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SIMULATION AND PERFORMANCE ANALYSIS OF HIGH-EFFICIENCY MULTILEVEL BOOST CONVERTER

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Abstract: This research aims to optimize the efficiency of the boost converter with a cascaded technique to increase efficiency with a more complex circuit, using two Boost converters assembled in series and two PWM signals so that the circuit performance is more stable. The method used in this research is to compile a circuit with suitable components and calculations designed and then optimized using mathematical and differential analysis and select the switching frequency (40KHz) that gives the best performance in the circuit, then simulate the cascaded boost converter and regular boost converter circuits in MATLAB Simulink with duty cycle variations from 5%-76% to compare the performance of the two topologies in improving efficiency. The results of testing the efficiency showed that the cascaded boost converter circuit has a more significant input current than the output current to reduce power losses and increase efficiency in the circuit from its minimum efficiency of 52% to a maximum of 90%. The increased efficiency in the cascaded boost converter is directly proportional to the rise in the duty cycle. The study explicitly presents and validates theoretical results while experimentally verifying them. The main contribution of this study is the introduction of a new high-efficiency DC-DC cascaded boost converter, which achieves the highest efficiency (90%) compared to other DC-DC boost converter topologies documented in existing literature.

Keywords: Boost converter, Cascaded Boost, Duty cycle, Efficiency, Output Voltage

Abstrak: Penelitian ini bertujuan untuk mengoptimasi efisiensi *boost converter* dengan teknik *cascade* untuk meningkatkan efisiensi dengan rangkaian yang lebih kompleks, dengan menggunakan dua buah *Boost converter* yang dirangkai secara seri dan dua buah sinyal PWM agar kinerja rangkaian lebih stabil. Metode yang digunakan dalam penelitian ini adalah dengan menyusun rangkaian dengan komponen yang sesuai dengan desain dan perhitungan yang telah dirancang kemudian dioptimasi menggunakan analisis matematis dan diferensial serta memilih frekuensi pensaklaran (40KHz) yang memberikan performa terbaik pada rangkaian, kemudian mensimulasikan rangkaian *boost converter* bertingkat dan *boost converter* biasa pada MATLAB Simulink dengan variasi *duty cycle* dari 5% -76% untuk membandingkan performa kedua topologi tersebut dalam meningkatkan efisiensi. Hasil pengujian efisiensi menunjukkan bahwa rangkaian *cascade*d *boost converter* memiliki arus input yang lebih signifikan dibandingkan arus output sehingga dapat mengurangi rugi-rugi daya dan meningkatkan efisiensi pada rangkaian dari efisiensi minimum 52% menjadi maksimum 90%. Peningkatan efisiensi pada konverter *boost* bertingkat berbanding lurus dengan peningkatan *duty cycle*. Penelitian ini secara eksplisit menyajikan dan memvalidasi hasil teoritis sambil memverifikasinya secara eksperimental. Kontribusi utama dari penelitian ini adalah pengenalan konverter *boost* bertingkat DC-DC efisiensi tinggi yang baru, yang mencapai efisiensi tertinggi(90%) dibandingkan dengan topologi konverter *boost* DC-DC lainnya yang didokumentasikan dalam literatur yang ada.

Kata Kunci: Konverter *Boost*, *Boost* bertingkat, *Duty Cycle*, Efisiensi, Tegangan *Output*

INTRODUCTION

Ideally, the efficiency of the DC-DC converter is 100%, which means there is no power loss in the converter. However, practically, the converter's efficiency is lower than 100%. The decrease in converter efficiency is due to the high power loss in the semiconductor. Low converter efficiency can lead to underutilizing electric power on the load (Anung & Hidayat, 2014).

Conventional Boost converters require semiconductors, producing high conduction and switching losses in high-voltage applications (Pahlevi et al., 2023). A small capacitance value can lead to a voltage below the desired limit and cause a high-voltage ripple (Mansouri et al., 2023).

Many converters are used to achieve high efficiency by using high ratios and a minimum number of components. (Sutrisno & Gozali, 2022). The converter can generate excessively high amplification when operated at a high-duty cycle. Nevertheless, the electrical components could be enhanced and possess parasitic features that diminish voltage amplification during high-duty cycles (Allehyani, 2022). In addition, parasitic components and significant component losses can reduce efficiency. This problem can be solved by adjusting the regular Boost converter circuit (Leyva-Ramos et al., 2017). Quadratic techniques can be applied to modify the Boost converter circuit. The application of the quadratic circuit technique, commonly known as Cascaded, works by stringing several Boost converter series controlled by more than one Pulse Width Modulation (PWM) signal (Mazta et al., 2016).

In quadratic boost converters with additional components that are not well calculated, a significant voltage drop will be caused, and efficiency will be reduced (Fanani et al., 2014). Unstable operation can cause oscillations and undesirable increases in current and voltage amplitudes, posing a risk to all components involved (Lopez-Santos et al., 2020).

This study explicitly validates the results through simulation and testing of the presented Boost converter and Cascaded Boost. This study provides experimental confirmation that it has developed a novel high-efficiency DC-DC boost converter with the highest reported efficiency (90%), which surpasses the efficiency of previous research and other boost converter topologies that have been documented in the literature.

The objective of this research is to enhance the effectiveness of the Boost converter circuit by employing the Cascaded approach. This involves utilizing a more intricate circuit configuration consisting of two Boost converters connected in series and two PWM signals. This setup aims to ensure the circuit's more reliable performance. The Boost and Cascaded Boost converter circuits are tested for output voltage and efficiency using the MATLAB Simulink software. The method involves simulating the circuits and comparing the performance of the two converter topologies in terms of increasing efficiency and output voltage, which can be adjusted to meet the specific system requirements.

METHOD

Boost converter Simulation Circuit Design

The Boost converter circuit will be made with two versions by simulating two Converter topologies, namely, conventional Boost converter and Cascaded Boost converter, which will be done using the MATLAB Simulink tool. This tool has the advantage of rejecting interference and supporting tracking to refine its user performance (Wiryajati et al., 2024).

This study utilizes MATLAB Simulink to analyze and contrast two topologies' output voltage and high efficiency. The input voltage is set at 24 Volts, while the duty cycle varies from 5% to 76% to enhance the Boost converter's and Cascaded Boost's efficiency.

Table 1. Specification of Boost converter and Cascaded Boost converter

Parameters	Value
Input voltage (Vin)	24 Vdc
Resistor (R)	25 ohm
Switching Frequency (Fs)	40000hz
Output ripple (Δ_{VO})	0,1
Power (P)	400 watt
Output voltage (Vout)	100 Volt
Current ripple (Δ_{I})	0,4
Capacitor (C)	760μf
Inductor (L)	13,68 μH
***Duty cycle* (D)**	5%-76%

Output current (I_{out})	4 A

Design of Boost converter and Cascaded Boost converter

Boost converter and Cascaded Boost converter are designed using MATLAB Simulink. This test will use the specifications shown in Table 1 to simulate both converters.

To get the parameter values in the specifications that will be used in the Boost converter and Cascaded Boost circuits, the following calculations are carried out (Dera, 2020):

The duty cycle value can be found using the following formula:

$$D = \left(1 - \frac{V_{in}}{V_{out}}\right) x\ 100\%$$

$$D = \left(1 - \frac{24}{100}\right) x\ 100\%$$

$$D = (1 - 0{,}24) x\ 100\%$$

$$D = 76\%$$

Where: D= Duty cycle

Then to find the resistance value as follows:

$$I_{out} = \frac{Power}{V_{out}}$$

$$I_{out} = \frac{400}{100}$$

$$I_{out} = 4\ A$$

Where: I_{out} = Output current

The formula for finding the output power value is as follows:

$$P_{out} = V_{out} . I_{out}$$

$$P_{out} = 100\ x\ 4$$

$$P_{out} = 400\ watt$$

Where: P_{out} = Output power

The formula for finding the resistance value is as follows:

$$R = \frac{{V_{out}}^2}{P_{out}}$$

$$R = \frac{100^2}{400}$$

$$R = \frac{100^2}{400}$$

$R = \frac{10.000}{400}$

$R = 25\ ohm$

Where: R = Resistance

Before determining the inductor's value, another parameter must be sought to calculate the ripple current (ΔI), which is assumed to be % of the output current.

$\Delta_I = Assumption\ (\%)\ x\ I_{out}$

$\Delta_I = 0{,}4$

$L = \frac{D(1-D)^2 xR}{2\ x\ fs}$

$L = \frac{0{,}76(1-0{,}76)^2 x25}{2\ x\ 40.000}$

$L = 13{,}68\ \mu H$

Where: f = Frequency (Hz), Δ_I = Ripple current, L = Inductor

Before determining the value of the capacitor, another parameter that must be sought is to calculate the voltage ripple (ΔVo), which is assumed to be what % of the output voltage:

$\Delta V_{out} = Assumption\ (\%)\ x\ V_{out}$

$\Delta V_{out} = 0{,}1$

$C = \frac{V_{out} x\ D}{Rx\Delta V_o xf}$

$C = \frac{100x\ 0{,}76}{25x\ 0{,}1x40.000}$

$C = 760\mu\ f$

Where: ΔV_{out} = Output voltage ripple, C = Capacitor

The formula for finding the efficiency that will be used to calculate the automatic results of the Boost converter and Cascaded Boost simulations in MATLAB Simulink is as follows:

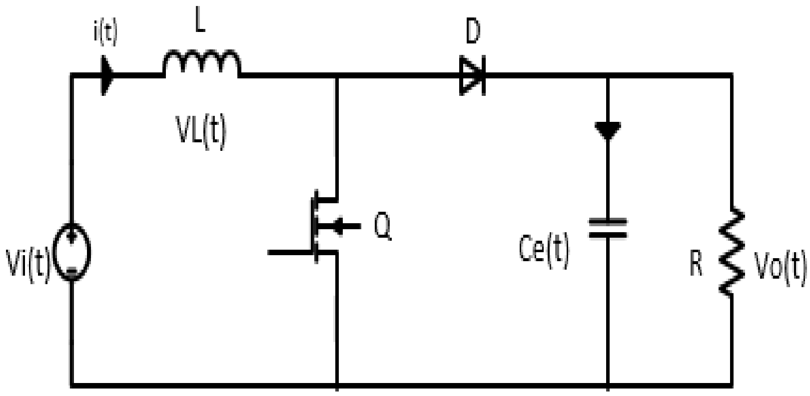
$\eta = \frac{P_{out}}{P_{in}}$

Where: P_{out} = Output power, P_{in} = Input power.

Then, the Cascaded Boost calculation also uses the specifications in Table 1. The Cascaded Boost circuit is a series of combined Boost converters in each parameter. Thus, when simulated on MATLAB Simulink, the Cascaded Boost converter can obtain an output voltage up to twice as large as the conventional Boost converter output voltage of 200 Volts.

Boost converter

This type of converter is a crucial part of a Switch Mode Power Supply (SMPS), which includes components like MOSFETs for semiconductor switching and at least one energy storage device like a capacitor, inductor, or hybrid. As part of its core function, the inductor stores electrical energy before releasing it to the load. The Boost converter generates an output voltage higher than the input voltage, thanks to the voltage produced at the load by the energy stored in the inductor and the input voltage. (Padillah & Saodah, 2014). At the converter's output, capacitor and inductor-based filters are often kept to lower the ripple voltage. Below, in Picture 1, you can see the schematic of a Boost converter [13].



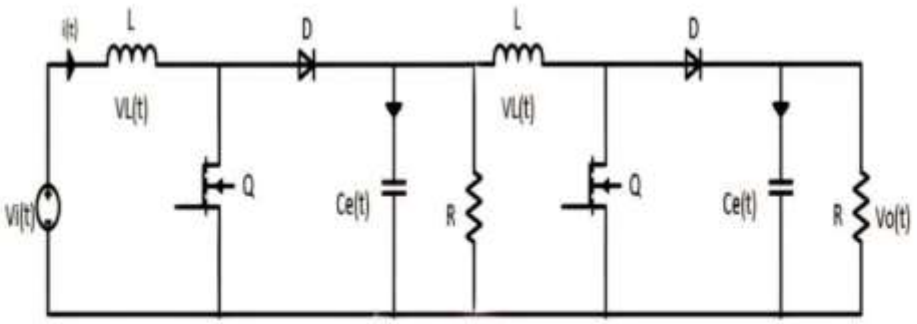
Picture 1. Boost converter Circuit

Description:

$V_i\ (t)$= Input Voltage (V), $V_L\ (t)$= Inductor Voltage, L = Inductor (H), $i\ (t)$ = Current (A), D = Diode, C_e (t) = Capacitor (F), Q = Switch (MOSFET), $V_o\ (t)$= Output Voltage (V), R = Resistance (Ohm)

Cascaded Boost converter

A cascaded Boost converter can provide more advantages than a regular Boost converter because it combines both [14]. This converter is produced by combining two identical Boost elements and connecting them simultaneously. The circuit has an input voltage source, Vin, two switches that can be controlled individually, two diodes D1 and D2, two capacitors C1 and C2, and two inductors, L1 and L2, as depicted in Picture 2. [15]:



Picture 2. Cascaded Boost converter Circuit

Analysis of Results

The success of this research is determined by the ability of the Boost converter to raise the voltage to the intended measurement's maximum value of 100 Volts. Additionally, the Cascaded Boost should achieve double the maximum output voltage of the Boost converter, reaching 200 Volts, with a duty cycle of 76%. For research to be successful, Cascaded Boost must exhibit high efficiency.

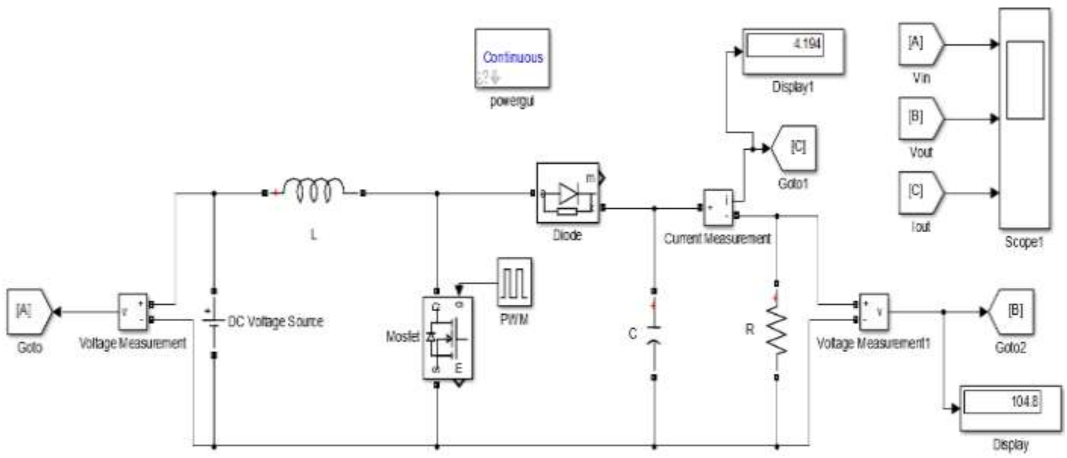
Then, using MATLAB Simulink, we will compare the simulation results of duty cycles ranging from 5% to 76% for the Boost converter and Cascaded Boost topologies to demonstrate that the Cascaded Boost topology is more stable and efficient than the standard Boost converter.

RESULTS AND DISCUSSION

Results

Simulation of Boost converter

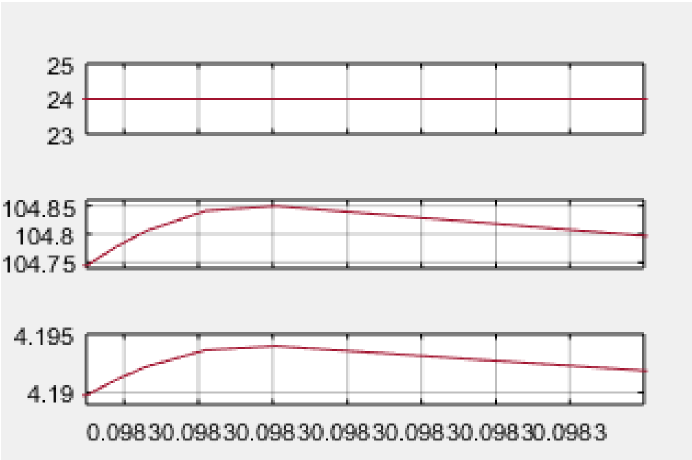
The Boost converter assembled in MATLAB Simulink is simulated with a constant input voltage value of 24Volt and a duty cycle of 76%.



Picture 3. Simulation of Boost converter Circuit

In Picture 3. Simulation of the Boost converter circuit with PWM (Pulse Width Modulation) control. The boost converter functions to increase the output value more significantly than the input voltage value. As a switch, MOSFET is one of the four main components: the diode, inductor, capacitor, and resistor. Power-switching components that use pulse width modulation (PWM) with varying duty cycles include transistors, field effect semiconductors, and metal oxides (MOSFETs). An increase in output voltage can be achieved by adjusting the components in response to variations in duty cycle values.

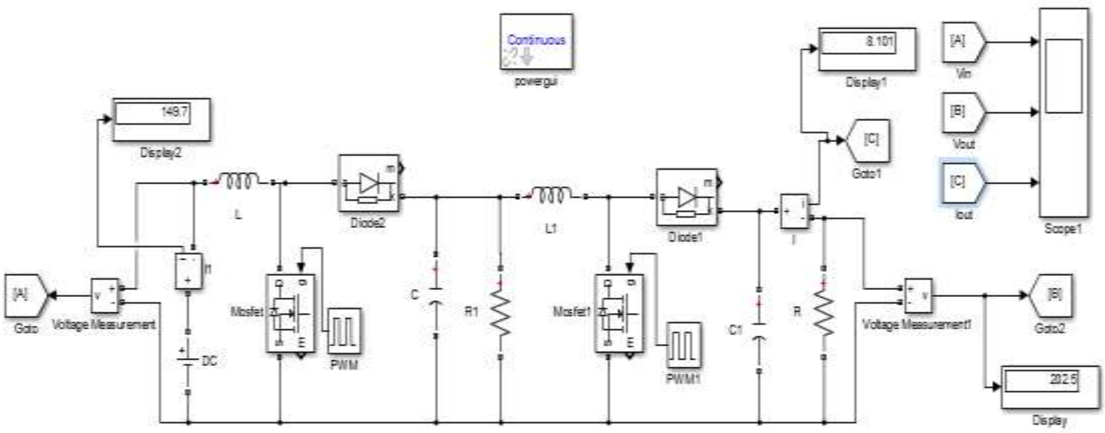
Picture 4 displays the simulation results of the Boost converter circuit.



Picture 4. Boost converter Simulation Result

Simulation of Cascaded Boost converter

The Boost converter assembled in MATLAB Simulink is simulated with a constant input voltage value of 24Volts and a duty cycle of 76% on each PWM.

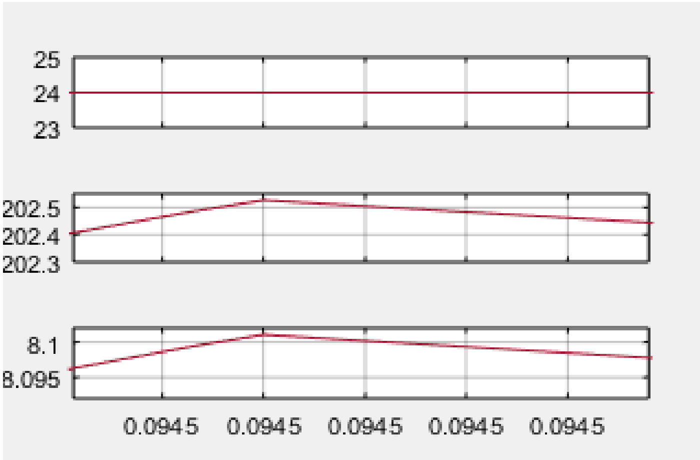


Picture 5. Simulation of *Cascade*d *Boost* *converter* Circuit

As depicted in Picture 5. A Cascaded circuit activates two Boost converter circuits, with the output voltage of the first Boost converter serving as the input for the second Boost converter. The combined output value of the two Boost converters is then produced. The Cascaded Boost converter consists of two metal oxide semiconductor field effect transistors (MOSFETs), two Pulse Width Modulation (PWM) signals, two inductor coils, two diodes, two filter capacitors, and two load resistors. These components compose the four significant elements of the converter.

The Cascaded Boost circuit employs two PWM signals to minimize power losses resulting from the power allocation to the load. Therefore, the output voltage of the Cascaded Boost can achieve the intended peak voltage.

Picture 6 displays the simulation results of the Cascaded Boost converter circuit.



Picture 6. Simulation Result of Cascaded Boost converter

Discussion

The voltage test results for the Cascaded Boost converter and Boost converter circuits are as follows, entered using the parameter values listed in Table 1. MATLAB Simulink is utilised to simulate the system. The purpose of conducting output voltage testing is to ascertain the capacity of each topology to elevate the voltage.

Table 2. Test Result of The Output Voltage of The Boost converter and Cascaded Boost converter

Vin (V)	*Duty cycle*	*Boost converter*		*Cascaded Boost converter*	
		Vout (V)	Time(s)	*Vout (V)*	Time(s)
24	5%	30.09	1	24.93	2
24	10%	33.65	1	27.89	3

24	20%	42.37	1	35.53	4
24	30%	51.65	2	46.56	4
24	40%	61.03	3	63.16	3
24	50%	70.39	8	89.22	6
24	60%	86.96	5	130.7	6
24	70%	98.02	7	186.1	8
24	76%	104.8	3	202.5	8

The output voltage can be adjusted by changing the duty cycle from 5% to 76% while keeping the input voltage constant at 24 Volts. For example, when the duty cycle is set at 76%, the Boost converter produces an output voltage of 104.8 volts, while the Cascaded Boost converter results in an output voltage of 202.5 volts.

In addition, the Boost converter and Cascaded Boost converter undergo efficiency testing. The efficiency is determined by calculating the ratio of output power to input power during the duty cycle test. The duty cycle ranges from 5% to 76% for both the Boost converter and the Cascaded Boost converter. The current flowing into and out of the circuit can be determined by simulating the circuit using MATLAB Simulink.

The results of the efficiency tests for the standard Boost converter and Cascaded Boost converter are shown in Tables 3 and 4, respectively.

Table 3. Efficiency Test Result of Cascaded Boost converter

Vin (V)	*Duty cycle*	$\boldsymbol{I_{out}}$ *(A)*	$\boldsymbol{I_{in}}$ (A)	Vout (V)	Efficiency
24	5%	0.99	I.98	24.93	52%
24	10%	1.11	2.24	27.89	57%
24	20%	1.42	3.11	35.53	73%
24	30%	1.86	4.88	46.56	73%
24	40%	2.52	8.55	63.16	77%
24	50%	3.56	16.75	89.22	79%
24	60%	5.22	36.97	130.7	77%
24	70%	7.44	90.05	186.1	64%
24	76%	8.1	149.7	202.5	90%

The efficiency test results of the Cascaded Boost converter are exceptional. As the duty cycle value increases, the output voltage also increases. The input current value exceeds the output current value, and this relationship is directly correlated with the duty cycle value. Specifically, as the duty cycle value increases, the power loss in the

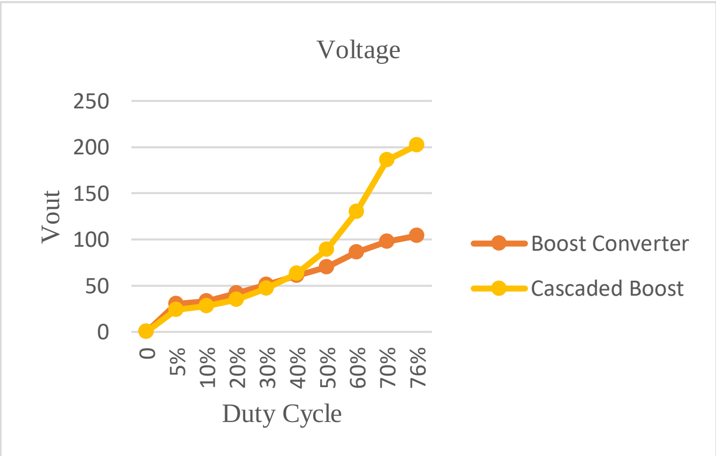
Cascaded Boost converter decreases. The Cascaded Boost converter achieves a maximum efficiency of 90% when the duty cycle value is 76%.

Table 4. Boost converter Efficiency Test Result

Vin (V)	*Duty cycle*	I_{out} *(A)*	I_{in} (A)	*Vout (V)*	Efficiency
24	5%	1.2	0.002	30.09	75%
24	10%	1.34	0.003	33.65	63%
24	20%	1.7	0.001	42.37	24,93%
24	30%	2.06	0.006	51.65	61,03%
24	40%	2.44	0.010	61.03	59,11%
24	50%	2.81	0.031	70.39	26,77%
24	60%	3.48	0.002	86.96	15,64%
24	70%	3.92	0.021	98.02	76,53%
24	76%	4.2	0.010	104.8	17,86%

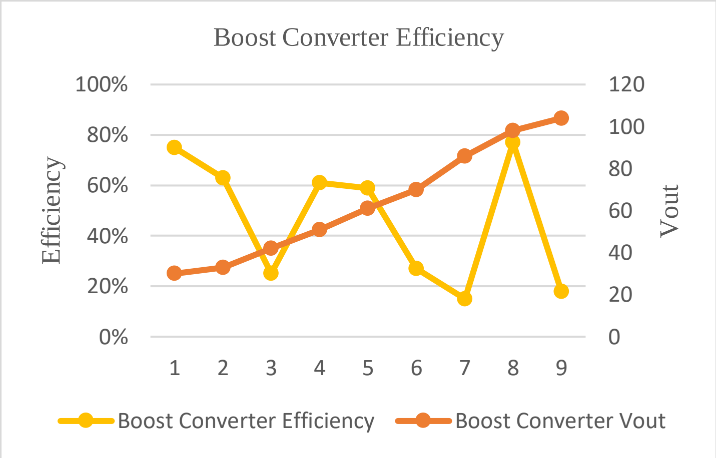
When analysing the efficiency generated in the Cascaded Boost converter experiment, it becomes apparent that the regular Boost converter has a lower efficiency. As the duty cycle value increases, the output voltage will also increase. Nevertheless, this causes a reduction in the input current in contrast to the output current, leading to power loss in the typical Boost converter. With a duty cycle of 76%, the Boost converter achieves an efficiency of 17.86%.

Picture 7 demonstrates that when the duty cycle value is altered, both the Boost converter and the Cascaded Boost converter respond by increasing the output voltage.

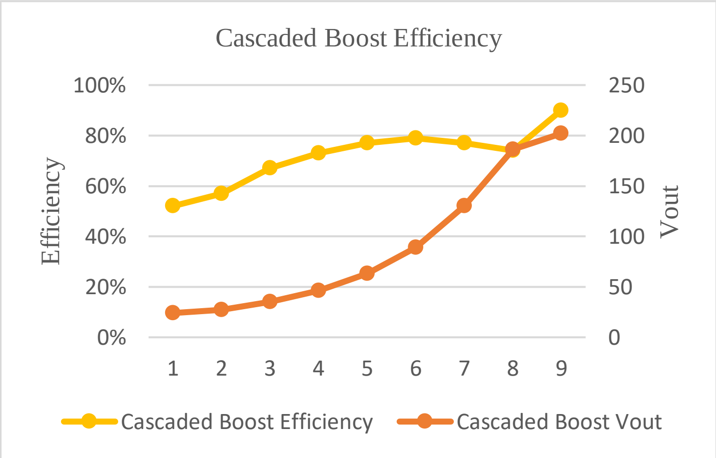


Picture 7. Output Voltage of Boost converter and Cascaded Boost converter

The graph compares the output voltage of the Boost converter and Cascaded Boost converter at different duty cycle values, ranging from 5% to 76%. It demonstrates that the voltage of the Cascaded Boost converter is double that of the Boost converter, reaching 202.5 Volts when the duty cycle value is 76%.



Picture 8. (a) Output Voltage of the Boost converter



Picture 9. (b) Output Voltage of the Cascaded Boost converter

The efficiency of two converters according to their output voltage is (a) Boost converter and (b) Cascaded Boost converter.

Each Converter circuit's performance is evaluated by evaluating the efficiency against a fixed output voltage and input voltage variation. The efficiency value can be calculated by (9).

Based on the efficiency test findings in Pictures (a) and (b), it is evident that the efficiency of the Cascaded Boost converter surpasses that of the conventional Boost converter as the duty cycle value increases from 5% to 76%. This comparison takes into account the varied output voltages of the two converters. This Cascaded Boost converter demonstrates an impressive efficiency of 90% and produces an output voltage of 202.5 volts when operated with a duty cycle of 76%. In comparison, the Boost converter achieves an efficiency of 17.86% with a duty cycle of 76%, which gives an output voltage of 104.8 Volts. This demonstrates that implementing the Cascade approach in the Boost converter circuit can enhance the circuit's dependability and double the output voltage compared to a standard Boost converter circuit.

After describing the results of the research, it is concluded that getting a high-efficiency value of the boost converter circuit, can be done by simulating the circuit in Matlab Simulink, the multilevel boost converter circuit can be modified by using two circuits connected in series and simplified components. Selection and calculation of component values utilizing analytical and differential methods are very important so in this multilevel boost converter circuit simulation using a switching frequency value of 40Khz which has been tested by trial and error on a multilevel Boost converter circuit in Mathlab before finally using it in this study. Calculation of component values such as the value of resistors, capacitors, and inductors also affects the performance and efficiency of the entire system more optimally.

In the simulation results of the multilevel boost converter with Mathlab simulink, after getting the appropriate component values as presented in this paper, the boost converter can reach twice the output voltage of a conventional boost converter and does not experience a voltage drop up to a duty cycle value of 76%. The efficiency test results show that the performance of the cascaded boost converter can be more stable in maintaining and increasing the efficiency of the circuit, even the efficiency of the cascaded boost converter circuit can reach 90% so that it can prevent the reduction of electric power in the load.

CONCLUSION

In this research, upon analysing the output voltage, it becomes evident that the cascaded boost converter can significantly amplify the output voltage, surpassing the input voltage by more than eight times. A cascaded boost converter can increase the voltage to twice the output voltage of a standard boost converter, specifically reaching 202.5 volts with a duty cycle of 76%. Although the efficiency of the cascaded boost converter is 90% with a duty cycle of 76%, the conventional boost converter only achieves 17.86% efficiency with the same duty cycle. This increase in efficiency can reduce losses due to excessive heat in the power switch, thus giving the device a longer lifetime. If the DC source is obtained from the converter, then the device can reduce the power factor on the network.

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