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# Controlling of DC-DC Buck Converters Using Microcontrollers

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***Abstract*—This paper presents a technique to digitally control the output voltage of a DC-DC converter via a microcontroller. The voltage regulation and controlling were achieved utilizing an LM2596 buck converter. A digital potentiometer MCP41050 is utilized to smoothly control the regulated output DC voltage via the SPI digital protocol. The proposed design is manufactured and tested for various loads. This device is considered as a step-down voltage regulator capable of driving 3A load with high efficiency, excellent linearity, source-voltage variation, and load regulation. The results show that the system can control the output voltage with satisfactory performance and high accuracy. With various loads, the proposed system shows a mean square error of 0.015±0.037 volts tested with a regulated voltage of 5 volts. The efficiency improves from about 80% to around 91% at a 1 kΩ load. This design eliminates the possible errors that arise when manually varying the voltage of the buck converter; by means of using a microcontroller. Such a system ensures a proper digitally controlled output voltage with a better performance, which can be applied in various applications.**

***Keywords*—DC-DC buck converter, Percent voltage regulation, Efficiency, SPI Protocol, PCB, SMPS.**

## I. INTRODUCTION

Voltage regulators can be considered as one of the most essential systems utilized in various applications in our lives. Voltage regulators are classified into two classes, linear-mode regulators and switching-mode regulators. An example of a simple linear regulator consists of a control element-transistor that is operated in the linear-mode and connected in series with a variable load. The feedback part is designed between the unregulated input side and the regulated output. The target is to sense the variation of the output voltage and provides feedback error that will be compared with a predetermined reference voltage. This error causes the control element to compensate for any changes of the resulted voltage to maintain the final output voltage constant [1,2]. A simple representation of a basic op-amp series regulator is shown in Figure 1. The output voltage can be determined using the following relationship:

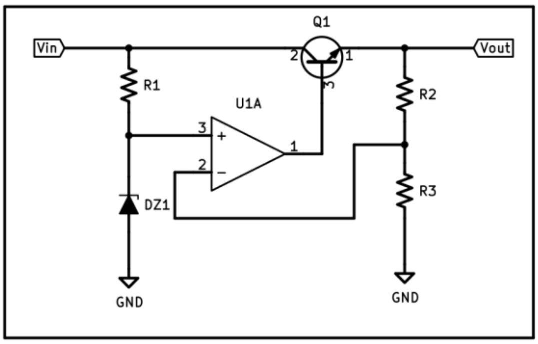

Figure 1: Basic series regulator using Op-Amp.

$$V_{out} = \left(1 + \frac{R_2 + r_e}{R_3}\right) V_{ref} \ . \qquad (1)$$

where $V_{ref}$ is the reference voltage, $r_e$ is the base-emitter resistance = 26 mV/$I_{EQ}$ and it can be neglected because it has a very low value compared with $R_2$ or $R_3$.

In this circuit, the difference between the output voltage and the input voltage is dropped across the control element. Since the transistor is operated in its linear region it will dissipate a considerable amount of power, which dramatically affects the overall efficiency of the circuit [3,4].

Buck converters are DC-DC step-down switching regulators. They have many advantages over linear regulators. For example, the power efficiency is significantly higher, especially when the input voltage is much higher than the targeted output voltage [3,5]. A basic step-down (buck converter) switching regulator using a MOSFET device as the main switching element is shown in Figure 2 [6-8].

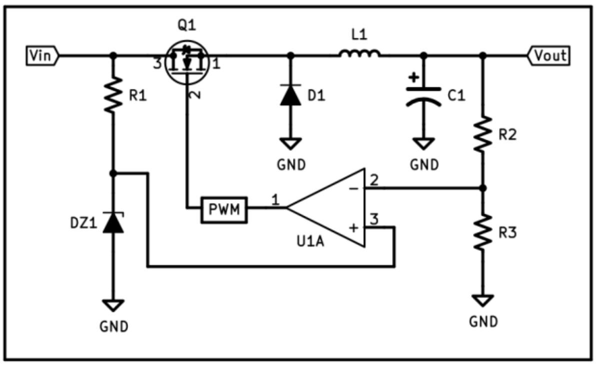

Figure 2: Basic step-down switching regulator using op-amp.

In the circuit shown in Figure 2, the diode $D_1$ is reversed biased when $Q_1$ is ON, energy will build up in the inductor $L_1$ and the capacitor $C_1$. When $Q_1$ is off, $D_1$ will conduct which provides a path for the current stored in the inductor $L_1$ to flow through the load -as long as $R_L$ is not too high. The capacitor $C_1$ is utilized to smooth the DC output voltage to a constant value. The resistors $R_2$ and $R_3$ are high-value resistors, used to sense the output voltage. This voltage will be compared with $V_{ZD1}$ to control the Pulse Width Modulator (PWM) circuit. Equation (2) is used to calculate the DC output voltage of the buck converter that is shown in Figure 2.

$$V_{out} = D \times V_{input}. \qquad (2)$$

where *D* is the duty cycle which can be determined using the following formula.

$$DutyCycle = \frac{t_{on}}{t_{on} + t_{off}}. \qquad (3)$$

In switching regulators the control element operates as a switch. Hence a greater efficiency than the linear types can be achieved. This is because when the transistor switches on and then off, this causes power to be dissipated only when it is in the on condition [3]. The working principle of the switched-mode power supplies is based on:

- performing the rectification process when rectifying the incoming AC power line voltage into DC,

- converting the rectified voltage to a high-frequency square-wave AC voltage by operating the transistors as a switch [9],

- utilizing lightweight transformers to shift the voltage level of the square voltage up or down [10],

- rectifying the AC voltage at the output of the transformer into DC. This is followed by a filtration stage applied to the resulted output voltage [3].

A new design of adjustable voltage linear regulator has been presented by improving the feedback circuit [11]. The feedback circuit is connected with an auxiliary circuit consists of a DC-DC converter, microcontroller, and op-amp (see Figure 1). The Pulse-Width Modulation (PWM) technique was used to adjust the output voltage. The Microcontroller samples the output voltage and current to detect any variations between the output voltage and current and the pre-defined values due to the tolerances in the components' parameters. This design has advantages as it is stable, with low noise, low ripple, and the possibility to adjust the output voltage. However, the efficiency of the design is relatively low and there is no possibility to monitor the output voltage and current.

Several papers have been discussing the improvements that can be made for the regulator systems in the literature [12-15]. The PI control and fuzzy logic control schemes were utilized and analyzed to provide an output of 12 volts from a source of 24 input voltage [16]. Saadatmand et al. have proposed the utilization of a neural network for controlling a buck converter [17]. Different controllers were designed such as the proportional-integral (PI) or proportional-integral-derivative (PID) with a neural network. The target is that the network adapts the parameters of the controllers to optimally control the converter performance. Mustafa et al. investigated the performance of the sliding mode (SM) control technique for DC/DC converter using the frequency response method [18]. The simulation results obtained from the system of buck converter confirmed that the SMC controller is a robust controller against load changes and it strongly less sensitive to disturbances like power supply variations. Smooth output voltage response observed with zero error steady-state and goes to stability faster.

Several studies have utilized microcontrollers for improving the performance of DC/DC converters. Viswanatha et al. investigated the application of converters in photovoltaic systems [19]. The target is to provide continuous and uninterrupted power delivering to the load utilizing microcontrollers. Zheliazkov proposed a scheme for digitally controlling the buck converters with minimal error [20]. Kovacevic and Stojanovic proposed a buck converter controlled with a microcontroller utilizing an Arduino demonstration board [21]. A PI system was implemented and its parameters were determined for optimal stability and time response.

## II. WORKING PRINCIPLE

In this work, a DC-DC converter is considered based on the utilization of LM2596 for controlling the output voltage. This device is considered a step-down voltage regulator capable of driving 3A load with high efficiency, excellent linearity, and load regulation. The maximum input voltage that can be fed into the proposed system is 40 volts with a TTL shutdown capability, thermal shutdown, and with current-limit protection [2]. The regulator requires only four external components. The functional block diagram of LM2596 is shown in Figure 3. A typical application is shown in Figure 4 and the output voltage is provided in Figure 2.

$$V_{OUT} = V_{REF} \times \left(1 + \frac{R_2}{R_1}\right). \qquad (4)$$

where $V_{REF} = 1.23V$.

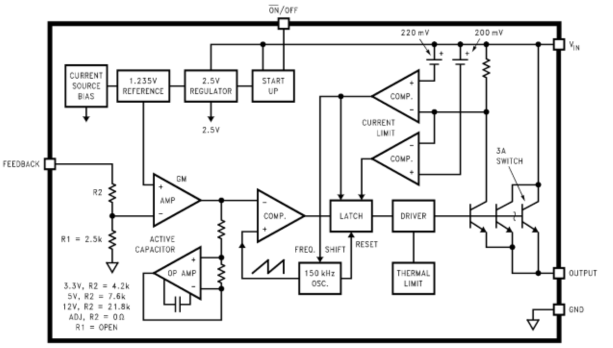

Figure 3: Functional block diagram of LM2596.

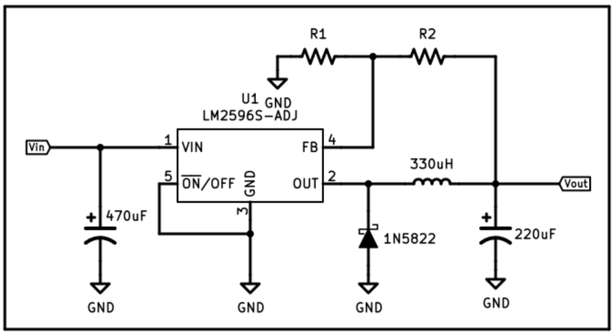

Figure 4: Typical application of LM2596

This paper deals with a buck converter controlled by a microcontroller utilizing an ATmega-based- Arduino Uno demonstration board to control the output voltage. The linear feedback circuit ($R_1$ and $R_2$) is modified with a digital potentiometer (MCP41050). This digital potentiometer has 50 kΩ, 256 taps with a resolution of 195Ω/tap and it's controlled via SPI protocol. Such a system provides better performance with a possibility to remotely and digitally controlling its parameters.

The proposed circuit is shown in Figure 5, where $R_1$ is replaced with a digital potentiometer in series with fixed resistance of 5.6 kΩ and $R_2$ is replaced with fixed resistance of 100 kΩ. The position of the digital potentiometer and values of 5.6 kΩ and 100 kΩ resistors are chosen carefully (by calculations and experiments) targeting a wide output voltage range and protecting the potentiometer (not to exceed the maximum ratings of digital potentiometer).

The value of $R_1$ can be determined by specifying the targeted minimum and maximum output voltages. For example with $V_{OUT,min.}$ = 4 volts and $V_{OUT,max.}$= 24 volts then substituting equation (4) in equation (5) and equation (6) the desired output voltages with $R_2$ of 100kΩ results in $R_{1,max}$ = 44.4 kΩ and $R_{1,min}$ = 5.6 kΩ.

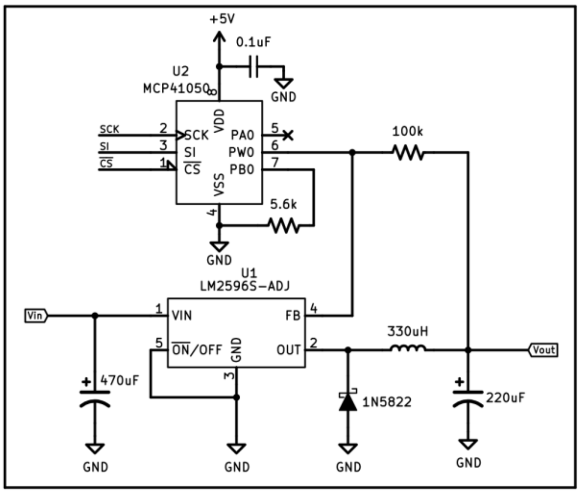

Figure 5: The circuit design of the proposed system.

$$R_{1,MAX} = \frac{R_2}{\dfrac{V_{OUT,MIN}}{V_{REF}} - 1} . \qquad (5)$$

and

$$R_{1,MIN} = \frac{R_2}{\dfrac{V_{OUT,MAX}}{V_{REF}} - 1} . \qquad (6)$$

Considering that $R_1$ is the value of the digital potentiometer connected in series with a 5.6 kΩ fixed-resistance. Accordingly, the total resistance of the digital potentiometer varies between 0 Ω to 38.8 kΩ. It should be considered that all inputs and outputs of the digital potentiometer should not exceed ($V_{DD}$+1V) concerning $V_{SS}$ where $V_{DD}$ in this work is 5 V and $V_{SS}$ is 0 V.

## III. THE MANUFACTURING PROCESS

The printed circuit board (PCB) layout of the switching-mode power supply (SMPS) is critical and requires special treatment for instance all the power tracks are kept short, direct, and thick as much as possible. The high-frequency components are kept away from control components and the feedback tracks are all routed away from inductors and noisy tracks and kept as much as short and thick as possible. Low-value ceramic capacitors are placed near each integrated circuit (IC); this will smooth the supply voltage which is used to power the IC [22]. A ground plane is kept on the component side and soldering side of the PCB, this will reduce noise and reducing ground loop errors, and absorb the EMI that may be radiated by the inductors [4].

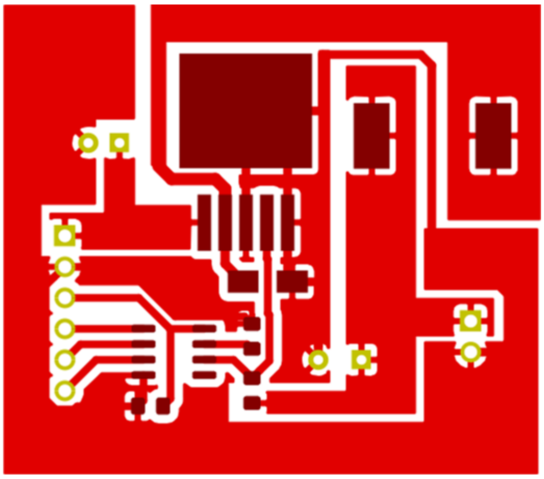

Figure 6: The top layer of the layout design.

The fabrication process was performed manually using a photoresist film where a copper-clad is coated with negative photoresist film then a negative layout is attached to it and exposed to Ultra Violate UV light. The PCB layout is shown in Figure 6. After about 10 minutes the board is developed in Sodium Carbonate to remove the unwanted photoresist film as shown in Figure7.

Figure 7: The developing process.

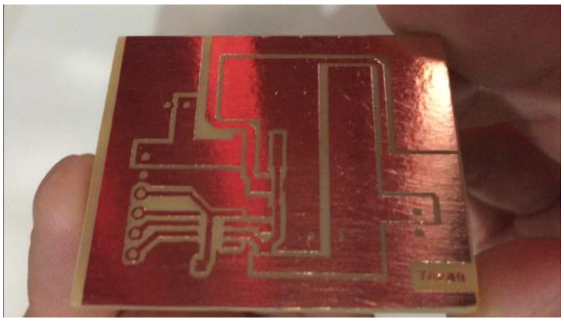

Figure 8: The PCB after etching and stripping

The unwanted areas of copper are etched using Ferric Chloride (etching process), then the photoresist is completely removed (stripping process) as shown in Figure 8. Finally, a layer of UV curable solder mask is applied, and then the components are manually soldered. The final Printed Circuit Board PCB is shown in Figure 9.

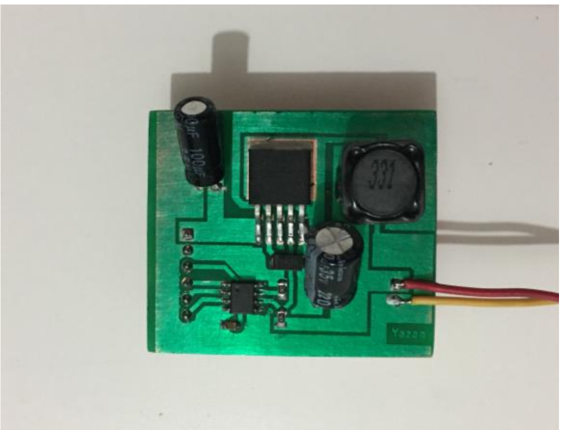

Figure 9: The final fabrication results of the PCB of the proposed system.

## IV. RESULTS AND DISCUSSIONS

ATmeag microcontroller with Arduino demonstration board and rotary encoder was used to test the designed system. The rotary encoder is used to increase or decrease the output voltage digitally utilizing the microcontroller with a specific protocol. The voltage step can be controlled using the microcontroller. In this work, the voltage range was from 4-24 volts with a 1-volt step. An SMPS was used to power the system. The experimental setup is shown in Figure 10.

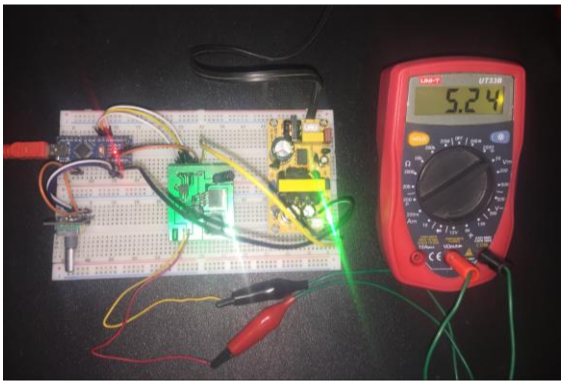

Figure 10: Image for the experimental setup.

Figure 11 shows the theoretically (targeted) output voltage ($V_{out}$) together with the experimental values. The results showed that the proposed system can regulate and control the output voltage with high accuracy. The graph shows limited nonlinearity in the output voltage. This can be due to the tolerances or the finite steps or the step-resolution in the digital potentiometer. The linear fit of the resulted volatges was with $R^2 = 0.998$, indicating that the proposed system was able to achieve the targeted voltage. This can be minimized by improving the resolution of reducing the voltage step.

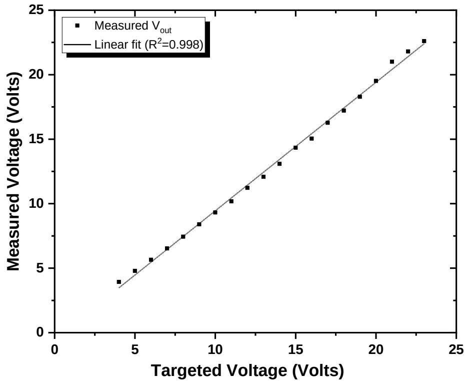

Figure 11: The measured $V_{out}$ as a function of the targeted $V_{out}$.

The resolution of the system is strongly affected by the resolution of the digital potentiometer. The digital potentiometer offers a resolution of 195 ohm/step. This provides a great capability to control the output voltage accurately. To improve the accuracy, the step voltage was adjusted to 0.1 volts by modifying the code. This improves the minimum possible step or changes in the voltage to be regulated..

The output voltage of the proposed system at various loads was tested at 5 volts with an unloaded output voltage as shown in Figure 12. The results showed that the system was able to control the output voltage to about 5 volts. However, the accuracy of the system deteriorates when the regulator was heavily loaded (i.e. low amplitude loads). The deviation of the regulated voltage between the targeted and the measured values were investigated with the mean square error (MSE) and the percent voltage regulation ratio (PVRR) of the measured output voltage. The results showed that the MSE of the measured regulated voltages at different loads was 0.015±0.038 volts with a PVRR of 1.65% ± 2.2%. Accordingly, the proposed system behaves better when compared with the reported values in the literature (i.e. PVRR = 15% [2]). Figure 13 shows the distribution of the error along at different loads for 5 volts regulated voltage.

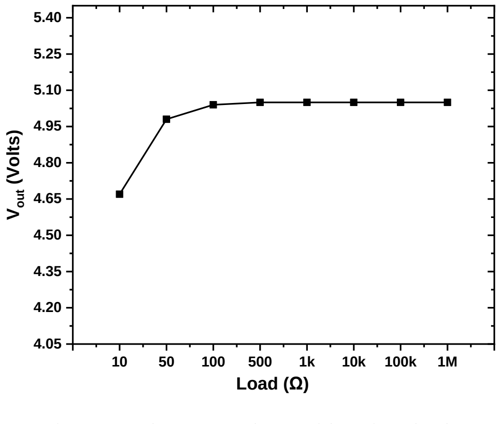

Figure 12: The measured $V_{out}$ with various loads.

Figure 14 shows the efficiency of the proposed regulator design at different voltages. The system showed a good performance in such the efficiency improves with the increase in the regulated voltage and, hence, the loading effect at the regulator. The efficiency improves from about 80% to around 91% at fixed loading impedance of 1 kΩ.

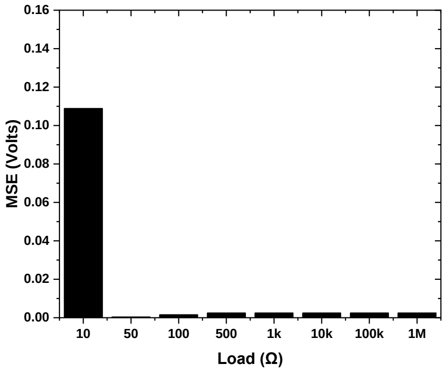

Figure 13: The MSE of a 5 volts regulated voltage at different loads.

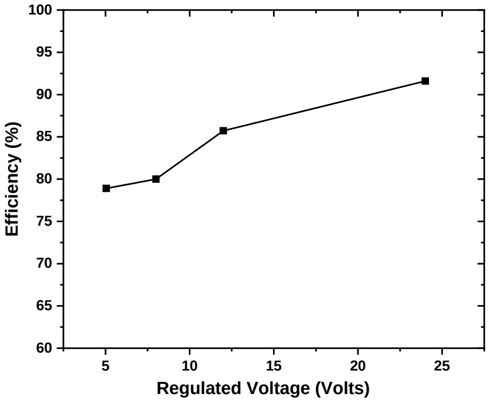

Figure 14: The efficiency of the regulator at 1 kΩ load and different regulated voltages.

The alternative models of such digital control of DC-DC converters usually utilize complex techniques. One of them is the utilization of the pulse-width-modulation technique (PWM) to introduce certain voltage at the feedback terminal of the DC-DC converter. They claim that would be a good method to control the output voltage. However, the practical implementation and experiment revealed unsatisfied results unlike the proposed system in this paper. The failure in the controlling process can occur in the downtime operations [23]. Other alternatives can be the utilization of a fully integrated circuit for power applications that involve registers, multiplexers, etc… to digitally construct digital controllers. However, usually, these alternatives are not suitable for relatively high power applications and require complex control software.

## V. CONCLUSIONS

In this paper, a simple, low-cost, yet efficient DC-DC buck converter controlled by a digital potentiometer is presented. The modified DC-DC buck converters design shows good results and accuracy compared with the conventional designs that involve potentiometers to control the output voltage. The modified design can be programmed for various output steps and embedded in different digital systems. This ensures a minimum voltage fluctuation across the regulated device, which in turn can be utilized in hybrid power supplies for tracking pre-regulator and to reduce the power consumed by the linear voltage regulator and improve the efficiency. An example is the utilization of a tracking pre-regulator technique. It allows the controller to adapt the voltage supplied to the linear regulator (or any device) to achieve a minimum power dissipation and better efficiency over a wide range of output voltage. Additionally, such a system provides an ability to remotely control the output voltage of the DC-DC converter (i.e. e.g. via wireless modules such as Bluetooth, GSM, or wifi modules).

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