Three level boost converter with MPPT for Photovoltaic application

Project report

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IEEE Student Branch, NITK

March 2023

ABSTRACT

This project report presents the design and implementation of a three-level boost converter with maximum power point tracking (MPPT) applications in Photo-Voltaic(PV) Cells. The need for MPPT arises from the fact that renewable energy sources such as solar and wind have variable output power that is affected by various environmental factors. Thus, to maximize the power output, it is necessary to track the maximum power point (MPP) of the energy source. Traditional boost converters suffer from limited efficiency, high voltage stress on the switch and output diode, and large output ripple.

On the other hand, a three-level boost converter offers a higher voltage conversion ratio, reduced voltage stress on the switches and output diode, and lower output ripple. It achieves these benefits by using an additional voltage level, which reduces the voltage stress on the switch and output diode. Additionally, by using MPPT algorithms, the three-level boost converter can track the MPP of the input energy source and optimize the power output.

Experimental results show that the proposed three-level boost converter with MPPT applications achieved a peak efficiency of 97.5 percentage , which is higher than traditional boost converters with MPPT. Overall, this project demonstrates that the three-level boost converter with MPPT applications is a promising solution for renewable energy sources.

Keywords: Three level boost converter, Maximum Power Point Tracking, Pulse Width Modulation, Closed Loop Control

ACKNOWLEDGEMENT

I would like to thank the following people for their support and guidance without whom the completion of this project in fruition would not be possible.

Deepanshu Gupta, Gayatri Kattimani, Rohan Rao H J, my project guides, for helping and guiding me in the course of this project .

IEEE student branch, NITK , for giving me this oppurtunity and guiding me throughout the course of this project.

I would also like to thank my family and friends for their constant support.

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Chapter 1

Introduction

Renewable energy systems have gained significant attention in recent years due to the increasing demand for clean and sustainable energy sources. However, renewable energy sources such as solar and wind energy are intermittent and variable, making it challenging to extract the maximum power from them. The Maximum Power Point Tracking (MPPT) technique is commonly used in renewable energy systems to extract the maximum power from the source. A boost converter is widely used to step up the voltage of the source to the desired level.

However, traditional boost converters have limitations in terms of efficiency when the input voltage is low or the load current is high. To overcome these limitations, a three-level boost converter has been proposed in recent years, which offers higher efficiency and reduced switching losses. The three-level boost converter provides additional voltage steps, resulting in a wider operating range than the traditional boost converter. Therefore, the TLBC is a suitable topology for MPPT applications.

This project aims to design and implement a three-level boost converter with MPPT applications. The proposed system is intended to extract the maximum power from a solar panel under varying environmental conditions. An MPPT algorithm will be implemented to track the maximum power point of the solar panel, and the performance of the proposed system will be compared with that of a traditional boost converter with MPPT.

This report presents a detailed analysis of the design and implementation of the proposed system. The report is organized as follows: Chapter 2 describes the operating principle of the boost converter, traditional and three-level topologies and their operating modes. Chapter 3 explains the various MPPT techniques. Chapter 4 presents the design and simulation of the proposed system. Finally, Chapter 5 concludes the report and discusses future work.

Chapter 2

Review Of Literature

2.1 DC-DC boost converter

2.1.1 Design and analysis of a traditional boost converter

A traditional DC-DC boost converter is shown in figure 1. It consists of a capacitor,inductor and diode, with a switching transistor, a MOSFET. The output of boost converter is stepped up by a factor, which is dependent on the duty cycle(D) and the switching frequency(f_s) of the MOSFET.

The MOSFET is turned on and off at a high frequency, because of which, the inductor charges and discharges. When the switch is turned on (T_{on}), the diode is reverse biased, hence, the circuit acts as two independent circuits, where the inductor charges and the capacitor discharges. When the switch is turned off (T_{off}), the diode conducts, hence the inductor discharges and capacitor charges. During this time, the output voltage is the voltage across the capacitor. The total time period, T_s or simply, T

$$T = T_{on} + T_{off} \tag{2.1}$$

Due to the high frequency of charging and discharging, we get a boosted output voltage across the load. The output voltage can be boosted to the desired value only when the volt-second balance of the inductor and amp-second balance of the capacitor is maintained, i.e. the inductor and capacitor must have fully charged and discharged in a cycle.

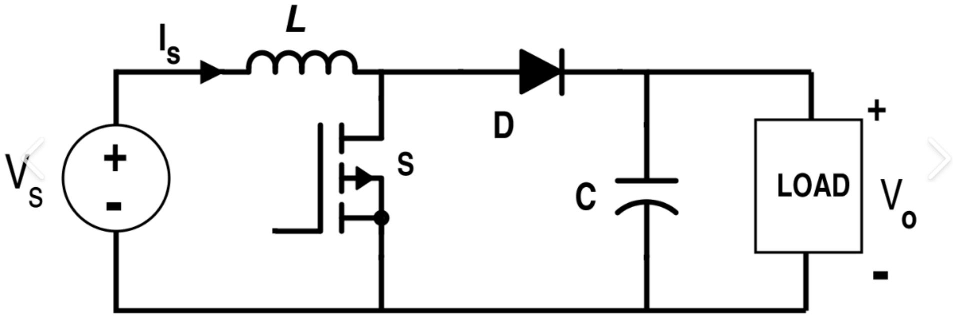


Fig 1: Boost converter

2.1.2 Duty cycle

The duty cycle(D) of the boost converter is defined as follows,

$$D = \frac{T_{on}}{T_{on} + T_{off}} = \frac{T_{on}}{T} \tag{2.2}$$

From this, we can say that,

$$T_{on} = DT \tag{2.3}$$

$$T_{off} = (1 - D)T \tag{2.4}$$

To derive the relation between input voltage, output voltage, and duty cycle, we verify the volt-sec balance across the inductor. When the switch is off, the voltage across the inductor is the input voltage V_{in}. When the switch is on, the voltage across the inductor is the difference between output and input voltage, i.e., V_{in} - V_o Applying volt-sec balance in a cycle,

$$V_{in}(T_{off}) + (V_{in} - V_o)(T_{on}) = 0 \tag{2.5}$$

Rewriting the equation in terms of Duty cycle,

$$V_o = \frac{V_{in}}{1 - D} \tag{2.6}$$

Hence, the output voltage of the boost converter can be controlled by the duty cycle of the converter.

This duty cycle also relates the input current,i.e., the inductor current(i_L), the capacitor current(i_C) and the output current(i_R). When the switch is on, the current through capacitor is the current through the load, i_R. When the switch is off, the current through capacitor is difference between load and inductor current, i_R - i_L Applying amp-sec balance in a cycle across capacitors,

$$i_R(DT) + (i_L - i_R)(1 - D)T = 0 \tag{2.7}$$

Therefore, the load current

$$i_R = \frac{i_L}{1 - D} \tag{2.8}$$

2.1.3 Voltage and current ripple

Due to the switching of the MOSFET, we see a ripple in the output current and voltage. In order to control the ripple, we need to select appropriate inductor(L) and capacitor values(C).

Current ripple is controlled by the value of inductor. Voltage across inductor when the switch is closed for a time, Δt = DT

$$V_{in} = L\frac{(\Delta i_L)_{closed}}{DT} \tag{2.9}$$

$$(\Delta i_L)_{closed} = \frac{V_{in}(DT)}{L} \tag{2.10}$$

The voltage across the inductor when the switch is open for a time, Δt = (1-D)T

$$V_{in} - V_o = L\frac{(\Delta i_L)_{open}}{(1-D)T} \tag{2.11}$$

$$(\Delta i_L)_{open} = \frac{(V_{in} - V_o)(1-D)T}{L} \tag{2.12}$$

Since the inductor current controls the load current, the inductor value can be chosen according to the permissible amount of ripple for the load current.

Voltage ripple is controlled by the value of the capacitor. The voltage ripple of output ΔV_R is equal to the voltage ripple across capacitor ΔV_c, since the load and capacitor are in parallel combination.

Current through capacitor i_c when the switch is closed for a time Δt = DT,

$$i_R = C\frac{(\Delta V_c)_{closed}}{DT} \tag{2.13}$$

$$(\Delta V_c)_{closed} = \frac{i_R(DT)}{C} \tag{2.14}$$

Current through capacitor i_c when the switch is open for a time Δt = (1-D)T,

$$i_L - i_R = C\frac{(\Delta V_c)_{open}}{(1-D)T} \tag{2.15}$$

$$(\Delta V_c)_{open} = \frac{(i_L - i_R)(1-D)T}{C} \tag{2.16}$$

Since the voltage across capacitor is the voltage across the load, the capacitor value can be chosen according to the permissible amount of ripple of output voltage.

2.2 Three level boost converter

The following image depicts a three-level boost converter. In this, a capacitor voltage divider is used in parallel with the load. To maintain the symmetry and balance of the converter, the capacitance of both capacitors must be equal(C_1=C_2), This in turn makes the center point voltage as $V_o/2$.

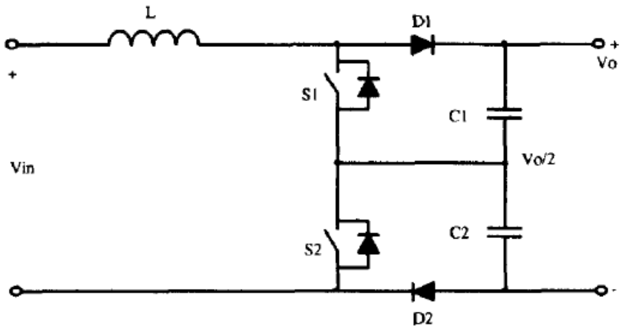


Fig 2: Three level Boost converter

The TLBC has four different states of operation, depending on which of the switches are on or off at a given time. This makes the TLBC more dynamic and can provide higher gain than a traditional boost converter.

2.2.1 Operating modes

TLBC has two different operating modes depending on the output required.

Region 1 - $V_{in} > V_o/2$

When the required output is less than twice the input voltage, then we apply the operating mode as shown in figure 3. In this operation mode, duty cycle $D < 0.5$

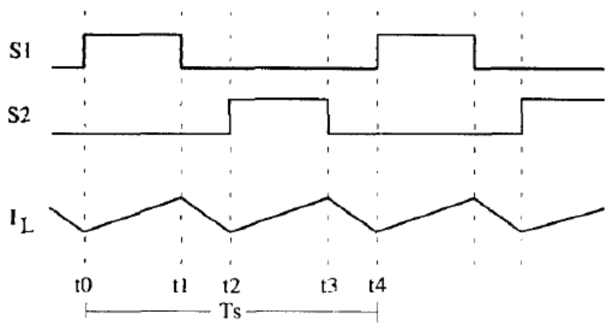


Fig 3: Operation waveform when $V_{in} > V_o/2$

The switch S1 is turned on for time DT and then turned off throughout the cycle. During this time, S2 is off. The switch S2 is turned on from T/2 to T/2 + DT.

In this operating mode, the expression for ripple current is given as follows. Voltage across inductor when switch S1 is closed is V_{in} - $V_o/2$

$$(\Delta i_L)_{closed} = \frac{(V_{in} - V_o/2)(DT)}{L} \tag{2.17}$$

Voltage across inductor when switch S1 is open is V_{in} - V_o

$$(\Delta i_L)_{open} = \frac{(V_{in} - V_o)(1 - D)T}{L} \tag{2.18}$$

In this equation, the maximum current ripple occurs when D=0.5 and at the point where $\frac{\partial \Delta i}{\partial V_{in}} = 0$. This point is $V_{in} = 0.25V_o$. Hence the expression for maximum current ripple is for the output of the system is,

$$\Delta i = \frac{V_o T}{16L} \tag{2.19}$$

The voltage ripple can be written

Region 2 - $V_{in} < V_o/2$

When the required output is more than twice the input voltage, then we apply the operating mode as shown in figure 4. In this operation mode, duty cycle $D > 0.5$

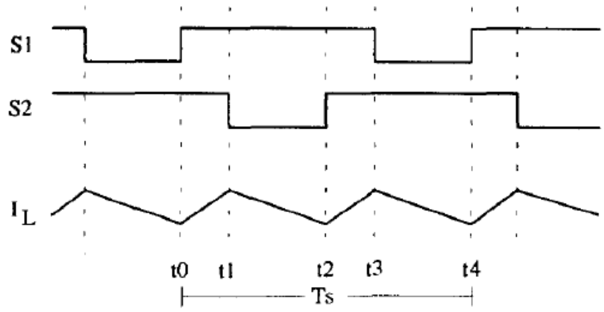


Fig 4: Operation waveform when $V_{in} < V_o/2$

The switch S1 is turned on for time DT and then turned off throughout the cycle. The switch S2 is turned on from T/2 to T/2 + DT. In this switching mode, both the switches are on for a short period of time, but the duty cycle of eacg switch remains the same.

In this operating mode, the expression for ripple current is given as follows. Voltage across inductor when one switch is closed is $V_o/2$ - V_{in}

$$(\Delta i_L)_1 = \frac{(V_o/2 - V_{in})(DT)}{L} \tag{2.20}$$

Voltage across inductor when both switches are closed is V_{in}

$$(\Delta i_L)_2 = \frac{(V_{in})(1 - D)T}{L} \tag{2.21}$$

In this equation, the maximum current ripple occurs when D=0.5 and at the point where $\frac{\partial \Delta i}{\partial V_{in}} = 0$. This point is $V_{in} = 0.75V_o$. Hence the expression for maximum current ripple is for the output of the system is,

$$\Delta i = \frac{V_o T}{16L} \tag{2.22}$$

In both of these operation modes, the voltage ripple across the load(Δv_o) is split between the two capacitors, the voltage ripple across each capacitor, is $\Delta v_o/2$. Hence the expression for voltage ripple across the load,

$$\Delta V_o = 2i_o \frac{DT}{C} \tag{2.23}$$

Chapter 3

Maximum Power Point Tracking Methods

3.1 Maximum Power Point Tracking

The PV cell exhibits a distinct Current vs Voltage characteristic curve, as depicted in Figure 5. This curve illustrates the short circuit current and open circuit voltage of the solar cell, with the maximum power point (MPP) denoting the point on the curve where the power output is at its highest. The Power vs Voltage curve reveals that the output power of a PV cell surges to a peak before diminishing as the voltage fluctuates between 0 and the open circuit voltage. To ensure optimal power output, the PV cell should operate at the voltage corresponding to the MPP (Vmp). However, the MPP is subject to variations in the PV cell, temperature, shading conditions, and irradiance.

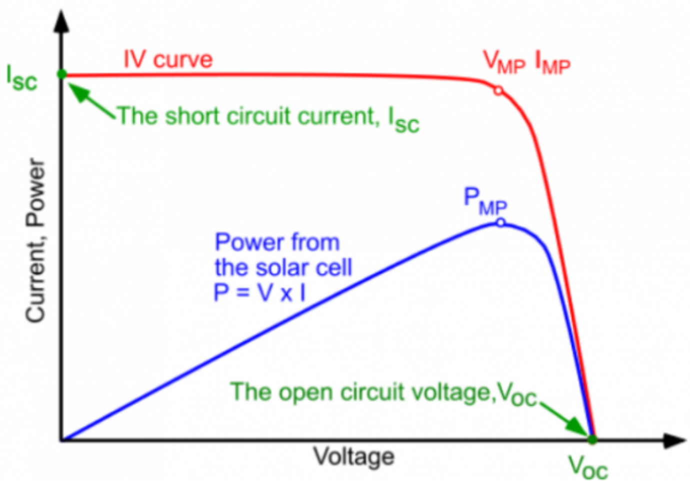


Fig 5: I-V and P-V Curve of a PV cell

A DC-DC converter is implemented as an MPP tracker for PV modules, with the PV module connected to the input of the converter. MPP tracking is performed by adjusting the duty cycle of the converter. There are two primary MPP tracking techniques:

The two major MPP tracking methods are as follows:

3.1.1 Perturb and Observe (P and O)

In the Perturb and Observe MPPT method, voltage is slightly perturbed, and the corresponding change in power output is observed to adjust the voltage accordingly and reach the Maximum Power Point (MPP). If the perturbation of a reference voltage results in a positive change in power output, it indicates that the system is moving towards the MPP, and the voltage must be perturbed in the same direction. Conversely, if the change in power output is negative, the system is moving away from the MPP, and the voltage must be perturbed in the opposite direction. .

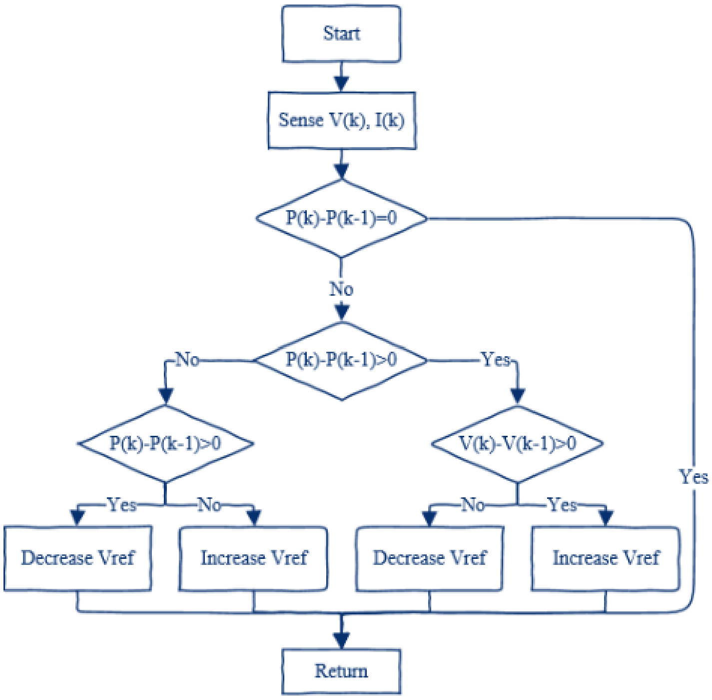


Fig 6: Perturb and Observe Method

This method is widely known for its simplicity and cost-effectiveness. However, it is not suitable in scenarios where environmental conditions change rapidly. Furthermore, during steady-state conditions, the output current and voltage signals oscillate around the MPP, resulting in losses

3.1.2 Incremental Conductance (INC)

In this MPPT method operate by comparing the instantaneous power output of the PV array with its incremental power, which is the rate of change of the power with respect to the change in the panel's voltage. The method is based on the observation that at the MPP, the incremental power is zero. Therefore, the algorithm is designed to track the MPP by adjusting the system's voltage based on the sign of the incremental power.

If the incremental power is positive, it implies that the system is not yet operating at the MPP and the system's voltage needs to be increased. On the other hand, if the incremental power is negative, it implies that the system has already passed the MPP and the system's voltage needs to be decreased. The algorithm adjusts the voltage until the incremental power becomes zero, which indicates that the system is at the MPP.

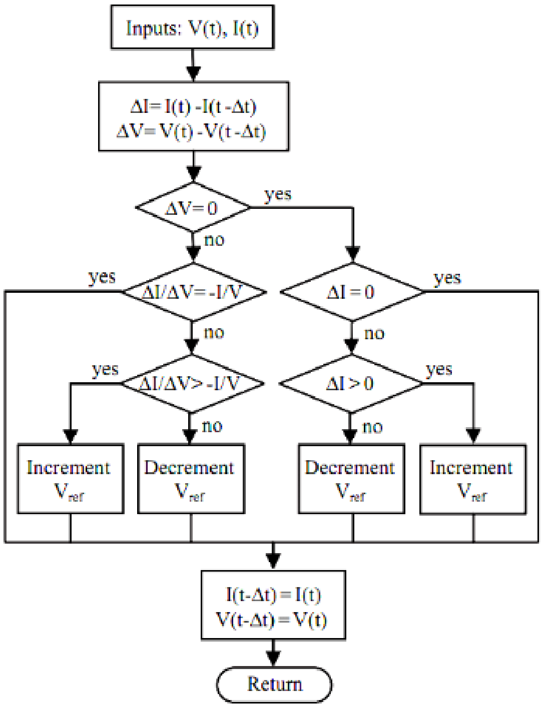


Fig 7: Incremental Conductance Method

The INC method has several advantages over other MPPT methods. It is able to track the MPP accurately and efficiently, even under rapidly changing environmental conditions. Additionally, the INC method is able to track the MPP even under partial shading conditions, which can be challenging for other MPPT methods.

However, the INC method also has some limitations. The method requires a precise measurement of the PV array's voltage and current, which may not be feasible in some situations. Additionally, the method may oscillate around the MPP if the system's voltage is adjusted too quickly.

In this project, we will be using the incremental conductance method for MPP tracking.

Chapter 4

Simulation and Results

4.1 TLBC - 325V to 400V boost

Firstly, we will simulate a three-level DC-DC converter using MATLAB/Simulink and analyze its performance for an input voltage of 325V and an output voltage of 400V, with an output power of 1kW. This boost from 325V to 400V is typically utilized in a grid-tied inverter. The simulation model of the three-level DC-DC converter is created using MATLAB/Simulink. The converter is fed with an input voltage of 325V through a voltage source, and a varying duty cycle of the PWM signal generated by the controller produces an output voltage of 400V. The controller is designed with a PI block, which generates the required duty cycle with respect to the error from the output and reference.

(P.T.O)

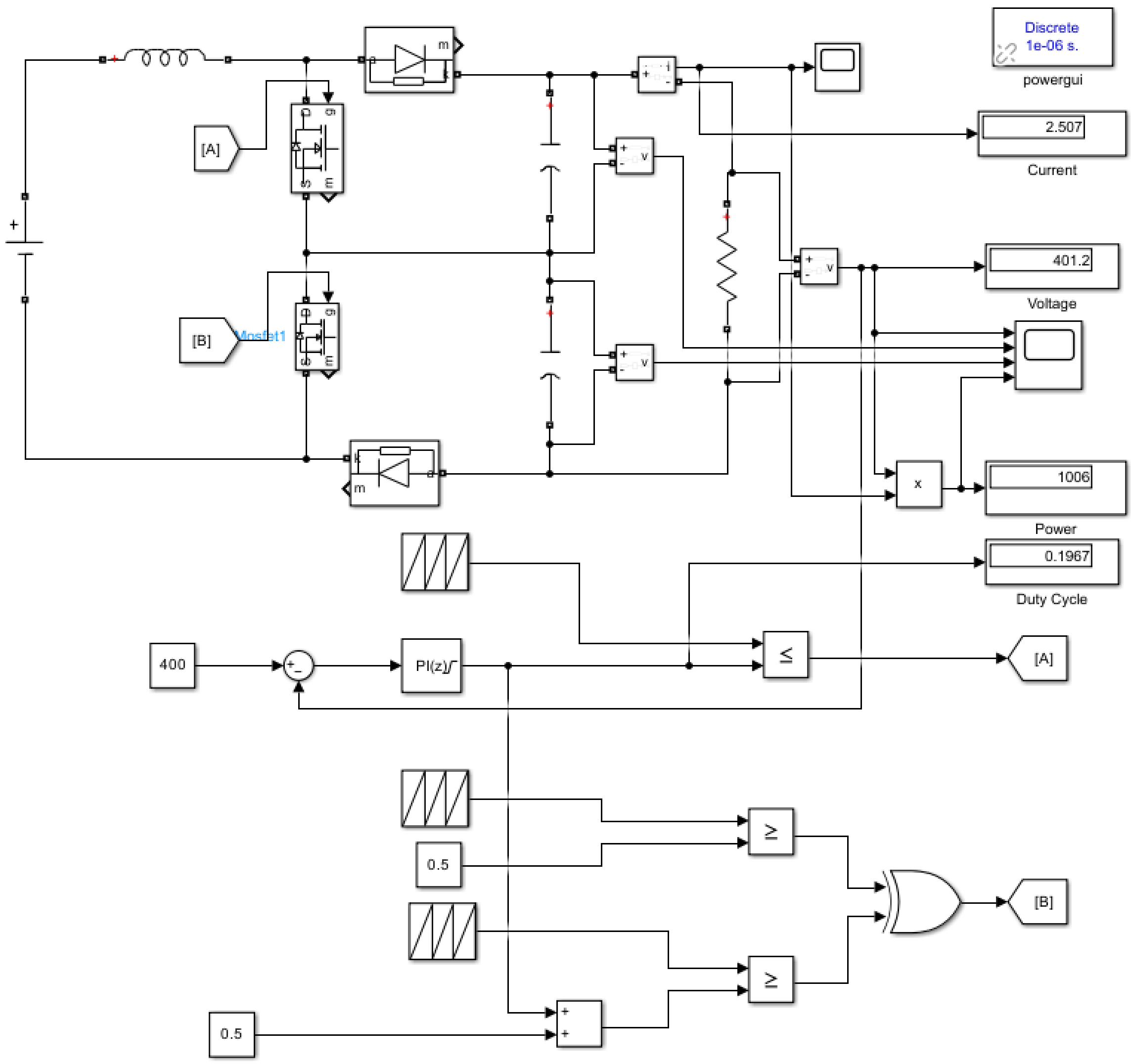


Fig 8: Simulink model of TLBC

The simulation is conducted for a duration of 100ms with a time step of 10us. The converter operates at a switching frequency of 20kHz. The value of the inductors is selected as 5mH, and the capacitance is chosen as 47uF. This is to maintain the voltage and current ripple values at a maximum of 5

The PWM generator outputs to both MOSFETs are determined based on the operation mode in region 1 (refer to figure). The controller's PI constants are evaluated as $K_p = 0.1$ and $K_I = 2$ by trial and error method. The voltage scope of the output is as follows,

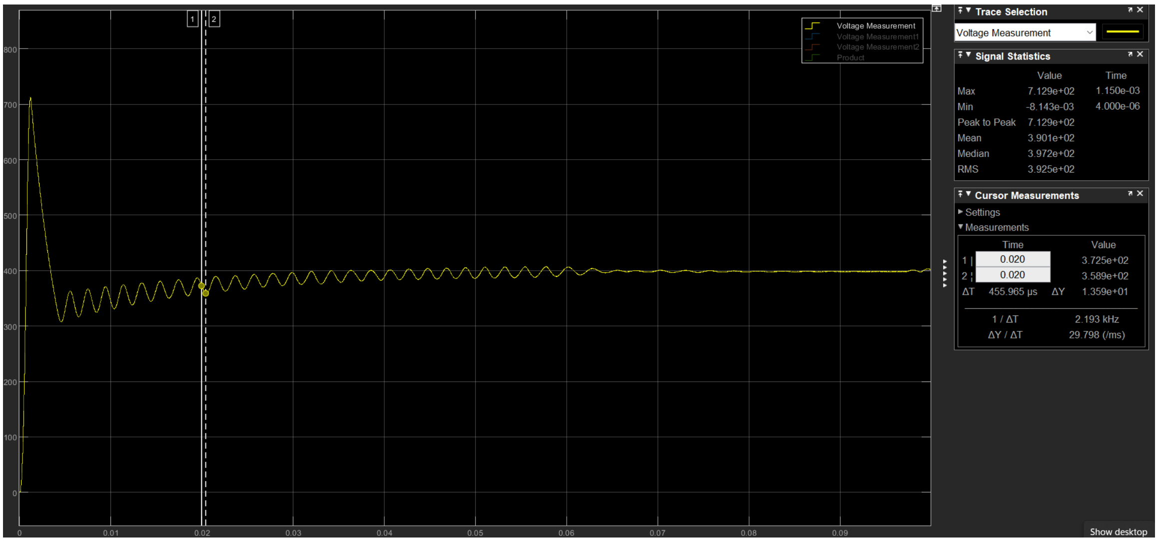


Fig 9: Output Voltage of TLBC

Under steady-state conditions, the voltage has the following values,

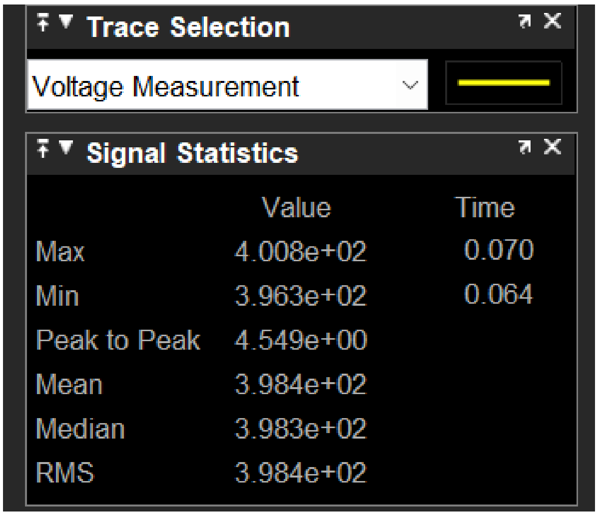
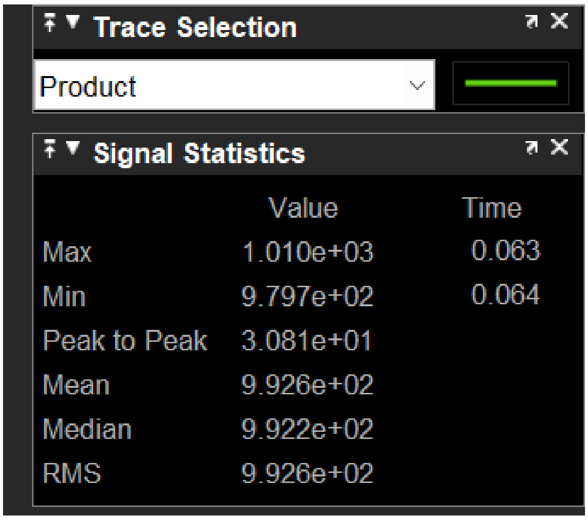


Fig 10: Output voltage parameters under steady-state conditions

The mean value of output is 398V and peak-to-peak ripple is around 5V. The mean output power is around 990W and has a peak-to-peak ripple of around 30W


Trace Selection

Product

Signal Statistics

	Value	Time
Max	1.010e+03	0.063
Min	9.797e+02	0.064
Peak to Peak	3.081e+01	
Mean	9.926e+02	
Median	9.922e+02	
RMS	9.926e+02	

Fig 11: Output power parameters under steady-state conditions

We are not able to achieve perfect output values due to losses in the MOSFETs, Diodes, inductor and capacitors.

4.2 TLBC with MPPT

In this simulation, we will model a TLBC using Simulink blocks for MPPT applications. The voltage and current inputs from the PV panel are fed into a MATLAB function generator, which utilizes the Incremental Conductance (INC) method to dynamically adjust the converter's duty cycle to track the MPP. The PWM generator is then employed to generate the switching signals for the converter.

For the simulation, we utilized a PV panel with the following specifications:

$$V_{oc} = 21V$$
$$I_{sc} = 2.88A$$
$$V_{mp} = 17.5V$$
$$P_{max} = 45.15W$$

$I_{mp} = 2.58A$ Irradiance of PV cell = $1kW/m^2$

Temperature of PV panel = $25°C$

PV cells per module = 36

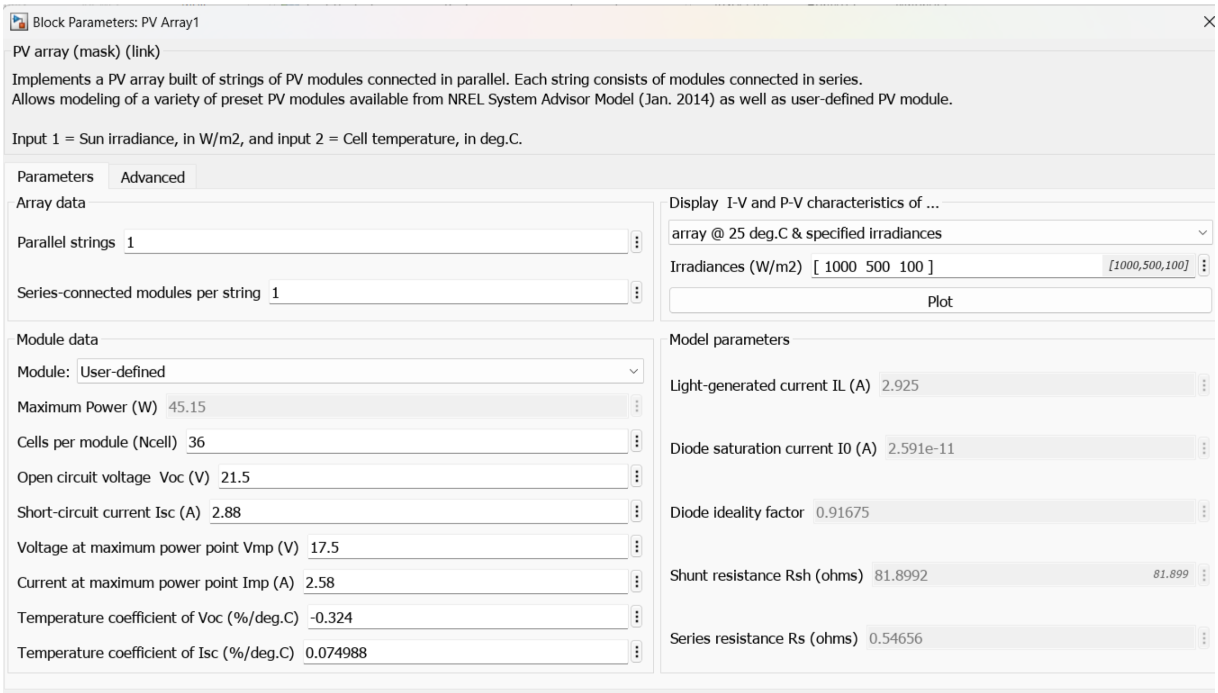


Fig 12: Specifications of PV module

For this PV panel, we must perform MPP tracking using the Incremental Conductance method. To achieve this, we use a MATLAB function generator to generate the TLBC's duty cycle to track the MPP.

The MATLAB function was coded using the INC algorithm to vary the duty cycle to achieve the MPP. The initial duty cycle was set to be 0.5. The MATLAB code for the function is as follows:

matlab-prettifier

```

function D = Duty_cycle(V_PV,I_PV)
Di=0.5
dD=0.0001
persistent Vold Iold D_old;
dataType = 'double';
if isempty(Vold)
    Vold = 0;
    Iold = 0;
    D_old=Di;
end
dV=V_PV-Vold;
dI=I_PV-Iold;
if (dV==0)
    if (dI==0)
        D=D_old
    else
        if (dI>0)
            D=D_old-dD
        else
            D=D_old+dD
        end
    end
```

```
elseif dI/dV==-I_PV/V_PV
    D=D_old
elseif dI/dV>-I_PV/V_PV
    D=D_old-dD
else
    D=D_old+dD
end
if D>=1 || D<=0
    D=D_old
end
D_old=D
Vold=V_PV
Iold=I_PV
```

Fig 13: Matlab Function to generate duty cycle

The voltage and current signals from the PV panel are used as inputs for this function, which operates in closed-loop control and finds the MPP point, but oscillates around it once steady state is reached.

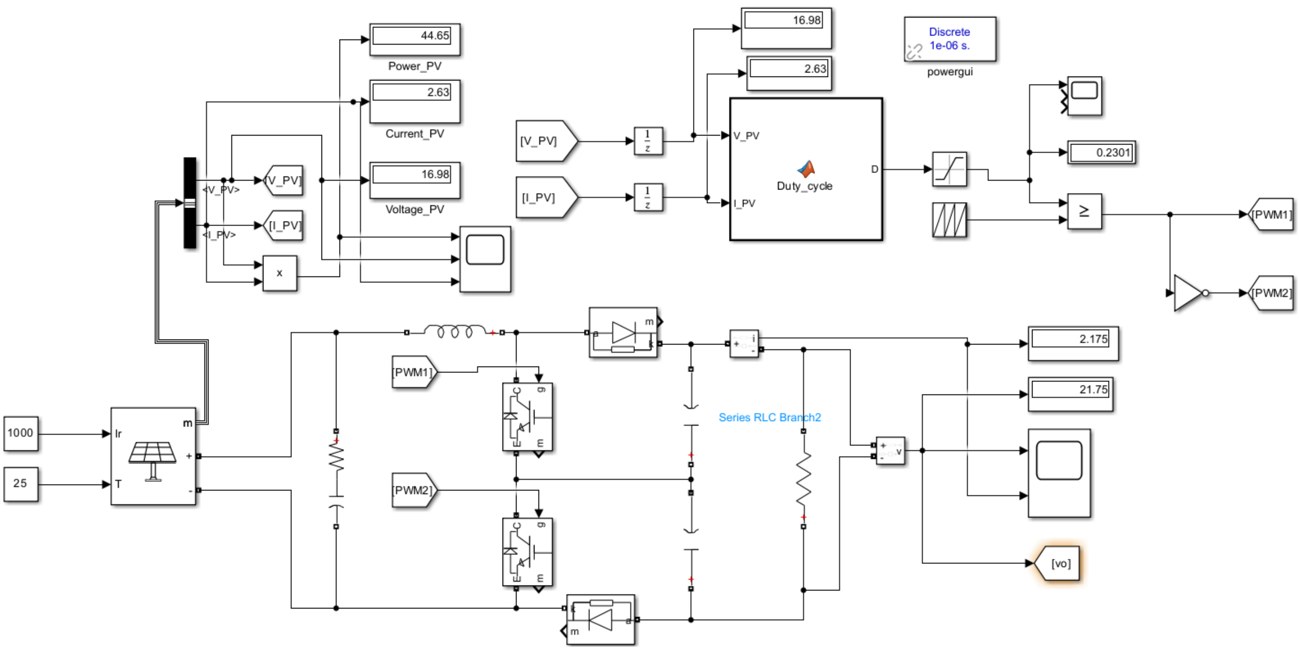


Fig 14: Simulink model of MPPT with TLBC

For the values of the inductor and capacitors, we have selected 0.5mH and 20uF respectively. These values were calculated to achieve a boost with 5% voltage ripple and 20% current ripple. We have set the resistance value at 10 Ohms.

The scope data for the output voltage and power from the PV panel is shown below.

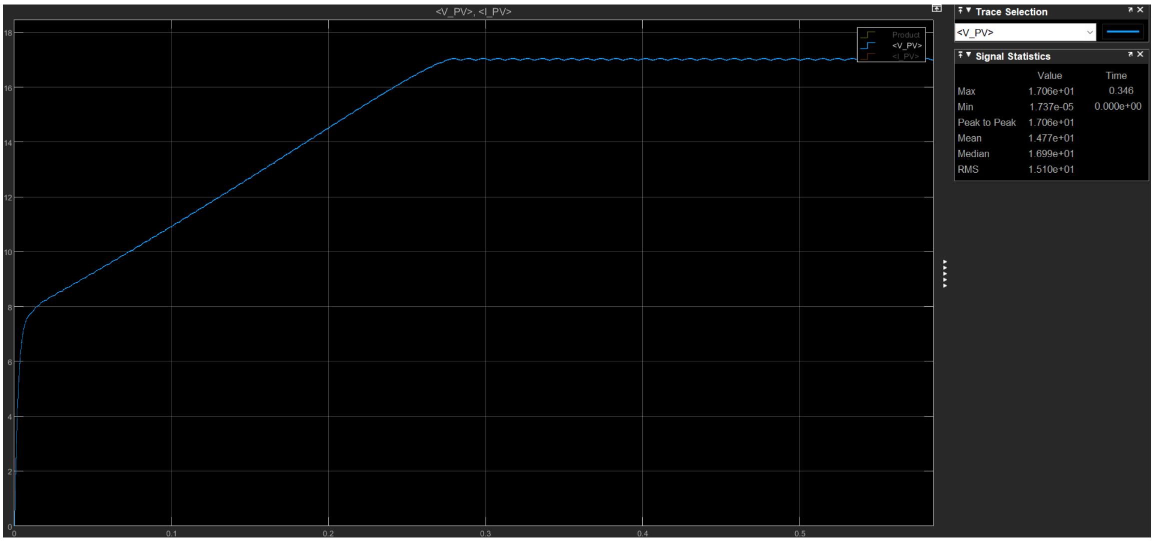


Fig 15: Output voltage of PV panel

Under steady-state conditions, the voltage of PV panel reaches 17V, which is close to the value of V_{mp}

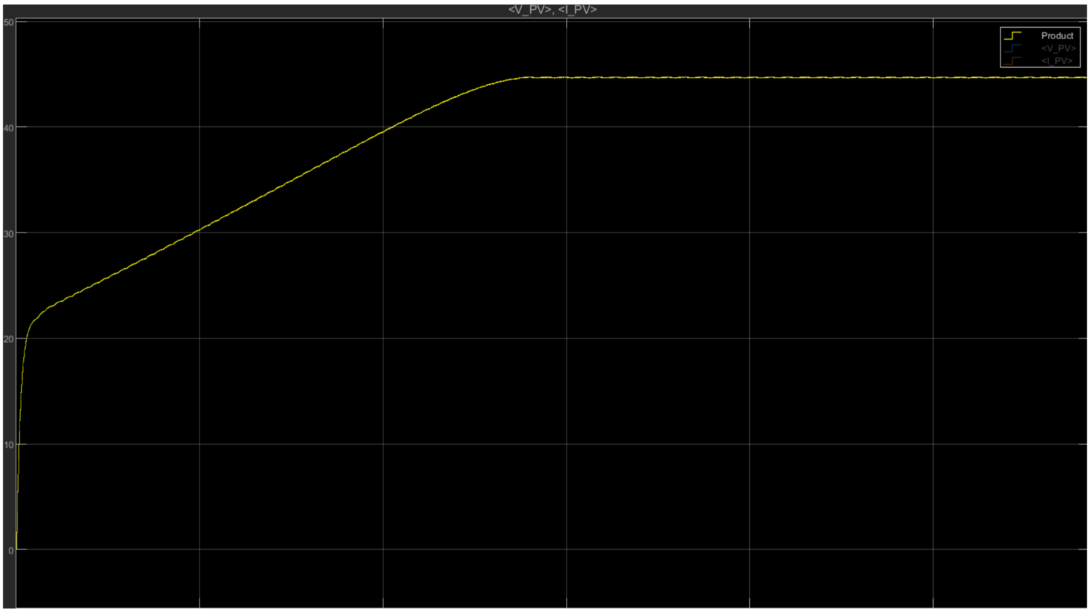


Fig 16: Output power of PV panel

The output power under steady-state conditions has the following data,

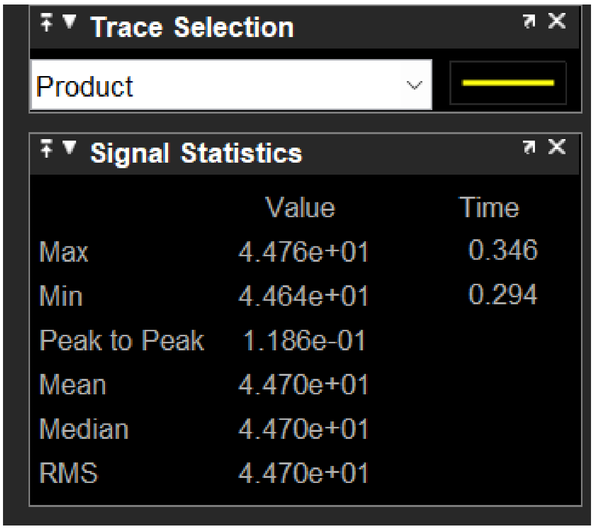


Fig 17: Output Power data of PV panel

As shown in the scope data, the output power is 44.7W with a peak-to-peak ripple of 100mW. This indicates that the designed TLBC model is able to perform MPPT. The efficiency of this TLBC in finding the MPP,

$$\%\eta = \frac{44.7W}{45.15W} * 100 = 99\% \tag{4.1}$$

Chapter 5
Conclusion

In this project, a three-level boost converter with MPPT applications has been designed, implemented, and tested. The results show that the proposed system offers higher efficiency and improved performance compared to the traditional boost converter with MPPT. The MPPT algorithm successfully tracks the maximum power point of the solar panel, resulting in maximum power extraction from the source. The three-level boost converter offers more voltage steps and a wider operating range than the traditional boost converter, making it a better topology for MPPT applications.

The proposed system can be extended in several ways. First, the proposed system can be integrated with a battery storage system to store the excess power generated from the solar panel. Second, the proposed system can be used in combination with other renewable energy sources such as wind and hydro to develop a hybrid energy system. Finally, the proposed system can be scaled up to a larger capacity for commercial and industrial applications, such as electric vehicles and hybrid electric vehicles to improve their performance and efficiency.

In conclusion, the three-level boost converter with MPPT applications is a better solution for renewable energy systems than the traditional boost converter with MPPT. The proposed system offers higher efficiency and improved performance, and its applications are vast and varied. Therefore, the proposed system has the potential to play a significant role in the transition towards a sustainable energy future.

Bibliography