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Design Simulation and Hardware Construction of an Arduino-Microcontroller Based DC-DC High-Side Buck Converter for Standalone PV System

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ABSTRACT
This study primarily focuses on the design of a high-side buck converter using an Arduino microcontroller. The converter is specifically intended for use in DC-DC applications, particularly in standalone solar PV systems where the PV output voltage exceeds the load or battery voltage. To evaluate the performance of the converter, simulation experiments are conducted using Proteus Software. These simulations provide insights into the input and output voltages, currents, powers, and efficiency under different state of charge (SoC) conditions of a 12V,70Ah rechargeable lead acid battery. Additionally, the hardware design of the converter is implemented, and practical data is collected through operation, monitoring, and recording. By comparing the simulation results with the practical results, the efficiency and performance of the designed converter are assessed. The findings indicate that while the buck converter is suitable for practical use in standalone PV systems, its efficiency is compromised due to a lower output current.

KEYWORDS: *Arduino-microcontroller, DC-DC High-side Buck, Switching Frequency, Proteus, Output Voltage, Output Current, Efficiency*

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INTRODUCTION
Nowadays, there is a growing demand for power while the resources used for power generation are becoming increasingly insufficient. Traditional resources like fossil fuels contribute to global warming and the greenhouse effect. As a result, renewable energy resources are being utilized on a large scale for power generation. Since most renewable energy resources generate DC voltage, DC-DC power electronic converter circuits are extensively employed to convert one DC voltage level to another. Various converter topologies such as buck, boost, buck-boost, CUK, SEPIC, and ZETA are commonly used in photovoltaic (PV) applications to achieve regulated DC power based on the specific requirements. This study focuses on the implementation of an Arduino-microcontroller based DC-DC converter using the buck topology for a Stand-alone solar PV system [1].

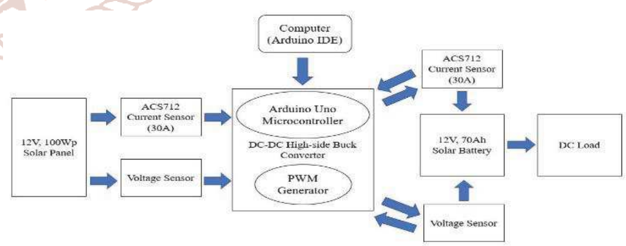


Fig. 1. Stand-alone PV system with Arduino-microcontroller based DC-DC High-side buck converter

The study showcases the development of an Arduino-microcontroller based DC-DC high-side buck converter for a standalone PV system through design simulation and hardware implementation. The power supply is used for both simulation and practical testing, replacing the 100 Wp solar PV module paired with a 12 V,70Ah rechargeable lead acid battery. Design calculations are meticulously performed based on the specifications of the chosen module and battery. Subsequently, modeling and simulation activities are conducted using Proteus software. The hardware design is then constructed with the calculated component values. The outcomes are meticulously documented and stored using an Arduino Data Logger Shield, accompanied by graphical representations. Finally, the efficiency and effectiveness of the designed converter are assessed.

OPERATION OF ARDUINO-MICROCONTROLLER BASED DC-DC HIGH-SIDE BUCK CONVERTER

The DC-DC high-side buck converter based on Arduino microcontroller primarily comprises storage elements (specifically inductor and capacitor), power electronic switches (transistor switches like BJT, MOSFET, or IGBT, and diode switch), and an Arduino microcontroller. In Figure 2, the inductor is linked with the capacitor to create an LC low pass filter, which aids in reducing the output ripple voltage. During the ON state, the inductor stores energy and discharges it to the load during the OFF state. The capacitor functions as a smoothing filter. A variable resistor is utilized for adjusting the duty cycle from 0% to 100%. A transistor switch like MOSFET is employed to regulate the duty cycle of the pulse width modulation (PWM) signal produced by the Arduino microcontroller and manage the energy flow between the input and output. When the switch is turned ON, the diode becomes reverse biased and supplies energy to both the inductor and the load [2].

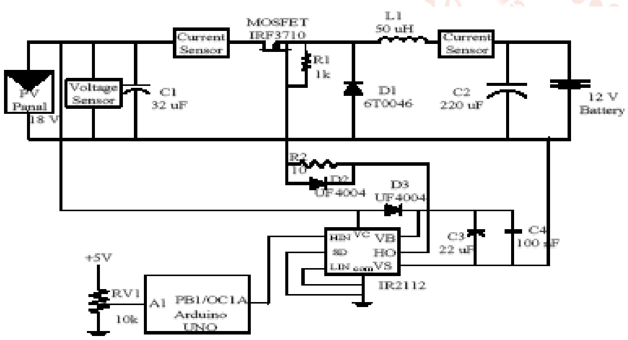


Fig. 2. Circuit Schematic for Arduino-microcontroller based DC-DC High-side Buck Converter

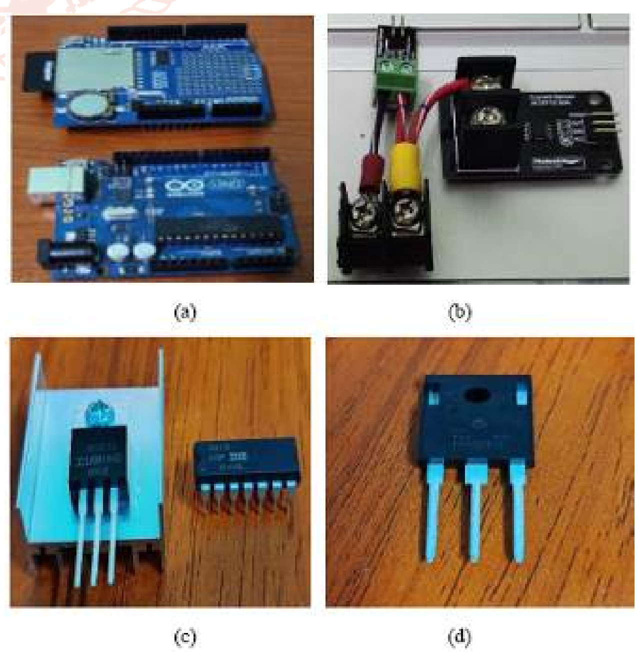
When the switch is in the OFF position, the diode will be forward biased, allowing the stored energy from the inductor current to be transferred to the load. The diode switch is designed to ensure continuous conduction even when the circuit is open (OFF). To trigger the MOSFET, a MOSFET gate driver is employed. The Arduino microcontroller is responsible for generating a PWM signal with the desired switching frequency (fs). Voltage and current sensors are utilized to detect and measure the voltage and current levels. The primary purpose of the DC-DC buck converter is to decrease a higher input DC voltage to a lower output DC voltage level [3].

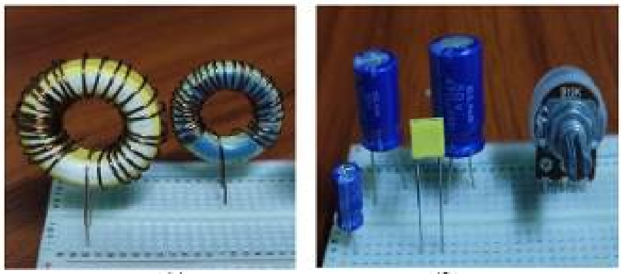
MAIN COMPONENTS NEEDED FOR STAND-ALONE PV SYSTEM WITH ARDUINO-MICROCONTROLLER BASED DC-DC HIGH-SIDE BUCK CONVERTER

The hardware circuit is constructed by gathering the components depicted in Fig. 2. The primary component in this circuit includes:

- Arduino UNO board and Arduino Data Logger Shield: This combination is utilized to supply the PWM signal to the Gate terminal of the MOSFET and for real-time measurement and data logging of input/output voltage and current.
- Voltage and Current Sensor: These sensors are employed to detect and quantify the input/output voltage and current of the high-side buck converter.
- MOSFET and Schottky Diode: These semiconductor devices are utilized for the necessary switching operations.
- MOSFET driver: This circuit is responsible for driving the gate of power MOSFETs in applications requiring high-speed switching.

The key components utilized for the Arduino-microcontroller based DC-DC high-side buck converter are illustrated in Fig. 3.





(e) (f)

Fig. 3. Circuit components used in High-side Buck Converter: (a) Arduino UNO Board with data logger shield, (b) Voltage Sensor and Current Sensor, (c) MOSFET and MOSFET Driver, (d) Schottky Diode, (e) Self-made Inductors and (f) Capacitors and Variable Resistor

MATHEMATICAL DESIGN CALCULATION OF ARDUINO-MICROCONTROLLER BASED DC-DC HIGH-SIDE BUCK CONVERTER

In order to determine the accurate rating of circuit components, the mathematical equations specified for Arduino-microcontroller based DC-DC high-side buck converter design are utilized. Equation (1) is employed to compute the desired output voltage based on the maximum input voltage. The inclusion of converter efficiency (η) in the duty cycle (D) calculation enhances the accuracy of the duty cycle value. Equation (2) is utilized to determine the maximum output current required for this particular design. Equation (3) provides a reliable estimation for the appropriate inductor ripple current. Equation (4) is used to calculate the correct power transistor switch current. Equation (5), in conjunction with the desired switching frequency (fs), aids in selecting the suitable inductor. A smaller inductance (L) results in a reduced inductor size. Equation (6) considers the peak-to-peak ripple voltage to calculate the minimum input capacitance. Lastly, Equation (7) considers the output ripple voltage to calculate the minimum output capacitance.

$$D = \frac{Vout(desired)}{Vin(max) \times \eta} \tag{1}$$

$$I_{out(max)} = \frac{Pmax}{Vout(desired)} \tag{2}$$

$$\Delta I_L = (0.2 \text{ to } 0.4) \times I_{out(max)} \tag{3}$$

$$I_{SW(max)} = \frac{\Delta IL}{2} + I_{out(max)} \tag{4}$$

$$L = \frac{(Vin(max) - Vout) \times D}{fs \times \Delta IL} \tag{5}$$

$$C_{in(min)} = \frac{Iout \times D \times (1-D)}{fs \times \Delta Vpp} \tag{6}$$

$$C_{out(min)} = \frac{\Delta IL}{8 \times fs \times \Delta Vout} \tag{7}$$

METHODOLOGY

The Arduino-microcontroller based high-side buck converter is designed to reduce the DC voltage from the solar panel input range of 17V-18.05V to the output range of 11V to 14.7V. The converter operates at a switching frequency of 31.375 kHz and has realistic values for efficiency (90%), input capacitance ripple voltage (75mV), and output capacitance ripple voltage (20mV). The calculated values include the duty cycle (0.98), inductor ripple current (1.39A), inductance (50uH), input capacitance (32uF), and output capacitance (249uF). The simulation model of the Arduino-based low-side buck converter is performed using Proteus 8 Professional Software, considering the estimated and calculated values based on Equations (1) to (7). The PWM output signal from the Arduino microcontroller, operating at the desired switching frequency of 31.375 kHz, is measured using a virtual instrument (oscilloscope), while the voltage, current, and power values are measured using virtual instruments (voltmeter, ammeter, and wattmeter). A low pass filter is added to the circuit to obtain a purely DC output voltage, and a metal oxide field effect transistor (MOSFET) is used as the power transistor switch for faster switching speed.

The necessary components for the hardware construction are selected based on the maximum transistor switch current and maximum solar input voltage. This is because components like MOSFET, inductor, capacitor, diode, and resistor need to be able to withstand these specifications. The hardware design is then tested, analyzed, and measured using measuring instruments such as a digital oscilloscope, laboratory DC power supply, RLC meter, and digital multimeter. The real-time measuring results, obtained using a 12V, 100W solar panel and a 12V, 70Ah rechargeable battery, demonstrate that the Arduino-microcontroller based DC-DC high-side buck converter circuit can successfully produce the expected results.

ARDUINO-MICROCONTROLLER BASED DC-DC HIGH-SIDE BUCK CONVERTER DESIGN SIMULATION

A simulation model of a DC-DC high-side buck converter based on Arduino microcontroller is developed using the block diagram illustrated in Figure 1. The input voltage is set to 18 V, based on the PV module specifications. The output of the converter is linked to charge a 12.0 V battery. The values of inductance and capacitance for the circuit are determined using the equations provided in Section 4. The simulation model design is depicted in Figure 4.

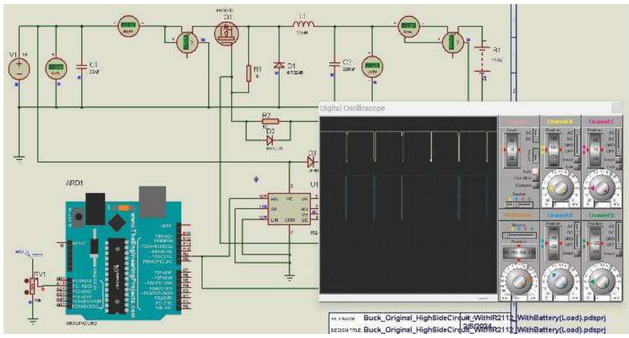
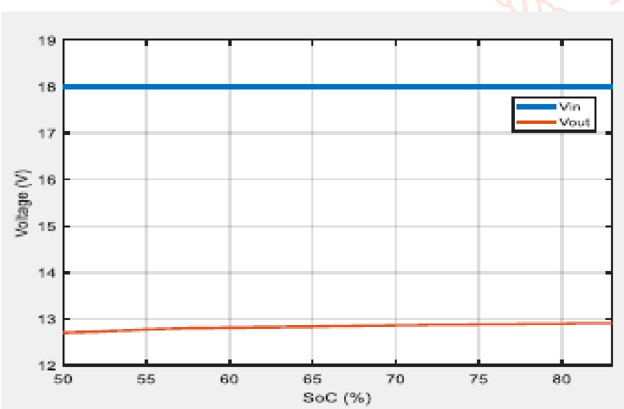


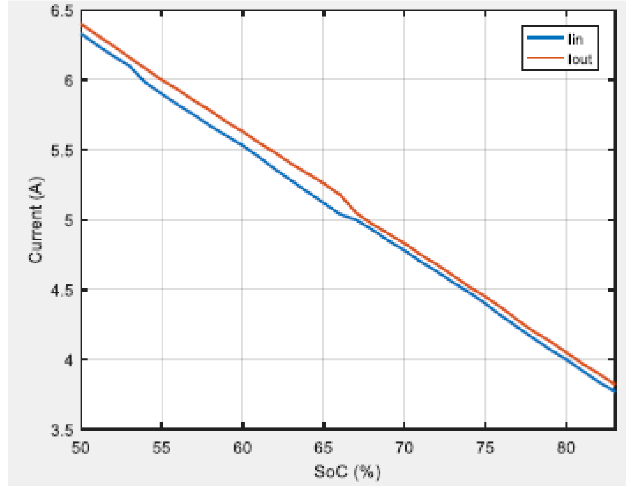
Fig. 4. (31.375 kHz) Arduino-microcontroller based DC-DC High-Side Buck Simulation Test by Proteus Software

During the simulation test, the converter's input/output voltage, current, and power are assessed using virtual measuring instruments. The duty cycle remains consistent at 0.98 per unit. The PWM signal is observed at the MOSFET driver's input and the MOSFET's Gate terminal through a virtual oscilloscope. The simulation is conducted by considering different battery SoC levels to gather realistic data. The simulation outcomes of the converter design are illustrated in Figure 5.

In Figure 5(a), the voltage output is lower than the input voltage, falling within the range of 12.7 V to 12.9 V. This specific voltage range is suitable for charging the battery safely. In Figure 5(b), the output current is slightly higher than the input current. This increased output current helps in minimizing power losses within the system. Moving on to Figure 5(c), the efficiency shows a slight improvement as the State of Charge (SoC) of the battery increases. The efficiency range is between 71% and 73%, with an average efficiency of approximately 72%.



(a)



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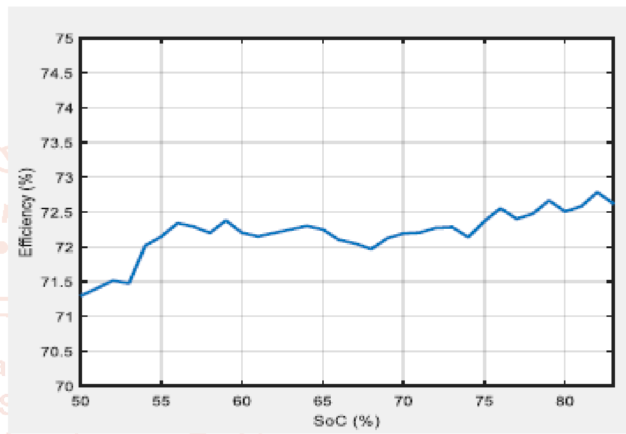
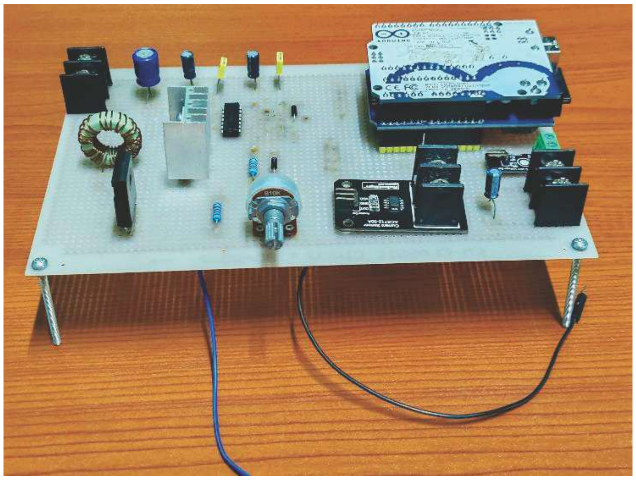


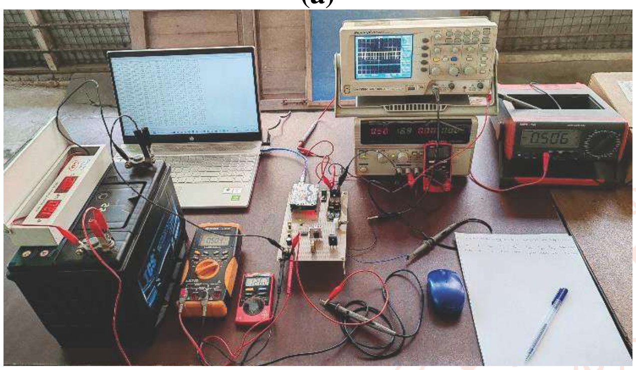
Fig. 5. Simulation Results for: (a) Voltage vs. Battery SoC, (b) Current vs. Battery SoC and (a) Efficiency vs. Battery SoC of High-side Buck Converter

HARDWARE DESIGN CONSTRUCTION OF ARDUINO-MICROCONTROLLER BASED HIGH-SIDE BUCK CONVERTER

The hardware design of the high-side buck converter, which is based on an Arduino microcontroller, is implemented using the simulation model depicted in Figure 4. Instead of using the voltage from the PV module, the input voltage is sourced from the power supply and set to 18.1 V. The output of the converter is connected to charge a 12.0 V,70Ah battery. The values of the circuit parameters, such as inductance and capacitance, are determined using the equations presented in Section 4. The hardware construction and experimental setup are illustrated in Figures 6(a) and 6(b).



(a)

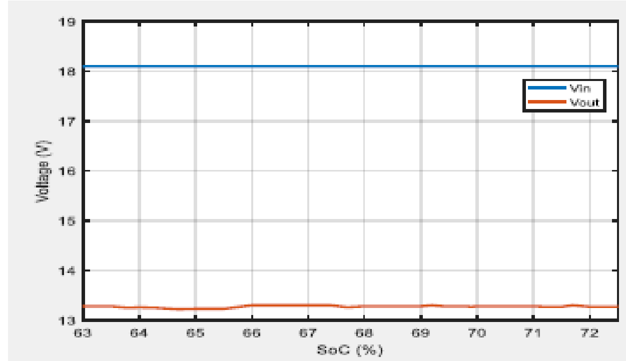


(b)

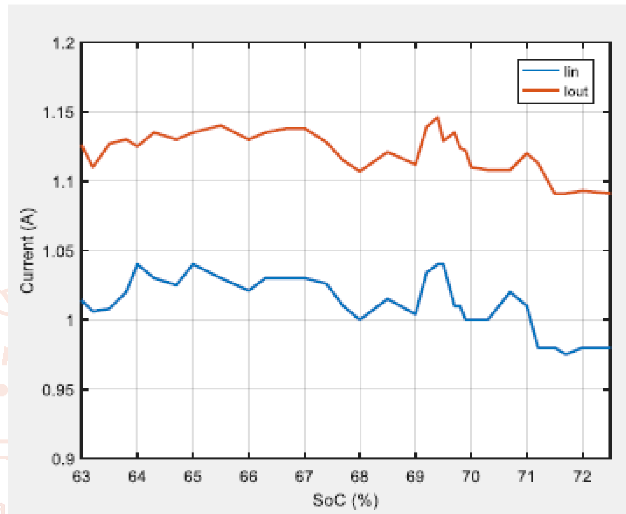
Fig. 6. (a) Hardware Design of Arduino-microcontroller based DC-DC High-side Buck Converter and (b) Practical Setup with buck converter

During the experimental test, the converter's input voltage and current are measured using sensors, while the output voltage and current are measured with digital multimeters. The duty cycle is maintained at a constant value of 0.98 per unit. The Pulse Width Modulation (PWM) signal is observed at the Gate terminal of the MOSFET using a digital oscilloscope. In the experimental process, a discharged 70Ah, 12V lead-acid battery is recharged from 61% to 73% State of Charge (SoC) using the designed hardware circuit. Data from the experiment, which includes various battery SoC levels, is gathered every 20 minutes from 9:30 am to 4:30 pm and presented in Fig. 7.

In Figure 7(a), the voltage output is lower than the input voltage, measuring approximately 13.28V. This voltage is sufficient for safely charging the battery. In Figure 7(b), the output current is slightly higher than the input current, which helps in reducing power losses within the system. Moving on to Figure 7(c), the efficiency shows a slight improvement as the State of Charge (SoC) of the battery increases. The efficiency range falls between 80% and 83%, with an average efficiency of around 81.5%.



(a)



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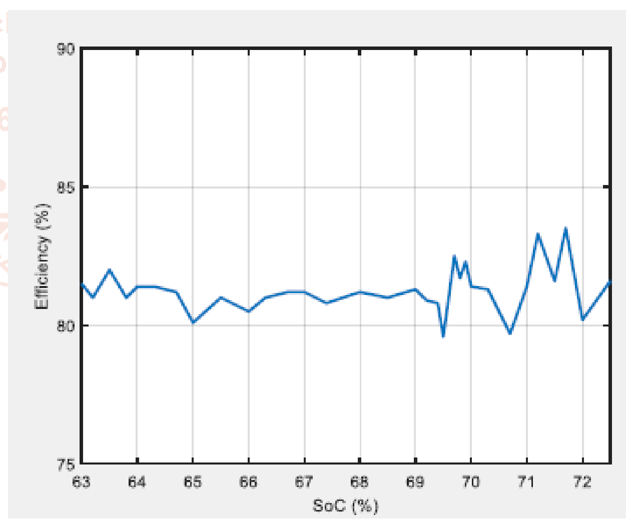

Figure 7. Practical Results for: (a) Voltage vs. Battery SoC, (b) Current vs. Battery SoC and (a) Efficiency vs. Battery SoC of High-side Buck Converter

CONCLUSION

In a standalone solar PV system, buck converters play a crucial role in reducing the high PV output voltage to a level suitable for the load or battery. This study focuses on the design, modeling, and construction of an Arduino-microcontroller based DC-DC high-side buck converter. The circuit is designed to utilize power from the supply for charging a 12V battery, rather than directly from the solar PV module. Both simulation and practical tests were conducted to measure input and output parameters. The experimental results showed higher output voltages compared to the simulation, which are adequate for battery charging. However, the output currents from the experimental tests were lower than those from the simulation, leading to increased power losses and reduced system efficiency. Despite being suitable for practical use, the designed high-side buck circuit is deemed less efficient due to the lower output currents. Future research should focus on implementing a new current booster buck circuit and a closed-loop control technique to enhance converter efficiency using an appropriate MPPT method.

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