

Research Article

Experimental Learning of Digital Power Controller for Photovoltaic Module Using Proteus VSM

Abhijit V. Padgavhankar and Sharad W. Mohod

Department of E & TC Engineering, PRMITR, Sant Gadge Baba Amravati University, Maharashtra 444602, India

Correspondence should be addressed to Abhijit V. Padgavhankar; abhijit595@rediffmail.com

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The electric power supplied by photovoltaic module depends on light intensity and temperature. It is necessary to control the operating point to draw the maximum power of photovoltaic module. This paper presents the design and implementation of digital power converters using Proteus software. Its aim is to enhance student's learning for virtual system modeling and to simulate in software for PIC microcontroller along with the hardware design. The buck and boost converters are designed to interface with the renewable energy source that is PV module. PIC microcontroller is used as a digital controller, which senses the PV electric signal for maximum power using sensors and output voltage of the dc-dc converter and according to that switching pulse is generated for the switching of MOSFET. The implementation of proposed system is based on learning platform of Proteus virtual system modeling (VSM) and the experimental results are presented.

1. Introduction

The growing market for renewable energy technologies has resulted in a rapid growth in the need for power electronics. Due to the global concern about climate changes and sustainable electrical power supply, renewable energy is increasingly becoming more popular all over the world.

With the virtual system modeling (VSM) facility, it can transform the product design cycle, in terms of reduced time and cost. There are various tools that are available like NI LabView, MATLAB/SIMULINK, Multisim, Orcad, and so forth. In looking to understand the best solution for gaining the engineering knowledge practically, it is necessary to have knowledge of simulation. Laboratories can be expensive and time-consuming and difficult to understand [1]. The purpose is to use electronics simulation tool such as Proteus VSM for engineering education program. In many applications, dc-dc converters are used to produce a regulated voltage or current [2, 3]. In many applications solar PV modules were developed for power satellites in space program, battery chargers, and distributed power systems. In high power applications parallel connected converters are used to provide power [4–6].

The interfacing of PV modules with buck converter and boost converter was developed [7]. In closed loop, the feedback signal to the microcontroller is designed to maintain the output voltage level constant [8]. In many dc-dc converter circuits, the power device selections are very important. The parameters greatly affect the maximum switching frequency of the converter and how much is the current; the converter can be designed for these purposes [9].

Proteus VSM, developed by Labcenter Electronics Ltd., was founded in 1988. The Proteus Design Suite is wholly unique in offering the ability to cosimulate both high and low level microcontroller code in the context of a mixed-mode SPICE circuit simulation. Proteus's VSM has microcontroller programming tool, environment, with its many software features and hardware options. Many researchers and engineers use Proteus for testing and rapid prototyping in the product development process. In institutions of higher education, Proteus can be useful for the electronics engineering students to understand complex theories and connect these to practical problems. Proteus VSM is now chosen as the tool for the course projects due to its ability to provide hands-on experiences for students, which is particularly

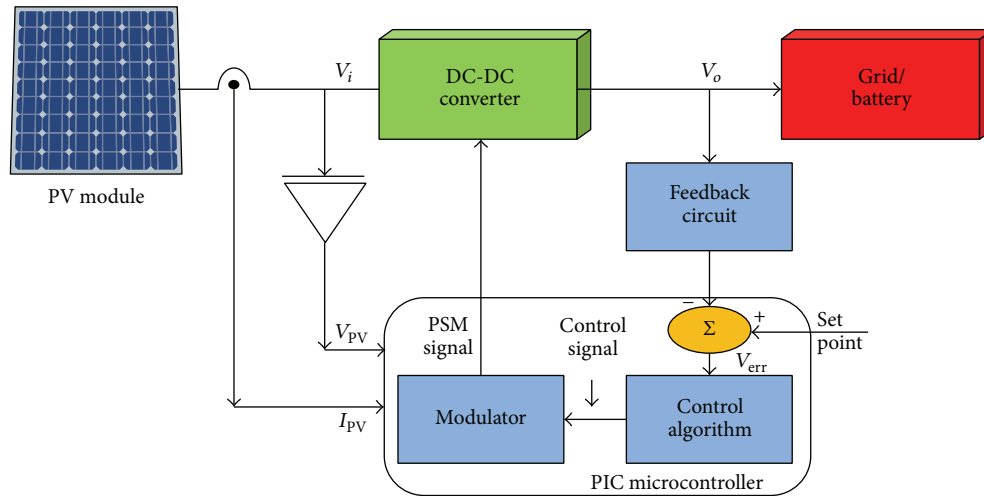


FIGURE 1: Block diagram of DC-DC converter using PIC microcontroller as digital controller.

important for electronics engineering technology programs. This paper investigates the learning of software for utilization and implementation of digital controller for maintaining the maximum power due to variation in environmental conditions for photovoltaic modules.

Proteus VSM is already unique in its capability to run near real-time simulations of complete microcontroller systems; its real power comes from its ability to perform these simulations in single step mode. Proteus VSM is equipped with comprehensive diagnostic or trace messaging. This allows you to specify which components or processor peripherals are of interest at any given time and receive detailed textual reporting of all activity and system interaction. This is invaluable as a debugging aid, allowing you to locate and fix problems in both software and hardware much faster than you could when working on a physical prototype. Proteus VSM also provides extensive debugging facilities including breakpoints, single stepping, and variable display for both assembly code and high level language source. Proteus VSM is uniquely suited to teach students about the design and operation of embedded systems solutions. Full virtual debugging interface is available in software, obviating the need for expensive hardware and facilitating freedom and flexibility to design and develop microcontroller solutions without the need for a physical prototype to the students.

The paper is organized as follows. Section 2 gives operating configuration. Section 3 presents Proteus based implementation. Section 4 presents simulation and experimental results, and Section 5 presents conclusion.

2. Operating Configuration

The proposed design configuration for photovoltaic module is mainly consisting of (i) buck converter and (ii) boost converter and digital controller PIC16F628A microcontroller. The schematic blocks of the proposed system with dc-dc converter with microcontroller are developed using Proteus VSM platform. The real-time microcontroller is implemented

by using MikroC and MPLAB programming. The block diagram of proposed system is shown in Figure 1. Power stage input which is the output of PV module is sensed by using voltage and current sensor which sent to the digital controller; the output voltage of power stage is applied to digital controller through feedback circuit as an error voltage by comparing with set point voltage. According to this voltage digital controller produces pulse skipping pulses (PSM) to switch the MOSFET.

In the proposed scheme PIC16F628A microcontroller takes the decision to generate the switching pulses to turn ON and OFF the switches. MikroC or MPLAB programming software tool can be used to build source code and, after compiling, the hex file can be generated. Generated hex file is very easy to burn in microcontroller memory using Proteus VSM. A wide range of microcontrollers is available in the software, where as in this paper PIC16F628A microcontroller is used in Proteus platform for switching the converters.

The solar PV module (V_{PV}) is connected to the dc-dc converter to maintain the generated dc voltage constant which is connected to dc grid or the battery or dc load. The output voltage (V_o) is sensed and sent to the digital controller through feedback circuit. Feedback circuit contains the comparator which compares the V_o and set point voltage. Also PV module output and current which are the inputs to power stage are sensed by using voltage and current sensors, respectively, to monitor the maximum power point. Generated error voltage by comparator is applied to the PIC microcontroller. The PIC16F628A has onboard voltage reference, V_{ref} , and comparators. In the proposed application, the V_{ref} set point is at 2.5 V. According to set voltage, pulse skipping modulation is provided to the gate of MOSFET to turn ON and OFF.

2.1. Solar Cell Module. A solar PV module consists of a number of N_s solar cells in series and the equivalent circuit of the physical model of the solar cell is given in Figure 2.

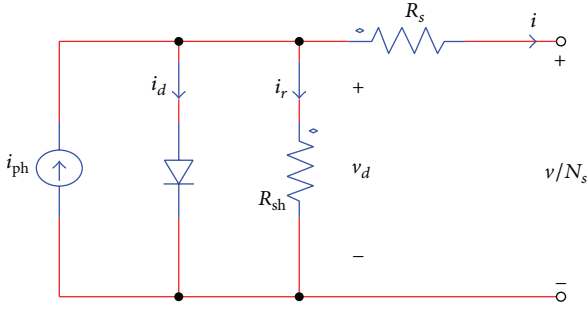


FIGURE 2: Equivalent circuit diagram of solar cell.

TABLE 1: Specifications of photovoltaic module.

Sr. number	Electrical characteristics	Value
01	Product code	SLP011-12
02	Number of cells	36
03	Standard light intensity S_o	1000
04	Ref. temperature T_{ref}	25°C
05	Maximum power P_{max}	11 W
06	Voltage at P_{max}	17.6 V
07	Current at P_{max}	0.63 A
08	Open-circuit voltage V_{oc}	21.1 V
09	Short-circuit current I_{sc}	0.68 A
10	Temperature coeff. of V_{oc}	$-(80 \pm 10) \text{ mV}/^\circ\text{C}$
11	Temperature coeff. of I_{sc}	$(0.065 \pm 0.015\%)/^\circ\text{C}$
12	Operating temperature	-40°C to 85°C

The solar cells are made from semiconductor cells and are usually arranged in modules. There are different types of solar cells available in the market and are under development as sensitized nand-crystalline cells for high efficiency and low cost. The datasheet parameters of physical PV module are shown in Table 1.

The solar cell describes the inverse relationship between current and voltage and the equations that describe a solar cell are as follows:

$$i = i_{ph} - i_d - i_r, \quad (1)$$

$$i_{ph} = I_{sco} \cdot \frac{S}{S_o} + C_t \cdot (T - T_{ref}), \quad (2)$$

$$i_d = I_o \cdot \left[e \cdot \frac{q \cdot v_d}{A_k} \left(\frac{1}{T_{ref}} - \frac{1}{T} \right) \right], \quad (3)$$

$$i_r = \frac{v_d}{R_{sh}}, \quad (4)$$

$$v_d = \left(\frac{v}{N_s} + i \cdot R_s \right) \quad (5)$$

$$T = T_a + k_s \cdot S, \quad (6)$$

where q is the electron charge ($q = 1.6 \cdot 10^{-19} \text{ C}$); k is the Boltzmann constant ($k = 1.3806505 \cdot 10^{-23}$); S is the light intensity input; T_a is the ambient temperature input; v is the

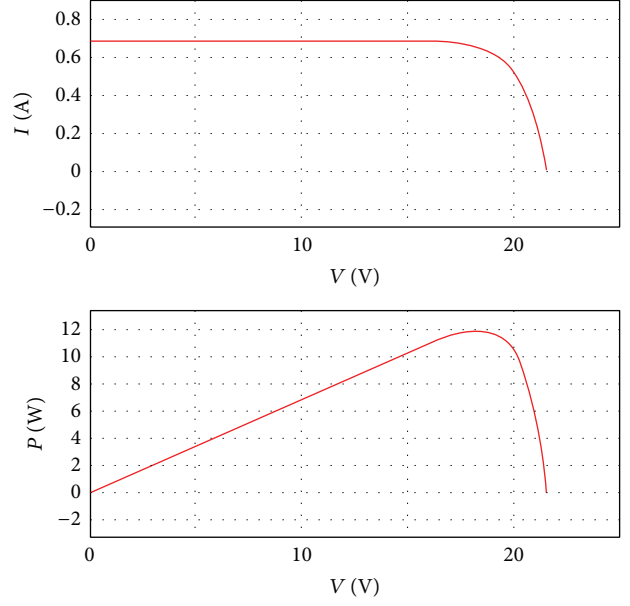


FIGURE 3: Characteristics of current versus voltage and power versus voltage.

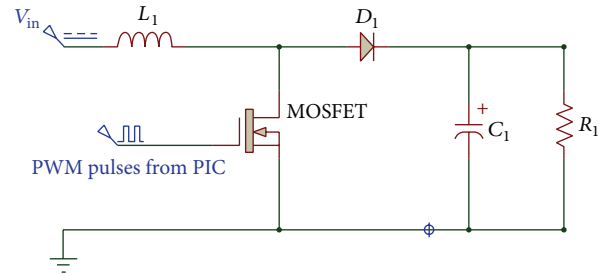


FIGURE 4: Boost converter circuit diagram.

voltage across the entire solar module; and i is the current flowing out of the positive terminal of the solar module.

The photovoltaic module provides power to the load which often operates away from the maximum operating point of module. The characteristics curves for solar cell simulated module are as shown in Figure 3.

2.2. DC-DC Boost Converter Configuration. The boost converter configuration by assuming continuous conduction mode of operation is shown in Figure 4.

The equations are considered when the main switch is ON and are shown in

$$\begin{aligned} \frac{di_L}{dt} &= \frac{1}{L} (V_{in}), & \frac{dv_o}{dt} &= \frac{1}{C} \left(-\frac{v_o}{R} \right), \\ 0 < t < dT, & Q : \text{ON}, \\ \frac{di_L}{dt} &= \frac{1}{L} (V_{in} - v_o), & \frac{dv_o}{dt} &= \frac{1}{C} \left(i_L - \frac{v_o}{R} \right), \\ dT < t < T, & Q : \text{OFF}. \end{aligned} \quad (7)$$

TABLE 2: Designed parameters for boost converter.

Parameters	Value
Inductor, L	1 mH
Capacitor, C	47 uF
Duty cycle, D	5% to 95%
Switching frequency, f_{sw}	75 KHz
Load resistance, R_L	37.5 Ω
MOSFET	IRF540

The following parameters are necessary for the power stage: (i) input voltage range V_{min} and V_{max} and (ii) nominal output voltage V_{out} and maximum output current I_{out} . The first step to calculate the switch current is to determine the duty cycle, for the minimum input voltage. The minimum input voltage is used because this leads to the maximum switch current. Consider the following:

$$D = 1 - \frac{V_{in \min} \times \eta}{V_{out}}, \quad (8)$$

where η is the efficiency of the converter.

The efficiency is added to the duty cycle calculation, because the converter has to deliver also the energy dissipated. Consider the following:

$$\Delta I_L = \frac{V_{in \min} \times D}{f_s \times L}, \quad (9)$$

where f_s is the switching frequency and L is the selected inductor value. Consider

$$L = \frac{V_{in} \times (V_{out} - V_{in})}{f_s \times \Delta I_L \times V_{out}}. \quad (10)$$

To reduce losses, Schottky diode is used. Consider the following:

$$I_f = I_{out \max}, \quad (11)$$

$$C_{out \min} = \frac{I_{out \max} \times D}{f_s \times \Delta V_{out}}. \quad (12)$$

Table 2 shows the designed value of components for boost converter as per above equations.

2.3. DC-DC Buck Converter Configuration. The state equations corresponding to the converter in continuous conduction mode are used by applying Kirchhoff's voltage law on the loop containing the inductor and Kirchhoff's current law on the node with the capacitor branch connected to it. When the ideal switch is ON, the dynamics of the inductor current $i_L(t)$ and the capacitor voltage $v_C(t)$ are given in (13) and (14).

The buck converter configuration with ideal switching devices is considered as shown in Figure 5. Consider the following:

$$\frac{di_L}{dt} = \frac{1}{L} (V_{in} - v_o), \quad \frac{dv_o}{dt} = \frac{1}{C} \left(i_L - \frac{v_o}{R} \right), \quad (13)$$

$0 < t < dT, Q : ON$

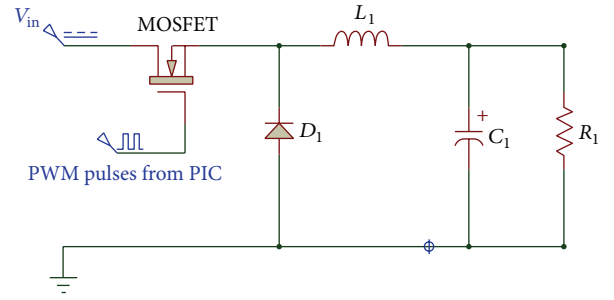


FIGURE 5: Buck converter circuit diagram.

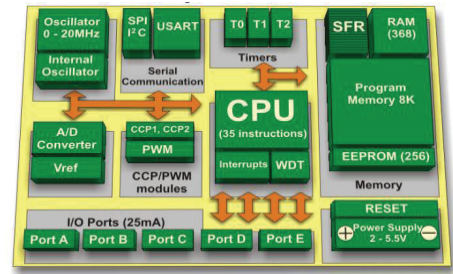


FIGURE 6: Block diagram of PIC microcontroller.

TABLE 3: Designed parameters for buck converter.

Parameters	Value
Inductor, L	1 mH
Capacitor, C	470 uF
Duty cycle, D	5% to 95%
Switching frequency, f_{sw}	75 KHz
Load resistance, R_L	3 Ω
MOSFET	IRF540

and when the switch is OFF they are presented by

$$\frac{di_L}{dt} = \frac{1}{L} (-v_o), \quad \frac{dv_o}{dt} = \frac{1}{C} \left(i_L - \frac{v_o}{R} \right), \quad (14)$$

$dT < t < T, Q : OFF.$

The critical inductor is calculated in (10). Consider the following:

$$L = \frac{R}{2f_s} (V_{in} - V_o). \quad (15)$$

The critical capacitor is calculated assuming change in voltage as in (11). Consider the following

$$C = \frac{D}{8Lf_s^2 \Delta V_o} (V_{in} - V_o). \quad (16)$$

Table 3 shows the designed value of components for buck converter as per above equations.

2.4. Pulse Skip Modulation (PSM) and Pulse Width Modulation (PWM). One of the simplest modulation techniques

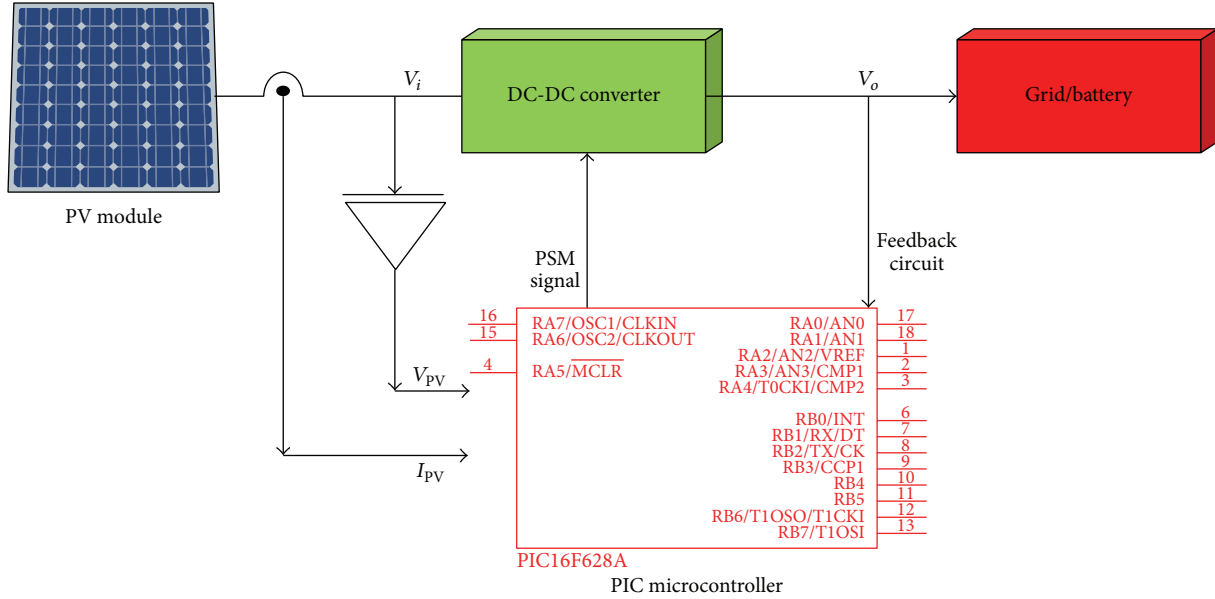


FIGURE 7: Digital power controller scheme in Proteus.

used for controlling a dc-dc converter is pulse skipping modulation (PSM), which is also known as pulsed frequency modulation (PFM). In a PSM system, the modulator generates a train of pulses to turn the converter power switch ON and OFF. The pulses have a fixed pulse width and period. As long as the dc-dc converter output is below the desired target, the PSM pulse continues to run the converter switch. This operation will result in decreasing pulse density as the converter output reaches its target, or as the output loading decreases. When the converter output falls below the target, or as the output loading increases, the PSM pulse density will increase. Similarly the PWM is used to maintain the constant output voltage by varying the ON and OFF period of the pulse.

3. Proteus Based Implementation

Proteus VSM includes a number of virtual instruments like an oscilloscope, logic analyzer, function generator, pattern generator, counter timer, virtual terminal, and simple voltmeters and ammeters. In addition, it provides dedicated master/slave/monitor mode protocols.

Proteus provides detailed measurements on graphs and performs other analysis types such as frequency, distortion, noise, or sweep analyses of analogue circuits. It is capable of supporting schematic capture for both simulation and PCB design. The proposed designed prototype is implemented for buck and boost converter. The PIC microcontroller block diagram is shown in Figure 6.

The controller tends to maximise the output power from photovoltaic module by adjusting the duty cycle so that the solar cell module will always be at its maximum power at all times. Digital controller automatically increases or decreases the voltage applied to the pulse generator (PWM) in order to

change the duty cycle of the converter according to the PV module output voltage. The maximum power point loop is used to set the corresponding V_{ref} to the input; the voltage regulator loop is used to regulate the solar output voltage according to reference, which is set as maximum operating point and control scheme is shown in Figure 7.

This firmware modulator generates the PSM pulses on the RB7 pin (port B, bit7), to drive the gate of MOSFET switch of converter. When the dc-dc converter output is below the desired value, the firmware continuously sends out PSM pulses to increase the converter output. Once the dc-dc converter output exceeds the target, the controller will skip the PSM pulses until the output voltage, or current, falls below the threshold and the control cycle repeats.

The program is simulated in Proteus VSM and it has ability of interaction between software running on a microcontroller and analog or digital signal connected to it. It simulates the execution of object code (machine code), like a real chip. The programming logic using PIC is written with the help of flowchart. PIC performs the modulator function in firmware. To get the maximum power point, many methods have been proposed. The program is developed using the flow chart and is shown in Figure 8.

Timer0 of the microcontroller is used to generate a time base for the firmware modulator. Timer0 is enabled and the TMR0 register is loaded with a reload value. When Timer0 overflows, an interrupt occurs. In the interrupt routine, TMR0 is again loaded with the reload value. The reload value determines the time base of the PSM signal. In this program, the TMR0 reload value is chosen to produce a time base of 50 microseconds when the microcontroller runs from a 16 MHz crystal. The comparator has several configurations, which allow the comparators to compare external voltage to the V_{ref} voltage. To select this configuration, the comparator control register CMCON must be set. In it only C2 comparator of

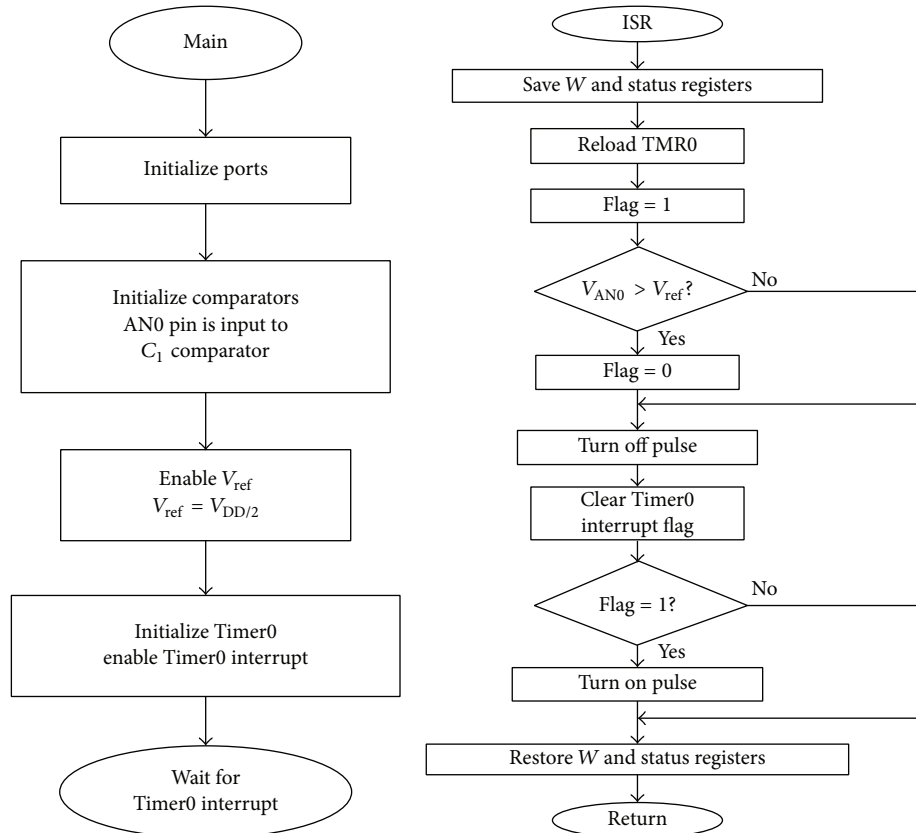


FIGURE 8: Flowcharts of program.

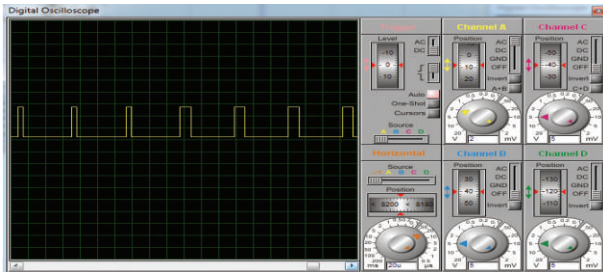


FIGURE 9: Generated PSM pulses on CRO screen1.

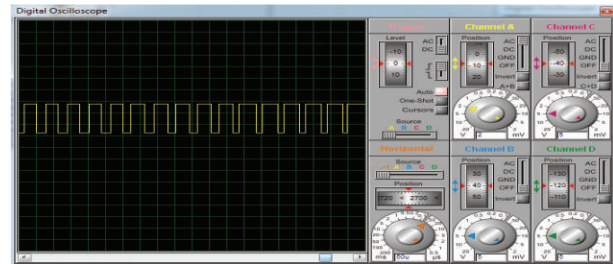


FIGURE 10: Generated PSM pulses on CRO screen2.

the PIC is used to compare the feedback voltage on the AN1 pin to the internal voltage reference V_{ref} . If the dc-dc converter output is lower than the desired value, then the feedback voltage presented on AN1 is lower than V_{ref} . The voltage control algorithm performed in firmware becomes very simple; if the voltage on AN1 pin is lower than V_{ref} , then produce PSM output pulse; else voltage on AN1 pin is higher than V_{ref} , then skip PSM output pulse shown in Figure 9 where the duty cycle of PWM pulse varies approximately in between 5% and 30% and 30% and 95% as shown in Figure 10.

The actual implemented hardware is shown in Figure 11 and its PWM output pulses on DSO are shown in Figures 12



FIGURE 11: Experimental setup.

and 13. Thus simulated result of digital power controller is exactly matched with actual hardware results.

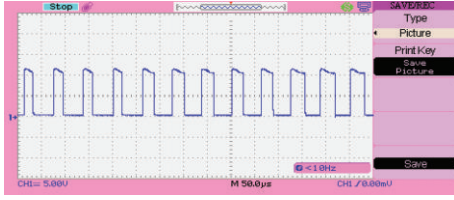


FIGURE 12: Generated PSM pulses on DSO.

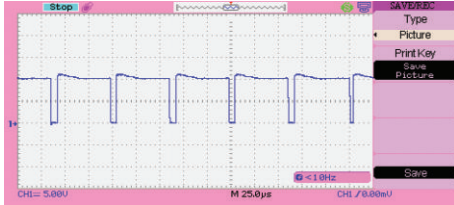


FIGURE 13: Generated PSM pulses on DSO.

4. Proteus Simulation and Experimental Results

The dc-dc converter with PIC16F628A is designed for compatible load to achieve maximum power from photovoltaic modules. The buck converter results are shown in Table 4.

Table 4 shows the input voltage V_{in} , output voltage V_o , and output current I_o , when considering load of 3Ω . From the table, it is clear that change in V_{in} , output voltage maintain constant which approximately 1.5 V and I_{out} is 0.39 A which are shown in Figure 14 by green and red colour, respectively.

Table 5 shows the boost converter result, in which input voltage changes to down from high value; the output voltage V_{out} is maintained constant at approximately 24 V with output current I_{out} 0.63 A. The response of digital controller for boost converter is shown in Figure 15.

Here the design of buck converter is for obtaining the output voltage step down of 1.2 V, and output current is 0.39 A where the input voltage varies from 5 V to 100 V and boost converter is for obtaining the output voltage step up of 24 V, and output current is 0.63 A where the input voltage varies from 17.6 V to 6 V. From responses of buck and boost converter it is verified. Simulated and actual hardware results are approximately matched with each other. Therefore using PIC16F628A microcontroller these dc-dc converters work efficiently for photovoltaic module.

5. Conclusion

The effectiveness of student learning becomes more easy and effective using Proteus software in the laboratory without implementing the physical prototype of a design. The role of digital power controller in the renewable energy system is important to maintain the output voltage and current to a required suitable level. The purpose of proposed scheme is for maximum power operating point to adjust the photovoltaic operating voltage close to maximum under changing atmospheric condition. To realize the prototype

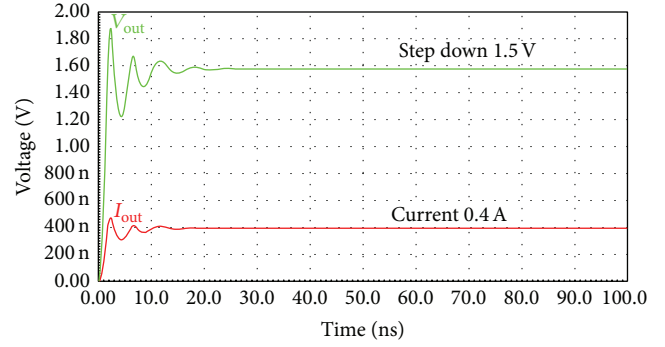
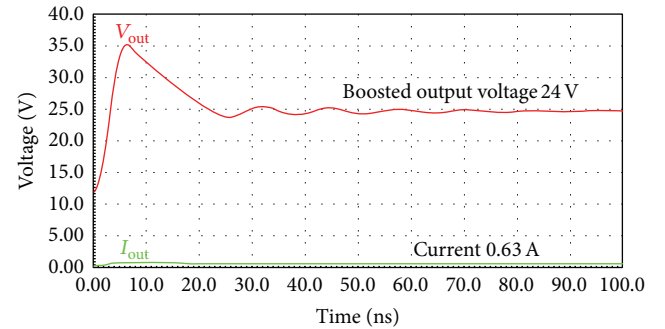
FIGURE 14: Response of buck converter when $V_{in} = 5$ V.FIGURE 15: Response of boost converter when $V_{in} = 17.6$ V.

TABLE 4: Result of buck converter.

Sr. number	V_{in} (volts)	V_{out} (volts)	I_{out} (amp)
01	5	1.189	0.39
02	10	1.189	0.39
03	15	1.199	0.39
04	25	1.199	0.39
05	50	1.199	0.39
06	100	1.210	0.39

TABLE 5: Observation table for boost converter.

Sr. number	V_{in} (volts)	V_{out} (volts)	I_{out} (amp)
01	17.6	23.9	0.64
02	15	23.8	0.63
03	12	23.8	0.63
04	10	23.8	0.63
05	8	23.8	0.63
06	6	23.8	0.63

experience without implementing it, using Proteus VSM is easy for implementation and execution. The desired logic according to flowchart can be programmed using MPLAB or MikroC compiler and generate hex code file and burning in PIC16F628A microcontroller in Proteus VSM is simple process. PIC microcontroller is used as a digital controller for dc-dc converter where investigation for photovoltaic module application using Proteus VSM software and result are satisfactorily executed and verified with physical prototype.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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