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Thermal Management of Lithium Ion Batteries: Integrating Renewable Energy and Battery Energy Storage System at High Altitude Areas and Minus 30 Degree Celsius

K Kranthi Kiran[1], P Ghosh[2], AA Mujumdar[3]
[1]*Assistant Engineer* , [2]*Professor Department of Mechanical Engineering,* [3]*Professor, Department of Electrical Engineering, College of Military Engineering, Pune, India*

Abstract: Lithium-ion batteries play a very important role in the present energy source, the lithium-ion batteries are gaining the present market due to its performance, ageing characteristics, thermal response, energy density, and safety at temperature range 5° C to 40° C but at low temperature and high temperature the lithium-ion batteriesshow different characteristics due to reduce energy density and state of charge with decrease or increase in temperature. This paper highlights the technique to maintain the temperature of battery with external heating so that the batteries can works to its full capacity.This study focuses on method to maintain the temperature of the battery approx. 5° C to 40°C. In cold weather the batteries have to maintain the temperature above 5° C and in hot temperature we need to maintain the temperature below 35°C -40° C. This study focusses on providing an environment for the batteries and its control system at high altitude and -30° Cto provide energy to its optimum level. At high altitude and sub-zero temperature, the sun rays are available in abandoned and this can be used to charge the batteries

Keywords: Sub-zero temperature, state of charge, portable environmental chamber, external heating, thermal insulation, solar array design.

I. INTRODUCTION

Secondary batteries are used widely in industrial trucks, material-handling systems, emergency and backup power supplies, etc. In recent years, their importance has increased significantly due to applications in consumer electronics including computers, surveillance system, and mobile towers etc. More recently, rechargeable batteries have attracted renewed interest as energy sources for electric and hybrid power source system.

Battery energy storage in utility systems enables efficient utilization of low-cost base-load energy, offering advantages such as peak shaving and support for several other grid functions. This leads to reduced utility costs and improved compliance with environmental regulations. Studies indicate that battery storage can provide benefits across all sectors of modern electric utilities, including generation, transmission, distribution, and end-use applications.

Advanced battery technologies, however, offer greater potential for cost reduction and expanded market opportunities. These advantages arise from expected improvements such as lower costs, reduced system size, minimal maintenance requirements, and higher reliability even under highly variable operating cycles. Battery storage also provides significant support for solar, wind, and other renewable energy systems where power generation is intermittent. In such cases, batteries are charged when energy is available from the source and discharged when generation is absent. Operating characteristics vary considerably depending on the specific application. For photovoltaic systems, common uses include rural electrification, telemetry, telecommunications, remote home power supply, and lighting.[1]

The primary cause of the low-temperature degradation has been associated with the change in physical properties of liquid electrolyte and its low freezing point, restricting the movement of Lithium Ion between electrodes and slowing down the kinetics of the electrochemical reactions [2].

Two main approaches have been proposed to overcome the low temperaturelimitations of Lithium-Ion batteries: coupling the battery with a heating element to avoid exposure of its active components to the low temperature and modifying the inner battery components. Heating the battery externally causes a temperature gradient in the direction of its thickness.

Even though the temperature uniformity could be improved by an intermittent heating method, it still requires additional energy, heating devices, and thermal management systems, increasing the mass and volume of the battery system and lowering the energy efficiency [3]. Additionally, modification of components inside the battery does not compromise the gravimetric and volumetric capacities of the battery to the extent that additional heating devices do.[3]

The main limitations of both electrode materials at low temperatures are significant polarization, slow charge transfer kinetics, and high resistance, caused by decreased conductivity of electrons and Lithium Ion and the formation of unstable or too thick insulating Solid Electrolyte Interphase or Cathode Electrolyte Interphase layers. When low-freezing-point electrolytes are used and electrodes thicknesses are reduced, desolvation of Lithium Ion and its migration through insulating layers to electrodes become the most critical step [4]. On the other hand, studies showed that the anode part of Lithium-Ion Batteries at low operating temperatures contributes more to the overall cell resistance than the cathode part [5]. Moreover, deposition of metallic lithium and growth of dendrites, formed from the side reactions with electrolyte during charging, shorten battery life and cause safety problems [6,7]. The low temperature effect on the cathode is studied more diminutively than the anode, assuming it inhibits performance mainly due to the interconnected processes [8]. Depending on the type of batteries and conditions, additional challenges may arise, such as dissolution and deposition of transition metals on the separator, clogging the pores devoted for Lithium Ion [9]. Therefore, the physicochemical properties of the separator also play a vital role in sustaining the low temperatureperformance of Lithium-Ion Batteries. Fig. 1 illustrates the main possible low temperature limitations of Lithium-Ion Batteries.

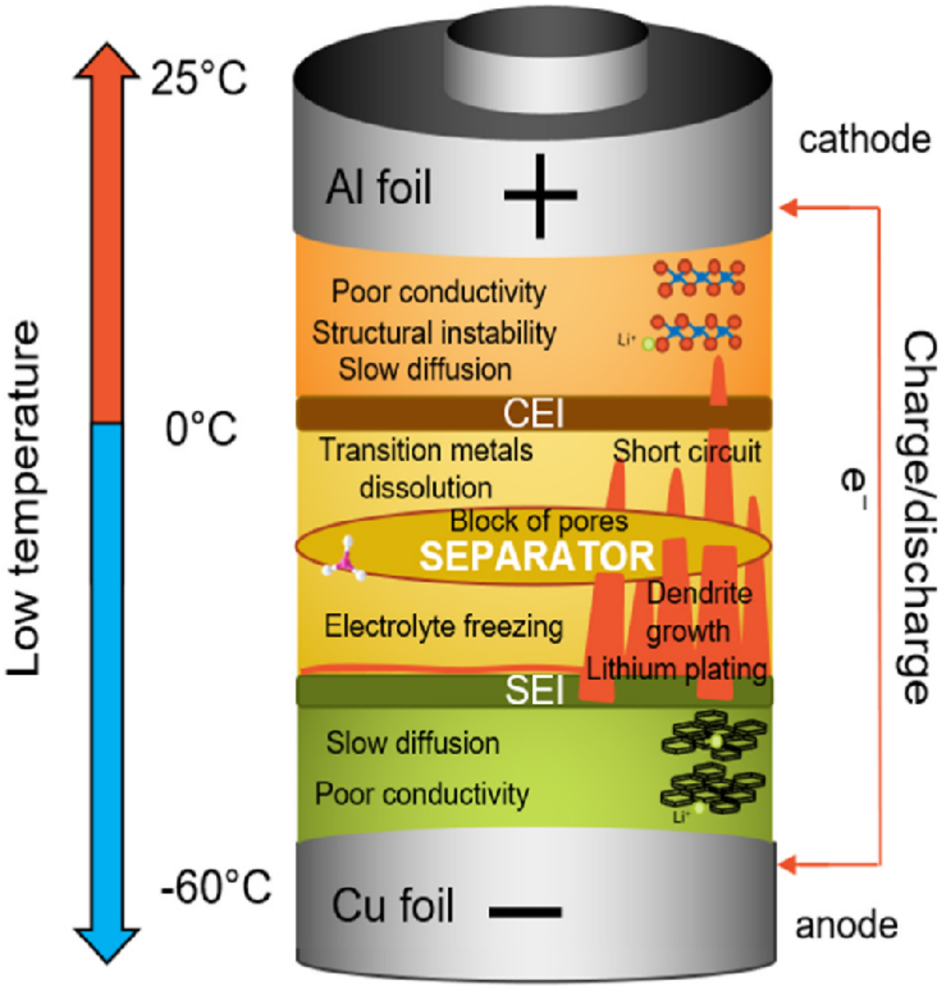

Figure. 1. Illustration of the essential problems affecting the Lithium-Ion batteriesperformance at low temperatures[3]

At high altitude areas, where the lowest temperaturei.e -30^{o} C is recorded, the batteries performance is drastically affected due to increase in solidification of the electrolyte. The state of charge (SOC)vs temperature graph plotted in MATLAB/Simulink is shown as below for detail explanation.

The graph as shown below is plotted by using the relation as below:

$SOC(T) = SOC_{min} + (SOC_{max} - SOC_{min}).\ (1 / (1+e^{-(T - Tmid)/w})$

SOC_{min} = minimum SOC at very cold temperature

SOC_{max} = Maximum SOC at warm temperature

T_{mid}= Temperature where SOC is about halfway

w = controls how steeply S-Shaped SOC curve increases with temperature

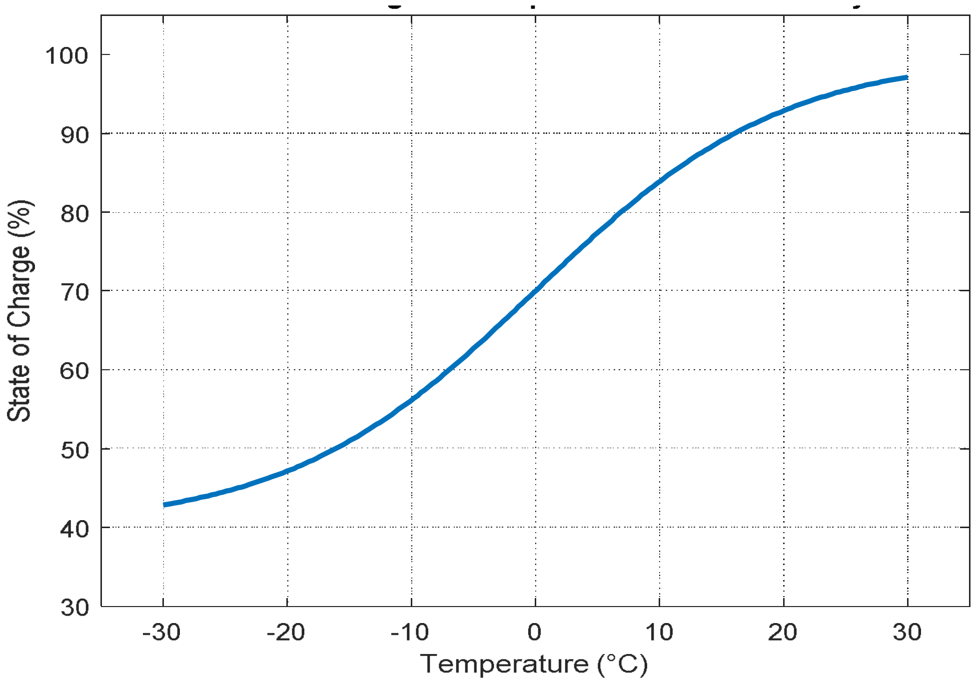

Figure 2: State of Charge vs sub-zero temperature

The graph illustrates the relationship between State of Charge (SOC) and temperature for a lithium iron phosphate battery over the range of −30°C to +30°C, exhibiting a characteristic sigmoid (S-shaped) curve. At very low temperatures, around −30°C, the SOC is relatively low (approximately 43%), and the curve increases gradually, indicating that the battery's usable capacity is significantly limited due to sluggish electrochemical reactions and high internal resistance. As the temperature rises from about −10°C to +10°C, the curve becomes much steeper, showing a rapid increase in SOC; this region represents a transition zone where battery performance improves quickly as internal resistance decreases and chemical activity becomes more efficient. Beyond this range, from +10°C to +30°C, the curve begins to flatten, and SOC approaches its maximum value (close to 100%), suggesting that the battery is operating near optimal conditions and that further increases in temperature have only a minimal effect on usable capacity. Overall, the curve demonstrates that SOC does not vary linearly with temperature but instead follows a nonlinear trend, where performance is poor at low temperatures, improves rapidly in moderate conditions, and stabilizes at higher temperatures.

II. METHODOLOGY

The lithium iron phosphate ($LiFePO_4$) batteries havegained the application in the present scenario. The lithium-ion batteries show a wide range of properties in the temperature range of 5^{o} C to 45^{o} C but at temperature below 0^{o}C the battery efficiency and state of charge is drastically affected due to the electrochemical reactions. This study is focused on the study of providing a feasible thermal environment for the battery and battery management system so that the batteries work efficiently.

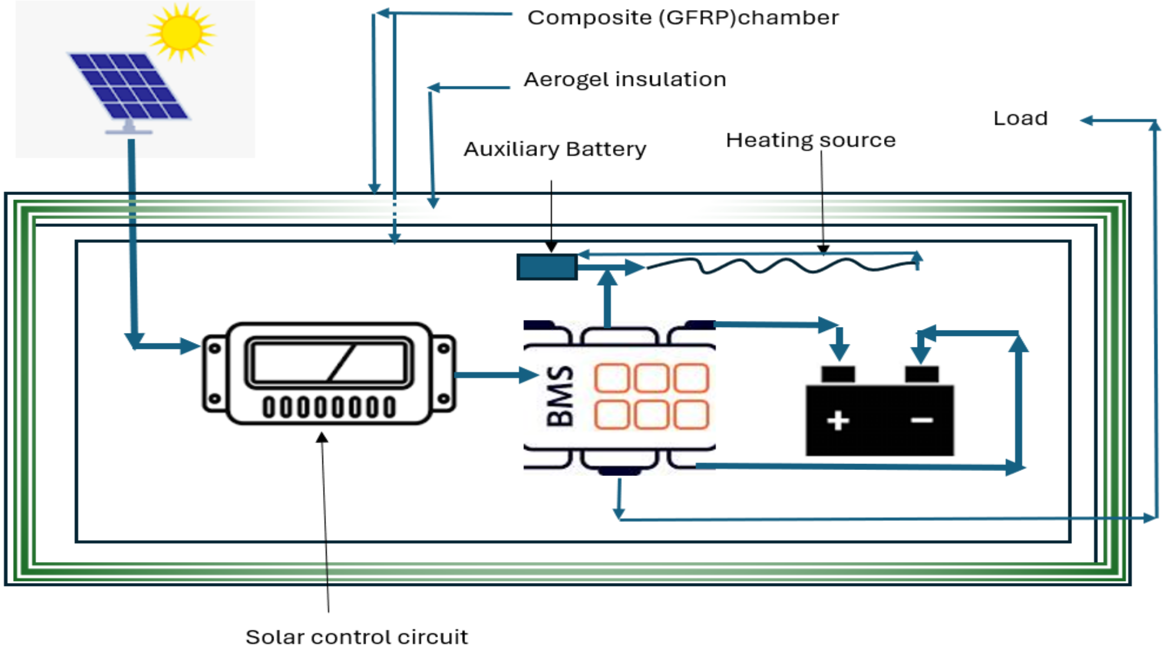

Figure 3: Layout of environmental chamber including all equipment's

A. Equipment's details:

battery Type: lithium-ion phosphate ($LiFePO_4$)
Dimensions: 1.5 m L x .75 m W x 0.4 m H
Battery capacity: 24 V, 150 Ah,
Battery management system
Charging is from solar panel
Auxiliarybattery : 1 Nos 150 Ah
Load connected : 150 watt
For 24 Hrs: 150 x 24 = 3600Wh or 3.6 Kwh
Considering battery voltage : 24 Volt
Current of the battery : 3600/24 =150 Ah
Total Ah (x + nx) considering one day autonomy = 150+2 x150 = 450 Ah
(1 + 1Standby+1auxilary battery)
Total number of batteries required = 450/ 150 = 3 Nos
Considering 2 days autonomy, the total power required = 3600 x 3 = 10800Wh
Charge controller efficiency =90%
The total power required =10800/90%
=12000Wh
DC to DC convertor efficiency =90%
The total power required =8000/90%
=13333.33 say13350Wh

B. Solar panel Array design

The batteries are charged with the solar panel, the sun at high altitude areas like Leh ladakhis 4 Hrs. therefore the total power requires to charge the battery is 13350 Wh, with 24-25 volts for charging. The voltage available with the solar panel is 40.5 volt, thus the battery management system will maintain the charging voltage for the batteries.

Total power require to charge the batteries =13350Wh
Sun rays available at high altitude area =4 Hrs
The Power per hour =13350/4
=3337 Ah say 3350 watt

Solar Panel capacity = 700Wp, Max volt: 40.5 V, Max Amps : 17.29 Amps,
Total number of panels require =3350/700
=4.78 Nos say 5 Nos
Total Ampere = 3350/40.5 = 82.7Amps
Total panels in parallel =82.7/17.29
=4.7 Nos say 5nos(i.enumber of series is one)

C. *Environmental chamber*

The environmental chamber is used to provide a suitable environment for the batteries, further improve the performance of the battery even at -30^o C. The environment chamber plays a very important role for the efficient function of the batteries. Therefore, the design of the environmental chamber is a crucial part of the system. The dimension the environmental chamber dimensions isevaluated as 1.5 m L x 0.75 m W x 0.4 m H. The outer and internal compartment is made of Glass reinforced plastic and the thermal insulation Aerogel of 25 mm thick is incorporated between the outer and inner chamber

Battery dimensions: 520mm L x 270mm W x 220mm H
Considering the dimension of the controller, same as one battery =4 nos x .52 x.27x .22 m = 0.124 m^3 considering 40% extra for phase change materials 1.5 mL x .75m W x.4 m H = 0.450 m^3

D. *Heat Load calculation*

The batteries can work in the day time, as the sun dawn start the temperature to fall. To maintain the temperature in the environmental chamber additional heating source will be provided, the power required for the heating load is supplied from the auxiliary battery of capacity of 150 Ah. The heating require to maintain the temperature inside the chamber is +10^o C and the external temperature is considered as -30^o C.

3.4.1 Heat transfer surface area:
Walls: A_{walls} = 2(LW + LH + W H)
= 2 ((1.5 x .4)+(.75 x .4)+(1.5 x .75))
= 2.05 m^2

3.4.2 The following data is considered for insulation
For properly insulated enclosure (thickness = .02m)
U-Value (Overall heat transfer coefficient) = 0.4 W/m^2.K
Inside temperature to be maintained at 10^o C and outside temperature is -30^o C

<u>Heat loss due to conduction</u>

Q_{cond} : U x A_{walls} x ΔT
= .4x 2.05 x 40
= 32.8 Watt

3.4.3 Heat loss due to Air infiltration (tight room)
For sealed insulated space:
Air change per hour (ACH~ 0.3)
Q_{air} = 0.33 x ACH x Volume X T Δ
= 0.33x .3 x 0.45 x 40
= 1.782 Watt

3.4.4 Total Heat requirement
Q_{total} = Qcond + Qair
= 32.8+1.782
= 34.5Watt

3.4.5 FOS for the design at extremely cold (-30^{o}C) and 25-30% FOS
Q_{design} = 1.3 x 34.5
= 44.9 Watt

3.4.6 Total energy required for 4 hours
For 4 hours = 4hrsx3600 sec =14400 Sec
Q = Power × Time

Q =45 × 14400
Q = 648000J say Q ≈ 648 kJ
Considering FOS = 25%
Q_{total} = 648x1.25 =810 kJ
3.4.7 Design: 25 mm thick of Aerogel sheet is considered as insulation
d = 0.025 m
Typical thermal conductivity of Aerogel: k ≈ 0.015 W/m·K , thickness: 25 mm
Heat loss formula (Steady Conduction):
Q=(kA ΔT)/d
Q=(.015 x 2.05x40)/.025 = 49.2 watt
So heat loss ~ 49.2 watt continuously
3.4.8 Heating source
For external heating IR lamp is used
Air density = 1.2 Kg/m^3
Mass = 0.450 x 1.2 = 0.54 Kg
The heat require to raise the temperature of air in the chamber =m x c x T △
= 0.540 x 1005 x 40
= 21708 J

Where
Q = Heat required (Joules)
m = Mass of air (kg)
c = Specific heat of air ≈ 1005 J/kg·°C
ΔT = Temperature rise (°C)
Power relation: Time = Q / P
To overcome the heat loss of 49.2 watt, we meet to consider the heating source of 35+50 = 85 watt say 90 watt
Using 45 x 2 w IR lamp the time required to raise the temperature of the chamber is
Time = Q/P = 21708/90
= 241.2 sec i.e4.1 min

The IR lamp of 45 watt of 2 nos is used, as every time it is not require to increase the temperature from -30^{o} C to $+10^{o}$ C. Once the chamber is heated to the required temperature range, small duration of heat adding is sufficient to maintain the desired temperature. At this time one IR lamp be used to maintain the temperature. The IR lamp on and off is monitors by the thermocouple sensors.

III. CONCLUSION

At high-altitude locations mere ambient temperatures can drop to −30°C, battery performance deteriorates significantly due to increased electrolyte viscosity and reduced ionic mobility. These conditions lead to higher internal resistance, lower charge acceptance, reduced discharge capacity, and decreased overall efficiency. In addition, prolonged exposure to extreme cold can accelerate degradation and shorten battery lifespan. Variations in individual cell performance within a battery pack may further cause imbalance, generating internal heat and uneven thermal distribution, which can negatively affect reliability and energy utilization if not properly controlled.

To address these challenges, an integrated thermal management system is proposed to maintain optimal battery operating conditions in cold environments. The batteries are charged with solar panels(solar energy is abounded at high altitude) The system includes a well-insulated chamber of size 1.5 m x .75 m x0.4m (L X W x H)with aerogel insulation of 25mm thick to minimize heat loss and a controlled infrared of (1 + 1 standby) heating mechanism powered by an auxiliary battery of 150 Ah, the infrared lamp activates automatically when temperatures fall below safe limits. This setup ensures a stable internal temperature above $+10^{o}$ C, improving battery efficiency and longevity. The designedportable and movable thermally regulated environmental chamber especially suitable for critical applications in remote and high-altitude regions, including communication systems, medical backup power, military installations, and renewable energy storage, ensuring reliable and uninterrupted operation under extreme conditions.

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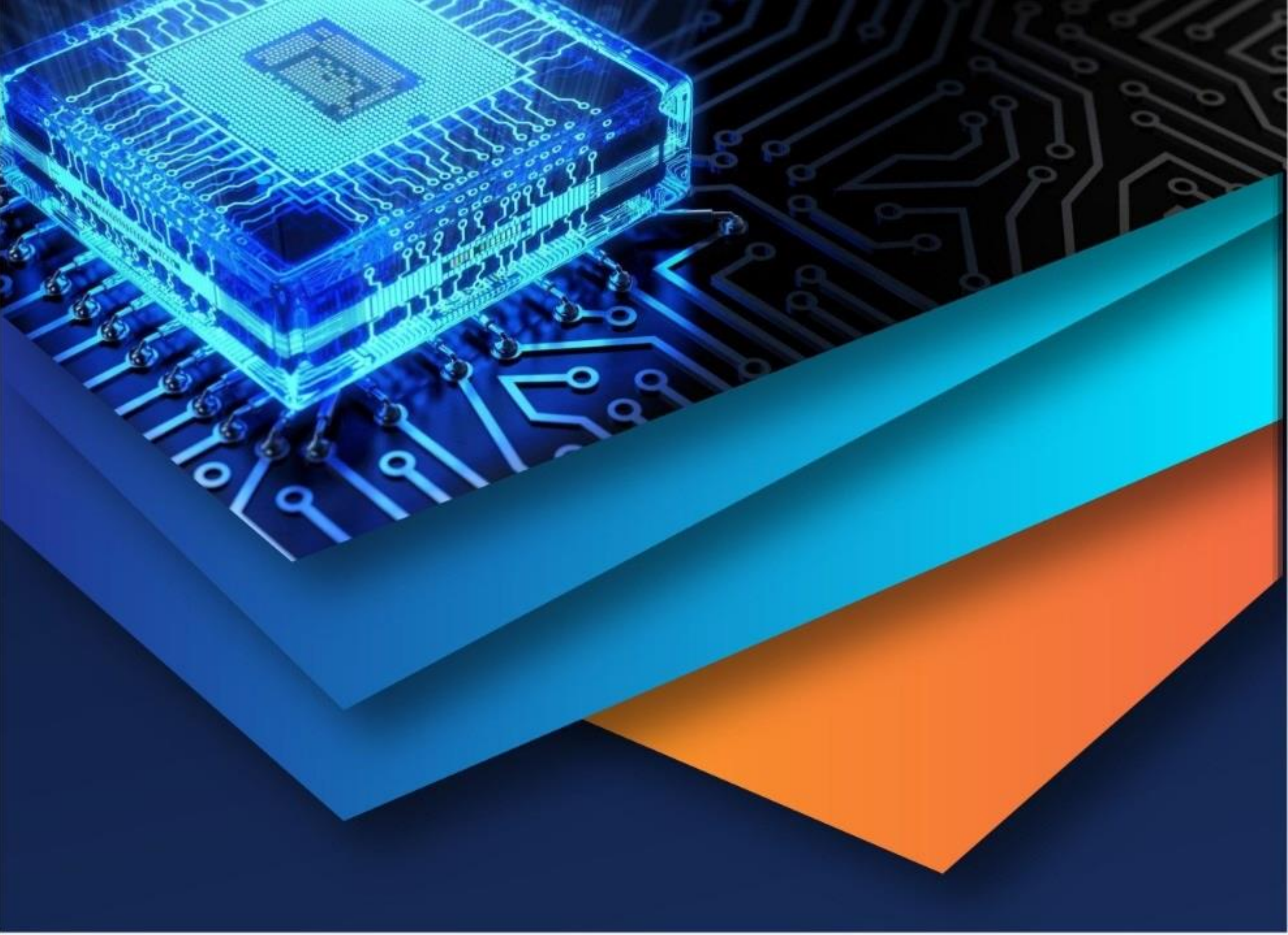

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