Design And Performance Analysis of a Solar-Powered Boost Converter with Inductor Variations Controlled by Arduino Uno

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Abstract *- This research designs and makes analysis of the performance of a solar panel-based DC-DC boost converter topology using an Arduino Uno microcontroller. Boost converter is given a variation of inductor wire with 30 turns and 60 turns using a diameter of 1 mm. This research was conducted to obtain the highest characteristics and efficiency of the performance of the boost converter that has been designed and made for each inductor wire turn variation. In this research, data analysis will be carried out, namely the effect of duty cycle on voltage and current, and how the effect of variations in the number of inductors turns on the efficiency of the boost converter. This circuit uses an arduino uno microcontroller to generate and control the duty cycle on pulse width modulation (PWM) to regulate and increase the desired output voltage. The inductor on the DC-DC boost converter with a wire variation of 60 turns at a diameter of 1 mm gets the highest efficiency with an average efficiency of 67.13 %, while the inductor wire with 30 turns gets an average efficiency of 66.32 %. The maximum voltage generated by the solar panel used as the main source of electrical energy in the boost converter is 20.0 V and the control system that has been applied to the arduino uno microcontroller can control and generate a duty cycle with a ratio of 0 % - 90 %. The boost converter circuit made gets low efficiency due to the presence of MOSFET components that work in non-ideal conditions, which causes excessive power losses.*

Keywords: *Boost Converter; Pulse Width Modulation; Inductor Winding Variation; Efficiency*

INTRODUCTION

Fossil fuels such as coal, oil and natural gas are energy that will run out if used continuously. Fossil energy has been used as the main fuel for electricity generation, transportation, and industrial processes in Indonesia for the past few decades (Giwangkara, 2021). Energy consumption in every country increases with the growth of its population and economy (Raj & Praveen, 2022).

The increasing need for fossil fuels as the main fuel for power generation has caused enormous environmental problems that impact public health (Gasparotto & Da Boit Martinello, 2021; Giwangkara, 2021). With these problems, the use of renewable energy sources such as foltovoltaic (PV) systems is increasingly being considered (Koç et al., 2022). PV systems have shortcomings during operation, namely voltage fluctuations and low DC output voltage produced (Anshory et al., 2024). In order to meet the needs of a promising and growing industry, a boost converter is required to increase the low output voltage, as well as eliminate voltage fluctuations at the output of solar panels (Raj & Praveen, 2022).

Boost converters are becoming a clear necessity to achieve the requirements of industrial electricity needs (Allehyani, 2022). Boost converters can produce a higher output voltage compared to the input voltage without having to dissipate excess power on solar panels (Shaw, 2019).

Conventional boost converters are widely used in step-up applications mainly because of their simple structure (Koç et al., 2022). In research (Pauzi et al., 2020) it is also said that the boost converter is a DC-DC converter circuit that can convert a smaller input voltage, into a larger output voltage with the same polarity.

However, in practice the extreme duty cycle of the switch, the parasitic components (inductance, and capacitance), and the acquired power losses will limit the achieved voltage gain (Lopez-Santos, 2020).

DC-DC converter elements often work under non-ideal conditions and have certain parasitics or non-idealities, such as the equivalent series resistance (ESR) of inductors and capacitors, the parasitic resistance of diodes and metal oxide semiconductor field effect transistors (MOSFETs) during conduction, and also the forward voltage drop of diodes (Vishwanatha & Yogesh V. Hote, 2017).

In DC-DC boost converters the size of the inductor greatly affects the overall size of the converter (Srija et al., 2019). Inductor is one of the passive elements of an electrical circuit that can store electromagnetic energy generated by the electric current passing through it. The ability of an inductor to store electromagnetic energy depends on its inductance value, with Henry units (Fitriani & Fitri, 2022).

Inductors in DC circuits are formed by cylindrical cores or toroid coils where the toroid is a solenoid that is curved to form a circle. Inductance is calculated from length, surface area, core material, and number of turns (Siswanto et al., 2015).

The output voltage of the boost converter is controlled by controlling the duty cycle on the pulse width modulation (PWM) (Alfaris & Yuhendri, 2020). The higher the frequency of the PWM pulse generated, the larger the inductor size required and the greater the output voltage produced (Marahatta et al., 2022).

Changing the size of the PWM is done by using switching components in the form of MOSFETs, as well as the use of gate drives that function as signal amplification and safety between the control circuit and the main circuit (Alfaris & Yuhendri, 2020).

The results obtained in the research (Pauzi et al., 2020) that the boost converter successfully increases the output voltage of the 48 Volt Lithium Ion battery charging circuit. Then in other research such as (Alfaris & Yuhendri, 2020; Marahatta et al., 2022), the research results show that the greater the duty cycle, the greater the output voltage produced.

This research designs and makes a conventional boost converter topology, based on solar panels using an Arduino Uno microcontroller to control the desired PWM (duty cycle) signal, and varies the number of inductor turns in the boost converter. The final goal of the boost converter design is to determine the effect of the boost converter circuit that has been given inductor variations on the efficiency of the power produced.

RESEARCH METHODS

Design And Operation

The data collection method used is quantitative method. The results of the data obtained in this study will be analyzed and made in the form of graphs.

The effect of duty cycle on voltage increase will be compared with previous literature studies. In this study, data analysis will be carried out, namely the effect of duty cycle on voltage and current, and how the effect of variation in the number of inductor turns on the performance of the boost converter design that has been made specifically on the resulting efficiency (η).

$$\eta = \frac{P_{out}}{P_{in}} \times 100\%$$

Boost converter consists of various power electronic components such as

MOSFETs, capacitors, diodes, resistors, and inductors (Mustari, 2019). MOSFET is used in this circuit because it has a fast response, when switching in ON or OFF conditions.

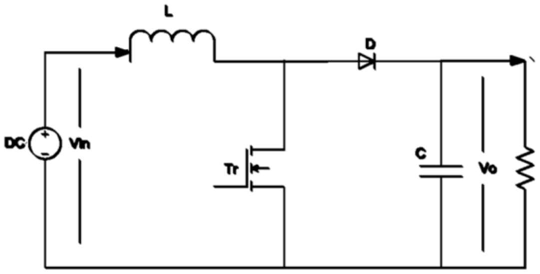

Figure 1. Boost Converter Circuit

The boost converter work process begins with the switching process, resulting in two different circuits as shown in Figure 2 and Figure 3 (Anshory et al., 2024). When the MOSFET is ON, the inductor voltage is equal to the input voltage. And the diode is in a pre-voltage reverse condition. When the switch condition is ON, there will be an increase in current in the inductor or inductor magnetization process (Assyidiq et al., 2017; Hauke, 2009). The voltage in the inductor and capacitor is equal to:

$$L\frac{di}{dt} = Vin$$

$$C\frac{dv}{dt} = -\frac{v}{R}$$

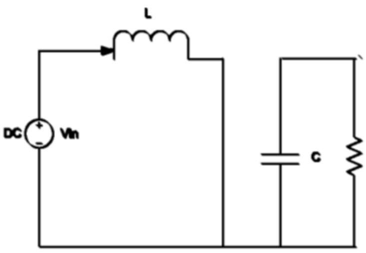

Figure 2. DC-DC Converter ON position.

The mathematical equation for the boost converter in the ON position is shown in equation (1)

$$V_L = Vin = L\frac{diL}{dt}$$

$$\frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{DT} = \frac{\text{Vin}}{L} \qquad (1)$$

$$\Delta i_{L(ON)} = \frac{\text{DTVin}}{L} = \frac{\text{DVin}}{LF}$$

The second condition is when the MOSFET is OFF. The diode in the boost converter is in forward prestressed condition. The energy that has been stored in the inductor will be flowed through the diode to charge the capacitor and supply the load. So there will be a transfer of power collected during the ON condition to the capacitor (Assyidiq et al., 2017; Hauke, 2009). The voltage across the inductor and capacitor is equal to:

$$L\frac{di}{dt} = -v + Vin$$

$$C\frac{dv}{dt} = i - \frac{v}{R}$$

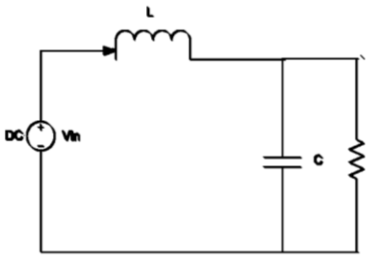

Figure 3. DC-DC Converter OFF position.

The mathematical equation for the boost converter in the OFF position is shown in equation (2).

$$\frac{\text{di}_L}{dt} = \frac{-V_{out}}{L}$$

$$\frac{\Delta i_L}{\Delta t} = \frac{-V_{out}}{L} \qquad (2)$$

$$\frac{\Delta i_L}{(1-D)T} = \frac{-V_{out}}{L}$$

$$\Delta i_{L(OFF)} = \left(\frac{-V_0}{L}\right)(1-D)T$$

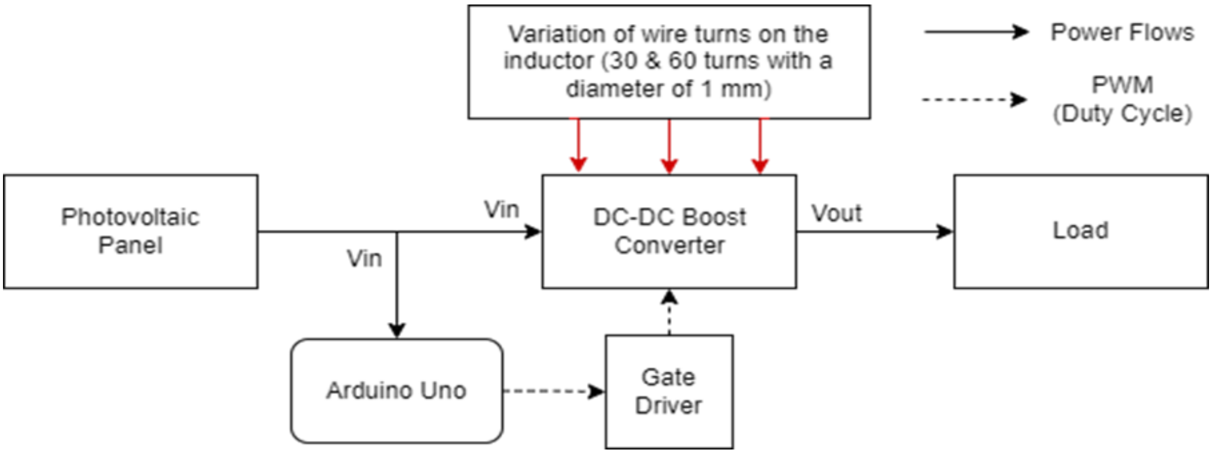

Figure 4. Block Diagram of a DC-DC Boost Converter

Figure 4 displays the block diagram for the design of the power supply system in the boost converter. This block diagram illustrates the configuration developed in the DC-DC Boost Converter with variations in the number of inductors turns with a fixed diameter.

The main energy source used is from solar panels that utilize sunlight radiation to produce direct current (DC) (Raj & Praveen, 2022). The arduino uno microcontroller will generate a PWM signal with a predetermined frequency and become a control system.

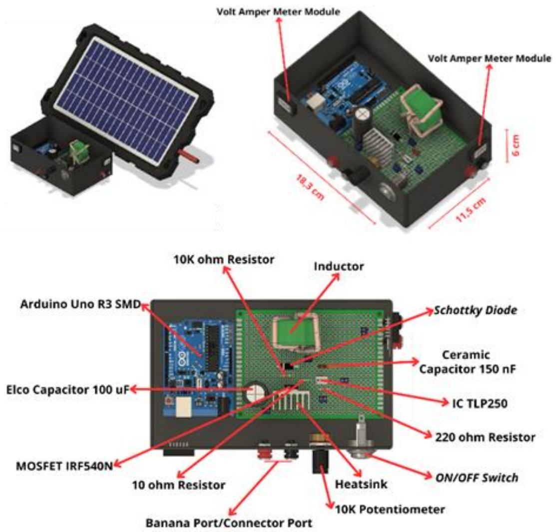

Figure 5. Device design

The control system aims to produce a varied output voltage by adjusting the amount of duty cycle on the PWM signal. This aims to get different efficiency results in the boost converter after being given variations in inductor windings. The boost converter is designed by varying the number of wire turns on the inductor by 30 and 60 turns and the diameter of the inductor wire by 1 mm. The design of the device used can be seen in Figure 5.

Table 1. DC-DC boost converter parameters.

Parameter	Symbol	Value
Input Voltage	Vin	$19.5\ V - 20.0\ V$
30 Turns Induktance	L	$4.07\ mH$
60 Turns Induktance	L	$16.3\ mH$
Resistance	R	$102\ \Omega$
Capasitance	C	$100\ \mu F$
Switching Frequency	f	$25\ KHz$
Duty Cycle	%	$10 - 60\ \%$
Output Voltage	$Vout$	$20.3\ V - 46.4\ V$

The inductance value and series resistance on the inductor can be calculated using the formula below:

$$L = \frac{N^2 x\ \mu_0\ x\ \mu_r\ x\ A}{\ell_{ef}}$$

$$R = \frac{\rho \ell}{A}$$

DC-DC Boost Converter Modeling

The boost converter circuit consists of a control circuit, gate driver circuit, and boost circuit. The first step in making a boost converter circuit starts with making a control circuit.

The control circuit is made to generate a PWM signal and set the duty cycle value we want, this circuit also functions as an output voltage controller on the boost converter by adjusting the duty cycle value using a 10K potentiometer connected to PIN A1 arduino uno. Control is done by supplying a PWM signal that controls the ON and OFF periods of the switch / Mosfet (Anshory et al., 2024).

After the control circuit design has been carried out, then design the gate driver circuit. The gate driver circuit is used to amplify the PWM signal that has been generated by the Arduino Uno, and is useful for activating and switching the IRF540N MOSFET component contained in the boost circuit (Alfaris & Yuhendri, 2020). The gate driver circuit used is IC TLP250.

After designing the gate driver circuit, proceed with designing the boost circuit used to increase the voltage received from the solar panel. The boost circuit uses an IRF540N MOSFET. MOSFET will receive a PWM signal (duty cycle) given by the output leg of the gate driver circuit, which then the signal will affect the length of the MOSFET gate in the ON and OFF positions.

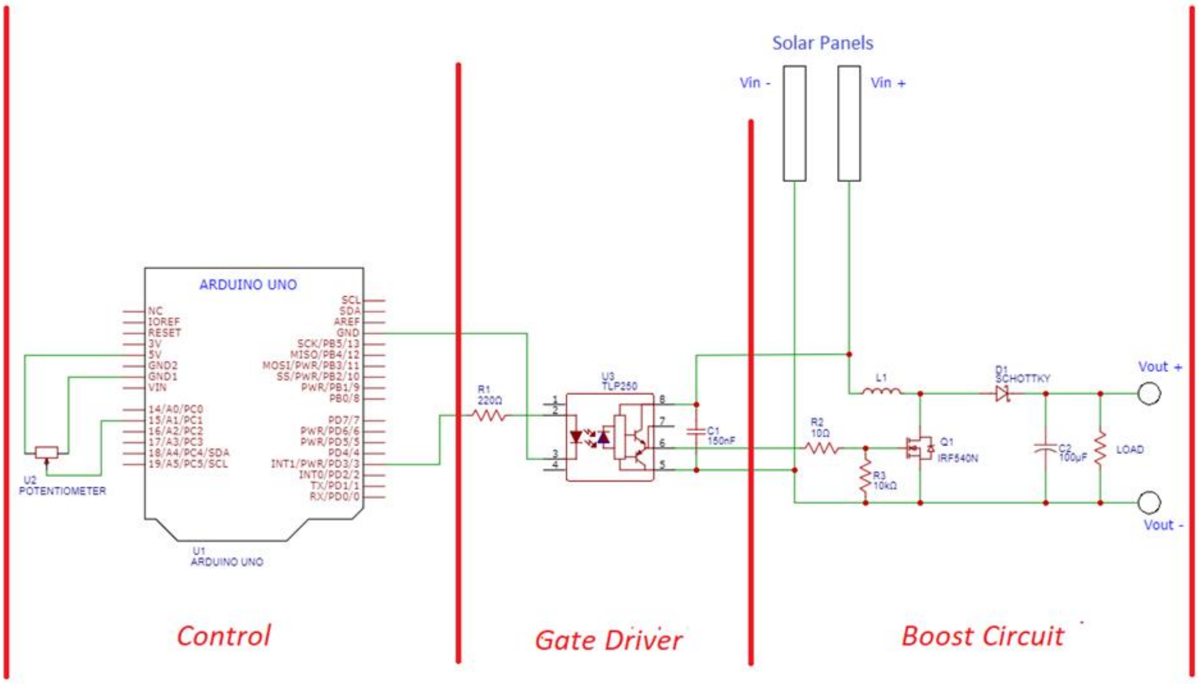

Figure 6. DC-DC boost converter circuit

These conditions will affect the size of the increase in output voltage produced due to the energy conversion that occurs in the inductor in this boost circuit. During the electrical energy conversion process, the boost converter only modifies the DC output voltage and current levels, without changing the input power value (Anshory et al., 2024). Figure 6 is the modeling of the DC-DC boost converter circuit that has been designed.

RESULTS AND DISCUSSION

To determine the performance of the boost converter that has been designed, especially related to the optimization of the efficiency that occurs, the boost converter that has been designed will be implemented and analyzed. The author will analyze the effect of inductor wire winding variation, and the effect of duty cycle on voltage rise, current strength, and boost converter efficiency.

Results

Photovoltaic

In this research, a 100 Wp photovoltaic system used as the main source in the boost converter was tested. The PV module was tested based on electrical characteristics. $LUX - P$ characteristics are parameters that will provide information about the operational conditions of the photovoltaic system shown in Figure 7.

Figure 7 shows the $LUX - P$ characteristics of the PV module. The $LUX - P$ curve illustrates the relationship between light intensity and power generated by the PV module used. In this research, two PV modules with the same specifications are used which are written in table 2.

Table 2. Electrical parameters of the 100 Wp photovoltaic panel.

Parameter	Symbol	Value
Peak Power	$Pmax$	100W
Cell Efficiency	%	16.93%
Max. Power volt	Vmp	17.8 V
Max. Power current	Imp	5.62 A
Open circuit volt	Voc	21.8 V
Short circuit current	Isc	6.05 A
Operating temperature	^{0}C	$-4^{0C}\ to{+}8^{0C}$
Max. system voltage	VDC	1000 $V\ DC$

Since the characteristics of the electricity generated will vary with changes in environmental conditions, this test is important to determine the results of differences in characteristics of how efficiently the two PV modules can generate electricity from sunlight.

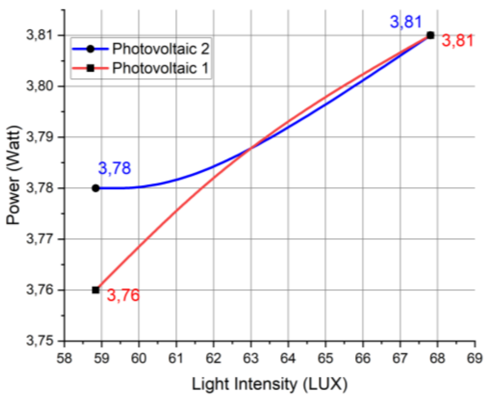

Figure 7. Graphic LUX - P characteristics of PV module

From the graph above, it is obtained that the characteristics of the power produced are not much different between the two PV modules used as the main source of electrical energy in the boost converter. It can be concluded that the two solar panels can be used as a power source in this research.

Control Circuit Testing

Control testing begins by verifying that the code made can run with the desired function. The author uses an oscilloscope to ensure that the Arduino Uno microcontroller can generate the voltage and frequency that has been set, and can control the PWM (duty cycle) value using a potentiometer by looking at the PWM graph display and the duty cycle value displayed on the oscilloscope display. In this test, three experiments were carried out with duty cycle variations of 30 %, 60 %, and 90 %.

30 %

60 %

90 %

Figure 8. Testing the control circuit on the Arduino Uno

PWM wave testing in Figure 8 above is said to be successful because the pulse width graph displayed on the oscilloscope display can change according to the desired data. When the author increases the duty cycle using a potentiometer, the pulse width signal in the ON (DT) state will widen and the pulse width signal in the OFF $(1-D)T$ state will be smaller, and vice versa.

Boost Converter Experiment Results

Testing of the boost converter with variations of inductors of 30 and 60 turns at a diameter of 1 mm has been carried out. MOSFET switching operates at a frequency of 25 KHz, an output capacitor of 100 μF, a load of 102 Ω, and light intensity that varies according to environmental conditions. An arduino uno based controller is used to generate the PWM signal. Pulse width modulation works by varying the pulse width ($Tons$) of the output wave with a constant frequency.

The MOSFET in the boost converter will receive a PWM signal (duty cycle) given by the output leg of the gate driver circuit, which then the signal will affect the length of the MOSFET gate in the ON or OFF position. This condition will affect the size or size of the increase in output voltage obtained. Tables 3 and 4 are the data taken in this research.

Table 3. Inductor with 30 turns at 1 mm Diameter

Intensitas Cahaya (LUX)	Frekueansi (Hz)	Duty Cycle (%)	Vin (V)	Vout (V)	Iin (A)	Iout (A)	Pin (W)	Pout (W)	Efisiensi (%)
37,450	25,000	10%	19.5	20.3	0.29	0.16	5.65	3.24	57.43
122,800	25,000	20%	19.8	23.9	0.37	0.18	7.32	4.30	58.72
121,100	25,000	30%	19.7	27.3	0.46	0.23	9.06	6.27	69.28
116,400	25,000	40%	19.5	31.8	0.62	0.26	12.0	8.26	68.38
134,600	25,000	50%	19.8	38.2	0.93	0.35	18.4	13.3	72.60
125,900	25,000	60%	19.7	45.2	1.38	0.43	27.1	19.4	71.49

Table 4. Inductor with 60 turns at 1 mm Diameter

Intensitas Cahaya (LUX)	Frekueansi (Hz)	Duty Cycle (%)	Vin (V)	Vout (V)	Iin (A)	Iout (A)	Pin (W)	Pout (W)	Efisiensi (%)
37,450	25,000	10%	19.5	20.9	0.31	0.18	6.04	3.76	62.23
122,800	25,000	20%	19.7	23.8	0.39	0.20	7.68	4.76	61.95
121,100	25,000	30%	19.6	27.2	0.49	0.24	9.60	6.52	67.97
116,400	25,000	40%	19.6	31.8	0.65	0.28	12.7	8.90	69.89
134,600	25,000	50%	20.0	38.8	0.95	0.34	19.0	13.1	69.43
125,900	25,000	60%	19.7	46.4	1.42	0.43	27.9	19.9	71.32

From the table, it is obtained that the greater the duty cycle, the greater the output voltage value. Duty cycle occurs when there is a comparison of the time when the MOSFET signal reaches the ON and OFF conditions in one signal period.

Discussion

Effect of duty cycle on voltage with variations of 30 and 60 turns

In Figure 9, previous research (Assyidiq et al., 2017; Marahatta et al., 2022) found that the increase in output voltage in the boost converter will be directly proportional to the increase in duty cycle. The voltage increase in the boost converter occurs due to the MOSFET switching process and energy conversion in the inductor. When the MOSFET switch is ON (DT), the amount of duty cycle (D) will affect the length of the MOSFET gate in a closed state, so that the input current stored in the inductor will be more and more.

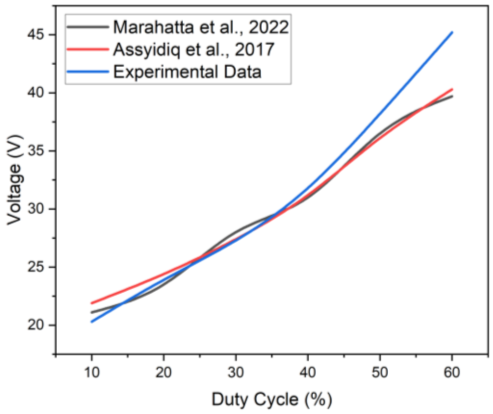

Figure 9. Effect of duty cycle on voltage in previous research

Then the average current (IL) stored in the inductor in the magnesitation process will be released and rectified by the schottky diode when the MOSFET switch is OFF $(1 - D)T$, which causes an energy conversion that will increase the output voltage on the boost converter.

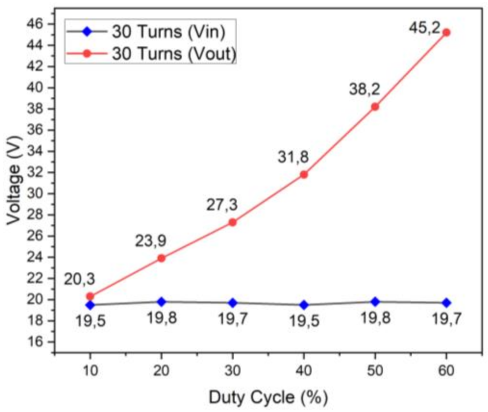

Figure 10. Voltage graph on a 30 turns inductor with a diameter of 1 mm

Therefore, the increase in boost converter output voltage is influenced by the magnitude of the duty cycle. Figures 10 and 11 show the phenomenon of the effect of duty cycle on voltage in this research. The results obtained are the same as the results in previous studies (Assyidiq et al., 2017; Marahatta et al., 2022), the greater the duty cycle, the greater the output voltage produced.

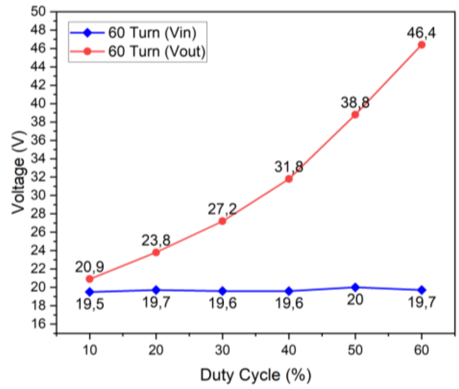

Figure 11. Voltage graph on a 60 turns inductor with a diameter of 1 mm

Effect of duty cycle on current with variations of 30 and 60 turns

The increase in current in the boost circuit is influenced by several things, namely the length of the switch switch in the ON state, when the switch switch is OFF, the series resistance and the ability of the inductor to store current (L). When the switch is ON (DT), there will be energy storage in the inductor. Figure 12 is the phenomenon of the effect of duty cycle on the input current in the boost converter that has been made.

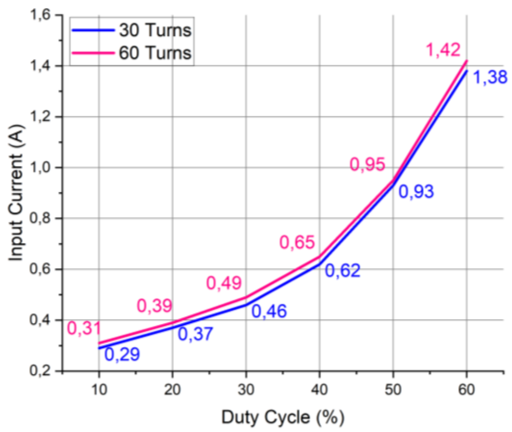

Figure 12. Graph of the effect of duty cycle on input current

The greater the duty cycle ON (DT), the more current will flow through and stored in the inductor. The increase in input current occurs to meet the needs of energy conversion at the output of the boost converter.

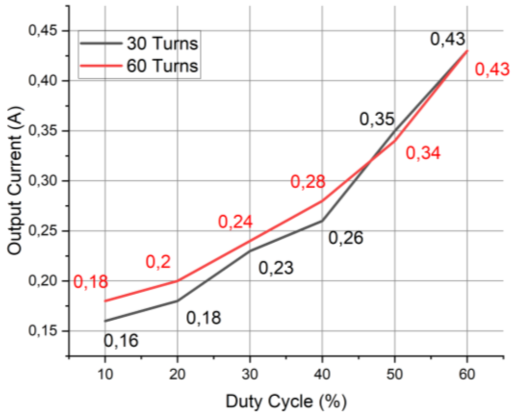

Figure 13. Graph of the effect of duty cycle on output current

The current in the inductor will be converted into a higher voltage when the switch is OFF. The amount of output current in Figure 13 depends on the amount of load used.

From the graphs in Figures 12 and 13 above, it can be seen that the higher the duty cycle, the magnitude of the current will also continue to increase, and the magnitude of the output current will not exceed the magnitude of the input current due to maintaining the power balance in the boost converter.

Efficiency of the boost converter

The efficiency of the boost converter is influenced by several factors, for example the inductor inductance factor (L), inductor series resistance (R), MOSFET switching process, power losses in the inductor and MOSFET, inductor average current (IL), frequency, current ripple (ΔIL), and continuous current mode (CCM) conditions in the boost converter circuit.

Power loss factors and CCM conditions greatly affect the efficiency value produced by the boost converter. The greater the power loss in the boost converter, the lower the efficiency. The amount of current ripple in the boost converter will also greatly affect the value of power loss generated in the inductor or MOSFET.

The greater the ripple current, the greater the heat generated in each component used, therefore the greater the power loss.

In addition, the boost converter in continuous current mode (CCM) will get a higher efficiency when compared to discontinuous current mode (DCM) conditions, this is because when the boost converter is in CCM condition, the current in the inductor will never reach zero.

The effect of inductors on boost converter efficiency is to consider several things, for example the number of turns and wire diameter. The more turns the inductance value will be higher, but the resistance value will also be higher.

The calculation below is the calculation of resistance and inductance in the variation of wire turns on the inductor:

1. 30 turns inductor

$$R = \frac{1.68\ x\ 10^{-8}\ x\ 3.66}{0.785\ x\ 10^{-6}} = 0.078\ \Omega$$

$$L = \frac{30^2 x\ 4\pi\ x\ 10^{-7} x\ 2000\ x\ 220\ x\ 10^{-6}}{0.122}$$

$$L = 0.00407\ H$$

2. 60 turns inductor

$$R = \frac{1.68\ x\ 10^{-8}\ x\ 7.32}{0.785\ x\ 10^{-6}} = 0.156\ \Omega$$

$$L = \frac{60^2 x\ 4\pi\ x\ 10^{-7} x\ 2000\ x\ 220\ x\ 10^{-6}}{0.122}$$

$$L = 0.01630\ H$$

Inductors with high inductance values can reduce the current ripple in the boost converter. All of these matters will affect each other on the high efficiency obtained in the boost converter.

1. 30 turns inductor

$$\Delta I_L = \frac{0.6\ X\ 19.7}{0.00407\ x\ 25{,}000} = 0.116\ A$$

$$I_L = \frac{0.43}{1 - 0.6} = 1.07\ A$$

2. 60 turns inductor

$$\Delta I_L = \frac{0.6\ X\ 19.7}{0.01630\ x\ 25{,}000} = 0.029\ A$$

$$I_L = \frac{0.43}{1 - 0.6} = 1.07\ A$$

From the above calculations it can be seen that the condition of the boost converter in this study works in continuous current mode (CCM). The highest efficiency is found in the inductor with 60 turns of wire. Inductors with a variation of 60 turns have the most optimal efficiency because they have a balance between the ability of inductance and the value of resistance, so that inductors with 60 turns have a smaller current ripple value compared to inductors with 30 turns.

The graph in Figure 14 is the result of calculating the average efficiency of variations of 30 and 60 turns of inductor wire with a diameter of 1 mm. The average efficiency is influenced by several factors contained in the boost converter circuit, namely current ripple, average current in the inductor, resistance, inductance, and power losses.

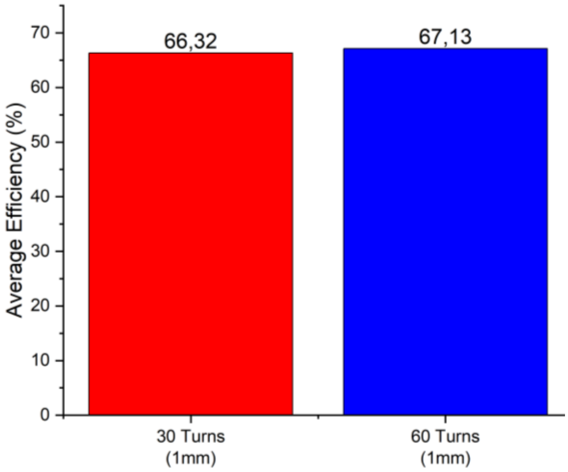

Figure 14. Average inductor efficiency

The average efficiency in this study produces a low efficiency value because it has limitations on the use of MOSFET components. The MOSFET in this study experienced a fairly high temperature increase (heat) when used even though it was used a heatsink. So that it results in high power losses during the MOSFET switching process.

CONCLUSION

Based on the results of the DC-DC boost converter design using inductor wire variations with 30 and 60 turns at a diameter of 1 mm. It can be concluded that the magnitude of the duty cycle affects the increase in output voltage and strong input and output currents. The current in the boost converter will continue to increase with the magnitude of the duty cycle. But the resulting output current will not be greater than the input current, so the output power of the boost converter will not be able to exceed the input power of the boost converter.

Inductors with wire variations of 60 turns in diameter 1 mm get the greatest efficiency with an average efficiency of 67.13 %. This is because the inductor variation with 60 turns has better inductance capability, the small value of series resistance in the inductor, and the small value of current ripple that occurs in the boost converter. The maximum voltage generated by the solar panel used as the main source of electrical energy in the boost converter is 20.0 V and the control system that has been designed on the Arduino Uno microcontroller can control and generate a duty cycle with a ratio of 0 % - 90 %. The boost converter circuit that has been made gets low efficiency due to the presence of MOSFET components that work in non-ideal conditions, which causes excessive power losses.

In the research that has been done, the author suggests for further research that this research can be developed using signal processing modulation techniques, varying different inductor sizes, or using other topologies such as the coupled inductor topology. This research can be applied to the use of solar power systems in household electricity, electric car charging, or charging systems that require a high enough voltage.

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