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A Novel Three-Phase to Nine-Phase Transformation Using a Special Transformer Connection

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Abstract*: Multiphase (more than three-phase) electric drive system is the priority of an important research in the last decade. Three-phase supply is available from the grid, however for many industrial applications multiphase supply is necessary. In the multiphase power transmission and multiphase rectifier systems, the number of phases investigated is a multiple of three. This paper proposes a technique to obtain nine-phase output from three-phase supply system using special transformer connections. The primary windings of the transformer connected in star input and secondary side of the transformer connected in star output. The output phases with requisite phase angle of 40^0 between each phase is obtained using appropriate turns ratios. The connection scheme is designed and simulated in MATLAB/Simulink environment. From the simulation results, it is observed that, a pure nine-phase sine-wave of fixed voltage/current and frequency is obtained.
***Keywords*: converting transformer, multi-phase, nine-phase, Three-phase, turns ratio**

I. INTRODUCTION

Multiphase (more than three-phase) electric drive system is the priority of an important research in the last decade. Three-phase supply is available from the grid, however for many industrial applications multiphase supply is necessary for its operation. There are different methods to transform three-to-nine-phase using 18-pulse converter, carrier based PWM technique, multilevel converter and multiphase transformer. These are more complex to design for higher ratings or a pure sine wave will not be acquired or harmonics will be more. Multiphase power transmission system is also explored in the literature because multiphase transformers are required at the input of rectifiers. In the multiphase power transmission and multiphase rectifier systems, the number of phases investigated is a multiple of three. Therefore, the variable speed multiphase drive system examined in the literature are mostly of five, seven, nine, eleven, twelve, and fifteen phases. Multiphase systems are advantages compared to three-phase systems have brought relevant to researcher interest. The applicability of multiphase systems is enquired into in electric power generation [1]-[7], transmission [8]-[14], utilization [15]-[32]. The research on six phase transmission systems was proposed due to increasing cost of right-of-way for transmission corridors, environmental issues, and different severe licensing laws. Six-phase transmission lines can produce the same power capacity with a lower line voltage and smaller towers as compared to a standard double circuit three-phase line. The calculus of the six-phase smaller towers may also lead to the depletion of magnetic fields and electromagnetic interference [11]. The research on multiphase generators has latterly started and only a small number of referrals are available [1]-[7]. The work on multiphase power generation has investigated asymmetrical six-phase (two sets of stator windings with 30^o phase displacement) induction generator configuration as a solution for the use in renewable energy generation. The research on multiphase drive systems has been significantly developed since the beginning of this century due to advancement in semiconductor devices and digital signal processors technologies [17]-[21]. It is to be emphasized here that ac/dc/ac converters generally supply the multiphase motors. Thus, the focus of current research on multiphase electric drives is limited to the modelling and controlling the power converters [22]-[32]. Little effort is being made to develop any static multi winding transformation system to change the phase number from three-phase to n-phase (where n > 3 and odd). An exception is, proposing a novel phase transformation system which is three-phase to five-phase system. In [31] and [32], the authors presented a solution for three-phase to five-phase conversion and three-phase to seven-phase conversion.

Multiphase, especially a 6-phase and 12-phase, systems are found to produce less amplitude ripples with higher frequency in an ac-dc rectifier system. Thus a 6-phase and 12-phase transformers are designed to feed a multi-pulse rectifier system. The reason of choice for a 6-, 12-, or 24-phase system is that these numbers are multiples of three and designing this type of system is simple and straightforward. However, increasing the number of phases certainly enhances the complexity of the system. No such designs are available for an odd number of phases.

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In three-phase to five-phase transformation [31], primary winding connected in a star as three-phase input. Phase difference between in each phase is 120^0 apart. secondary winding connected in a star as five-phase output. Phase difference between in each phase is 72^0 apart. Thus, with this technique, a pure five-phase sine-wave of fixed voltage and frequency is obtained. In three-phase to seven-phase transformation [32], primary winding connected in a star as three-phase input. Phase difference between in each phase is 120^0 apart. secondary winding connected in a star as five-phase output. Phase difference between in each phase is 51.42^0 apart. Thus, with this technique, a pure seven-phase sine-wave of fixed voltage and frequency is obtained.

This paper proposes a special transformer connection scheme to obtain a balanced three-phase to nine-phase supply. The remainder of the paper is organized as follows: In section 2, presents the winding arrangement nine-phase star output where as In section 3 presents simulations results of three-phase to nine-phase transformation. Finally to conclude that three-phase to nine-phase transformation in section 4.

II. WINDING ARRANGEMENT OF NINE-PHASE STAR OUTPUT

The objective of the work is to design and implement three phase to nine phase transformation using a special transformer connection. The Fig. 1. shows the block diagram of three-phase to nine-phase transformation.

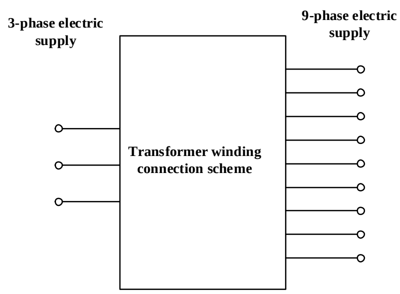

Fig.1. Block representation of the system.

The fixed three-phase voltage and fixed frequency is available in grid supply can be transformed to the fixed voltage and fixed frequency nine-phase output supply. The output magnitude may be made variable by connecting the autotransformer at the input side.The input and output supply can be arranged in the following manners:

Input star, output star;

Input star, output nonagon;

Input delta, output star;

input delta, output nonagon;

Since input is a three-phase system, the windings are connected in normally were as, the output/secondary side star connection is discussed in the following sections. The nonagon output connection may be derived following a similar approach. Thus, only star output connection is discussed in this paper.

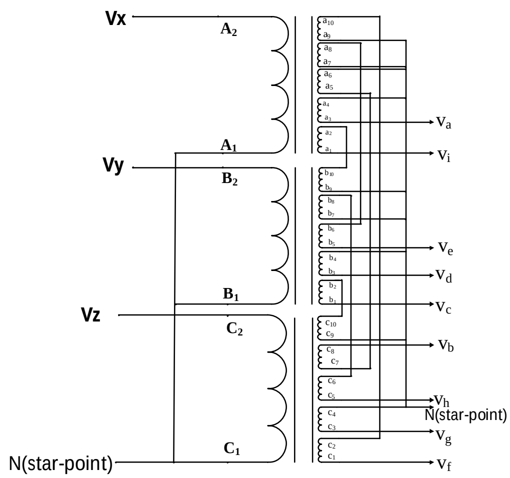

Fig. 2. Transformer winding arrangement of three-phase to nine-phase transformation (star-star)

Volume 5 Issue III, March 2017
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International Journal for Research in Applied Science & Engineering Technology (IJRASET)

The Fig. 2. shows the winding arrangement of three-phase to nine-phase transformation. Three separate cores are designed with each of them carrying one primary coil and five secondary coils are wound. Six primary terminals connected in an appropriate manner resulting in star/delta connections, and the 30 secondary terminals are connected in a different fashion resulting in a star/nonagon output. The Fig. 3 shows the winding connection along with turns ratios and the corresponding phasor diagram is shown in Fig. 4. The construction of output phases with requisite phase angles of 360/9 = 40^o between each phase is obtained using appropriate turn ratios and the phasor equation as given in (1). The turn ratios are different in each phase. The choice of turn ratio is the key in creating the phase displacement in the output phases. The turn ratios between different phases are given in Table I.

Table I -Turn Ratio Secondary Turns (N_2) To Primary Turns (N_1)

Name of winding	Turn ratio N_2/N_1	Name of winding	Turn ratio N_2/N_1	Name of winding	Turn ratio N_2/N_1
a_1a_2	0.394	b_1b_2	0.394	c_1c_2	0.394
a_3a_4	1.000	b_3b_4	1.000	c_3c_4	1.000
a_5a_6	0.394	b_5b_6	0.394	c_5c_6	0.394
a_7a_8	0.7422	b_7b_8	0.7422	c_7c_8	0.7422
a_9a_{10}	0.7422	b_9b_{10}	0.7422	c_9c_{10}	0.7422

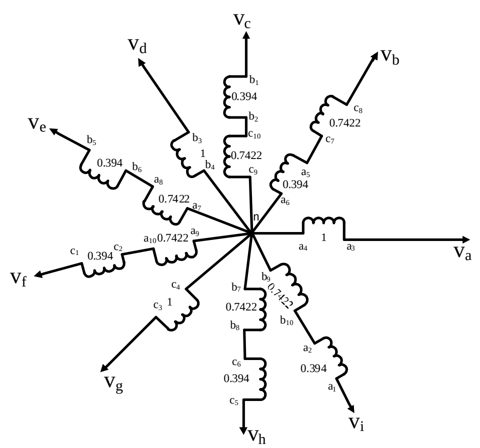

Fig. 3. Transformer winding connection of three-phase to nine-phase transformation (star-star)

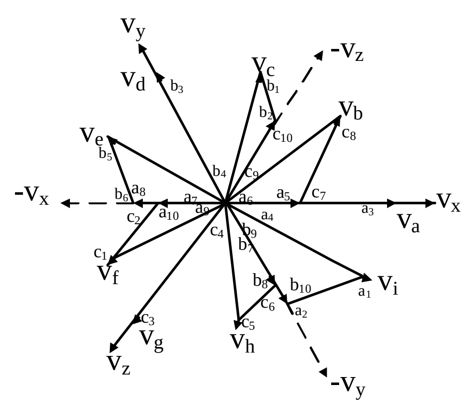

Fig. 4. Phasor diagram of three-phase to nine-phase transformation (star-star)

Volume 5 Issue III, March 2017
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International Journal for Research in Applied Science & Engineering Technology (IJRASET)

The input phases are represented with letters "X", "Y" and "Z" and the outputs are represented with letters "a", "b", "c", "d", "e", "f", "g", "h" and "i" as illustrated in Fig. 3. The output phase "a" is along the input phase "X". The output phase "b" results from the phasor sum of winding voltage "a_6a_5" and "c_7c_8", the output phase "c" results from the phasor sum of winding voltage "c_9c_{10}" and "b_2b_1", the output phase "d" is along the input phase "Y", the output phase "e" results from the phasor sum of winding voltage "a_7a_8" and "b_6b_5", the output phase "f" results from the phasor sum of winding voltage "a_9a_{10}" and "c_2c_1", the output phase "g" is along the input phase "Z", the output phase "h" results from the phasor sum of winding voltage "b_7b_8" and "c_6c_5", the output phase "h" results from the phasor sum of winding voltage "b_7b_8" and "c_6c_5", the output phase "i" results from the phasor sum of winding voltage "b_9b_{10}" and "a_2a_1". The mathematical basis for this connection is the basic addition of real and imaginary parts of the vectors. For example, the solution for (1) gives the turn ratio of phase "b" (V_b taken as unity)

$$v_x\left[\cos\left(\frac{2\pi}{9}\right)+j\sin\left(\frac{2\pi}{9}\right)\right]-v_z\left[\cos\left(\frac{\pi}{9}\right)-j\sin\left(\frac{\pi}{9}\right)\right]=1\text{.......(1)}$$

Equating real and imaginary parts and solving for V_x and $V_{z.}$

$$|v_x|=\left|\frac{\sin\left(\frac{\pi}{9}\right)}{\sin\left(\frac{\pi}{3}\right)}\right|=0.394\text{............(2)}$$

$$|v_z|=-\left|\frac{\sin\left(\frac{2\pi}{9}\right)}{\sin\left(\frac{\pi}{3}\right)}\right|=0.7422\text{.......(3)}$$

Equation (4) is the result of solutions of (1). Similarly for other equations also

$$\begin{bmatrix} v_a \\ v_b \\ v_c \\ v_d \\ v_e \\ v_f \\ v_g \\ v_h \\ v_i \end{bmatrix}=\frac{1}{\sin\left(\pi/3\right)}\begin{bmatrix} \sin\left(\pi/3\right) & 0 & 0 \\ \sin\left(\pi/9\right) & 0 & -\sin\left(\pi/9\right) \\ 0 & \sin\left(\pi/9\right) & -\sin\left(\pi/9\right) \\ 0 & \sin\left(\pi/3\right) & 0 \\ -\sin\left(\pi/9\right) & \sin\left(\pi/9\right) & 0 \\ -\sin\left(\pi/9\right) & 0 & \sin\left(\pi/9\right) \\ 0 & 0 & \sin\left(\pi/3\right) \\ 0 & -\sin\left(\pi/9\right) & \sin\left(\pi/9\right) \\ \sin\left(\pi/9\right) & -\sin\left(\pi/9\right) & 0 \end{bmatrix}\begin{bmatrix} v_x \\ v_y \\ v_z \end{bmatrix}\text{.........(4)}$$

Volume 5 Issue III, March 2017
ISSN: 2321-9653
International Journal for Research in Applied Science & Engineering Technology (IJRASET)

$$v_a = v_{max} \sin(\omega t) \quad (5)$$

$$v_b = v_{max} \sin\left(\omega t + 2\pi/9\right) \quad (6)$$

$$v_c = v_{max} \sin\left(\omega t + 4\pi/9\right) \quad (7)$$

$$v_d = v_{max} \sin\left(\omega t + 6\pi/9\right) \quad (8)$$

$$v_e = v_{max} \sin\left(\omega t + 8\pi/9\right) \quad (9)$$

$$v_f = v_{max} \sin\left(\omega t - 8\pi/9\right) \quad (10)$$

$$v_g = v_{max} \sin\left(\omega t - 6\pi/9\right) \quad (11)$$

$$v_h = v_{max} \sin\left(\omega t - 4\pi/9\right) \quad (12)$$

$$v_i = v_{max} \sin\left(\omega t - 2\pi/9\right) \quad (13)$$

$$v_x = v_{max} \sin(\omega t) \quad (14)$$

$$v_y = v_{max} \sin\left(\omega t + 2\pi/3\right) \quad (15)$$

$$v_z = v_{max} \sin\left(\omega t - 2\pi/3\right) \quad (16)$$

Therefore, by summing the voltages of two different coils, one output phase is created. It is important to note that the phase "a" output is generated from only one coil namely"a_3a_4" in contrast to other phases which utilizes two coils. Thus, the voltage rating of "a_3a_4" coil should be kept to that of rated phase voltage to obtain balanced and equal voltages.

III. SIMULATION RESULTS

To realize the effectiveness of the proposed connection scheme, it is designed and implemented in MATLAB/Simulink environment. The Fig. 5 shows three-phase input voltage. The corresponding output voltage waveforms for the designed transformer scheme is shown in Fig. 6. It can be observed that the output is a balanced nine-phase supply for a balanced three-phase input.

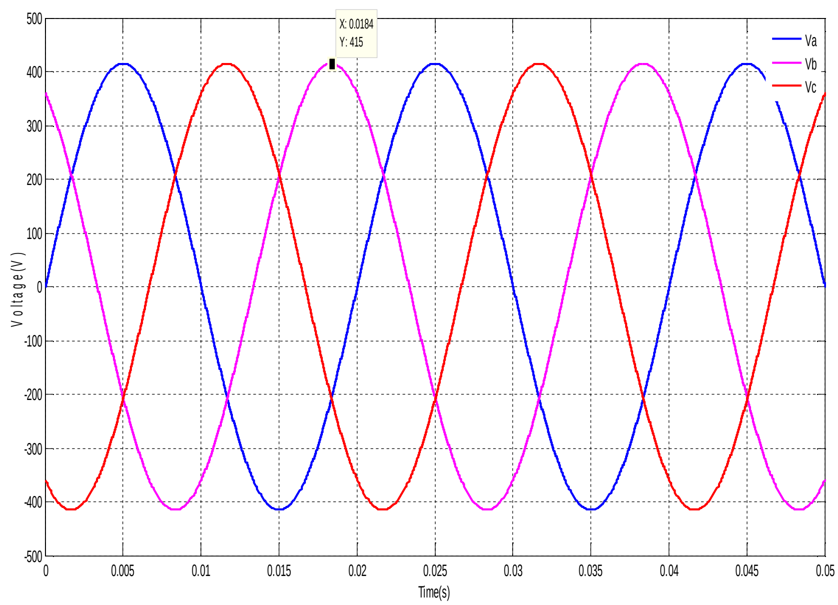

Fig. 5. Input voltage (Three-phase).

Volume 5 Issue III, March 2017
ISSN: 2321-9653

International Journal for Research in Applied Science & Engineering Technology (IJRASET)

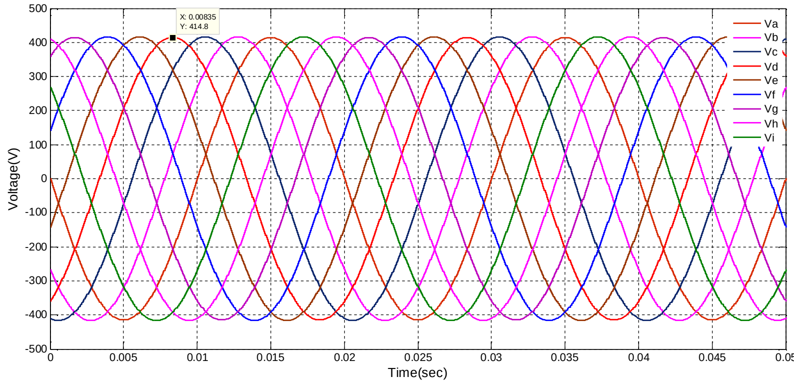

Fig. 6. Output voltage of three-phase to nine-phase transformation.

Further, an RL (R= 300 Ω, L= 40 mH) load is connected to study the performance of the transformer. The Fig. 7 and 8 shows the voltage and current at the load side. The output voltages can be altered by simply varying the taps of the autotransformer.

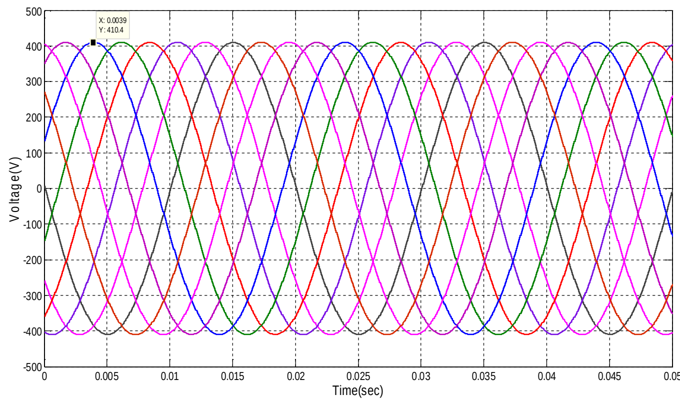

Fig. 7. Load voltage of three-phase to nine-phase transformation.

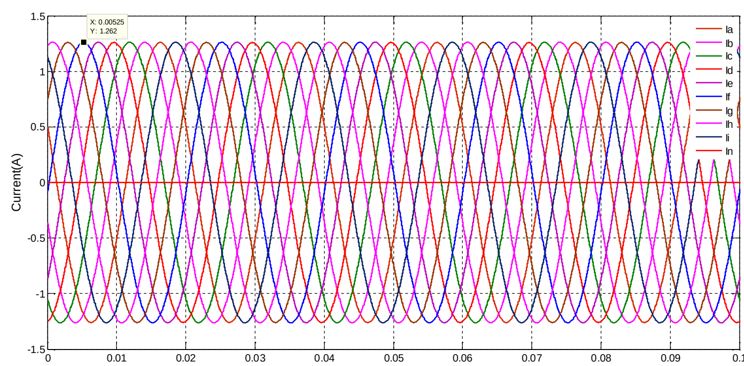

Fig. 8. Load current of three-phase to nine-phase transformation.

IV. CONCLUSIONS

This paper proposes a novel transformer connection scheme to transform the three-phase grid power to a nine-phase output supply. The connection scheme and the phasor diagram along with turn ratios are presented. To realize the effectiveness of the connection scheme, it is designed and implemented in MATLAB/Simulink under no-load and RL loading condition. The simulation results proved that the proposed connection scheme is efficient in transforming three-phase to nine-phase supply. It is expected that the proposed connection scheme can be used in drives and multiphase applications.

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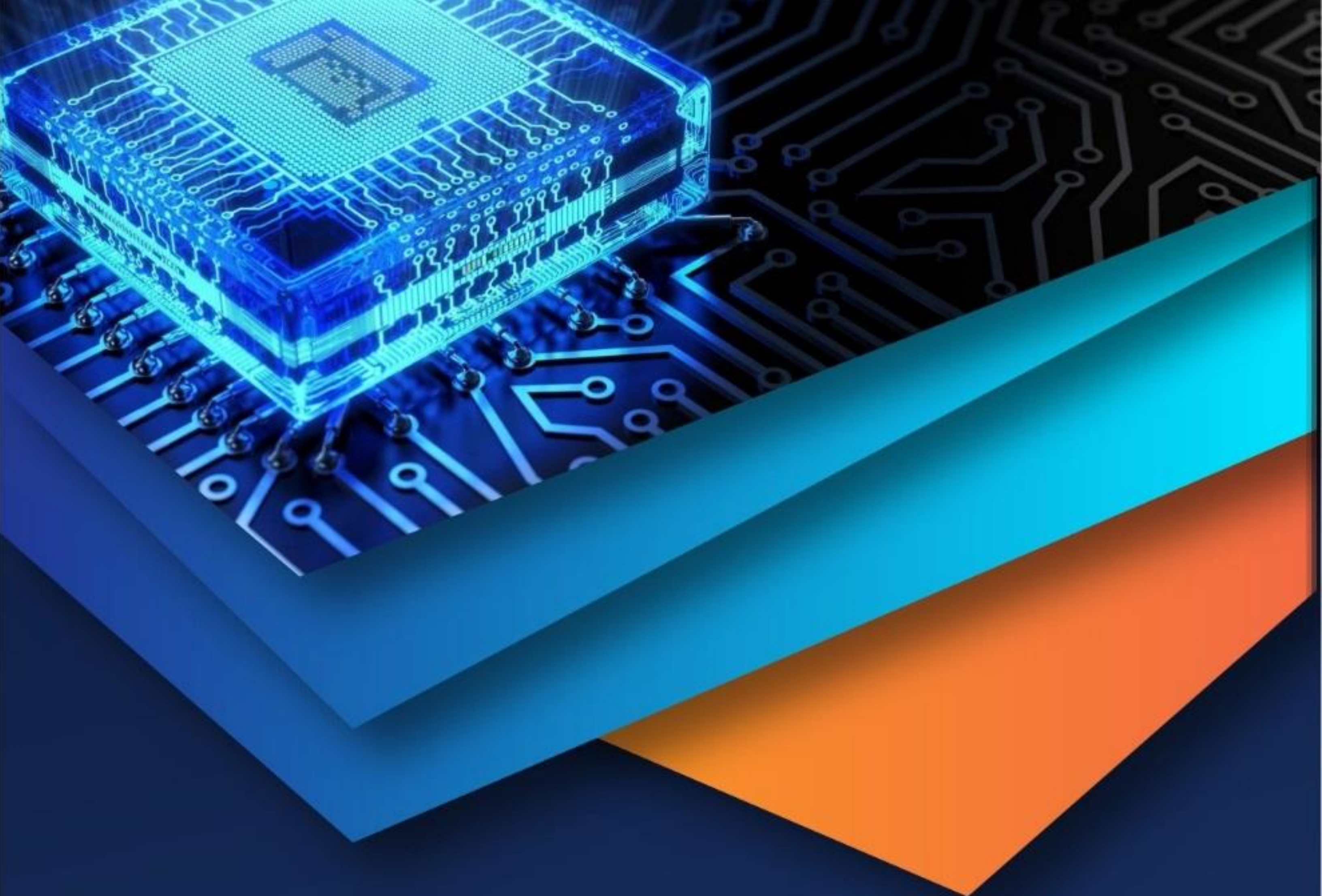

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