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Wind Resource Assessment: Optimizing the Weibull Distribution Curve

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Abstract: In this paper, it was analyze the wind speed characteristics and provide projections of optimal wind resources by comparing data at different hub heights using wind power law. We have acquired data from an operational project site in the western part of India using data points acquired from the site from August 2017 to February 2018.Weibull distribution probability distribution function and cumulative distribution function for wind speed and other parameters involved in an accurate wind resource assessment methodology. To predict wind regimes, the Weibull probability function is commonly used. A comparison of alternative methods for estimating Weibull parameters of a wind regime is presented in this research. For the estimation, five alternative methods are discussed and employed. The study examined wind speed time series data at two sites over the course of a year. Although all five methods produce similar results when plotting error versus wind speed, the standard deviation method produces the best results.

Keywords: Wind, statistics, wind resource assessment, renewable energy, probability density modelling, Weibull Distribution, statistical modelling

I. INTRODUCTION

According to the Energy Outlook Report of 2021 by IEA India is the world's third-largest energy-consuming country [1]. According to the same report, it was also observed that energy use in India has increased almost two-fold since the early 2000s[1]. While this is a positive indicator of economic growth it also indicates that India, with a background of depleting coal reserves and high thermal power dependency, stands at the brink of a massive energy crisis. If India were to face such a crisis one of two things might ensue; a massive rise in the per-unit cost of electricity or long hours of load shedding, both due to the economics of demand and supply. In such a scenario and with India's goal of attaining carbon neutrality by the year 2070[2] the renewable energy sector should be utilized to the maximum potential.

Resource assessment is the preliminary check for project viability at an identified potential project site. In the case of solar power plants, this process is relatively simple and most of the parameters do not have unprecedented variations and more or less follow a pattern that is predictable. Wind resource assessment, however, has been posing problems in the recent past. It has been observed that wind patterns are changing and becoming unpredictable primarily owing to climate change which we shall discuss through the length of this paper. In light of this, wind resource assessment has become particularly tedious and error-prone, project commissioning has become tougher and the existing units are largely underdelivering in terms of generation. Due to these existing utilities are incurring a loss and new companies are facing major bottlenecks in assessing project viability. To overcome these roadblocks and for wind power to emerge as a dependable power source, it is imperative that the wind resource methodology be re-evaluated and optimization techniques should be employed to improve its reliability. Through the course of this paper, we shall try to analyze various optimization techniques for wind resource assessment optimization and outline the best possible route for the Indian industry scenario.

II. WIND SCENARIO IN INDIA

According to *prem chaurasia et al* [2], India has the second to largest wind market across Asia and fourth largest across the globe. It is also common knowledge that India has pioneered the most ambitious energy expansion initiatives. Wind power generation has seen a considerable boom in recent years in the country. As of 28 February 2021, the sum total of the installed capacity in India for wind power generating units was 38.79 GW which was the fourth largest installed wind capacity in the world according to The Ministry of New and Renewable Energy (MNRE), Government of India [4]. According to studies conducted by the National Institute of wind energy (NIWE), most of (95%) India's wind potential exists in 7 windy states of the country; Gujrat, Rajasthan, Maharashtra, Tamil Nadu, Madhya Pradesh, Karnataka and Andhra Pradesh.

With talks about repowering of existing wind turbines (refer to Policy for Repowering of the Wind Power Projects-2016, MNRE) [5] with a background of a considerable change in wind patterns, it becomes that the existing and abundant wind resource be exploited to its full potential. This would not only ensure a sustainable shift from thermal power to renewable energy sources but also keep the national grid safe by injecting reactive VARs into the grid and saving it from a disastrous blackout seen in Chicago due to overdependency on the solar resource which brought forth to the iconic duck curve study [6].

III. RECENT CHALLENGES IN WIND POWER GENERATION

Westerlies also known as westerly winds impact the weather and climate on both a local and global scale. They have a high influence on precipitation patterns, ocean circulation and steering tropical cyclones, thus discovering their change in pattern as the climate warms is extremely important.

Along the planet's middle latitude, westerlies blow from West to east. However, the westerlies have been migrating poleward over the last few decades. But there has been continuous debate on whether this poleward migration of westerlies will continue since the release of atmospheric carbon dioxide is increasing and leading to increased temperature. But, due to our limited knowledge about the westerlies, this scientific debate is still on thus posing the question of its movement. The flow of air is affected by the difference in temperature between the neighbouring regions or between the ocean and land areas that are nearby. This impact is supported by an instance in which the researchers discovered that the speed of wind is reduced along the Northern Hemisphere when some parts of tropical Atlantic, western Pacific and Greenland experience higher temperatures.

Human activities have highly affected the climate and thus the temperature is rising at a rapid rate. But it has also come to notice that in larger, long-term warming patterns, temperature cycles are going back and forth in between the warmer and cooler periods and this change can last for even decades. Researchers also found some reductions in wind power potential in both China as well India even though the change is small (around 1% in China and 2% in India).

IV. WIND RESOURCE ASSESSMENT

The process by which wind power developers predict the future energy production of a wind farm is known as wind Resource assessment. The most significant phase in developing a community wind project is wind resource evaluation, which serves as the foundation for evaluating initial feasibility and cash flow predictions, as well as obtaining finance. Anemometers and wind direction vanes, which are sensors that sense wind speed and direction, a data recorder, and a meteorological mast, or tower, are the three basic components of the wind resource assessment apparatus.

V. WEIBULL DISTRIBUTION

In a general data-oriented regime wind is most appropriately represented by Weibull probability distribution function and using this has now become a common academic practice for optimisation research purposes [7]. Although some experts criticise the 2-parameter Weibull model for its theoretical inadequacies in representing real-world wind velocity patterns, everyone agrees that it is the industry standard [8].

The Weibull probability distribution function can be defined as follows:

$$f(v) = (k/c)(v/c)\hat{}(k-1)\ \exp\left[(-v/c)\hat{}k\right]$$

Where,

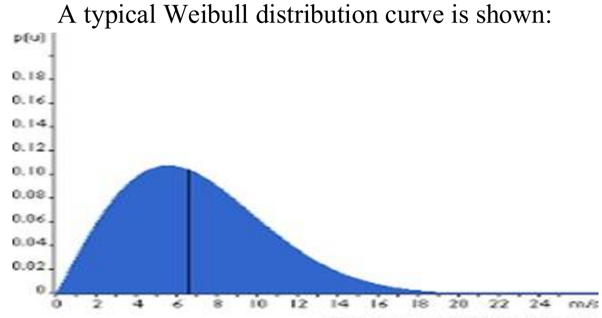
v = wind speed in m/s

c = Weibull scale parameter in m/s

k = Weibull shape parameter

It is to be noted here that the Weibull shape parameter is dimensionless [9]

A typical Weibull distribution curve is shown:



(Source: Danish Wind Industry Association)

The Weibull parameters can be estimated using a variety of methods. Even with the same set of wind data, the parameter values obtained differ depending on the approach utilised. As a result, a comparison of different ways of evaluating Weibull parameters is possible. In this work, an attempt has been made to suggest the optimum approach based on such a comparison.

VI. EXPERIMENTAL DATA SAMPLES

Wind speed at hub heights of 100m, 80m, 50m, 20m at 10-minute intervals, coordinates of the site, Temperature at 10-minute intervals, pressure at 10-minute intervals data are acquired for the course of this simulation from a site in Kaythar, Tamil Nadu a place with high wind potential according to the wind energy atlas [].

VII. DATA VALIDATION

According to NREL's wind resource assessment handbook [7] to ensure that the data being used for analysis is free from errors and accurate, cleaning and validation of data are required. This is to ensure optimal results free of random errors.

The data is evaluated on the following criteria for data validation:

1) If the data is complete
2) If the data is reasonable
3) If the data is free of errors

The results of data validation on the available data set are as follows: -

a) General System checks

- Data records: Expected data fields for each parameter = 52,560 (144 entries per day)
  Number of available data sets = 52,505
- Time Sequence: All expected time sequences are present at 10-minute intervals.

b) Measured Parameters check: These tests form the basis of data validation and can be broadly classified as:

- Range test
- Relational Test
- Trend Tests

The tables appended below give the criteria of all these tests for wind-related data used in the course of this study.

Range Test Criteria

Sample Parameter	*Validation Criteria*
Wind Speed: Horizontal	
•Average	offset < Avg < 25 m/s
• Standard Deviation	0 < Std.Dev < 3 m/s
•Maximum wind gust	offset < Max < 30 m/s
Wind Direction	
•Average	0 < Avg < 360
• Standard Deviation	3< Std Dev< 75
• Maximum Gust	0° < Max. ≤ 360°
Temperature	
•Seasonal Variability	5°C < Avg. < 40°C
Barometric Pressure	
• Average	94 kPa < Avg. < 106 kPa

Trend Test Criteria

Sample Parameter	*Validation Criteria*
Wind Speed Average	All sensor Types
• 1 Hour Change	< 5.0 m/s
Barometric Pressure Average	
• 3 Hour Change	≤ 1 kPa

Relational Test Criteria

Sample Parameter	*Validation Criteria*
Wind Speed: Horizontal	
• Max Gust vs. Average	Max Gust ≤ 2.5 * Avg.
• 40 m/25 m Average Δ**	≤ 2.0 m/s
• 40m/25mDailyMaxΔ	≤5m/s
• 40m/10mAverageΔ	≤4m/s
• 40m/10mDailyMaxΔ	≤7.5m/s
Wind Direction	
• 40m/25 m Average Δ	≤ 20°

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After undertaking all these validation tests on the data, we calculate the data recovery rate, which is defined as a percentage of total collected data records to the total possible data records in a given time interval. The data records collected can be calculated by removing the number of invalid records from the total data records possible.

$$Data\ Recovery\ Rate = \frac{Data\ Records\ Collected}{Data\ Records\ Possible} * 100$$

So, from the above relation data recovery rate in the data set under consideration = 76%

VIII. METHODS OF CALCULATING WEIBULL PARAMETERS:

The methods that would be discussed in the scope of this paper are as follows:

A. Method of Moments
B. Empirical method
C. Most likelihood method
D. Power Density method

A brief about the mathematics involved in each of these methods is as follows:

1) Method of Moments: This is the most common estimation that has been employed over time. It is often used as an alternate to the most likelihood method and is believed to give a more accurate representation of the dataset.

In the scope of this method, the value of shape factor can be estimated as follows:

$$k = \left(\frac{0.9874 * v}{\sigma}\right)^{1.0983}$$

The scale parameter can be computed as follows:

$$c = \frac{v}{gamma\left(1 + \frac{1}{k}\right)}$$

The term (1+1/k) is treated as a gamma function.

Where,

gamma(x)= (x-1)!

Note: The standard deviation σ is iteratively calculated in this method by:

$$\sigma = c\left[gamma\left(1 + \frac{2}{k}\right) - gamma^{2\left(\frac{1}{k}+1\right)}\right]^{0.5}$$

It is recommended that for an initial estimate, Rayliegh shape parameter (k=2) can be used to initiate the iterations.

2) Empirical Method: For shape factor, k varying between 1-10, empirical estimation can be made in accordance of the following formula:

$$k = \left(\frac{\sigma}{v}\right)^{-1.086}$$

Where, the denominator represents the mean wind speed while the numerator represents the standard deviation.

The scale parameter, c can further be computed by the formula:

$$c = \frac{v}{gamma\left(1 + \frac{1}{k}\right)}$$

The term (1+1/k) is treated as a gamma function.

Where,

gamma(x)= (x-1)!

3) *Maximum Likelihood Method:* This a widely used strategy for estimation of Weibull parameters. MLM is a function known as likelihood function for wind speed data in the format of time series. This is an iterative method solved using the Newton Raphson technique.

The Weibull parameters are computed according to this method as follows:

$$k = \left[\frac{\sum_{i=1}^{n} \ln(vi)}{\sum_{i=1}^{n} vi^{k}} - \frac{\sum_{i=1}^{n} \ln(vi)}{n}\right]^{-1}$$

$$c=\left(\frac{1}{n}\sum_{i=1}^{n} vi^{k}\right)^{\frac{1}{k}}$$

4) *Power Density Method:* In the computation of shape and scale parameters is done by initially calculating the energy pattern factor Ept. The dependency of the Energy pattern factor is impending upon the turbine aerodynamic design and is related to wind speed data. This energy pattern factor can be determined as follows:

$$Ept = \frac{\frac{1}{n}\sum_{i=1}^{n} vi^{3}}{\left(\frac{1}{n\sum_{i=1}^{n} vi}\right)^{3}}$$

Post the calculation of the energy pattern factor the Weibull shape parameter k can be computed as follows:

$$K = 1 + \frac{3.69}{Ept^{2}}$$

The scale parameter can be calculated as calculated in the method of moments in an iterative manner.

IX. EXPERIMENT AND ANALYSIS

A. Wind speed data

The data that was acquired was in 10-minute intervals. For better analysis of the data, it was converted to 1 hour data. This is established in Table I.

Further, the monthly average wind speed was calculated to derive a better understanding of the monthly wind patterns in the region. This is established in Table II.

Finally, a frequency distribution table was formulated to obtain the frequency distribution curve for the wind speeds. This is established in Table III.

Table I. Wind Speed Dataset IN Hourly Average Format (10 m hub height)

Hour (h)	*Wind Speed (m/s)*	*Hour (h)*	*Wind Speed (m/s)*	*Hour (h)*	*Wind Speed (m/s)*
1	4.60	9	9.897714286	17	6.057428571
2	5.73	10	9.935142857	18	6.116714286
3	7.04	11	9.255571429	19	6.632857143
4	7.26	12	7.742285714	20	6.587857143
5	8.82	13	8.205857143	21	5.359857143
6	9.70	14	7.574285714	22	5.752571429
7	9.22	15	7.681	23	6.535285714
8	9.16	16	7.209	24	6.913

Table II- Windspeed dataset in monthly average format

Month	*Wind Speed (m/s)*	*Month*	*Wind Speed (m/s)*	*Month*	*Wind Speed (m/s)*
January	7.614908121	May	8.034087366	September	6.634994492
February	5.746796553	June	7.968589583	October	6.734081305
March	5.977417787	July	8.204159722	November	5.774048953
April	4.014431118	August	7.84565233	December	7.07424888

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Similar tables were also formulated for the hub heights of 100m, 50m, 20m and 10m.

B. Results and Determination of Weibull Parameters

The scale and shape parameters, k&c for each numerical computation technique for hub heights of 10, 20, 50, 100 & 102 m are presented in tables IV, V, VI, VII, VIII respectively.

Weibull parameters for each technique for 102 m hub height have been plotted along with the histograms of measured average wind speeds. From observation it is deduced that the most frequent wind speed is 7.48m/s for 102m hub height.
Weibull parameters for different hub heights by four estimation methods:

Table IV: Hub height =102m

Parameter	MOM	EM	MLM	PDM
k	3.00031	3.15	3.203	3.0532
c	5.05664	5.15632	4.83245	4.56432

Table V: Hub Height =100 m

Parameter	MOM	EM	MLM	PDM
k	3.25	3.15	3.203	3.0532
c	5.05664	5.15632	4.83245	4.56432

Table VI: Hub height= 80 m

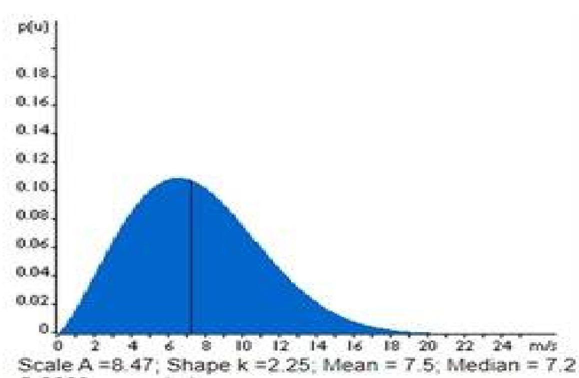
Parameter	MOM	EM	MLM	PDM
k	3.25	3.15	3.203	3.0532
c	5.05664	5.15632	4.83245	4.56432

Table VII: Hub Height = 50 m

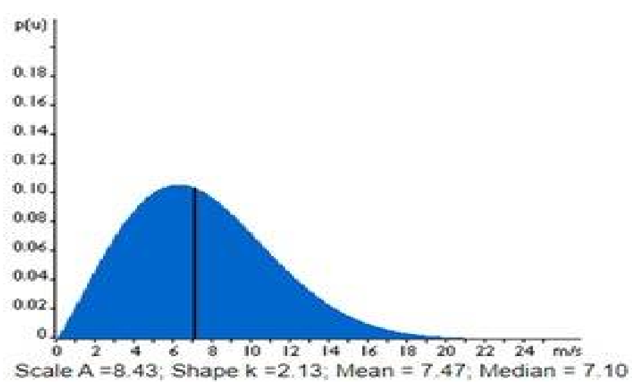
Parameter	MOM	EM	MLM	PDM
k	3.25	3.15	3.203	3.0532
c	5.05664	5.15632	4.83245	4.56432

Table VIII: Hub height = 20 m

Parameter	MOM	EM	MLM	PDM
k	3.25	3.15	3.203	3.0532
c	5.05664	5.15632	4.83245	4.56432



Weibull Dustribution Curve Using MOM Method



Weibull Dustribution Curve Using EM Method

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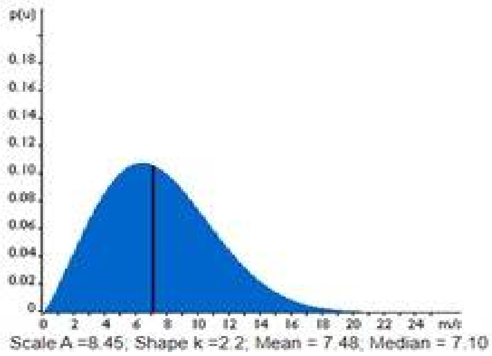
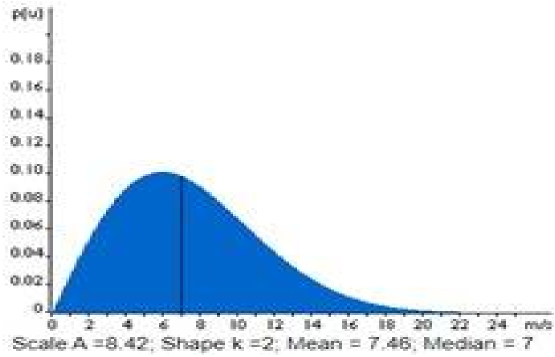


Weibull Dustribution Curve Using MLM Method



Weibull Dustribution Curve Using PDM Methos

C. Statistical analysis

To determine which method deemed the most accuracy at each of the hub heights various statistical analysis methodologies were employed.

Three tests were used to carry out this analysis, they are as follows:

1) Root mean square error (RMSE)
2) Chi-square error
3) Efficiency of the method

RMSE essentially defines a measure of the standard deviation of the residual data points along the regression line. It defines the spread of the data points away from the regression line. It gives an estimate as to what is the concentration of data along the best fit line. It is a very commonly used statistical check for the verification of data oriented experimental results.

While this method gives a good measure of the accuracy but can only define the forecasting errors beyond which it loses its utility. This is due to the fact that this method is scale dependent and is majorly used for the estimation of error values of a specific variable and not between different variables. The most accurate parameters of estimation shall contain the lowest value of RMSE as defined by:

$$\text{RMSE: } \left[\frac{1}{n}\sum_{i=1}^{n}(y_{i,m} - x_{i,w})\text{^}2\right]\text{^}1/2$$

Where;

$y_{i,m} -$ *frequency of the observation of the ith calculated value from the data set*

$x_{i,w} -$ *frequency of ith calculated value from weibull distribution*

$n -$ *number of observations*

The chi-square test gives an estimate of the measure best fit goodness of the data and is usually used when there is one nominal variable present. It is employed to evaluate if the number pf observations in every category fits a theoretical expectation.

The best results are observed when the value obtained after using the chi squared test are close to zero.

The formula applied to undertake this test on the dataset is as follows:

$$\chi^2 = \sum_{i=1}^{n}\frac{(y_{i,m} - x_{i,w})\text{^}2}{x_{i,w}}$$

Where;

$y_{i,m} =$ *observed frequencies*

$x_{i,w} =$ *expected outcome frequencies (Counts of observations)*

Finally, the efficiency of method gives a linear relationship between the calculated results and the measured data.

The efficiency of method id calculated as follows:

$$R^2 = \frac{\sum_{i=1}^{n}(y_{i,m} - z_{i,v})^2 - \sum_{i=1}^{n}(y_{i,m} - x_{i,w})^2}{\sum_{i=1}^{n}(y_{i,m} - z_{i,v})^2}$$

The ideal value of efficiency would be one while using this statistical check.

Tables IX, X, XI, XII and XIII provide the comparison of the three statistical tests for the four numerical methods undertaken in the scope of this study for the hub heights of 102m, 100m, 80m, 50m and 20m respectively. This study was undertaken to come up and analyze the best method for Weibull parameters in Kaythar, Tamil Nadu at various hub heights.

Table IX: Hub height=102 m

Tests	MOM	EM	MLM	PDM
RMSE	0.01789	0.01981	0.01475	0.01739
χ^2	0.00672	0.00824	0.00457	0.00635
R^2	0.99965	0.99957	0.99976	0.99967

Table X: Hub height = 100m

	MOM	EM	MLM	PDM
RMSE	0.01826	0.01976	0.01756	0.01756
χ^2	0.00778	0.00838	0.00449	0.00489
R^2	0.87687	0.87648	0.87638	0.87967

Table XI: Hub height = 80m

Tests	MOM	EM	MLM	PDM
RMSE	0.01778	0.01974	0.01325	0.01718
χ^2	0.00782	0.00874	0.00450	0.00628
R^2	0.087928	0.87953	0.87962	0.87923

Table XII: Hub height = 50m

Tests	MOM	EM	MLM	PDM
RMSE	0.016640	0.01892	0.01267	0.01750
χ^2	0.00864	0.00968	0.00493	0.00650
R^2	0.8843	0.88883	0.888893	0.888870

Table XIII: Hub height = 20m

Tests	MOM	EM	MLM	PDM
RMSE	0.01790	0.01990	0.01480	0.01740
χ^2	0.00685	0.00835	0.00477	0.00655
R^2	0.78648	0.78660	0.78682	0.78685

X. DISCUSSION

In this numerical analysis, data series from wind monitoring station placed at Kaythar, Tamil Nadu, India were used to come up with come up with the best approach for the formulation of a Weibull distribution. The findings of this study are derived from hourly, monthly and annual values.

The shape parameter, denoted by k in the Weibull functions indicates the spread of a distribution curve of wind speeds. A lower value of k suggests that the variation in windspeed is large and vice versa.

The variation the in the value of k at various hub heights is indicated as below:

The scale parameter, denoted by c indicates the magnitude of mean wind speed annually. The value of c in the data set under conditions varies as follows for different hub heights:

The shape and scale factors, which are parameters of Weibull distribution conclude the wind speed that is most suitable for a highly efficient wind energy conversion system as well as the speed range over which operation is expected.

XI. CONCLUSION AND FUTURE SCOPE

In this research paper, we studied four different methods to determine the values of k and c i.e., shape parameter and scale parameter respectively. We observed how efficiently Weibull parameters can be calculated with minimum errors. Out of the four methods, the maximum likelihood method and power density method are more efficient as compared to the empirical method and method of moments. While calculating the Weibull parameters it was found that the maximum likelihood method gives the best Weibull distribution for a given wind speed.

It was also noted that the error in computation increases with a reduction in hub height.

A statistical method was also carried out to rank the methods using RMSE, chi-square and efficiency of the method- R2. According to RMSE and chi-square for the most likelihood method smallest values were calculated. The calculated values by these three methods have magnitudes very close to each other, therefore the most likelihood method (MLM) without any doubt shows the best performance.

XII. ACLKNOWLEDGEMENTS

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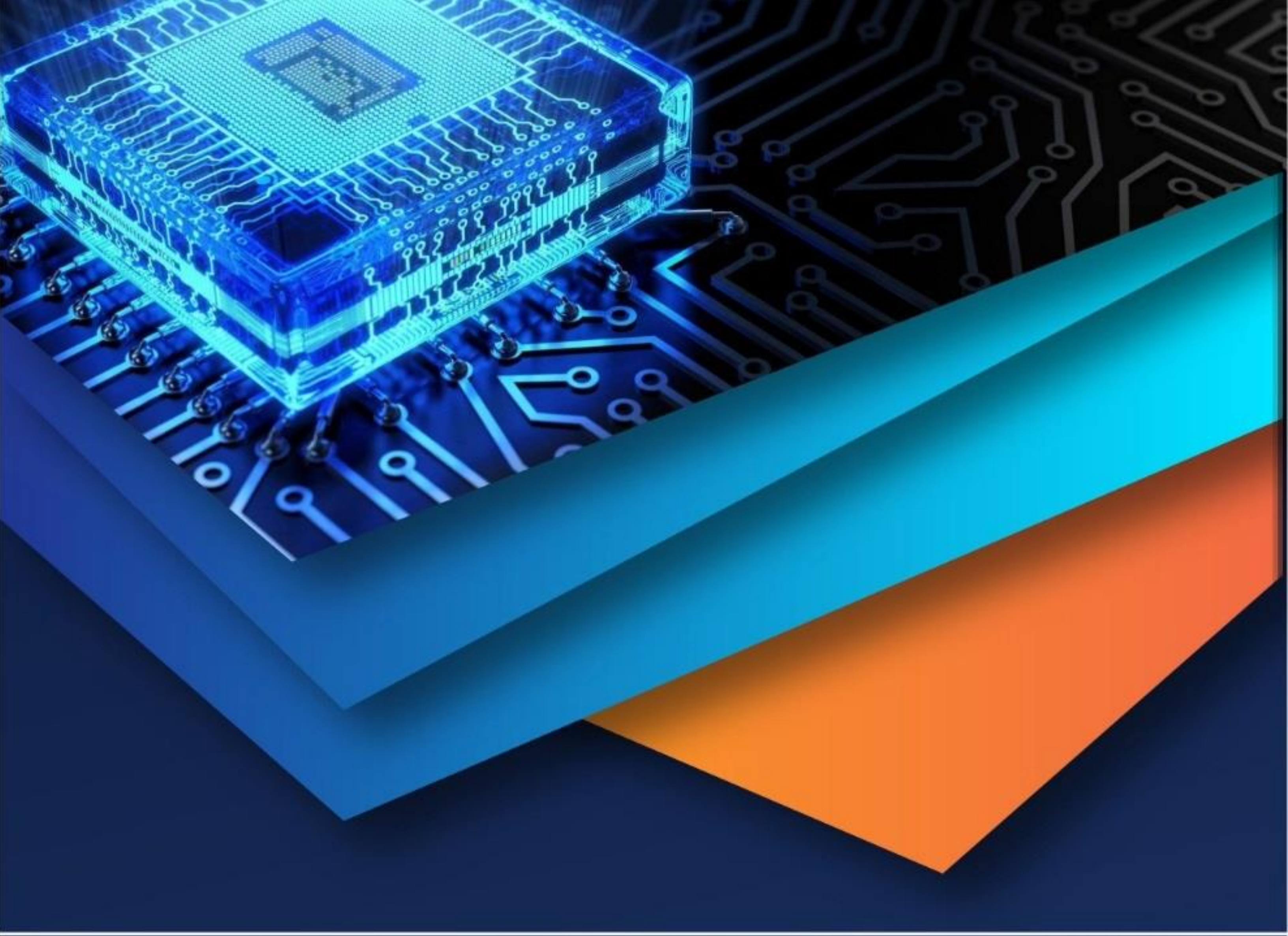

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