SSRG International Journal of Electrical and Electronics Engineering
ISSN: 2348-8379/ https://doi.org/10.14445/23488379/IJEEE-V13I1P112

Volume 13 Issue 1, 123-131, January 2026

Original Article

Design of a Digitally Controlled Low-Power Buck-Boost Converter for Efficient Power Management

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Received: 07 November 2025 Revised: 09 December 2025 Accepted: 08 January 2026 Published: 14 January 2026

Abstract - *Every day, new electronic products are designed and tested. Every product is thoroughly tested before it is released into the market. The bench power supply is necessary to power and test the product. A bench power supply is a power converter that can supply DC power to the load. These power supplies usually have a variable output voltage range of 0-32V. The power supply made in this project is a two-switch buck-boost converter with a dual LCD and Bluetooth-based wireless display. The buck boost converter is a kind of DC-DC converter, and it can deliver a voltage that is higher than, or at most equal to, its input voltage. Because of this, it can be operated with a 12V standard battery or a wall plug. The display system serves as a means to observe the DC-DC converter by showing voltage, current, power, and status. The display system has an LCD and Bluetooth-based display, which allows the user to monitor the system at the bench or at a distance, as the workbench with the project being tested may become crowded and inconvenient to sit at and monitor, or the user may want to stand away from the bench for safety. After conducting tests with different KP and KI values, optimal values of the constants were found such that the converter has the best performance and stability. The maximum efficiency was achieved at about 92.44% with an output power of 24.25 W to 27.23 W for an input voltage of 11.95 V.*

Keywords - *DC-DC Converter, Buck-Boost Converter, PI Control.*

1. Introduction

A two-switch buck boost DC-DC converter is a non-inverting step-up or step-down DC-DC converter with a wide input and output voltage range. The following circuit can operate from a varying input voltage of 12V to 32V and produce 0V to 32V at 1A. As indicated by research, the maximum level of efficiency for the buck-type converter occurs in a discontinuous conduction mode when power is utilized at lower power levels through blocking reverse current flow [1]. Various levels of DC voltage are often required in EV applications for different electrical load demands. For this, the battery voltage will need to be controlled with care, evolving and changing in concert with particular characteristics of different loads. It is for this reason that the implementation of a properly designed power converter circuit is important, since it is a significant factor in the generation of various DC voltage outputs [2].

This DC-DC converter has dual types of operation, such as boost mode and buck mode. The buck mode, or step-down mode, is achieved by keeping S2 turned off and applying a PWM signal to S1 with an appropriate duty cycle. The voltage at the output may be modified through the modification of the pulse width of the PWM signal. When the duty cycle is increased, the output voltage rises, and when the duty cycle is reduced, the voltage at the output is reduced. The boost mode, or step-up mode, is achieved by keeping the switch S1 always Ton (Turned on) and applying a PWM signal to switch S2 with an appropriate duty cycle. The voltage at the output is again dependent on the pulse width as before. The operation of this DC-DC converter is done with the help of a microcontroller. An STM32 microcontroller is selected for the implementation of the controller.

A Proportional-Integral Control Algorithm (PI control) is written into the microcontroller, which helps generate the required duty cycle to obtain the desired output voltage. It is stated that by operating DC–DC converters in a multi-state process, it becomes possible to cancel Right Half Plane (RHP) zeros and other tasks such as equalizing the power loss of switches. The difficulty of controlling multi-variable systems was addressed by using feedback linearization techniques and fixed PI controllers. [3]. The Dual LCD and Bluetooth-based display is realized with the help of an Arduino Uno, a 16x2 LCD display, an HC05 Bluetooth Module, and the Arduino Bluetooth serial monitor app [A1]. The output voltage, current, and on/off state of the converter are sent from the STM32 to the Arduino Uno, which then sends the data to the LCD display and the app through the

Bluetooth module. This is a very important step for the management of power among various components.

2. Literature Survey

There are various steps up/down DC-DC converters available, such as the inverting buck-boost converter, SEPIC converter, and Cuk converter. The inverting buck-boost converter and the Cuk converter are single-switch type step-up/down converters needing only one PWM signal, making the control and gate driver requirements simple. In addition to this, the Cuk converter has inductors on the input and output sides, making the input and output currents smooth. However, these types of converters produce a negative output voltage instead of a positive voltage, making them unsuitable for many applications. Atif Sardar et.al. developed a wearable flexible solar based jacket retaining the flexibility, deformability, and production of maximum power from natural and artificial light [4]. In generating wind energy over the entire wind velocity profile, the buck-boost DC-DC converter offers greater versatility than a boost converter and is, therefore, a preferred choice for universal wind energy conversion systems [5].

The next option is a single-ended primary-inductor converter, or SEPIC for short. This is a single-switch, non-inverting step-up/down converter. The single switch requirement makes the PWM generation logic and the gate-drive requirements simple. However, the SEPIC converter has a series coupling capacitor that must handle huge amounts of ripple current. It also has two inductors, making the converter bulky. In addition to this, it has high current and voltage stresses. An alternative non-inverting step-up/down converter to the SEPIC DC-DC converter is the two-switch buck-boost converter. It has lower current and voltage stress compared to the SEPIC DC-DC converter. Although it requires two switches and two gate drivers, it is not too complex to realize. The DC/DC-based power supply can be made more robust or reliable by employing numerous inductors to carry current in different channels while also reducing ripples, or by paralleling converters [6].

A significant portion of all losses, including switching loss and conduction loss, is attributed to the power loss of semiconductor devices, particularly at high switching frequencies. Also, it is imperative to consider the key contributions made by the inductor, copper, and core losses towards the overall losses of CBBCs [7]. Transistor degradation imbalances specifically increase the RMS current of the output capacitor, which raises power loss and speeds up capacitor degradation. System reliability is impacted by this degradation because it generates thermal stress [8]. One type of DC/DC converter that is frequently used for high-energy conversion and power supplies is the buck converter. Electronic devices use these controllers to control the output voltage in response to fluctuations in the input voltage and load current. This means that to satisfy demand in real time, an effective control approach is needed. Numerous research studies report that buck converters can achieve adequate performance in their dynamic behavior by using genetic algorithm control techniques. However, the output voltage ripples and transients with significant overshoots are not highlighted [9].

The DC-DC converters based on inductors, Switched Capacitor (SC) converters, hybrid schemes, or linear regulators can all be used to construct power management units. Linear regulators have the advantages of being portable, possessing a short settling time, low ripple voltage, and being completely integrated on-chip. For large load currents up to several amps, inductor-based switching DC-DC converters can achieve high efficiency [10]. One of the key factors enabling the high adoption of renewables is Energy Storage (ES) Devices. For integrated Photovoltaic (PV) and Energy Storage (ES) systems, the buck-boost converter with a dc-coupled configuration demonstrates better performance at reduced cost and increased efficiency. [11]. The adaptable system of the buck-boost converter's step-up/down capabilities makes it an appropriate choice for a battery charging application using a solar panel with two internal subsections isolated by two bypass diodes. A capacitor has been added to the converter's input in this application [12]. The modulation of single-phase bridge inverters, which is essential to generating high-quality output over a wide range of input, has been the focus of significant study over the past few decades. The Carrier-based Pulse Width Modulation (PWM) is the most employed modulation technique for single-phase bridge inverters [13]. The Buck Boost Converter functions properly and is practical to implement for charging the 12Volt, 7.2 Ah battery being used by the researchers for their application of the buck boost converter as the solar panel output stabilizer [14].

For active power filter applications, the addition of a predictive control technique to the converter current loop enhanced transient response and current tracking ability [15]. Because of the significant voltage divergence between the Positive Input Voltage (Vi) and Negative Output Voltage (Vo), achieving high power efficiency is especially tricky in DC-DC converters, which generate negative voltages. To increase the battery life, it is necessary to optimize the DC-DC converter's power efficiency while generating a negative voltage [16]. To minimize performance deterioration and reduce hardware complexity, the DDPWM modulation technique has been presented as a systematic method to improve the effective resolution of DPWM and inhibit quantization-induced LCOs in digitally regulated power converters [17]. A high-speed DSP-based controller system is used to regulate the complex activities of this flexible converter. It makes use of the well-known PID approach, which is known for its proficiency at navigating tricky, nonlinear systems. Theoretical and simulation findings are supported by experimental data, which validate the converter's efficiency in EV applications [18]. A new high-gain hybrid boost-flyback converter is also introduced, with a voltage conversion ratio many times higher than the typical boost converter design [19]. Utilizing serial communication and MATLAB Simulink to control, a TMS320F288069 M DSP microcontroller is being utilized for real-time regulation. This makes it possible to use a buck regulator power control system without the Integrated Chip (IC), which is typically responsible for achieving the buck regulator's primary control loop [20]. Even with Sliding-Mode (SM) controllers' superior characteristics, linear controllers continue to rule many industrial applications. This is because the design of SM controllers necessitates more complex control methods and mathematical calculations. In contrast, the design of classical controllers may be implemented in a straightforward analogue form with less effort [21]. To optimize performance and efficiency, it is necessary to pick specific characteristics in the DC-DC converter's design. The lower switching loss is implied by the DC-DC converter's lower switching frequency. As conduction loss increases with high load current, switching loss also increases with high switching frequencies [22]. The design implementation and testing of the solar charge controller consist of the functional units, which are intriguing future projects with more detailed analytical results on the total system characteristics [23]. A bidirectional DC/DC converter is a critical part of the DC microgrid system. It helps keep the DC microgrid stable [24].

3. System Design

The power stage of the two-switch buck-boost DC-DC converter shown in Figure 1(a) consists of an input reverse polarity protection circuit, a boost-buck converter, and output reverse polarity protection. This input reverse polarity protection circuit is an active ideal-diode circuit made up of a P-Channel MOSFET and its associated control. The next block is the DC-DC converter circuit, as shown in Figure 1(b), the heart of the project. It is controlled using an STM32 microcontroller that generates PWM signals, which are fed to the gate drives. The output reverse polarity protection is a passive solution of an antiparallel Schottky diode. The diode is reverse-biased under normal conditions but conducts and clamps when a negative voltage is applied. The CuK and SEPIC type Buck-Boost converters are shown in Figure 2.

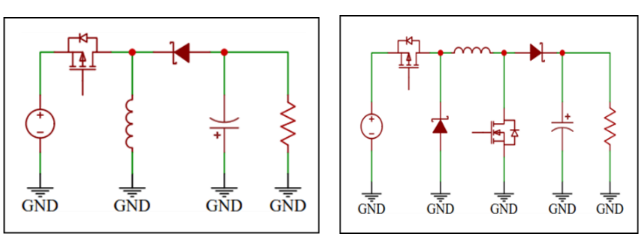


Fig. 1(a) Two-switch buck-boost, and (b) Inverting buck-boost converter.

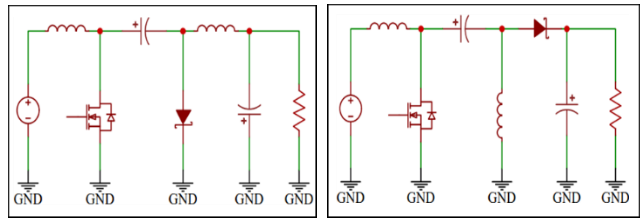


Fig. 2(a) Cuk converter, and (b) SEPIC type buck-boost converter.

The Dual LCD and Bluetooth-based display shown in Figure 3 consists of an Arduino UNO, an HC-05 Bluetooth module, an LCD, and an Arduino-Bluetooth serial monitor app.

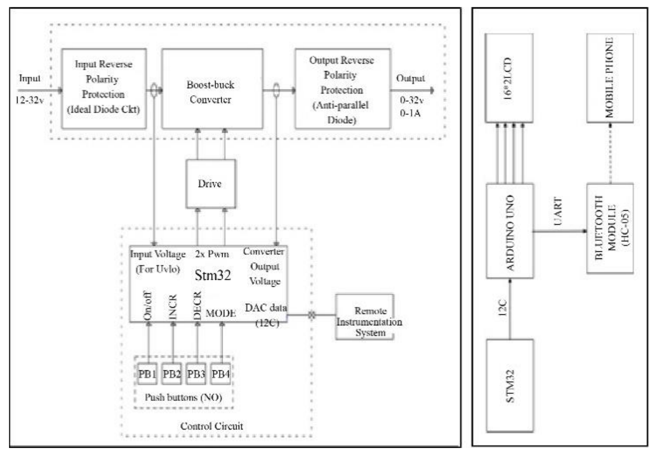


Fig. 3 DC-DC converter with dual LCD and bluetooth-based display

The output parameter values are transmitted by the STM32 (controller I2C device) to the Arduino UNO (agent I2C device). This Arduino displays the data on a 16x2 LCD and on the app.

4. Results and Discussion

4.1. DC-DC Converter and Design Calculations

The filter component values are calculated, taking the highest output voltage and the lowest input voltage at the highest output current. Based on these conditions, the values to be taken are:

$$VIN = 11V \quad (1)$$

$$VOUT = 32.5V \quad (2)$$

$$IOUT = 1A \quad (3)$$

$$V_{IN(min)} D = 1 - V_{OUT(max)} \quad (4)$$

$$V_{IN(min)} \cdot D_L \geq f_{sw} \cdot \Delta I_L \quad (5)$$

$$I_{OUT} \geq f_{sw} \cdot \Delta V_{OUT} \quad (6)$$

From the above equations, a 61μH inductor and 264 μF output capacitor are needed. A 68 μH inductor and three- 100 μF capacitors (to get 300 μF of output capacitance) are used in the DC-DC converter.

Table 1. Converter specifications

Parameters	Value
Input voltage range	12V – 32V
Output voltage range	0.5V – 32.5V
Maximum output current	1A
Absolute minimum input voltage	11V
Switching frequency	100kHz

4.2. Control Algorithm

An STM32 microcontroller controls the converter. The duty cycle of the PWM signals driving the MOSFETs is calculated by the microcontroller using a Proportional-Integral Control Algorithm (PI control).

$$s(t) = K_P \times e(t) + K_I \times \int e(t) \cdot dt \qquad (7)$$

$$s(t) = K_P . e(t) + K_I \times \int e(t) \cdot dt \qquad (8)$$

Since the PI control algorithm is implemented in a microcontroller, the integral term is coded as a summation, so the above equation gets modified to

$$s[n] = K_P \times e[n] + K_I \sum e[n] \qquad (9)$$

Where the error term is calculated as,

$$e[n] = V_{reference} - v_{out(measured)}[n] \qquad (10)$$

The output voltage is sensed by the microcontroller's ADC and compared with a reference. The error signal is then generated and fed to the PI control algorithm, which outputs a duty cycle value that will give the desired output voltage. A 100kHz PWM signal is desired, so the internal counter of the STM32 is configured to overflow upon reaching 700 counts. The STM32F103C8T6 has a clock frequency of 72MHz, which means counting to 700 will result in a PWM frequency of 72MHz/700 = 102.8kHz. If a duty cycle of 0% needs to be generated, the PI controller must output 0. If a duty cycle of 50% needs to be generated, the PI controller must output 350. If a duty cycle of 100% needs to be generated, the PI controller must output 700. Since there are two modes of operation (buck mode or boost mode), two duty cycle commands – Dbuck and Dboost – need to be generated to operate in the buck mode and boost. This can be achieved either by using two level-shifted carriers to generate the two PWM signals or by using a single carrier and two level-shifted reference signals [3]. The latter technique is chosen to generate the buck and boost mode PWM signals. The power stage and gate-driven circuit are shown in Figure 4. The PI controller is designed to output a value of up to 1200. When the output is between 0 and 700, the converter operates in buck mode with a duty cycle between 0 and 100% and when the output is between 700 and 1200, the converter operates in boost mode with a duty cycle between 0 and 85%. The buck mode duty cycle control value is equal to the PI controller's output in the 0-700 range, and the boost mode duty cycle control value is equal to the PI controller's output minus 700 in the 700-1200 range. The microcontroller circuit with push buttons is shown in Figure 5. The output reverse polarity protection is a passive solution of an antiparallel Schottky diode.

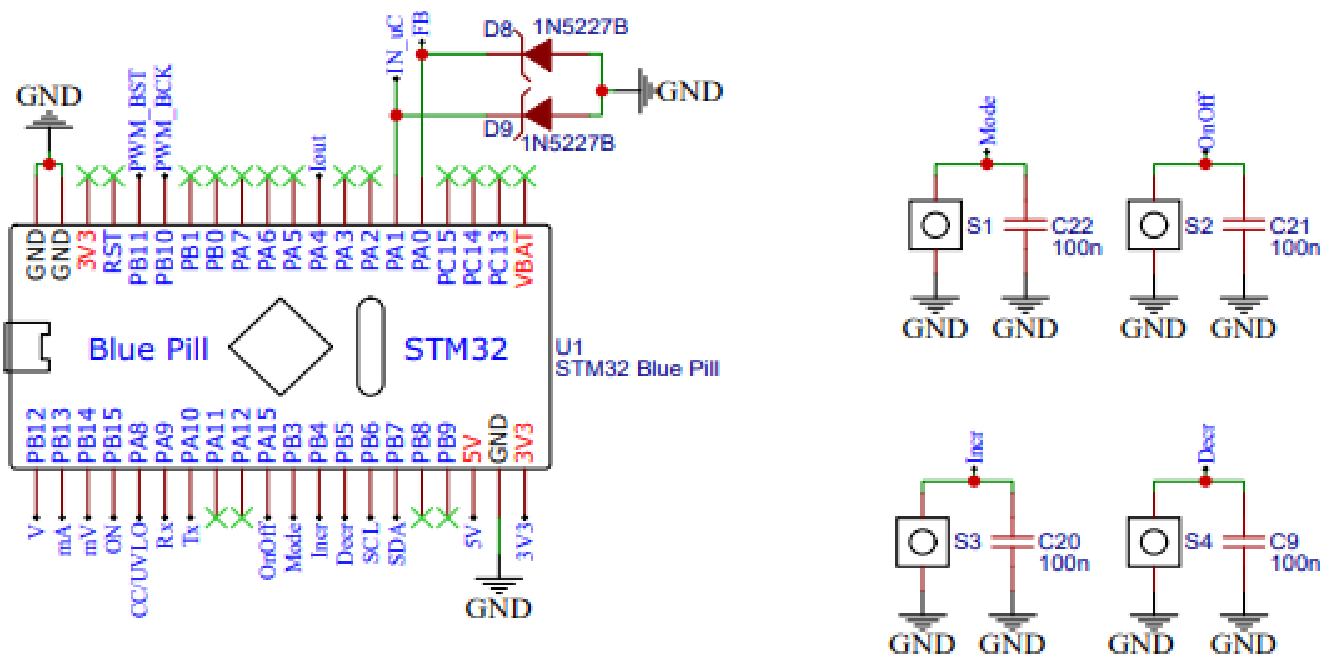


Fig. 4 Power stage and gate driver circuit

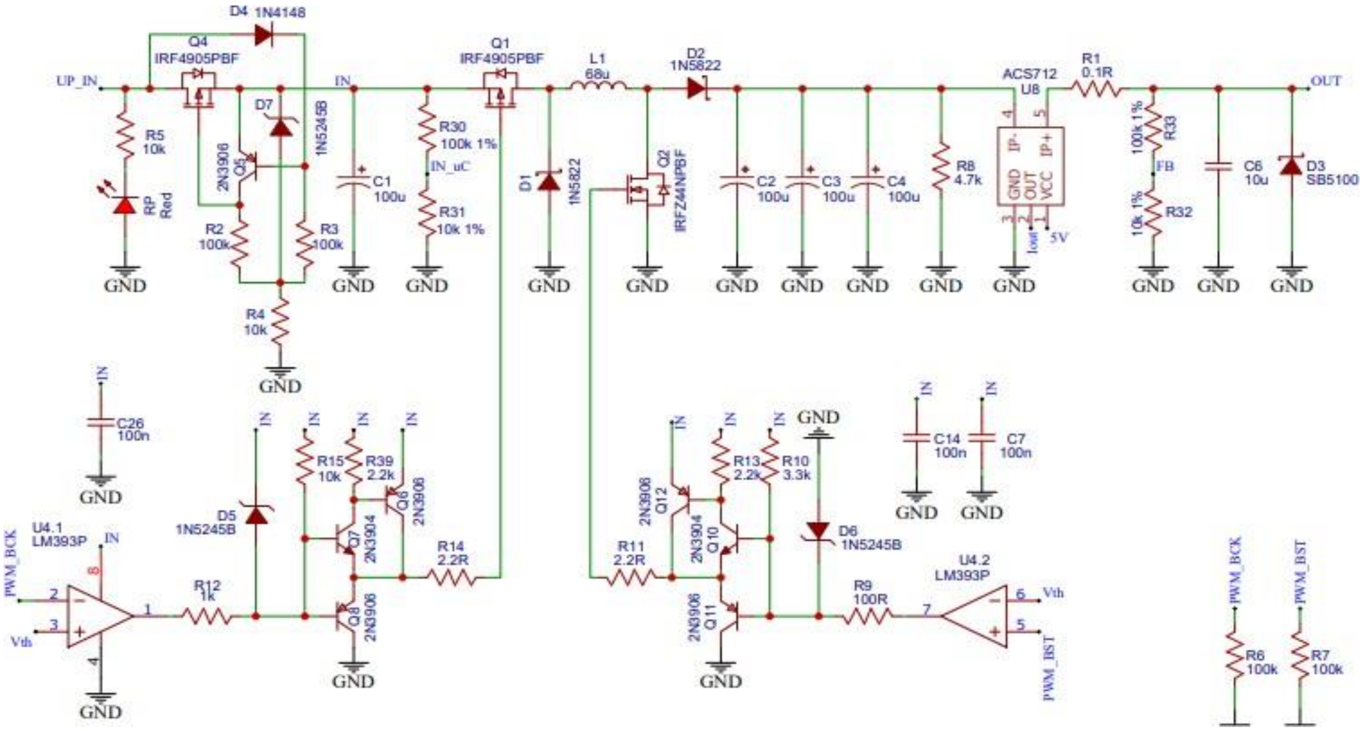


Fig. 5 Microcontroller circuit with push buttons

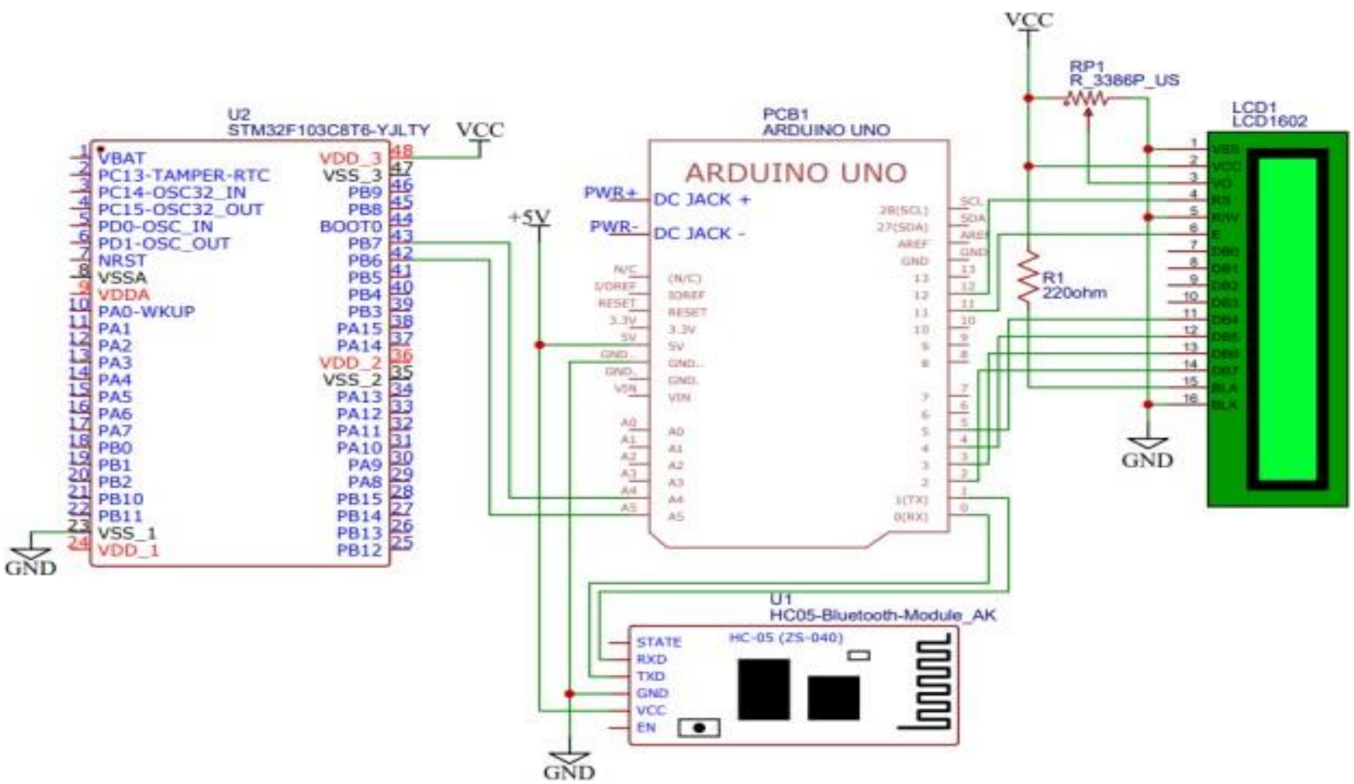


Fig. 6 Prototype Circuit Board (PCB) for the DC- DC

4.3. PCB Design and Assembled Prototype

The Prototype Circuit Board (PCB) designed for this project is a 2-layer board. Large, solid copper regions have been used to connect the components in the powerstage. The dual LCD and Bluetooth-based display is shown in Figure 7. The prototype of the hardware module depicted in Figure 8 shows the interface among various components.

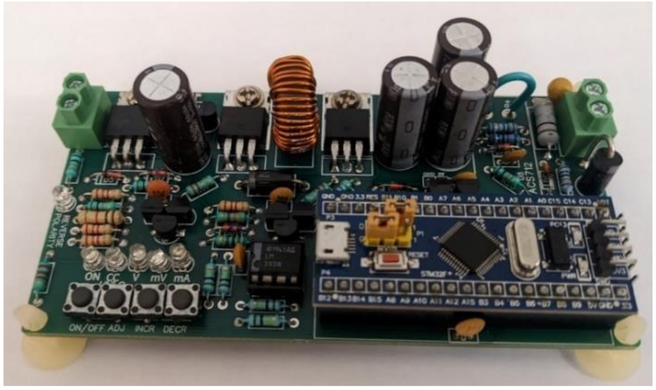


Fig. 7 Dual LCD and bluetooth-based display

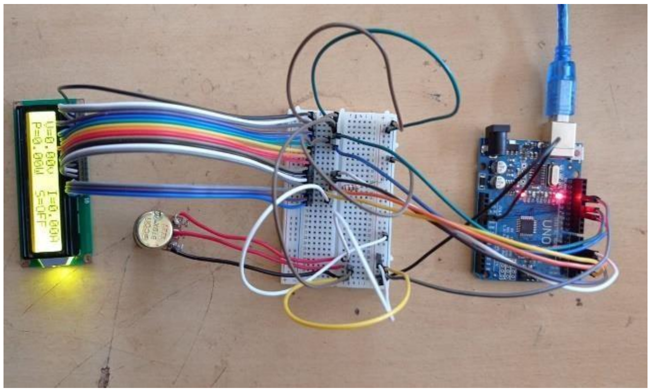


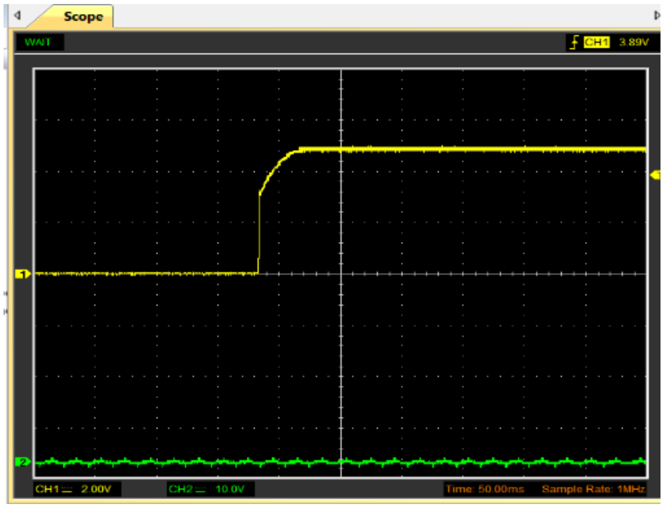
Fig. 8 The prototype of the hardware module

4.4. PI Controller Tuning

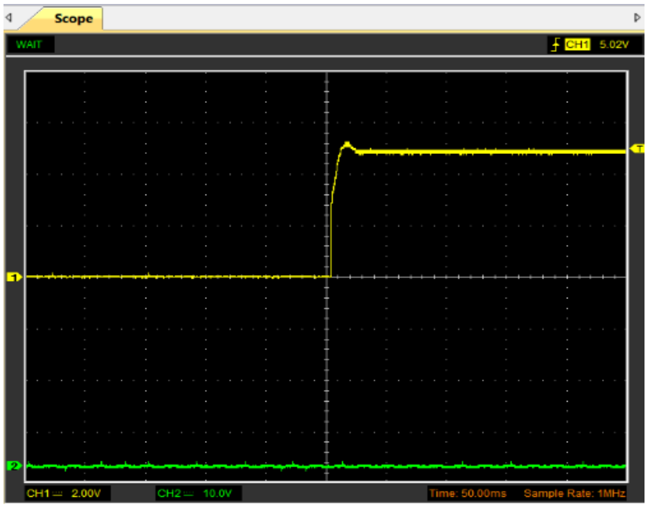
In order to get the desired converter response characteristics, the values of the proportional and the integral constants must be adjusted, or tuned, so that the desired rise time, overshoot response, load, and line step response are obtained. The PI constants are tuned such that the DC-DC converter's output has the smallest possible rise time and settling time with minimum or no overshoot and good load and line step response.

First, the proportional constant is increased in steps until the converter becomes unstable (starts oscillating/ is unable to maintain a constant duty cycle). Once that happens, the proportional constant is slightly reduced, and the integral constant is increased in the same manner. Saturating the output of the proportional path helps prevent an output overshoot during low load conditions, and saturating the integral path prevents an integral windup.

Once the PI controller is tuned, i.e., some suitable proportional and integral constant values are selected, the output voltage rise response, line, and load step response are checked for various input and output voltage conditions. Initially, the PI controller was tuned by setting the input voltage to 12V, the output voltage to 5V, and the load current to a few hundred milliamps. The effect of various K_P and K_I values on the output voltage rise is shown below.



(a)



(b)

Fig. 9 (a) Output voltage (K_P = 0.5, K_I = 0.001), and (b) Output voltage (K_P = 0.5, K_I = 0.005).

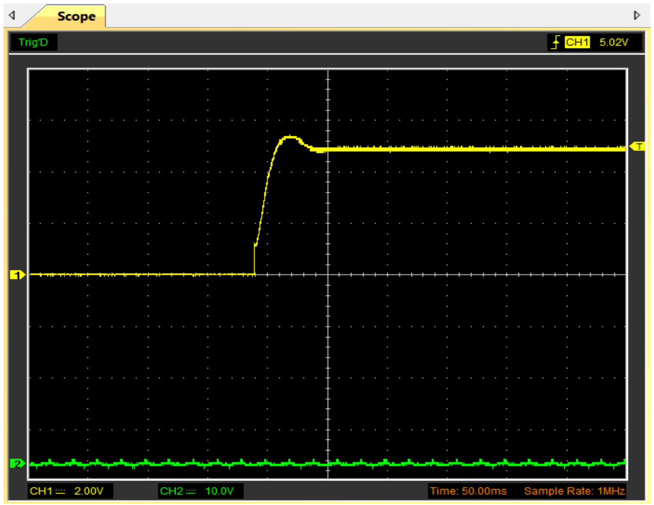


Fig. 10 Output voltage graph (KP = 0.1, KI = 0.001) with display of result

The above output rise graphs are captured for V_{IN} = 12V and V_{OUT} = 5V. Using K_P = 0.5 and K_I = 0.001 gives the best output voltage rise with no overshoot. The output voltage graph is shown in Figures 9 and 10 with different value of KP and KI.

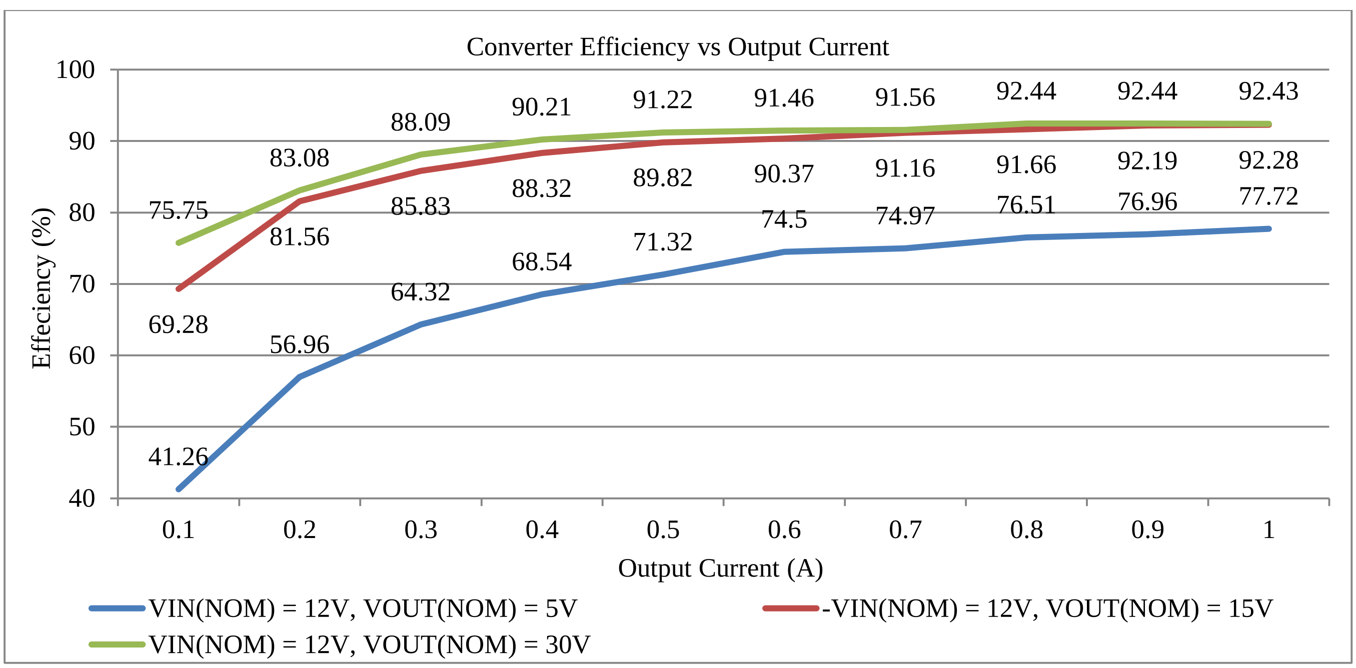
4.5. Efficiency Test

An efficiency test is carried out on a DC-DC converter to calculate the power conversion efficiency of the DC-DC converter, i.e., the amount of power that enters the DC-DC converter that actually exits the DC-DC converter. The power conversion efficiency of a DC-DC converter is expressed as the ratio of the output power to the input power in percentages. The power conversion efficiency of a DC-DC converter is measured by supplying power to the DC-DC converter while loading it at different levels with different voltages.

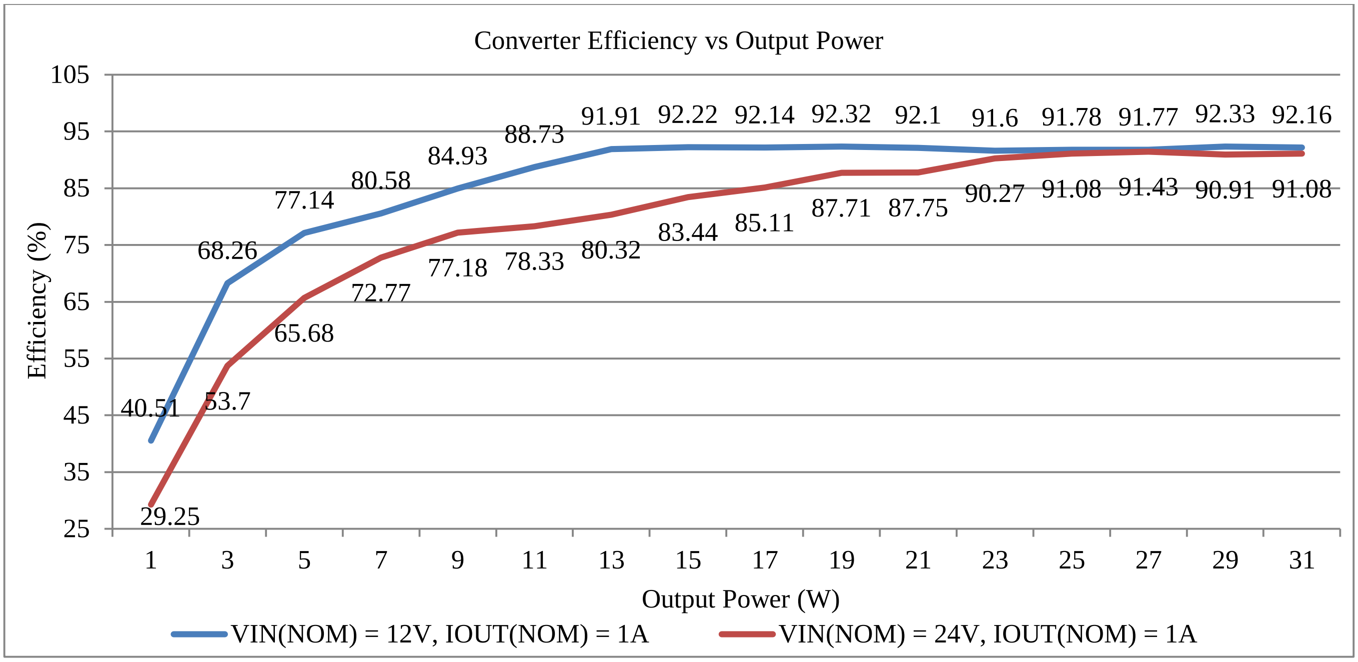
An LCD consisting of a matrix of 16 columns x 2 rows has been used to show output parameters of this DC-DC converter (output voltage, output current, output power, and ON or OFF state). All of the same information has been sent to the Arduino Serial Monitor application. Table 2 shows the Efficiency Characteristics data from the DC-DC converter in one case. The Efficiency Characteristics of the DC/DC converter are shown for both the current and power sweep tests in Figure 11.

Table 2. Efficiency characteristics data of the DC-DC converter for one case

VIN(NOM) = 12V, VOUT(NOM) = 30V						
VIN	IIN	PIN	VO	IO	PO	EF(%)
12.05	0.34	4.1	30.13	0.1	3.1	75.75
12.05	0.62	7.47	30.13	0.21	6.21	83.08
12	0.88	10.5	30.13	0.31	9.25	88.09
12	1.13	13.56	30.13	0.41	12.23	90.21
12	1.39	16.68	30.13	0.51	15.22	91.22
12	1.65	19.8	30.13	0.6	18.11	91.46
12	1.93	23.16	30.12	0.7	21.2	91.56
11.95	2.2	26.23	30.12	0.81	24.25	92.44
11.95	2.47	29.46	30.12	0.9	27.23	92.44
11.95	2.74	32.68	30.12	1	30.21	92.43



(a)



(b)

Fig. 11(a) Efficiency characteristics of the DC-DC converter (current sweep test), and (b) Efficiency characteristics of the DC-DC converter (power sweep test).

5. Conclusion

There are many different DC-DC converter topologies that are suitable for use in a compact and efficient bench power supply. From the literature survey conducted, there are broadly two types of buck-boost converters: inverting and non-inverting. The non-inverting category of buck-boost converters is chosen as they output a positive DC voltage compared to the inverting category. There are two candidate topologies: the Single-Ended Primary Inductor Converter (SEPIC) and the two-switch buck-boost converter. Each topology has its pros and cons. The SEPIC topology is a single-switch topology, making the control scheme easy. But this topology requires two inductors, a series of coupling capacitors, and features a high voltage and current stress, making it less suitable. The other option is the two-switch buck-boost converter, which only requires one inductor and has low current and voltage stresses, making it the topology of choice. For the control, a Proportional-Integral (PI) control scheme was chosen to generate PWM pulses with the required duty cycle to get the target output voltage. After conducting tests with different KP and KI values, optimal values of the constants were found such that the converter has the best performance and stability.

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