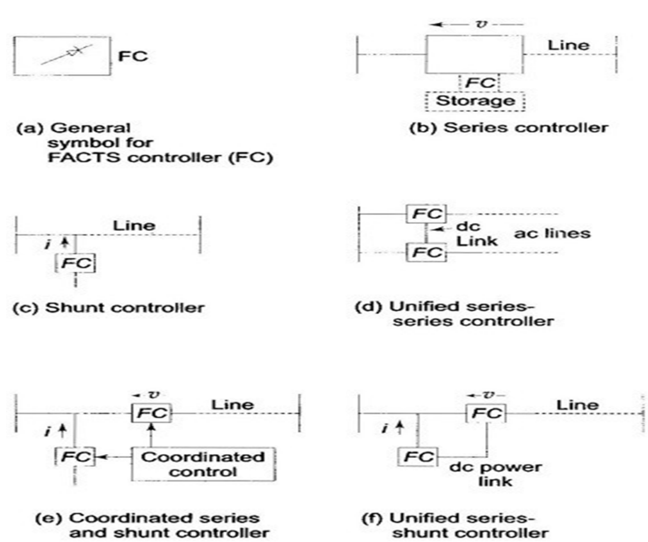
A. Conventional Mechanical and Static Regulators

On-Load Tap Changers (OLTCs): OLTCs are mechanical devices built into power transformers that allow adjustment of the transformer turns ratio, hence its output voltage, while it remains energized and supplying load. Their operation is usually automated through an Automatic Voltage Control (AVC) relay, which continuously monitors the system voltage. When the voltage deviates beyond a predefined deadband, the AVC triggers a tap change. The deadband prevents unnecessary or frequent switching caused by minor voltage fluctuations. However, because of their mechanical nature, OLTCs have a relatively slow response time, typically one operation every 3 to 10 seconds. As a result, they are suitable for correcting long-term or gradual voltage variations but are far too sluggish to handle rapid sub-second voltage swings that occur with highly dynamic industrial loads.

Capacitor Banks: Shunt capacitor banks are one of the simplest and most widely used methods for reactive power compensation. When connected in parallel with a load, they supply capacitive reactive power that offsets the inductive reactive power drawn by devices such as motors and transformers. This bank improves the power factor and provides a small voltage boost. While cost-effective capacitor banks only operate in fixed steps, which means their level of compensation cannot be varied continuously. Another drawback is their tendency to form a resonant circuit when combined with the system's inductive elements. If the resonant frequency aligns with one of the harmonic frequencies generated by nonlinear equipment (such as variable frequency drives), it can cause harmful amplification of harmonic currents and voltages. This resonance may lead to overheating or damage in capacitors and nearby electrical components.

Synchronous Condensers: A synchronous condenser functions similarly to a synchronous motor but without any mechanical load attached. Its role is purely electrical, regulating reactive power. By adjusting its DC excitation current, it can either generate (over-excited) or absorb (under-excited) reactive power dynamically. Beyond reactive power control, its rotating mass contributes inertia to the grid, increasing system stability and short-circuit strength. Although it is bulkier and more maintenance-intensive than static devices, it provides a level of dynamic support that older technologies cannot.

B. Thyristor-Based Controllers: The First Generation of FACTS Devices



The introduction of high-power thyristors marked a major technological leap leading to the first generation of Flexible AC Transmission Systems (FACTS). These systems enabled electronic fast-acting control of reactive power.

Static VAR Compensator (SVC): An SVC is a shunt-connected system designed to rapidly provide or absorb reactive power. It typically consists of a Thyristor-Controlled Reactor (TCR) operating alongside one or more banks of Fixed or Thyristor-Switched Capacitors (TSCs). The TCR's inductive current can be adjusted smoothly by changing the thyristor firing angle while the TSCs operate in discrete steps to supply capacitive reactive power. This arrangement provides continuous control over the total reactive power output [9]. Because of its electronic switching nature, the SVC reacts almost instantaneously compared to mechanical devices, making it particularly effective in reducing voltage flicker caused by fast-changing loads such as Electric Arc Furnaces (EAFs).

C. Voltage-Source Converter (VSC) Technology: The Second Generation of FACTS

With the advent of self-commutating semiconductor devices such as insulated-gate bipolar transistors (IGBTs), a new era of reactive power control began. Voltage-Source Converter (VSC) technology paved the way for the next generation of FACTS devices, offering higher precision, faster response, and improved efficiency.

Static Synchronous Compensator (STATCOM): A STATCOM is a VSC-based device that acts as a controllable voltage source connected in parallel to the grid. It generates a three-phase voltage and regulates the flow of reactive power by adjusting its terminal voltage relative to the system voltage [10]. When the STATCOM's output voltage is higher than the system voltage, it injects reactive power (capacitive mode). When it is lower, it absorbs reactive power (inductive mode).

Advantages of STATCOMs: STATCOMs resolve several key issues found in SVCs. Most notably, they can deliver full-rated reactive current even during deep voltage sags, providing strong voltage support when the grid is weakest [11]. Their response time is quicker due to the high-frequency switching of IGBTs. Moreover, modern STATCOMs use multi-level converter topologies that produce near-sinusoidal waveforms with minimal harmonic distortion, often eliminating the need for bulky harmonic filters. They make them more compact, efficient, and easier to install.

V. INDUSTRIAL APPLICATIONS

A. Electric Arc Furnaces (EAF) in Steel Manufacturing

Electric Arc Furnaces (EAFs) are among the most challenging industrial loads to manage. They draw highly erratic and nonlinear currents, which cause severe voltage flicker, harmonic distortion, and a poor power factor. Steel manufacturers often aim to raise the furnace operating power to boost productivity, but their efforts are usually limited by the utility flicker standards at the Point of Coupling (POC).

In one steel plant a 0–90 MVAR Static VAR Compensator (SVC) was installed with the goal of increasing furnace power from 65 MW to 84 MW without exceeding the flicker limits set by the utility. The SVC's purpose was to improve the power factor, suppress voltage flicker and harmonics, and stabilize the 34.5 kV furnace bus voltage. After installation, performance testing confirmed that the system exceeded expectations; the SVC maintained a power factor above 0.995 and kept total harmonic voltage distortion below 1.25%. This enhanced power quality enabled a 15% increase in furnace capacity, reducing melting time, cutting energy and electrode use, and ultimately improving production efficiency.

B. Hot Rolling Mills

Hot rolling mills rely on multiple large motors that operate in cycles as steel slabs are shaped. These motors create large swings in both active and reactive power demand. Such behavior leads to voltage fluctuations and often results in a poor power factor where reactive power demand can even exceed active power at certain moments.

To address this, the model of a hot rolling mill system in MATLAB-Simulink is used to design an optimized reactive power compensation strategy. The analysis revealed that installing a single, centralized compensator for the entire plant would be extremely costly and inefficient. Instead, a distributed approach was proposed. The idea was to install several smaller STATCOMs, each rated around 6 MVA, near the most dynamically demanding parts of the process, the roughing mill drives. The STATCOMs were controlled using a d-q reference frame technique to precisely regulate reactive current. Simulation results showed that this distributed configuration performed exceptionally well [12]. It drastically reduced the amount of reactive power drawn from the upstream grid, stabilized the local voltages, and prevented disturbances from spreading to the POC. Overall, the system achieved smoother operation, higher efficiency, and better voltage quality throughout the mill. Furthermore, harmonic distortion levels were minimized due to faster dynamic response and better current regulation. This approach ultimately provided a cost-effective and scalable solution for long-term power quality management in hot rolling mills.

VI. RESULTS AND DISCUSSION

The results across the sources demonstrate that effective management of reactive power (RP) generation and absorption is paramount for maintaining voltage stability and minimizing system losses, requiring both optimized local control (AVR) and sophisticated external compensation (FACTS).

A. *Dynamic Performance of the Automatic Voltage Regulator (AVR)*

1) Basic AVR Response: Simulation of the basic AVR model typically yields a highly oscillatory response. This poor damping indicates that the basic AVR structure is insufficient for reliable voltage regulation, especially under transient conditions caused by sudden RP generation or absorption demands.
2) Stabilizer Performance: Implementing a rate feedback stabilizer improves the system response by introducing a zero into the open loop transfer function. When constants are properly adjusted, the AVR with stabilizer exhibits a satisfactory response with reduced oscillation.
3) PID Controller Superiority: The AVR model compensated with a Proportional-Integral-Derivative (PID) controller demonstrates superior performance compared to the basic model and the model utilizing stabilizer rate feedback. The PID controller is highly effective in industrial control because the integral component introduces a pole at the origin, eliminating the steady-state error following a step function input. This results in a better transient response characterized by minimal peak overshoot and faster settling time.

B. *Impact of Loading Conditions and Reactive Power Flow*

Reactive power flow analysis confirms that system loading relative to the Surge Impedance Loading (SIL) dictates whether reactive power must be absorbed or generated:

1) Load equals SIL: When the load angle is the reactive power, it is MVar. This is the balancing point where inductive and capacitive effects cancel each other.
2) Lightly loaded (load < SIL): At a load angle the reactive power is MVar (negative). This indicates the line is generating RP (Ferranti effect), and shunt inductors or the generator (via AVR control) must absorb this excess RP to prevent voltage rise.
3) Heavily loaded (Load > SIL): At a load angle the reactive power is MVar (positive). This indicates that the system is consuming RP, requiring the AVR to increase generation and external compensators to inject reactive power to prevent voltage drop.

C. *Role of Compensation and Optimization*

Due to large and variable RP requirements, external compensation techniques are necessary:

1) Shunt Compensation: Shunt capacitors are commonly used for voltage control and load stabilization, installed near load areas to compensate for heavy load conditions and ensure satisfactory voltage levels.
2) Dynamic Compensation (FACTS): Flexible AC Transmission Systems (FACTS) devices such as the Static Var Compensator (SVC) provide dynamic RP control. An SVC can dynamically generate or absorb RP by controlling the firing angle of its thyristor-controlled reactor (TCR).
3) Optimization: The Reactive Power Optimization Oriented Control (RPOOC) method is effective for optimal RP supply, particularly under heavy load and long transmission line conditions, showing superior performance in reducing loss compared to the economic voltage difference method.
4) DER Impact: In systems with high penetration of Distributed Energy Resources (DERs), voltage problems can arise. Adding static or switched shunts on buses with voltage violations can help maintain voltages.

VII. CONCLUSION

Reactive power control is mandatory to maintain rated voltages at all nodes in industrial and long-distance transmission systems and to minimize losses.

The Automatic Voltage Regulator (AVR) is critical for system operation, regulating the generator's terminal voltage and RP output by controlling the excitation field. Simulation comparison proves that the dynamic performance of the AVR is significantly enhanced through the implementation of a PID controller, which eliminates steady-state errors and provides a faster, more stable response than the basic AVR or rate feedback stabilization.

External compensation devices are crucial for handling system-wide reactive power imbalances. The selection of compensators (shunt inductors or capacitors) depends on whether the connected load is below or above the Surge Impedance Loading (SIL).

Furthermore, the RPOOC method is demonstrated to be a practical tool for effective and optimum RP control, especially under heavy load. Recent developments utilize power electronics switching devices (FACTS) to solve reactive power control issues, offering high-speed dynamic regulation to maintain voltage stability and transfer power capability. Finally, in complex modern grids with DER penetration, control strategies must ensure sufficient reactive power reserves are available and manage regulator set points to prevent voltage violations and potential voltage collapse.

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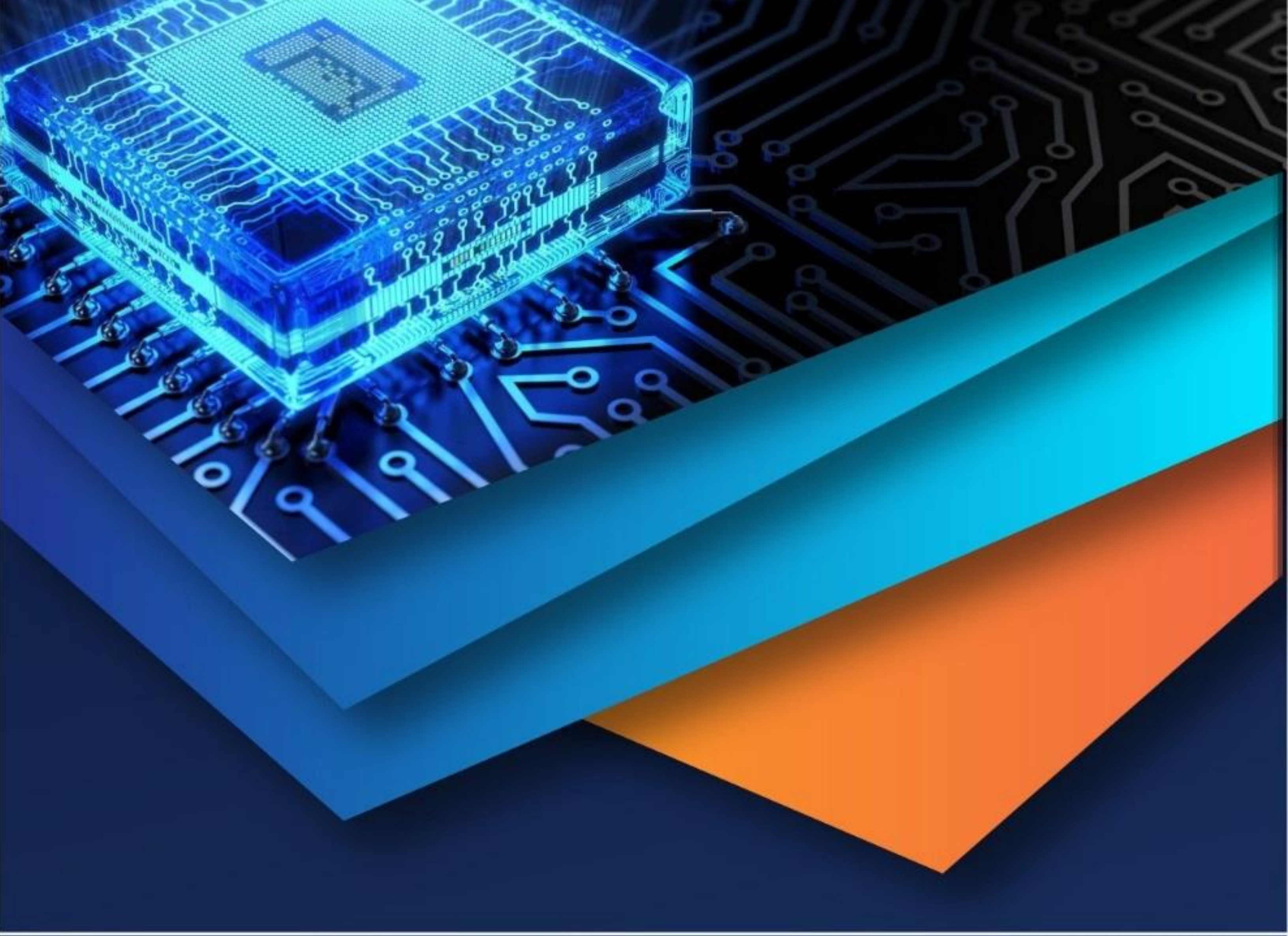

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