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Research Article

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Design and Control of DC-DC Multilevel Boost Converter for PV Applications

Enaam Abdul Khaliq Ali[1], Wedian Hadi Abd Alameer[2], Hussein Ghani AbdulKareem[3]

[1,2,3] Department of Electrical Engineering, College of Engineering, Mustansiriyah University, Baghdad, Iraq
*Email: enaamali2018@uomustansiriyah.edu.iq

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Abstract—This modular research aims to design and simulate an adaptive Multilevel Boost Converter (MBC) that produces multiple output voltages. In this paper, another improvement in (2N-1) capacitors and (2N-1) diodes in the structure of MBC, the main objective of the suggested design is to provide an ideal high voltage boost ratio using low power rating devices to reach a different voltage level at each step. The most significant features of MBC are a substantial boost gain at the limit value of duty cycle, running at a reliable continuous input current, no need for a transformer, and balanced capacitor output voltage, which permits working the MBC at a high switching frequency of 50 kHz. MPPT was designed for a PV array that realised low input current ripples. The selected converter's principle is simulated under different conditions to prove that the estimated planned topology functions at its maximum appropriate voltage gain, with a high efficiency of 99.6% at a duty cycle of 59.4%, with a high voltage gain of 7.38 at the same duty cycle, the system was designed and simulated using MATLAB Simulink.

***Index Terms*— Multilevel Boost Converter (MBC), MPPT, PV array.**

I. INTRODUCTION

Currently, attention is turning to using renewable or clean, environmentally friendly energy, such as wind and solar energy, as an alternative to traditional energy such as sulfur fuel, coal, and natural gas. Renewable energy has attracted many researchers because it is freely available and sustainable energy [1, 2], Photovoltaic power is one of the more viable energy sources since it is free, sustainable, scalable from small to big, and simple to combine with energy conversion devices [3]. The generation of electrical energy from solar energy depends on the PV system, which uses one or more photovoltaic cells to convert solar energy into electricity. These panels are made of semiconductors. The generated energy depends on temperature (℃), and radiation (MW, SPCM). Electronic transformers are used to process electricity from solar panels and to manage voltage and current at the load [4].

A potential technique to achieve a high voltage gain and high efficiency is via a DC-DC converter. This transformer-less DC-DC multilevel boost converter (MBC) uses a combination of a regular boost converter circuit and a switched capacitor approach to provide high-voltage, gain- and self-balancing outputs that keep the voltage constant throughout all levels of the converter. By just needing a single switching device linked to the ground, this topology also simplifies the gate drive needs and lowers the complexity of the control approach.

The circuit uses pulse width modulation (PWM) to control the voltage; it uses a single component for each of the following: switch, inductor, (2N-1) diode, and (2N-1) capacitor. This results in an output N times as large as a conventional boost converter operating under identical conditions. Adding diodes and capacitors to the basic converter design may raise the output voltage. Because of this, the circuit may convert energy in applications involving one-way current flow that call for self-balancing and multiple regulated voltage levels. [5, 6, 7]. The proposed technique is shown in Fig. 1.

II. MPPT CONTROL SYSTEM:

The PV module block presented in MATLAB/Simulink is modelled according to the type and module defined. The panel model described in this work is SunPower PL-SUNP-SPR-355-COM. The PV module produces a maximum power of 355.012 W at 1000 W $\cdot$ m^{-2}. Fig. 2 depicts the PV module characteristic I/V and P/V curves

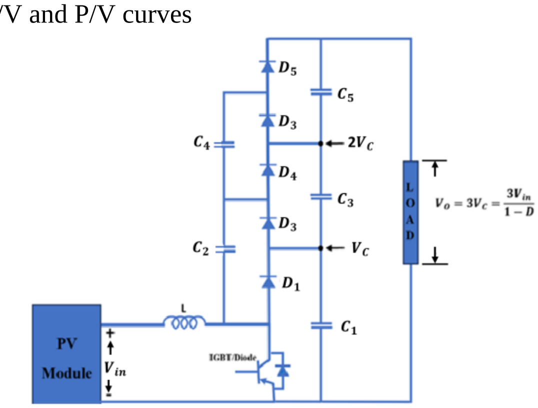


Fig. 1. DC-DC MBC Three-Level Proposed System.

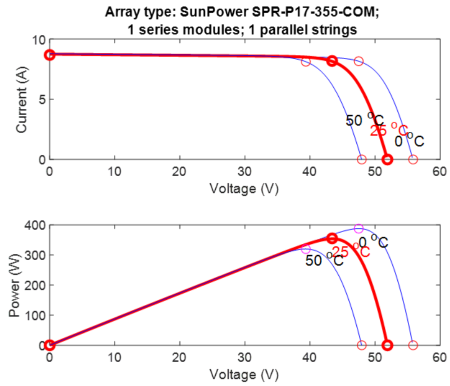


Fig. 2. Parameters for one module of the PV generator.

An example of a p-n semiconductor connection is a solar cell. Light causes a current to flow, and the amount of current that flows is directly proportional to the amount of solar irradiation. A solar cell's electrical circuit is shown in Figure 3.[2].

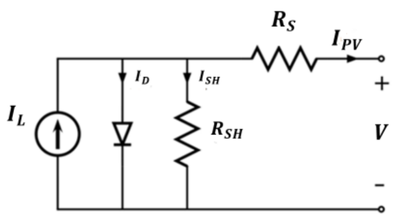


Fig. 3. Model of a solar cell's electrical circuit [2].

The I-V characteristics of the equivalent solar cell circuit may be determined using the following equations. Assigning a current to the diode is [8][9]:

$$I_D = I_o \left[exp\left(\frac{q(V + IR_s)}{KT} \right) - 1 \right] \quad (1)$$

While the solar cell output current is obtained by applying KCL:

$$I_{PV} = I_L - I_D - I_{SH} \quad (2)$$

$$I_{PV} = I_L - I_o \left[exp\left(\frac{q(V + IR_s)}{KT} \right) - 1 \right] - \frac{(V + I_{PV}R_s)}{R_{SH}} \quad (3)$$

Where: I_o is the reverse saturation current, K is the Boltzmann constant, T is the STC temperature, and the charge of the electron is q (1.9×10^{-19}C), V output voltage of solar cell in (V), R_s series resistance of the Solar cell Ω, R_{SH} shunt resistance of the Solar cell in Ω, I_L it is light light-generated current module, I_D represents the direct current, I_{PV} the output current of solar-PV.

The Perturb and Observe P&O is an algorithm that calculates the MPPT for the PV panel system suggested in the design of the system by using the Math Function Simulink block. The suggested system is based on MPPT and PI controller, as shown in Fig. 4.

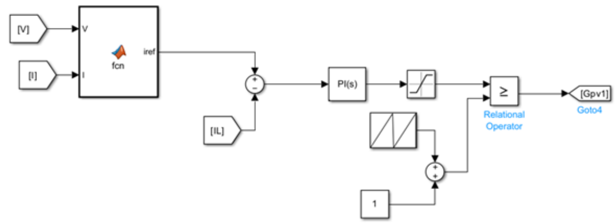


Fig. 4. Math Function and PI controller Simulink block.

III. Principle of Operation [10]

Two operating modes may characterise the MBC's operational concept: ON and OFF. In continuous conduction mode (CCM), the converter is operating with the following operational parameters during both modes:

During the switch-on state, the inductor is linked to the V_{in} voltage Fig. 5a, C_2's voltage is less than C_1's, C_1 clamps it using D_2 and the switch (S), as shown in Fig. 5b. At the same time, the voltage across C_2+C_4 is less than the voltage across C_1+C_3, C_3 and C_1 clamp the voltage across C_2 and C_4 via D_4 and switch (S) Fig. 5c.

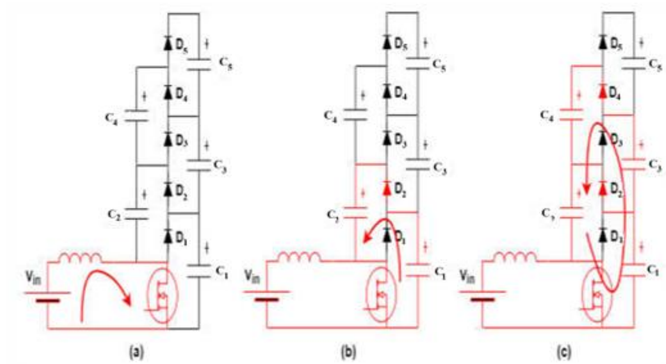


Fig. 5. The MBC operation when the switch is turned ON [10].

During the switch-off, the inductor current closes D_1 charging C_1, Fig. 6a. When D_1 closes, C_2 and the voltage in V_{in} plus the inductor's voltage clamp the voltage across C_3 and C_1 through D_3, Fig. 6b. Similarly, the voltage across the inductor plus V_{in}, C_4 and C_2 clamp the voltage across C_5, C_3 and C_1 through D_5. Finally, the voltage across C_1, C_3 and C_5 is clamped by C_2, C_4, V_{in} and the inductor's voltage, Fig. 6c.

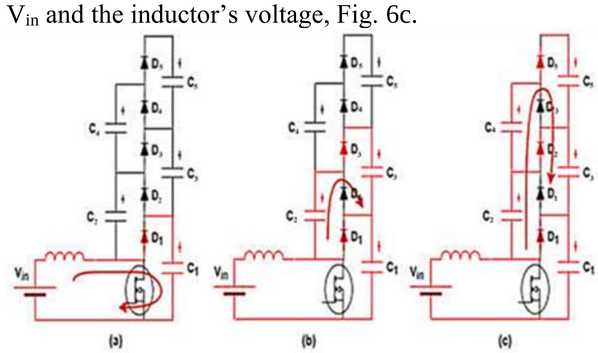


Fig. 6. Off state of MBC operation [10].

IV. DC-DC Multilevel Boost Converter Design

A. Voltage Gain [11]

Two operating modes may characterise the MBC's operational concept: ON and OFF. In continuous conduction mode, the converter operates with the following operational parameters during both modes:

The output voltage of the converter is equal to V_C, and the voltage across all output capacitors is the same. Consequently, the voltage gain of the suggested converter may be calculated using the formula below:

$$\frac{V_O}{V_{in}} = \frac{N}{1-D} \tag{4}$$

B. Inductor Design [12][13]

Assuming that $I_L = I_{in}$, then I_L, the inductor current, may be computed as:

$$V_{in}I_{in} = V_oI_o \tag{5}$$

$$V_{in}I_L = V_o\left(\frac{V_o}{R_o}\right) \tag{6}$$

$$I_L = \left(\frac{V_o}{V_{in}}\right)\left(\frac{V_o}{R_o}\right) \tag{7}$$

Sub. equation (4) in equation (7) yields

$$I_L = \frac{NV_o}{(1-D)R_o} \tag{8}$$

R_O The load resistance, to operate the converter in continuous conduction mode (CCM), the critical inductance value is calculated based on the duty cycle and output power, where f is the switching frequency

$$L_{crt} = \frac{D(1-D)^2R_o}{2f} \tag{9}$$

C. Capacitor design [10]

The MBC ensures consistent output voltage across all output capacitors (C_1, C_3, and C_5). Assuming that all capacitors have identical values, the output voltage across the load is:

$$V_{C1} = V_{C3} = V_{C5} = V_C \rightarrow V_O = 3V_C \tag{10}$$

The capacitance may be calculated using the voltage ripple of a capacitor (ΔV_O), which should not exceed 5%.

$$C = \frac{D}{R_O\left(\frac{\Delta V_o}{V_o}\right)f} \tag{11}$$

D. Switch design [10]

Fig. 5(a) the voltage that would be applied across the converter's switch

$$V_S = V_{C1} \tag{12}$$

Sub equation (10) into (12) results in decreased voltage stress on the switch in a three-level converter compared to a conventional converter with an output voltage

$$V_S = \frac{V_0}{3} \tag{13}$$

V. Results and discussions

MATLAB Simulink is used to simulate the MBC for a three-level system. The basic idea is PV fed a three-level boost converter as shown in Fig. 7

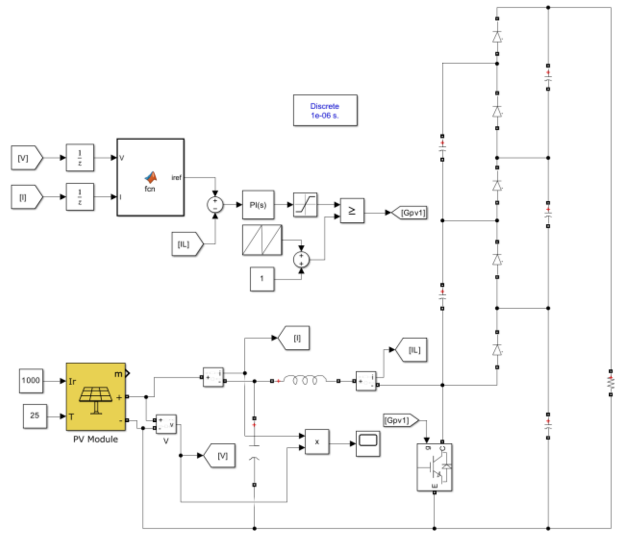


Fig. 7. The system simulation

The multilevel boost converter switch is supplied with a gate pulse with a switching frequency of 50 kHz and a 58.4% duty cycle of the PWM pulse. Table 1 displays the design parameters for the simulation circuit's multilevel boost converter.

TABLE I

DESIGN PARAMETERS OF MBC

Parameters	Values
V_{in} (V_{mpp})	43.4 V
V_o	213 V
D	0.594
C_1, C_2, C_3, C_4, C_5	650 μf
Inductor	168 μH
Load Resistance	135 Ω

Fig. 8 shows the relation between the MBC's output power and the PV system's input power gives an efficiency of about 99.6% at 0.594 of the duty cycle.

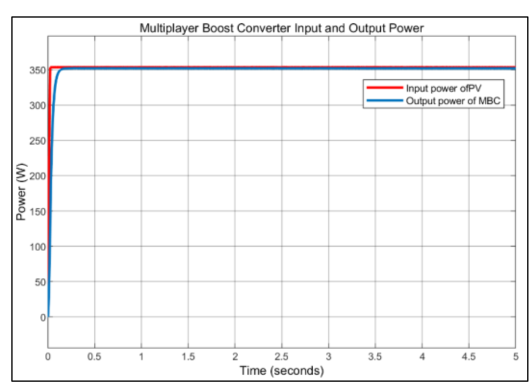


Fig. 8. The input power of the PV system and output power of MBC.

Fig. 9 displays the voltage input to the PV system and the voltage output to the MBC.

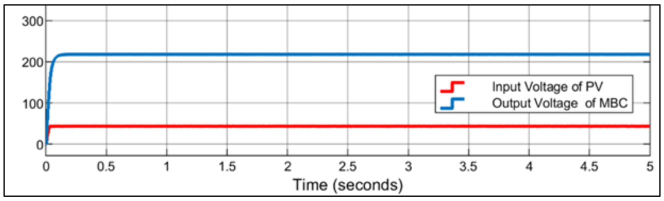


Fig. 9. The input voltage of the PV system and the output voltage of MBC.

The input current of the PV system and the output current of MBC are shown in Fig. 10.

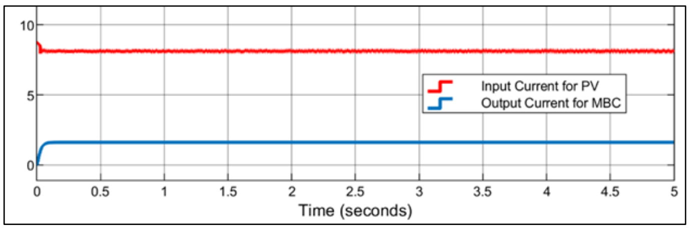


Fig. 10. The input current of the PV system and the output current of MBC.

The MBC's DC voltage input is 43.4 V, with a capacitor voltage (output) of 72.3 V and a total output of 145.2 V from C_1 and C_2. Adding C_1, C_2, and C_3 results in an output of 216.5 V, as shown in Fig. 11.

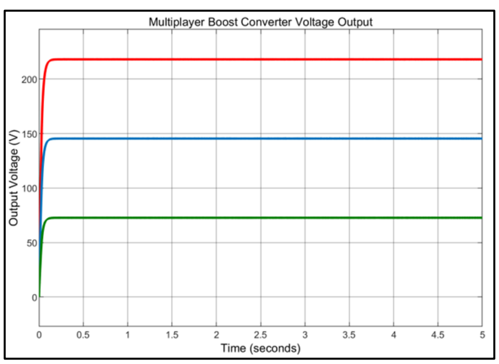


Fig. 11. Voltages of the capacitors of the MBC at 1000 W-m^{-2}.

Figures (12) and (13) (a, b and c) show the variation in output voltage, current, and power of PV and the proposed converter under reducing irradiance levels with constant cell temperature at 25°C. This indicates that the PV and converter voltage decrease with the decrease in irradiance levels.

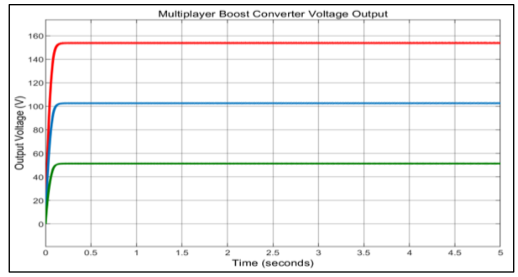
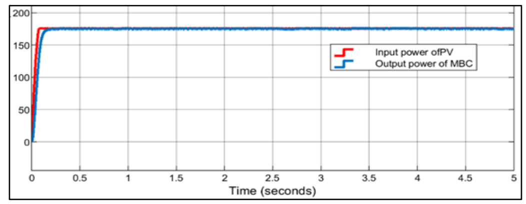
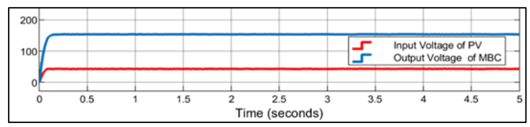


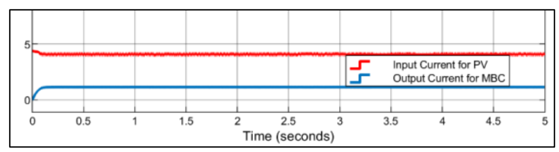
Fig. 12. Voltages of the capacitors of the MBC at 500 W/m^2.



(a)



(b)



(c)

Fig. 13. The input and output, (a) power, (b) voltage and (c) current, at 500 W·m^{-2}.

Table 2 shows the suggested converter's voltage gain as a duty cycle function. The data in the picture depicts the influence of the inductor's ESR (Equivalent Series Resistance) on the duty cycle and the voltage gain, as illustrated in Fig. 14.

The suggested converter's optimal operating point and efficiency were determined by testing its performance against a range of switching frequencies (10-100 kHz). The comparison of input and output power is used to assess efficiency. Fig. 15 shows that the converter achieved its maximum simulated efficiency of 99.6 % when running at 50 kHz with a duty cycle of 0.594 %.

TABLE (2)

ESR	D	$\frac{V_O}{V_{in}} = \frac{3}{1-D}$
0	0.594	7.38%
0.01	0.397	4.97%
0.05	0.388	4.9%
0.1	0.380	4.83%
0.5	0.371	4.76%
1	0.333	4.49%

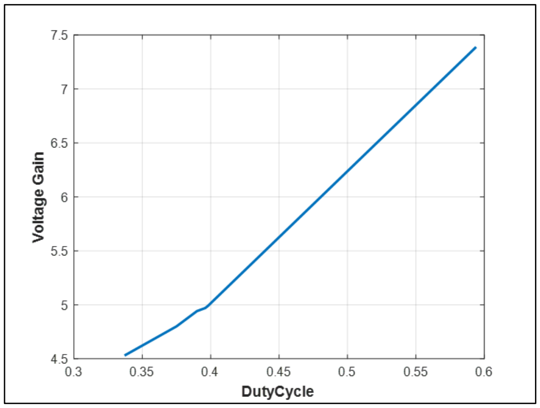


Fig. 14. Voltage gains against duty cycle by effect of ESR.

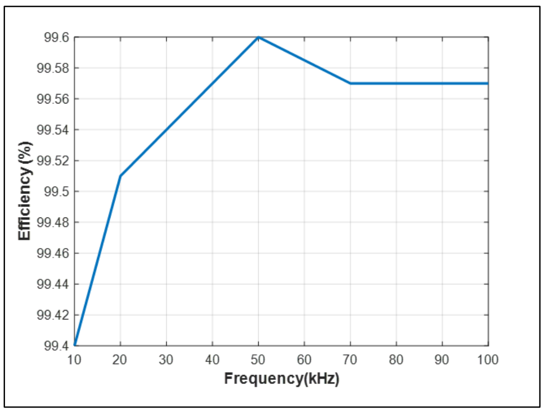


Fig. 15. Efficiency against frequency by effect of ESR.

V. Conclusion

At varying levels, the converter transforms a low input DC voltage into a high output DC voltage. It is possible to achieve any desired output voltage by integrating multilayer boost converters with ordinary boost converters in renewable power systems. The suggested design for the converter incorporates a switched capacitor circuit, one inductor, a switch, (2N-1) diodes, and (2N-1) capacitors into an N-level converter, making use of the conventional boost converter architecture. A stable input current, a high voltage gain of 7.4, and little voltage stress across the switch are the primary advantages of the suggested converter, which does not need an enormous duty cycle. Results for an input voltage of 43.7 V and an output voltage of 210 V at 350 kW are shown for the suggested converter. At a switching frequency of 50 kHz, the converter achieves 99.6% efficiency.

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Enaam Abdul Khaliq Ali is a lecturer in the Electrical Engineering Department at the College of Engineering, Mustansiriyah University, Baghdad, Iraq. She received her Ph.D. in Electrical Engineering from the University of Baghdad in 2022. She has been an Associate Professor at the University of Mustansiriyah College of Engineering, Electrical Department. Her research interests include industrial applications, power electronics, motor drives, and renewable energy. The research papers have been published locally and in Scopus journals. She can be contacted at email: enaamali2018@uomustansiriyah.edu.iq

Wedian Hadi Abd Alameer is a lecturer in the Electrical Engineering Department at the College of Engineering, Mustansiriyah University, Baghdad, Iraq. She received her Master's in electrical power systems engineering from the University of Uttar Pradesh, India, in 2014. Some research papers have been published locally and in Scopus journals.

Hussain Ghani Abdulkareem is a lecturer in the Electrical Engineering Department at the College of Engineering, Mustansiriyah University, Baghdad, Iraq. He received his Ph.D. in Electrical Engineering from the University of Ukraine in 2015. He can be contacted at email: hussain_ghani@uomustansiriyah.edu.iq