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Power Quality Control Center using Voltage-Sag Compensation and its Index Calculations- A Review

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Abstract: The role of the power quality control center (PQCC) in reducing the impacts of voltage sags on sensitive loads is examined. The center consists of back-to-back power converters, a dc bus, and a fuel cell distributed generator (DG) connected to the dc bus. It is shown that the range of voltage sags the system can ride through is determined by the current rating of the PQCC input-side inverter. Therefore, a three-stage operation scheme is proposed to improve on the system voltage sag ride-through capability. Stage 1 functions by maintaining the dc-link voltage at the same level as that before the sag. The PQCC input-side inverter would be protected from overloading during sag mitigation. The fuel cell remains undisturbed under this stage. Stage 2 is designed for compensating more severe sags. The purpose of introducing this stage is to decrease the input-side current through reducing the active power supplied by the upstream system. This is achieved by reducing the dc-link voltage and forcing the fuel cell to supply the balance of the active power. It is shown that this strategy can compensate for a voltage deviation of up to approximately double. For even more severe sags that cannot be compensated, the PQCC would reduce the dc-link voltage even further, such that the DG supplies the entire protected loads. This paper is predicting the voltage sag performance of distribution networks by estimating voltage sag indices. Two types of indices are analyzed in the present paper, they give, respectively, the average number of events and the average interruption duration of each kilovolt ampere served at the low-voltage level over the assessment period.

Keywords: Distributed generator (DG), fuel cell, power quality control center (PQCC), voltage sag, power distribution, power quality, probabilistic power system methods

I. INTRODUCTION

In recent years, there has been considerable interest in re-examining the configuration of the power distribution systems, specifically with the objective to deliver different levels of power quality to match customers' requirements [1]. Distributed generation (DG) systems [2], installed on the demand-side of customers, are proposed to be incorporated in such a flexible distribution system. However, introducing DG into an existing power system would pose new technical challenges, such as difficulties in voltage regulation due to the reversal of power flows from the DG and the increase in short circuit current [3]. If these and related technical challenges can be overcome, unbundling the distribution systems to meet the different needs of customers on power quality is an interesting idea. It could form the basis of designing the distribution systems of the future. Power quality control center (PQCC) [4] is one such possible design for the flexible electric power delivery system. It is designed not only to solve the above technique problems brought on by the DG but also to provide unbundled power quality services. The center is located between the high-voltage distribution systems and the customers. It consists of power electronics devices for controlling power flows, DG for the efficient use of energy and as a backup source, and computers for information processing, among other functions. The installation of mitigating devices at the system equipment interface can be a possible solution for customers, who rarely have the chance to request either specific tolerance level for equipment or improved power supply quality. However, these devices usually need to be equipped with energy storage facilities in order to compensate for the voltage sags. The amount of stored energy determines the extent of the severity of the sags for which load ride-through can be provided. Energy storage devices are expensive, and a tradeoff between ride-through capability and cost is required. Several indices have been proposed to assess the voltage sag performance of a power system [1]–[5]. They provide a count of event frequency and duration, the undelivered energy during events, or the cost and severity of the disturbances. Most of these indices are included in the draft of IEEE P1564 [1].A thorough analysis of power-quality indices, their advantages, and limitations, is presented in a CIGRE Working Group report [2].

II. PQCC STRUCTURE AND PROPOSED SAG RIDE-THROUGH SCHEME

In this section, the structure of the PQCC considered in the paper will be described, and the role of each of the component parts in the center in helping to achieve load ride-through is explained. The proposed voltage-sag ride-through scheme is also introduced. Due to the complexity and extensiveness of the upstream system, only balanced voltage sag events originated in the upstream power system are considered.

A. Uninterruptible Power Supply (UPS)-Type PQCC

Several types of PQCC for the realization of unbundled power quality services have been proposed [5], [11]. The PQCC shown in Fig. 1 is selected for consideration in this paper due to its simple and flexible configuration. The PQCC utilizes the basic idea of UPS system and consists of two PWM-controlled inverters (Inv.1 and Inv.2) and a dc bus. Unlike conventional UPS, however, the PQCC also entails a DG connected to the dc bus. The exact form of the DG will be discussed later. An intercon- nection transformer is included between the PQCC and the upstream power system. With such an arrangement, several levels of power supply quality can be created for customers [11]. There are three levels of power quality in the ac supply, named as ordinary quality (OQ), high quality (HQ), and super premium quality (SP), plus one quality level in dc. In this investigation, the SP, dc, HQ, and OQ loads are assumed to be linear and will not introduce harmonics into the power system.

The author of [11] also proposed that the upstream power system is interconnected to the PQCC through two feeders. Each feeder is equipped with hybrid transfer switches (HTSs) at the end terminals, as shown in Fig. 1. The switches are realized through the use of a pair of antiparalleled thyristors and a mechanical switch. Under normal operating condition, only one of the two feeders, called the primary feeder, would be used to supply the entire OQ, HQ loads and part of the SP, dc loads.

The HTSs on the primary feeder are then closed, while those on the standby feeder are open. When a fault occurs on the primary feeder, [11] proposed that its HTSs are opened to isolate the fault from the PQCC, and the HTSs on the standby feeder are closed. The PQCC is then supplied by the standby feeder. However, over the interval when the power transfer is switched from the primary to the standby feeders, OQ load would be disconnected by the solid-state relay shown in Fig. 1. The other loads are supplied by the DG. Inv.1 is then operating in the inversion mode during the power transfer.

It is clear that this upstream arrangement is intended to cater for faults that occur on the feeders. In practice, the feeders would constitute only a relatively small part of the upstream system, and the number of fault incidents on the feeders will be small compared to those on the much more extensive upstream transmission-distribution system. Hence, in practice, the transfer switches would rarely be called upon to operate. Furthermore, one notes that the DG plays an important role in maintaining the supply to the SP load. Hence, the role of the DG in the PQCC has to be examined more closely. This aspect of the work, and the precise form of the DG and its interaction with the network under system fault conditions, has not been addressed in [11]. In the present paper, it is proposed that the effects of upstream voltage sag on loads will be mitigated through the use of the DG in conjunction with the control actions of Inv.1. The HTS and the standby supply are not included in the present scheme.

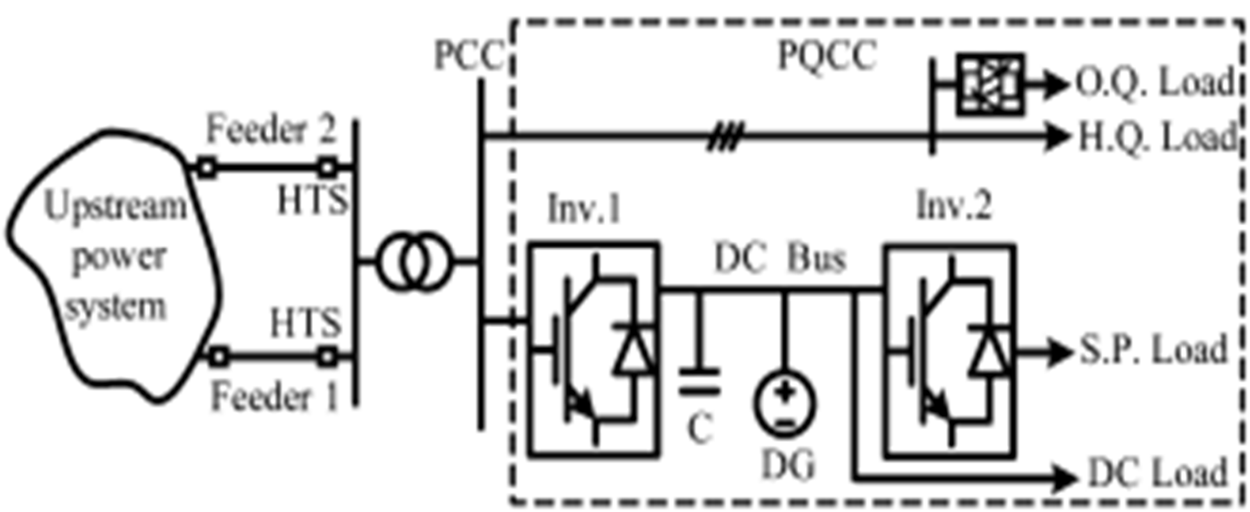


Fig. 1. Interior structure of the UPS-type PQCC proposed in [11].

B. Fuel Cell Distributed Generator

In this paper, the DG would take the form of a solid-oxide fuel cell (SOFC) power plant. SOFC is selected for consideration inthis paper because of its high fuel efficiency and environmental friendliness. It is an electrochemical system in which the chemical energy of fuel is converted directly into electrical energy through the electrode reaction between hydrogen and oxygen [12]. While the electrochemical dynamics of SOFC are highly complex, a simplified model describing the fuel cell steady-state output voltage is,

$$V_{dc} = E - rI_{\mathrm{FC}} \qquad (1)$$

Where E is the fuel cell internal EMF, and is the fuel cell stack current. The resistance accounts for the equivalent Ohmic and other losses, mainly due to the flow of ions in the electrolyte and electrodes [13]. From the SOFC internal electro thermodynamics, it is known that depends essentially on the rate of the reaction between the input fuel (hydrogen) and oxygen. A detailed explanation of the fuel cell dynamics can be seen in [12]. Typically, the time constants associated with the reactions are of the order of tens of seconds. Under sudden network changes, such as that of a voltage sag that has typical duration of much less than 1 s, E can be assumed to be constant. Therefore, under a short-duration sag condition, the SOFC can be represented by a constant EMF in series with a constant internal resistance, as described by (1). In adopting this model, the output power of the SOFC is P_{dg}, $P_{dg} = V_{dc}.I_{fc}$

C. Energy Indices

SARFI indices will not suffice to quantify the load drop effect by disturbances. Other variables, such as the unsupplied energy or the cost of interruptions, can be more useful. For instance, a load drop cost index is proposed in [5], with its calculation based on the assumption that an average cost of power interruption can be estimated for each category of short-duration interruption (instantaneous, momentary, temporary, sustained). Several indices that deal with the unsupplied energy due to a disturbance have been proposed: sag energy index (SEI) and average sag energy index (ASEI) are based on the concept of voltage sag energy as defined in IEEE P1564 [1]; the average system interruption frequency index (ASIFI) and average system interruption duration index (ASIDI) are load-based indices used to assess distribution reliability [9]. All of these indices can be used as a basis to assess voltage sag performance of distribution networks. Sensitive equipment can be separated into two groups: equipment for which no action is required to restart operation after a trip, and equipment whose reactivation requires some manual help and with an offperiod that can even last several hours. An index based on the unsupplied energy for the second group of loads is analyzed in this paper. Since it is similar to ASIDI, this acronym is also used here. Although ASIDI is an index aimed at assessing power distribution reliability, there are several reasons to use it for assessing voltage sag performance: an interruption in a manufacturing process can be caused by a voltage sag, and quantifying the nonsupplied energy as a consequence of voltage sags can be very useful to evaluate the performance of a site or system. Note that when calculating a reliability index, only interruptions longer than 5 min are considered [9]. This aspect is irrelevant in this work; the only requirement is a nonzero restoration time. In fact, if manual help is required to reactivate the operation, one can assume that the interruption will usually last more than 5 min.

III. MODEL DEVELOPMENT AND CONTROL SYSTEM DESIGN

In this section, a closed-loop control system necessary for the implementation of the above proposed sag mitigation scheme is developed. As Inv.1 plays a central role in the scheme, attention is, therefore, directed toward the design of the controller of Inv.1. The controller design for Inv.2 is not described because it is similar to that used in conventional inverter. Its main function is to maintain the terminal voltage of the SP load.

A. Mathematical Model of the PQCC

The PQCC model described by (13) is a nonlinear one. Small signal linearization around its dc operating point can be used to obtain suitable model for controller design. By introducing small perturbations to (13), one obtains both the system steady-state dc and small-signal ac models.

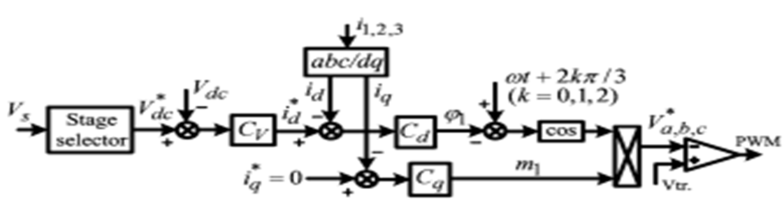


Fig.2 Proposed control scheme for Inv.1

$$\begin{bmatrix} L\dot{i}_d \\ L\dot{i}_q \\ C\dot{V}_{dc} \\ L'\dot{i}'_d \\ L'\dot{i}'_q \end{bmatrix} = \begin{bmatrix} 0 & \omega L & -\frac{m_1 \sin\varphi_1}{2} & 0 & 0 \\ -\omega L & 0 & -\frac{m_1 \cos\varphi_1}{2} & 0 & 0 \\ \frac{3m_1 \sin\varphi_1}{4} & \frac{3m_1 \cos\varphi_1}{4} & -\left(\frac{1}{r}+\frac{1}{R}\right) & -\frac{3m_2 \sin\varphi_2}{4} & -\frac{3m_2 \cos\varphi_2}{4} \\ 0 & 0 & \frac{m_2 \sin\varphi_2}{2} & -R' & \omega L' \\ 0 & 0 & \frac{m_2 \cos\varphi_2}{2} & -\omega L' & -R' \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ V_{dc} \\ i'_d \\ i'_q \end{bmatrix} \begin{bmatrix} v_p \\ 0 \\ \frac{E}{r} \\ 0 \\ 0 \end{bmatrix} \tag{13}$$

B. *Controller Design*

The main functions of Inv.1 are to regulate and to maintain unity power factor on the ac side. The proposed controller is given in Fig. 4. It is similar to the voltage-oriented control strategy described in [16]. This technique is adopted because it has a fixed switching frequency and the controller structure is simpler.

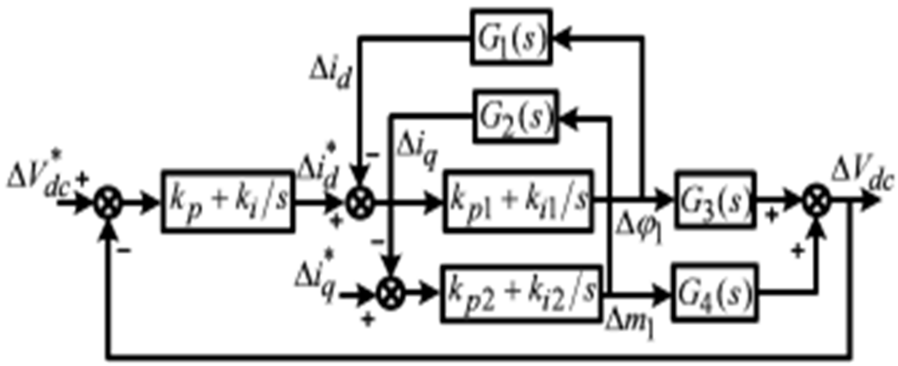


Fig.3 Simplified controller block diagram

Table 1
PARAMETRIC VALUES OF THE PQCC AND POWER SYSTEM

V_{s0} [V]	220	R [Ω]	12.8
L [mH]	1	R' [Ω]	0.472
C [μF]	200	L' [mH]	1.277
V_{dc0} [V]	800	ω [Hz]	60
r [Ω]	0.126	E [V]	815.75

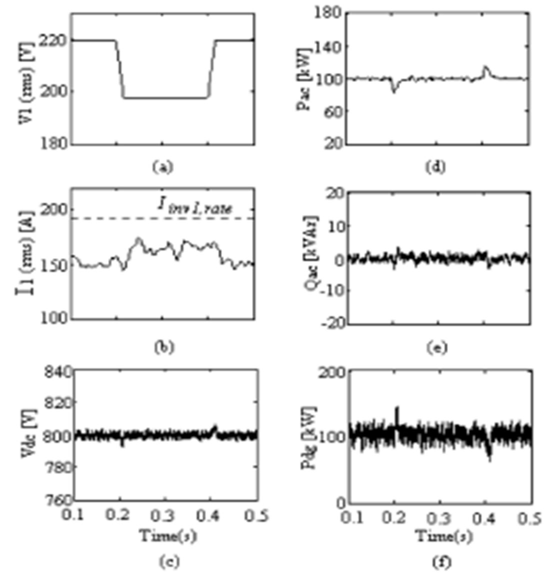
IV. SIMULATION AND RESULTS

A. *System Description*

A numerical example may now be used to demonstrate the proposed control scheme. The system parameters used are as given in Table I, which were calculated according to the following assumed active power distribution. The SOFC rating is 200 kW, and its parameters were obtained from [13]. The inductance is chosen to provide a fault level of approximately 400 kVA at the PQCC terminals. The capacitor in the dc bus is for filtering purpose, and its value is, therefore, chosen to be relatively small.

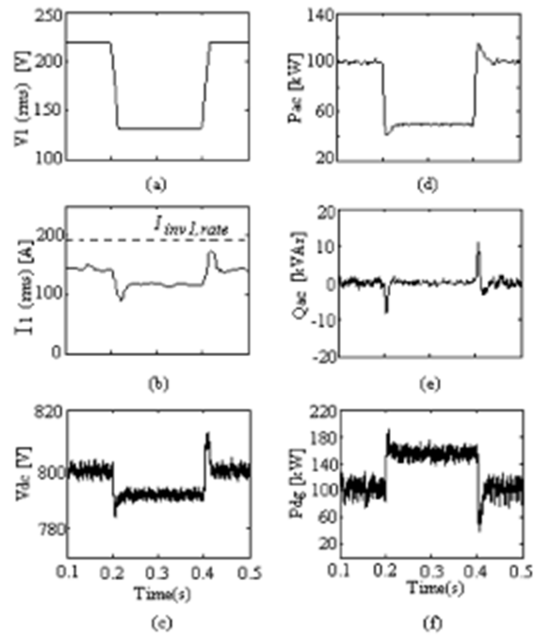
Table 2
PQCC STAGE SELECTOR SETTINGS

Stage	Sag ride-through range	V^*_{dc} [V]
1	$V_{sag} > 0.8V_{s0}$	800
2	$0.4V_{s0} < V_{sag} \le 0.8V_{s0}$	792
3	$V_{sag} \le 0.4V_{s0}$	784



Ride-through for a 90% voltage sag (Stage 1). (a) Phase "1" source voltage. (b) Upstream line current I_1 (rms), (c) dc link voltage. (d) Active power supplied by the upstream source. (e) Reactive power supplied by the upstream source. (f) Active power supplied by the DG.

Fig.4



Ride-through for a 60% voltage sag (Stage 2). (a) Phase "1" source voltage. (b) Upstream line current I_1 (rms), (c) dc link voltage. (d) Active power supplied by the upstream source. (e) Reactive power supplied by the upstream source. (f) Active power supplied by the DG.

Fig.5

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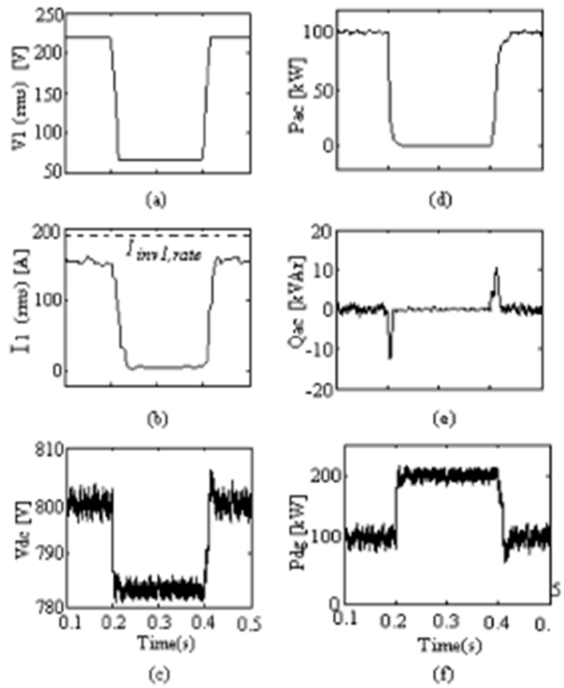

Ride-through for a 30% voltage sag (Stage 3). (a) Phase "a" source voltage. (b) Upstream line current I (rms)$_1$ (c) dc link voltage. (d) Active power supplied by the upstream source. (e) Reactive power supplied by the upstream source. (f) Active power supplied by the DG.

Fig.6

B. Simulation

Simulations using the model in Fig. 2 have been carried out to verify the proposed voltage sag ride-through scheme. The cases examined include those when the upstream voltage is depressed to 90%, 60%, and 30% of its nominal value. Each sag event lasts for 0.2 s. Results are shown in Figs.4-6.

Fig. 4 shows the system response under the 90% sag condition. It shows that the dc link voltage is constant before and during the sag. Active power supplied by the upstream network and the SOFC are almost unchanged over the sag duration. Line current increases under sag condition but is well within Inv.1 current rating. The upstream network is operating at unity power factor as is negligible throughout the interval.

Fig. 5 shows the ride-through situation under Stage 2 when the 60% sag occurs. In order to improve the system ride-through capability and based on Table II, is allowed to reduce slightly to 792 V, as shown in the figure. Pac is reduced to about one half of its original value during the sag. The upstream line current decreases as reduces over the sag state. Unity power factor is again achieved, except for the short instants at the beginning and the end of the sag.

For those more severe sags, such as the 30% voltage sag shown in Fig. 6, the PQCC supplies all the downstream loads. Upon the detection of the sag, is controlled to decrease to 784 V (i.e.V_2,). Both and the upstream line current reduce to zero almost instantaneously. When the sag is over, the dc link voltage is restored to its steady-state value. No large in-rush current is seen at the end of the sag.

C. SARFI Calculations

The calculation of both types of SARFI indices (SARFI and SARFI-Curve) is straightforward from the information provided by the procedure presented in [7]. Fig. 3 shows some index values obtained for a single site, the load node 6 of test system 1, at both medium- and low-voltage sides. Since no swells were experienced at the LV side of distribution transformers, only SARFI values with a voltage threshold equal to or lower than 90 can be obtained. Indices shown in Figs. 4 and 5 correspond to the entire test systems.

D. ASIDI Calculations

A detailed and accurate description of a load node (daily load variation curve, percentage of sensitive equipment represented by an acceptability curve, variation of this percentage) can be extremely complex. The main goal of this work is to compare the performance of the two test systems by assuming that the power demand is the same in both of them and estimating an index based on the not-supplied energy during the power interruptions caused by the voltage sags. The model used for this purpose assumes that only single-phase loads are installed at the LV side of distribution transformers and their vulnerability can be represented by the CBEMA, the ITIC, and the SEMI curves. The percentage of the load represented by each curve and the restoration time for each type of equipment are as follows:

(1) CBEMA: 5%, 1 h; (2) ITIC: 10%, 1.2 h; (3) SEMI: 15%, 1.5 h. The first study has been performed by using these values with all load nodes in both test systems. Note that the percentages of single-phase load represented by the acceptability curves do not add up to 100% because it is not assumed that all of the load is sensitive to voltage sags.

V. CONCLUSIONS

A new voltage sag mitigation scheme, which takes advantage of the flexibility offered by the PQCC, has been proposed. A three-stage operation scheme has been incorporated into the control of the inverters and the fuel cell power source in the PQCC. Analysis shows that the system ride-through capability can be extended considerably to cater for upstream voltage sags. Unlike previous schemes associated with the PQCC, the present scheme has the advantage of not requiring the use of standby feeders and the associated hybrid transfer switches. The scheme exploits more fully the flexible control features offered by the inverter and the ability of the DG in the PQCC. From the system mathematical model developed for the PQCC, analytical expressions suitable for use in the design of the control system of the inverters have been derived. The efficacy of the scheme is borne out by the simulation results.

Although the main conclusions derived from this work can be useful for utilities and manufacturers, the studies are a small sample of those that could be considered. Some protective devices (e.g., reclosers and sectionalizers) could be added to the system model used in this paper, and more features could be incorporated into some device models. In addition, the load model used in simulations and in the subsequent calculations have some limitations which are especially important when deriving energy-based indices: the index calculation should account for load variation and the equipment vulnerability should include the effect of a more sophisticated characterization of voltage sags (phase unbalance, point on wave, phase-angle jump). Finally, the failure of other power components, or even the failure of protective devices under a fault condition, should be considered for future works.

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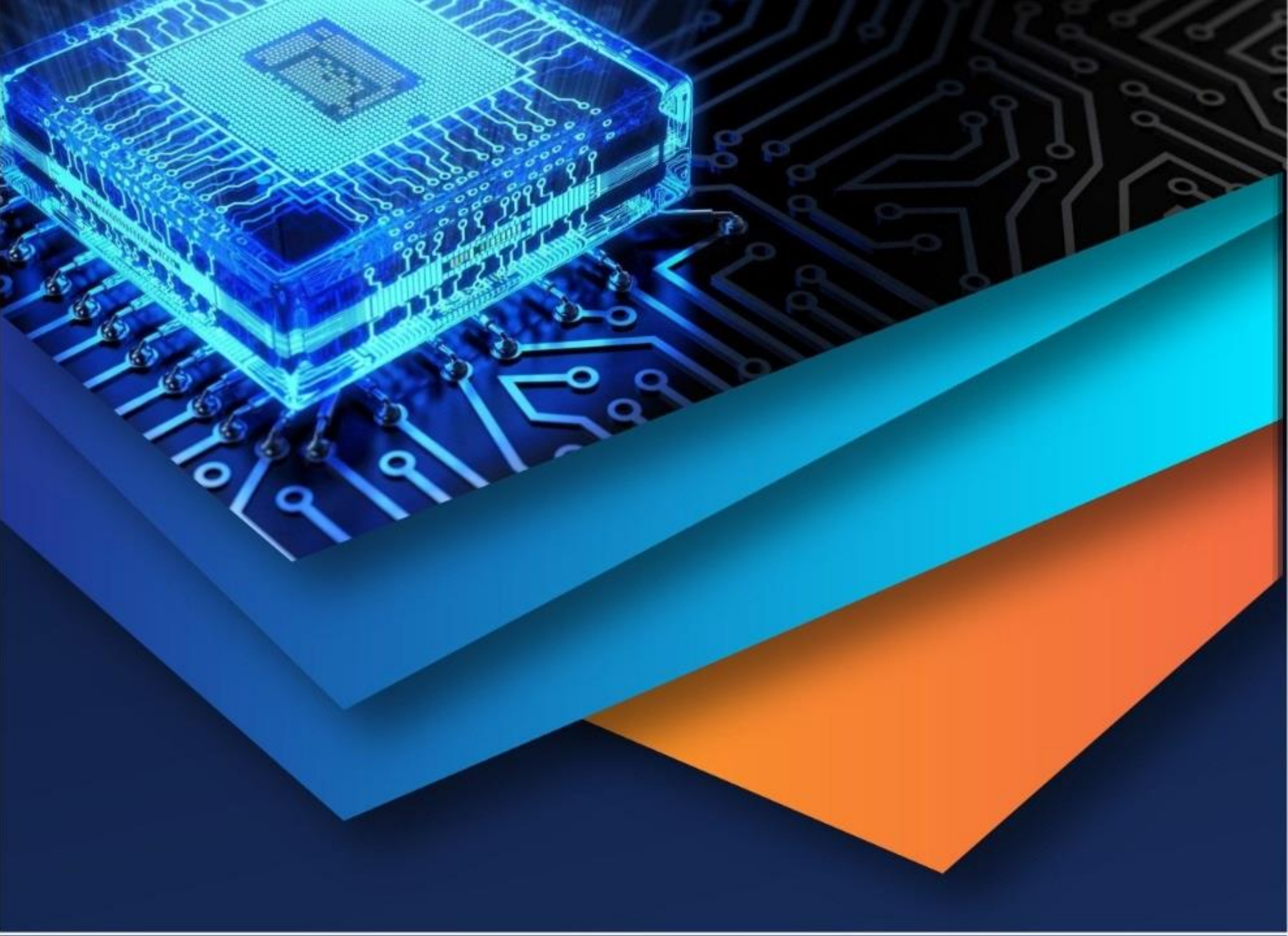

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