iJRASET
International Journal For Research in Applied Science and Engineering Technology



INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 9 **Issue:** I **Month of publication:** January 2021

DOI: https://doi.org/10.22214/ijraset.2021.32835

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International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.429
Volume 9 Issue I Jan 2021- Available at www.ijraset.com

Design and Implementation of a PV Generated Feed Forward Control Strategy of a Sepic Converter

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Abstract: ***The SEPIC is a DC-DC voltage converter which is used to converts unregulated DC voltage to a regulated DC voltage. It gives non inverted output for which it differs from other converters. The SEPIC can be used as buck and boost by varying its duty cycle according to the user's requirements. In this era of efficient use of energy and cost cutting, solar energy comes into prominence. Conversion of this freely available energy into useable form will reduce the burden on other resources; while at the same time expand our energy reserve. There has been an increase in demand for clean and sustainable energy sources, and solar energy is currently considered to be one of the most valuable and abundant yet low-maintenance clean sustainable energy source. Photovoltaic solar energy systems require DC-DC converter in order to regulate and control the varying output of the solar panel. The single ended Primary inductance Converter topology performs the operation of a buck-boost converter but with no voltage polarity reversal. The SEPIC plays the role of DC-DC converter and is used as an interface between the cell and the load. In this paper the PV system is used as a DC voltage source to SEPIC Converter and a battery is used in series with the load for charging purpose. To extract maximum power; the MPPT technique is used here. The whole circuit is simulated using MATLAB SIMULINK.***

Keywords: SEPIC, PV, DC-DC Converter, MPPT

I. INTRODUCTION

The world's excessive dependence on fossil fuels and other non-renewable energy sources have led to their depletion. Hence, today we look up to renewable energy sources, which are reliable and plentiful and will be easy to harness once the right kind of technology and infrastructure is made available. Solar energy, among them, is the most readily available one all around the world. While dealing with application of renewable energy sources, the electrical equipment designs require converters. The energy is harnessed from the source, and then it goes through the conversion stage, which is required to deal with the fluctuating and lower output voltage characteristics of renewable energy [1]. While many converter topologies are available today, the SEPIC topology is investigated into the design of Photovoltaic module for charging battery due to specific advantages [2]. This paper will focus on using solar energy for charging a battery connected series with the load of the SEPIC converter [5],[6],[7].

There are five main DC-DC converter topologies available today. Buck converter can reduce input voltage, Boost can increase voltage, while Buck-Boost, Cuk and SEPIC converters can both reduce and increase voltage [3]. However, the Single-Ended Primary-Inductor Converter (SEPIC) is the only DC/DC converter that can essentially function like a Buck-Boost converter but with the added advantage of producing a non-inverted output. It can be argued that Buck-Boost converters are cheaper as they only require a single inductor and capacitor, but these converters also suffer from high input current ripple. Current ripple can create harmonics, which in many cases will necessitate the use of large capacitors or an LC filter. This makes buck-boost inefficient and costly [4].

Cuk converter can compensate for the shortcomings of Buck-boost converters, and simultaneously can also produce non-inverted output voltage. However, his converter causes large amounts of electrical stress on its components, resulting in device failure or overheating.

SEPIC converters are able to solve all these problems. Furthermore, in SEPIC, the coupling capacitor energy from input to output enables the device to handle short circuits in a more controlled manner when compared to the traditional converter topologies. The SEPIC design uses minimal active components and 'clamped' switching waveforms that produce reduced noise from high frequency switching operations, hence dealing with issues causes my electromagnetic interferences.

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II. MODEL DESCRIPTION

The SEPIC converter (Fig.1) consists of a switch(Q) with duty cycle (d), a diode (D), two inductors (L_1 and L_2), two capacitors (C_1 and C_2) and a resistor load (R_L). When (Q) turns ON, the energy is stored in the inductor (L_1). At this time the inductor voltage equals to input voltage, and the energy stored in capacitor (C_1) will be transferred to inductor (L_2). The load is supplied by capacitor (C_2). When (Q) turns OFF, the energy stored in inductor (L_1) is transferred to (C_1). The energy stored in (L_2) is transferred to (C_2) through (D) and supplying the energy to load. The Output voltage for duty cycle (d) is given by as follows.

$$V_0 = V_S \times \frac{D}{(1-D)} \quad (1)$$

$$D = \frac{V_0}{(V_0 + V_S)} \quad (2)$$

When the switch is turned off output voltage drops to 0 V. SEPIC is useful in applications like battery charging where voltage can be above and below that of the regulator output [1].

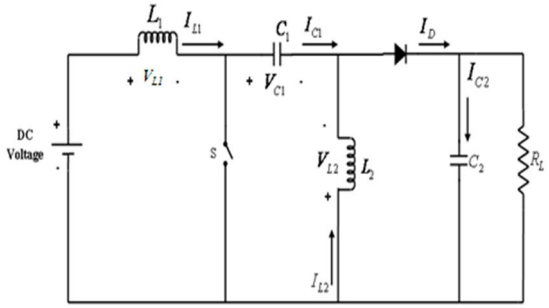


Fig.1 Basic SEPIC Converter

The fig. 2 and fig. 3 represent the operation of SEPIC converter when the switch is closed and open respectively.

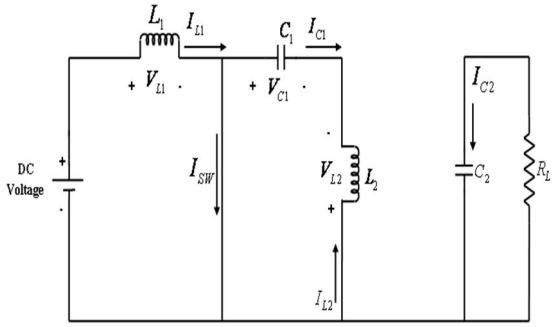


Fig.2 SEPIC When Switch Closed and Diode Off

A SEPIC is said to be in Continuous-Conduction Mode if the current through the Inductor (L_1) never go down to zero. At steady state operation the conditions are; both Inductors are very large and the currents in them are constant. Both Capacitors are very large and the voltages across them are constant. The circuit is operating in Steady State i.e. the voltage and current waveforms are periodic in nature. For the Duty Ratio of (D); the switch is closed for time (DT) and open for time(1-D)T. The Switch and Diode are ideal. The inductor current and capacitor voltage restrictions will be removed later to investigate the fluctuations in current and voltages. The inductor currents are assumed to be continuous here. In this analysis the average inductor voltages are zero and the average capacitor currents are zero.

When switch (Q_1) is turned on, current (I_{L1}) increases and the current (I_{L2}) increases in the negative direction. The energy to increase the current (I_{L1}) comes from the input source. Since (Q_1) is a short while closed, and the instantaneous voltage (V_{C1}) is approximately (V_S). The capacitor (C_1) supplies the energy to increase the magnitude of the current in (I_{L2}) and thus increase the energy stored in (L_2).

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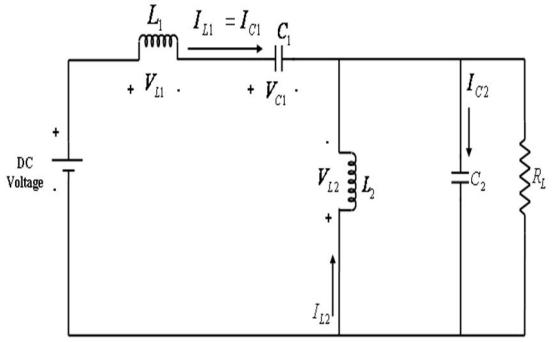


Fig. 3 SEPIC When Switch Open and Diode On

When switch (Q_1) is turned off, the current (I_{C1}) becomes the same as the current (I_{L1}), as the inductors will not allow instantaneous changes in current. Current (I_{L2}) will continue in the negative direction, in fact it never reverses direction. It can be seen from the diagram that a negative (I_{21}) will add to the current (I_{L1}) to increase the current delivered to the load.

So, while (Q_1) is off, power is delivered to the load from both (L_2) and (L_1). Coupling capacitor (C_1) is charged by (L_1) during this off cycle and will recharge (L_2) during the on cycle. The boost/buck capabilities of the SEPIC are possible because of capacitor(C_1) and inductor (L_2). Inductor (L_2) and switch (Q_1) create a standard boost converter, which generates a voltage (V_Q) that is higher than(V_S). Its magnitude is determined by the duty cycle of the switch (Q_1).

III. PV CELL MODEL

A Photovoltaic system converts solar energy into electrical energy. A photovoltaic system is made up of several photovoltaic solar cells. Depending upon the power plant capacity or based on the power generation, group of modules can be connected together to form an array. Solar PV systems are usually consisting of numerous solar arrays, although the modules are from the same manufactures or from the same materials, the module performance characteristics varies and on the whole the entire system performance is based on the efficiency or the performance of the individual components.

A solar cell is the building block of PV array. It has a p-n junction that transforms light energy into electric energy. When a solar cell is exposed to direct sunlight, excess electrons hole pairs are generated by light throughout the cell, thereby the p-n junction is electrically shorted and current will flow.

IV. MATHEMATICAL MODELLING OF PV MODULE

A PV array consists of several photovoltaic cells in series and parallel connections. Series connections are responsible for increasing the voltage of the module whereas the parallel connection is responsible for increasing the current in the array.

Typically, a solar cell can be modelled by a current source and an inverted diode connected in parallel to it. It has its own series and parallel resistance. Series resistance is due to hindrance in the path of flow of electrons from n to p junction and parallel resistance is due to the leakage current. In this model we consider a current source (I_{ph}) along with a diode and series resistance (Rse). The shunt resistance (Rsh) in parallel is very high, has a negligible effect and can be neglected.

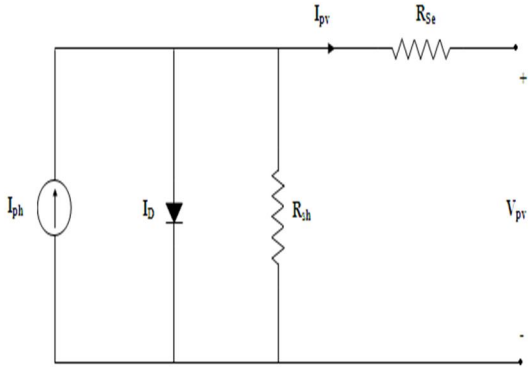


Fig.4 Equivalent Circuit Diagram of PV Cell

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The output current from a PV cell can be represented as;

$$I_{pv} = I_{ph} - I_d - I_{sh} \quad (3)$$

Where, I_{ph} is the photon generated current in the PV cell;
I_d is the current shunted through the diode;
I_{sh} is the current through shunt resistance;
Since a single solar cell typically produces a voltage only about 0.6V – 0.8V so they need to be connected in series to form a module.
The relation between photon generated current, solar irradiance and temperature can be represented as;

$$I_{ph} = \left[I_{ph,ref} + K_{Isc}\left(T - T_{ref}\right)\right]\frac{G}{G_{ref}} \quad (4)$$ Where, $I_{ph,ref}$ is the photon generated current at STC;

G is the solar irradiance intensity on the surface of PV cell (W/m^2);
G_{ref} is the irradiance intensity at STC ($1000W/m^2$);
K_{Isc} is the short circuit current temperature coefficient of solar cell
The relationship with diode saturation current with temperature can be expressed as;

$$I_0 = I_{0,ref}\left(\frac{T_{ref}}{T}\right)^3 \exp\left[\frac{qE_g}{Ak}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right] \quad (5)$$

The reverse saturation current at STC can be written as;

$$I_{0,ref} = \frac{I_{sc,ref}}{\exp\left(\frac{V_{oc,ref}}{AV_{t,ref}}\right) - 1} \quad (6)$$

Where; $I_{sc,ref}$ is the solar cell short –circuit current at STC;
$V_{oc,ref}$ is the solar cell open circuit voltage at STC ;
E_g is the band gap energy in the PV cell.

V. MPPT CONTROLLER

According to Maximum Power Transfer theorem, the power output of a circuit is maximum when the Thevenin impedance of the circuit (source impedance) matches with the load impedance. Hence our problem of tracking the maximum power point reduces to an impedance matching problem. MPPT algorithms are used to obtain the maximum power from the solar array based on the variation in the irradiation and temperature. The voltage at which PV module can produce maximum power is called 'Maximum Power Point' (or peak power voltage). Maximum power varies with solar radiation, ambient temperature and solar cell temperature.
In the source side; the solar PV system is used this thesis is used SEPIC convertor connected to a solar panel in order to enhance the output voltage so that it can be used for different applications like motor load. By changing the duty cycle of the SPEIC converter appropriately it can match the source impedance with that of the load impedance. Over the past decades many methods to find the MPP have been developed. These techniques differ in many aspects such as required sensors, complexity, cost, range of effectiveness, convergence speed, correct tracking when irradiation and/or temperature change, hardware needed for the implementation or popularity, among others [8]. There are several MPPT controllers like Perturb and Observe, Incremental Conductance, Fractional Short Circuit Current, Fractional Open Circuit Voltage, Fuzzy Logic, Neural Network. This paper implements the P & O MPPT technique to extract maximum power point for the operation. In the P&O method only one voltage sensor is used to sense the PV array voltage and hence the cost of implementation is less. The algorithm involves a perturbation on the duty cycle of the power converter and a perturbation in the operating voltage of the DC-link between the PV array and the power converter. Perturbing the duty cycle of the power converter implies modifying the voltage of the DC-link between the PV array and the power converter. In this method, the sign of the last perturbation and the sign of the last increment in the power are used to decide the next perturbation. On the left of the MPP incrementing the voltage increases the power whereas on the right decrementing the voltage decreases the power. If there is an increment in the power, the perturbation should be kept in the same direction and if the power decreases, then the next perturbation should be in the opposite direction. Based on these facts, the algorithm is implemented as show in the flowchart in Fig.5 and the process is repeated until the MPP is reached.

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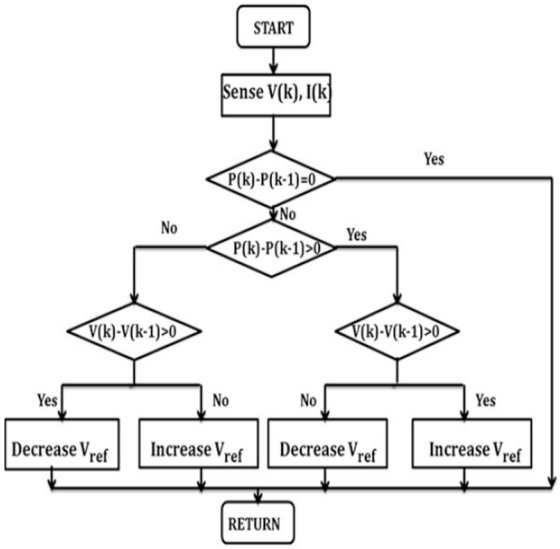


Fig.5 Flow chart of P & O Algorithm for MPPT

The operating point oscillates around the MPP. The time complexity of this algorithm is very less but on reaching very close to the MPP it doesn't stop at the MPP and keeps on perturbing on both the directions. To avoid such a condition, an appropriate error limit can be set or a wait function can be used to stop the increase in time complexity of the algorithm. In this algorithm only one sensor is used, that is the voltage sensor, to sense the PV array voltage and so the cost of implementation is less and hence easy to implement.

VI. PV AS A SOURCE TO SEPIC CONVERTER

The PV systems consists of solar module, DC-DC converter, MPPT Controller and PWM generators that are designed for charging a battery. The solar module has less efficiency with non-linear characteristics due to the variation of solar irradiance and temperature over time for which the MPP trackers are used to transfer maximum power generated in the module to load [6]. The SEPIC converter is used as a DC-DC converter for enhancing the level of PV voltage in the system with providing a regulated output voltage to the load along MPPT control mechanism. The complete PV power generation system for charging a battery is designed using Simulink Software and the simulation results are analysed. The general block diagram of the PV system is presented in fig.6.

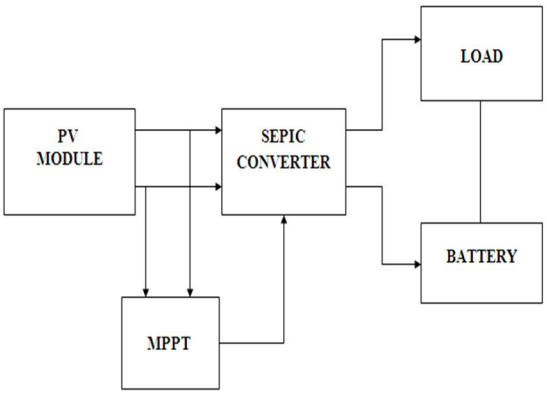


Fig.6 Block Diagram of the Complete System

The converter is designed to produce an output voltage of about 103V with rated power 305 W. The load coupled to the converter is chosen to be 37.5Ω and a switching frequency of 30 KHz is selected for this application. The output voltage of solar module is mainly varying in the range of 50 V to 60 V, for which the converter is modelled to operate in this range of input voltage. The designed values of parameters of SEPIC Converter are listed in Table 1.

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Table 1 Designed Parameters of SEPIC Converter

Parameters	Values
Input Voltage	50-60 V
Output Voltage	103 V
Rated Power	305 W
Switching Frequency	30 KHz
Capacitor	2.034 mf
Inductor	870 µH
Load Resistance	37.5 Ω

VII. SIMULATION RESULT AND DISCUSSION

The modelled PV power generation system using Perturb and Observation MPPT has been simulated in MATLAB/Simulink Software. In this work, the PV model is used as DC source to the SEPIC converter. The Lithium-ion battery is connected with load for charging and also it stores the regulated voltage giving by the SEPIC converter. The operating temperature and the solar irradiance level of the PV module are set to be 25ºC and 1000 W/m² respectively. To operate the switch of the SEPIC converter a train of pulses is required for which a pulse width modulator is used within the MPPT controller. The simulation results are presented in Fig. 7-10.

The Fig. 7, 8, 9 represent the output voltage, power and current waveform of the PV module respectively. These output responses are non-linear in nature and it gives unregulated fluctuating output voltage with high ripple; which is further regulated by the SEPIC Converter. The average PV module output power and voltage value obtained from the simulations are 300 W and 54.32 V respectively. In Fig. 10 the regulated output voltage across the load of PV system is shown. It observes that the P & O MPPT algorithm can effectively track the maximum power point and transfers the power generated by the PV module to load resistance. It provides a good regulation over rapid voltage fluctuation.

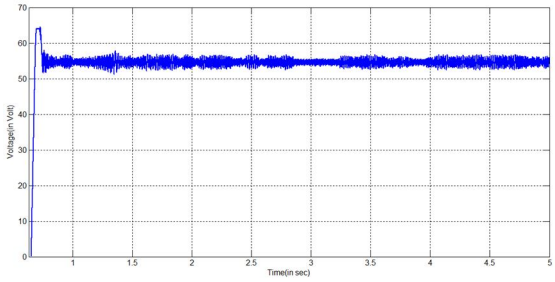


Fig.7 Output Voltage of PV Module

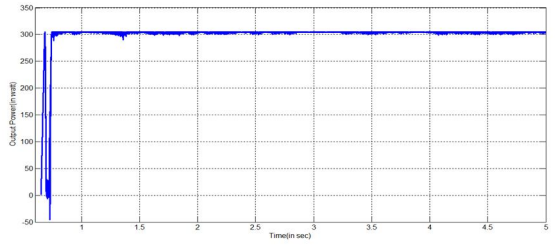


Fig.8 Output Power of PV Module

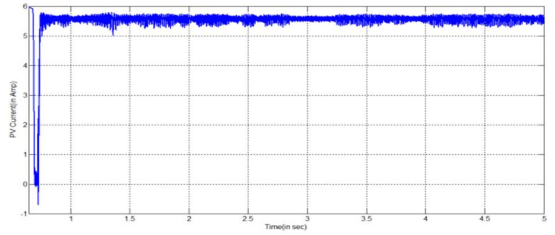


Fig.9 Output Current of PV Module

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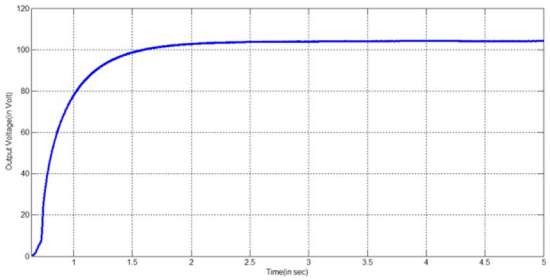


Fig.10 Output Voltage of PV Power Generation System across the SEPIC Converter

The output voltage of PV module and the output voltage of SEPIC Converter are shown above. It can be observed that the modelled P & O MPPT along with SEPIC Converter provide a better control over the PV output power.
The regulated output voltage is obtained across the SEPIC converter. The Lithium-ion battery is connected along with the resistive load for charging itself and also stores the regulated output voltage given by the SEPIC converter.

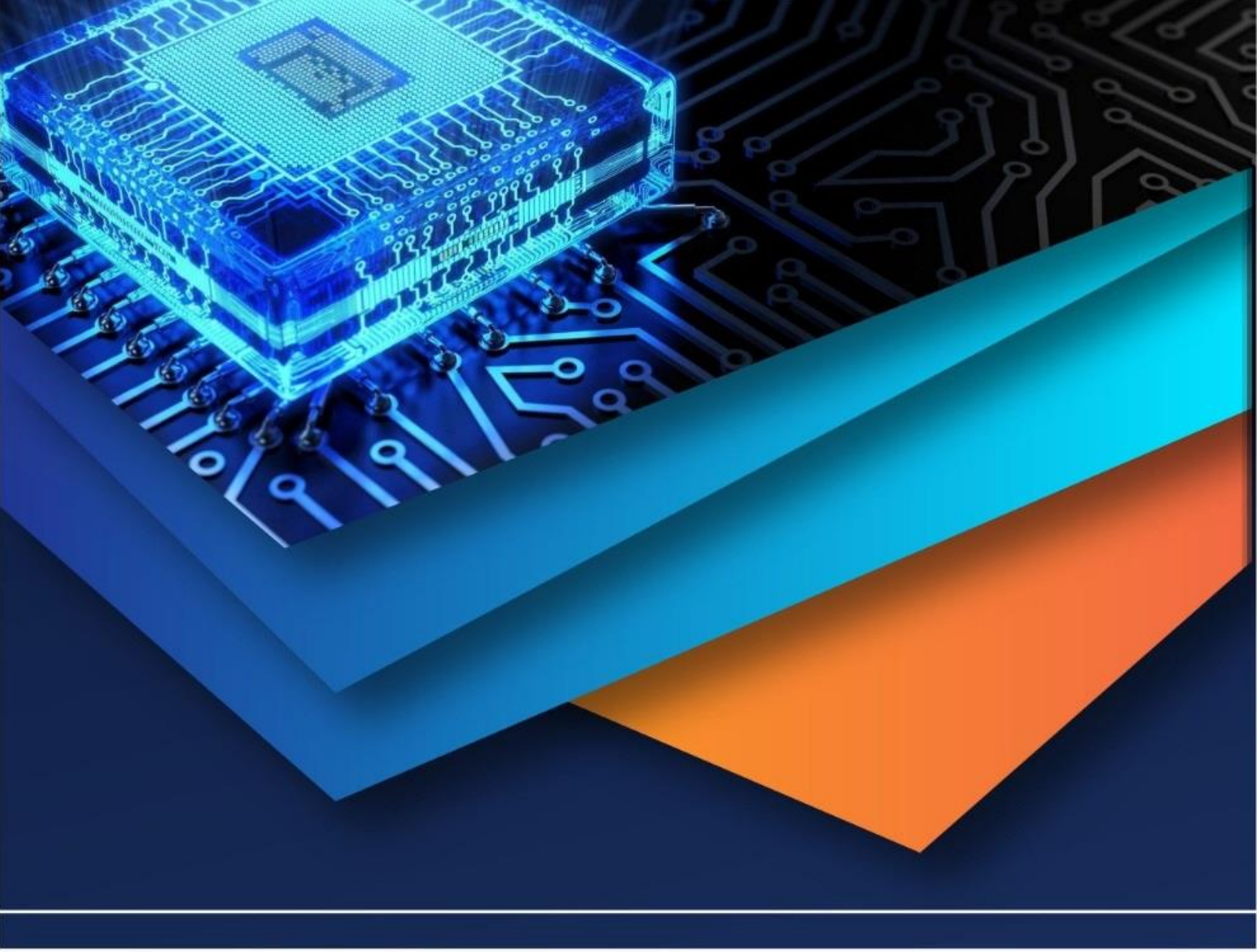
VIII. CONCLUSION

A PV as a DC voltage source to SEPIC Converter is designed for charging a Lithium-Ion battery connected in series with load. When the load requires no power at that time the battery is charged by the regulated voltage given by the SEPIC converter to the output. The complete model of the PV source to SEPIC is designed in MATLAB/SIMULINK software.

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