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Design and Implementation of a Microcontroller-based Non-inverting DC/DC Buck-boost Converter

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***Abstract*–This paper designs a low cost non-inverting DC/DC buck-boost converter to produce constant output voltage with high reliability and simple control manner. The proposed controller is based on closed loop voltage mode control technique with microcontroller ATmega8 to stabilize the output voltage of DC/DC converter. The microcontroller adjusts the duty cycles of the power switches according to the measured output voltage within limited range of the input voltage of DC/DC converter. The proposed DC/DC converter is simulated on Proteus Suite and experimentally implemented in continuous conduction mode (CCM) with unregulated DC input voltage between 8-25Vand 62.5 kHz switching frequency to obtain 15 V output voltage. The simulation and test results are satisfied the performance of the proposed DC/DC non-inverting buck boost converter design for stabilizing its output voltage at 15 V whatever change in the input voltage between 8 and 25 V or load change of converter.**

Index Terms –Microcontroller,buck-boost converter

I. INTRODUCTION

In recent years, DC/DC converters are widely used in several applications, such as wireless appliances, portable devices [1], [2], micro grid applications [3], charging batteries [4] and renewable energy systems [5-9] for stepping up or down the DC voltage with high efficiency. Typical efficiencies of DC/DC converters are between 70% and 95% as a result of losses in switching devices and other converter components. Normally, the output voltage of DC/DC should be regulated to meet requirements of variable loads or input voltage of DC/DC converter. The DC/DC converter topology are classified such as buck converter, boost converter [10-11], buck-boost converter, and cuk converter to transfer energy to the load at either lower or higher voltage than the source voltage. For example non-inverting buck-boost DC/DC converter can transfer energy to load at voltage either above or below the source voltage. It is composed of cascading connections of buck and boost converters as shown in Fig.1. with digital control to satisfy efficient operation. Circuit simulation is essential to obtain optimum performance of the system at steady state, studying transient response and estimated over all system components with their parameters with economical manner. Various software are used for circuit simulation such as Pspice, Multisim, Proteus design suite and MATLAB/Simulink. The circuit simulation is easy and simple in MATLAB. But, using MATLAB/Simulink [12] for electronic circuits has some limitations for hardware implementation [13-14]. Normally, the hardware components are selected according to the requirement of power-voltage rating among the broad range of products available in the market. This paper simulates non-inverting DC/DC buck-boost converter with microcontroller on Proteus ISIS ® Professional package [15]. The design project has light weight and portable electronic components. It is implemented in a certain range of input voltage using microcontroller ATmega8 to stabilize the output voltage at 15 V.

II. OPERATION OF NON-INVERTING BUCK–BOOST CONVERTER

A schematic diagram of non-inverting buck-boost converter is shown in Fig. 1 with the same polarities of both input and output voltages. It is composed of both buck and boost converters, with a single inductor-capacitor and two active power switches[16-17]. The DC/DC converter can work either a Buck-mode or Boost-mode through different combinations of buck and boost active power switch (SW_1-SW_2). The active power switches (SW_1-SW_2) are driven by two PWM signals of PWM_1 and PWM_2 respectively as shown in Table 1. PWM_1 and PWM_2 signals are generated with aid of microcontroller.

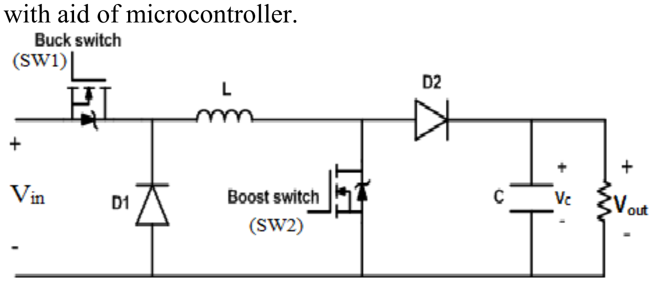


Fig. 1: Circuit of non-inverting buck-boost converter[16-17]

Table 1: Non-inverting buck-boost converter modes

Phase	Operating mode	Operating State of Power Switches	Output Voltage(V_{out})
1-	Boost	1-SW_1 is always on 2-SW_2 has duty cycle of K_2 at frequency f_s	$V_{out} = \frac{V_{in}}{1-K_2} - V_{d2}$ Where: K_2 is SW_2 duty cycle V_{d2} is the voltage drop on D_2
2-	Buck	1-SW_1 has duty cycle of K_1 at frequency f_s 2-SW_2 is always off	$V_{out} = K_1 V_{in} - V_{d1}(1-K_1) - V_{d2}$ Where: K_1 is SW_1 duty cycle V_{d1} is the voltage drop on D_1
3-	Preventing mode	1-SW_1 is always off 2-SW_2has duty cycle of K_2at frequency f_s	N/A

A- Operating Modes of the DC/DC Converter :

The operating modes of the DC/DC non-inverting buck-boost converter [10-11] are classified from Tabel 1 as follow:

1- Boost Mode:

The waveforms of this mode for different components of converter at continous current conduction mode (CCM) are shown in Fig. 2. In this mode as shown in Fig. 2, the power SW_1 is always ON, while the power switch SW_2 is operated with duty cycle K_2 at switching frequency f_s. Also, D_1 is turned off, while D_2 forms the boost switching leg for charging and discharging the inductor L. The mode analysis is given in Table 2.

Table 2: States of boost mode DC/DC converter [9]

Time interval	Switching mode	Inductor Current	Inductor Voltage
$0 < t \leq K_2T$	1-SW_2 is on 2-D2 is off	$i_L = \frac{V_{in}}{L}t + i_L(0)$ $\Delta i_L = \frac{K_2(1-K_2)V_{out}}{f_s L}$	$V_L = V_{in} = L\frac{di_L}{dt}$
$K_2T < t \leq T$	1-SW_2 is off 2-D2 is on	$i_L = \frac{V_{in}-V_{out}}{L}(t-K_2T) + i_L(K_2T)$ $\Delta i_L = \frac{K_2(1-K_2)V_{out}}{f_s L}$	$V_L = V_{in} - V_{out} = L\frac{di_L}{dt} < 0$

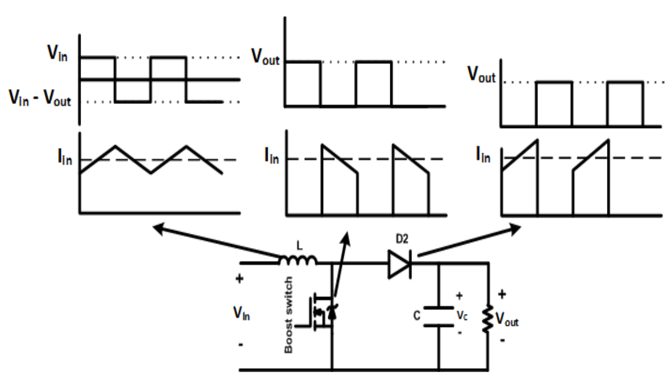


Fig. 2 Waveforms of a boost converter mode at CCM

2- Buck Mode:

The waveforms of the buck converter mode for its different components at CCM are shown in Fig. 3. The waveform indicates that the power switch (SW_1) has duty cycle K1 at switching frequency f_s, while the power Switch SW_2 is always in off state. Diode D_2 is always in on state as a result of switched off SW_2. The buck mode analysis is expreesed in Table 3.

Table 3: DC analysis for buck mode

Time interval	Switching mode	Inductor Current	Inductor Voltage
$0 < t \leq K_1T$	1-SW_1 is on 2-D1 is off	$i_L = \frac{V_{in}-V_{out}}{L}t - i_L(0)$ $\Delta i_L = \frac{(V_{in}-V_{out})}{f_s L}$	$V_L = V_{in} - V_{out} = L\frac{di_L}{dt}$
$K_1T < t \leq T$	1-SW_1 is off 2-D1 is on	$i_L = \frac{-V_{out}}{L}(t-K_1T)$ $\Delta i_L = \frac{(1-K_1)V_{out}}{f_s L} + i_L(K_1T)$	$V_L = -V_{out} = L\frac{di_L}{dt} < 0$

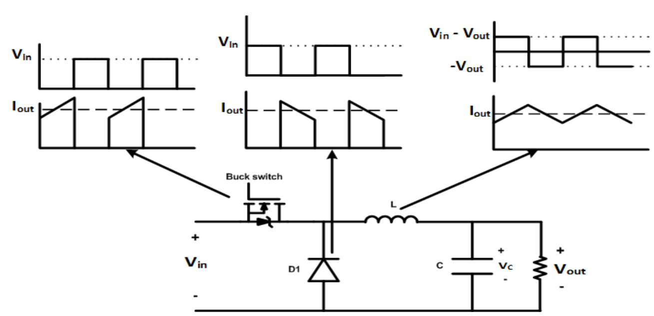


Fig. 3 Waveforms of buck mode at CCM [16-17]

3- Preventive Mode:

The probability of switching converter is, the power switch SW_1 is switched off , while the power switch SW_2 is switched on. This mode should be never occur in either buck or boost mode of DC/DC converter. To avoid the probability occurrence of this mode, the microcontroller should manage the pulse width modulation (PWM) according to Fig. 4, to switch the power switches SW_1 and SW_2. To satisfy such requirements the microcontroller should be provided with the following procedures:

1. Keep the frequency of both PWM signals the same.
2. The duty cycle K_1 must be greater than the duty cycle K_2
3. PWM_1 should be enabled before the PWM_2 signal.
4. PWM_1 should be disabled after the PWM_2 signal.

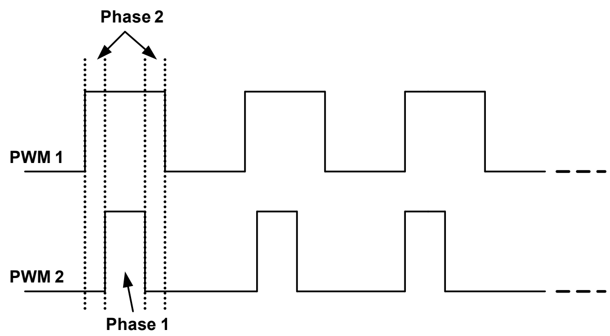


Fig. 4 Timing diagram of two PWM signals [16]

III. Voltage Mode Control of Buck-Boost Converter

Figure 5 shows the voltage-mode controlled diagram of DC/DC non-inverting buck-boost converter during its operating modes. The control voltage V_C is generated from the difference between the actual-output voltage and the desired-output voltage (or reference voltage). The voltage mode control is compared with the sawtooth voltage (or PWM ramp) at fixed frequency to generate PWM with specified duty cycle with the aid of microcontroller. The closed loop control system is mainly composed of three parts lists as follow:

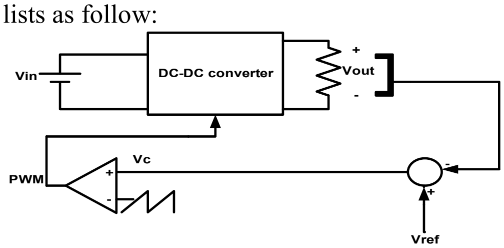


Fig. 5 Voltage mode control of DC/DC converter [11], [18]

A- Voltage scaling circuit: It is scaled the measured voltage level of DC/DC converter to the microcontroller voltage level (less than or equal to 5V). The voltage scaling circuit is a voltage divider with Op-Amp voltage follower as shown in Fig. 6

Fig. 6 voltage divider circuit(R1=10kΩ, R2=1kΩ).

B- PWM driving circuit: It is used in order to drive MOSFET transistor switches. The MOSFET transistor is a specialized type of transistor that is used for high frequency and current applications. An IRF9540 p-channel, IRF540 n-channel MOSFET transistors and BC546 BJT transistor are chosen. Schematic Diagram of PWM Driving Circuit is shown in Fig. 7

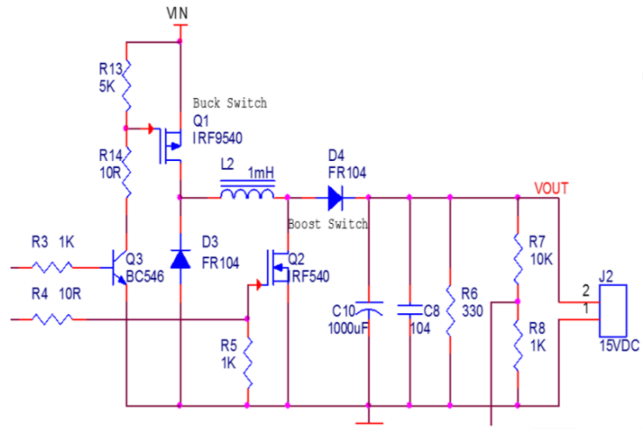


Fig. 7 Schematic Diagram of PWM Driving Circuit

C- Microcontroller unit: This unit is responsible for acquiring measured input and output voltages of DC/DC converter to generate PWM signal which are driving the switching circuit of the control algorithm.

4-Control algorithm: This algorithm is intended on BASCOM_AVR program [19]. The flow chart of the control algorithm is shown in Fig. 8

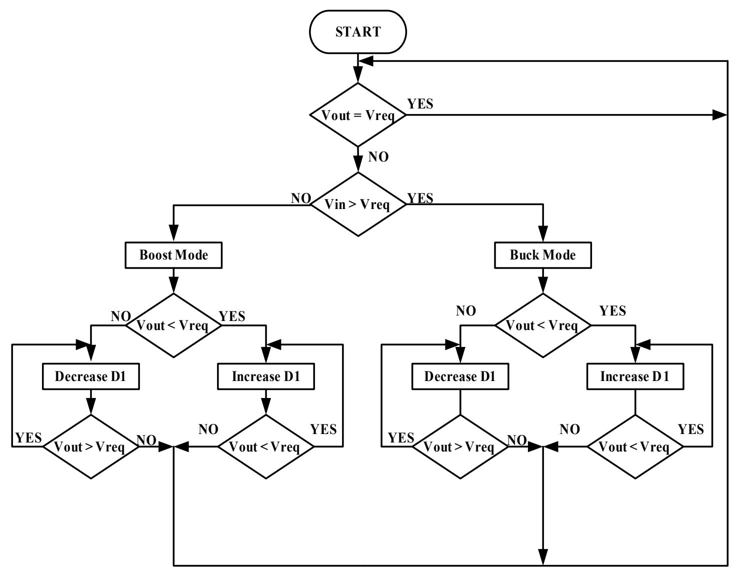


Fig. 8 Flow chart of the control algorithm

IV. Design of Non-Inverting Buck-Boost Converter

The design of non-inverting buck-boost converter **[9-11], [13-14], [20]** has the same basic of the inverting buck-boost converter. The converter is designed on the following considerations:

V_{out} = Output voltage = 15V

V_D = Diode forward drop = 0.525V

V_{in} = Minimum and maximum input voltage = 8-25V

I_{out} = Average output current = 1.0A

f_s = switching frequency = 62.5 KHz

The duty cycles K_1 and K_2 for driving SW_1 and SW_2 are calculated as :

$$K_1 = \frac{V_{out}}{V_{in\,(max)}} \qquad (1)$$

$$K_2 = 1 - \frac{V_{in\,(min)}}{V_{out}} \qquad (2)$$

The minimum and maximum input voltage are between 8 and 25 volts to produce constant DC output voltage 15V at maximum output current of 1A. Eq.1-2 compute duty cycle (K_1) between 60% to 100% and duty cycle (K_2) between 0% to 46% to satisfy the previous requirements.

A- Design of DC/DC Converter Components

Most DC/DC converter components are choosen in standard values with economical manner. The system components are selected as follows [14]:

1- Basic Design of Inductor

The minimum value of the inductor is computed from;

$$L_{min} = \frac{T * [(V_{in} - V_{sat1}) * K_1 - (V_{sat2} * K_2) - (V_{out} * (K_1 - K_2))]}{2 * I_{out}} \qquad (3)$$

Where:

T is PWM duration= $1/f_s$;

V_{sat1} is the saturated voltages of SW_1

V_{sat2} is the saturated voltages of SW_2

2- Basic Design of Capacitor

The minimum value of capacitor value at 1% or less of V_{out} variations are given as:

$$C_{min} = \frac{100 * I_{out} * (1 - K_1) * T}{V_{out}} \qquad (4)$$

3- Basic Selection of Diodes

The fast recovery diodes are selected because they have diffusion junction, low forward voltage drop, and high current capability with high reliability. The average diode current should be higher than the peak inductor current of the DC/DC converter. The diode reverse breakdown voltage should be greater than the maximum input voltage of the buck-boost circuit. Fast recovery diode FR104 is chosen to satisfy such requirements. It has peak repetitive reverse voltage V_{RRM} =400 V, average rectified output current I_O=1A and peak reverse current I_{RM}=5μA.

4- Basic Selection of Power Switches

Finally, the power MOSFETs switches are selected. The MOSFET power switches are chosen according to breakdown voltages that are greater than the maximum input voltage of the converter and they have very small conduction state voltage drop across them. The IRF9540 P-channel and The IRF9540 P-channel MOSFETs are selected to achieve implementation working of DC/DC converter for buck and boost switches respectively. The IRF9540 P-channel has breakdown voltage of 100V with $R_{DS(ON)}$=0.2Ω, while the IRF540 N-channel sustained breakdown voltage of 100v with $R_{DS(ON)}$=0.077Ω .

B- Simulation of DC/DC Buck-Boost Converter

The designed component parameters of the DC/DC converter are given in Table 4. The system simulation in Proteus suite is shown in Fig. 9

Table 4: DC/DC Converter Parameters

Parameters	Values
Inout voltage (*Vs*)	8:25 V
Output voltage (*Vo*)	15 V
Capacitor (C)	1000 μF
Inductor (L)	1.0 mH
Resistor (RL)	15Ω
D1 , D2	FR104
Switch MOSFET :S1	IRF9540
Switch MOSFET :S2	IRF540
Switching frequency, f_s	62.5 kHz

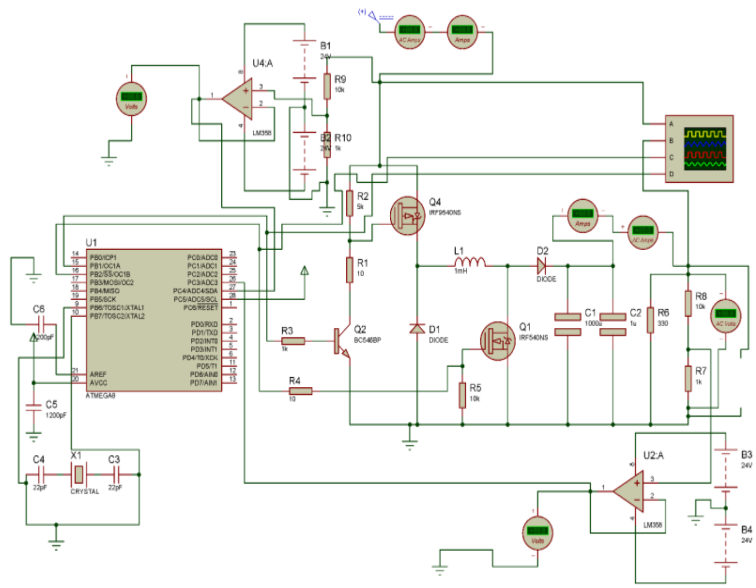


Fig. 9 Microcontroller-based DC/DC buck-boost converter simulation circuit

The microcontroller Atmega8 is programmed to generate the firing pulses with variable duty cycles for buck-boost converter according to the input voltage value to stabilize the output voltage of DC/DC converter. Atmega8 is an 8 bit microcontroller to recive bits from 0 to 255.

The DC/DC buck-Boost converter is controlled by microcontroller at variable input voltage 8:25 V to stabilize output voltage of DC/DC converter at 15 V. The digital oscilloscope of Fig. 10 shows the output voltage of 15 V where the voltage with 10 V input voltage with duty cycle in boost mode K_2 = 35%

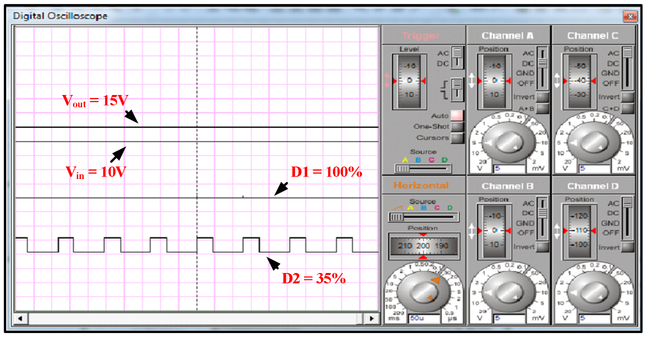


Fig. 10.The output at a digital oscilloscope for V_{in} = 10V, V_{out} = 15V, K_1=100% and K_2=35%

The output voltage at the digital oscilloscope of Fig. 11 is 15 V for input supply of 25 V with duty cycle K_1 = of 59% in buck mode situation.

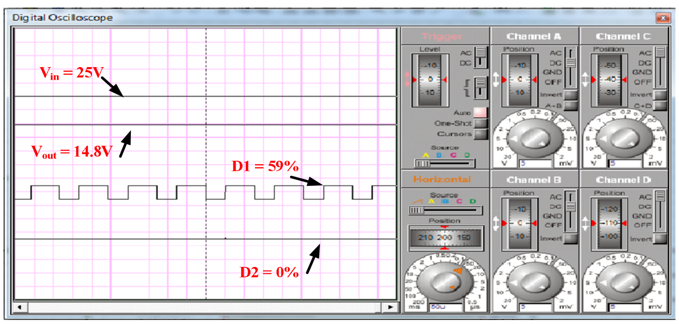


Fig. 11.The output at a digital oscilloscope for V_{in} = 25V, V_{out} = 14.8V, k1=59% and k2=0%

V. Implementation of DC/DC Buck-Boost Converter

The microcontroller-based dc-dc converter is implemented at Advanced Electric Laboratory of Power Systems in Faculty of Engineering, Minia University. The implemented system is shown in Fig. 12

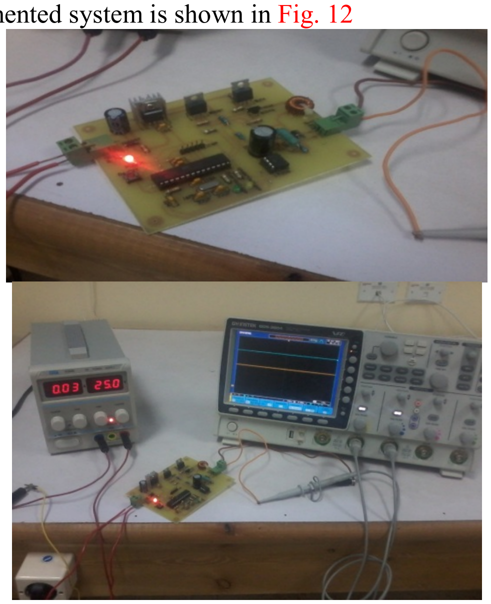


Fig. 12 Picture of Implemented Buck-Boost Converter

Figs.12-13 show the designed circuit of embedded buck-boost converter topology. The set-up experimental system is consists of microcontroller atmega8 with analog-to-digital converter (ADC), PWM module, MOSFET drive circuit, and a voltage divider. The frequency of the PWM is controlled by microcontroller atmega8 to switch MOSFET power switches. The 10-bit resolution ADC is used by the control program to measure signals of power flow control .

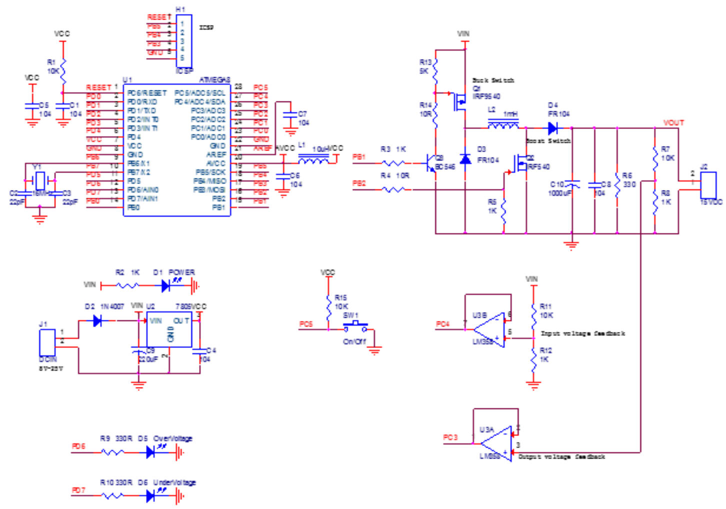


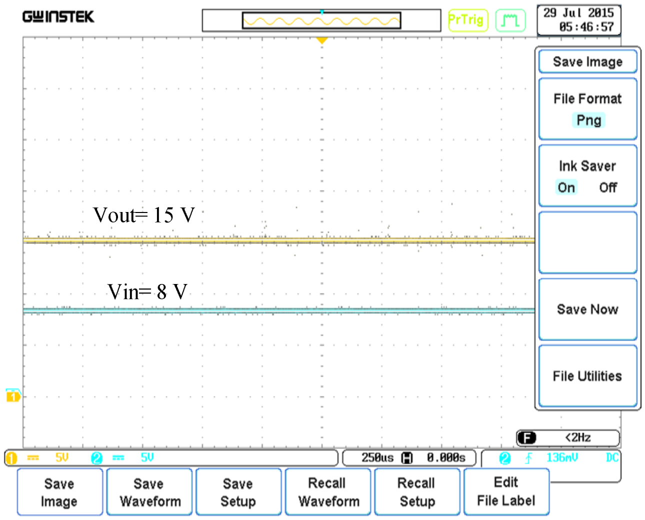
Fig. 13 Schematic diagram of implemented circuit

PWM_1 and PWM_2 are generated from the microcontroller to control the power switches of SW_1 and SW_2 respectively. 2.56V represents internal reference voltage of the ADC. Therefore, the ADC should have voltage range from 0-2.56 V to control the duty cycle. To match the control setting with power circuit measurements, the voltage divider should reduce the output voltage of 15 V to voltage level of 1.36V to suit with ADC requirements in microcontroller atmega8. The designed closed loop control system using microcontroller (atmega8) produces a PWM signal with duty cycle of 0.6 to 1.0 for buck switch SW_1 and 0.0 to 0.46 for boost switch SW_2 within the range of 8V to 25V of input voltage to stabilize the output voltage to15V. In case the input voltage is out of detection range, the whole system will be in sleep mode by microcontroller setting. AS the output voltage has unacceptable value, the circuit is shut down using protection circuit.

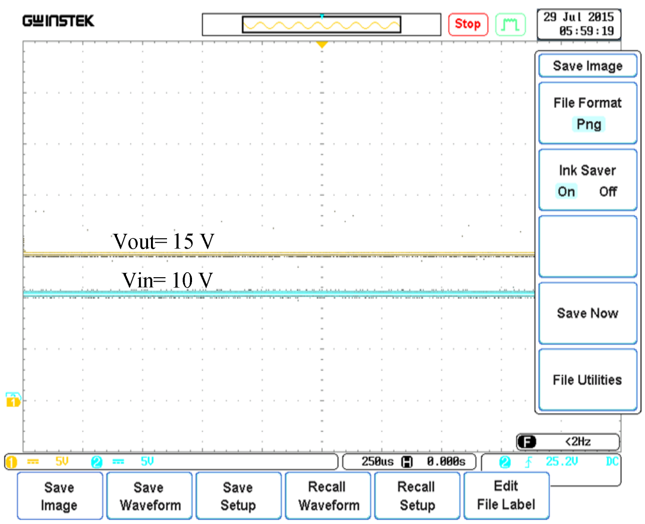
The proposed DC/DC converter based on closed loop microcontrooler system is implemented in the laboratory for different values of input votage that are listed in Table 5. The experimental results are shown on the oscilloscope of Fig. 14.

Table 5: Test cases of variable input voltages

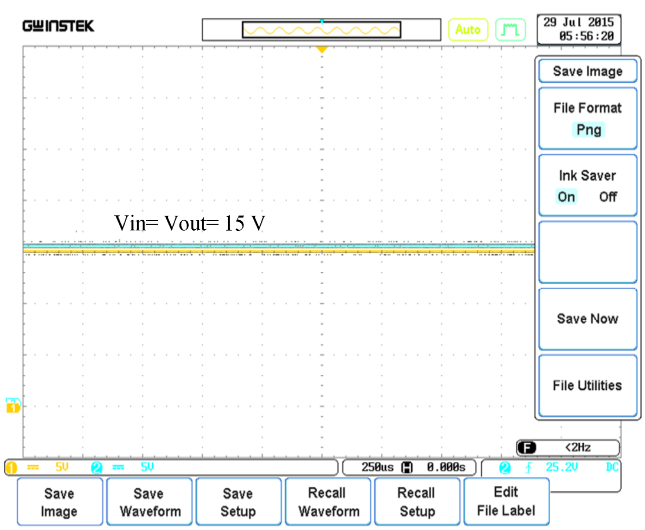
Test No.	V_{in}	V_{out}	Duty cycle K_2 of SW_2 (%)	Duty cycle K_1 of SW_1 (%)
1	8V	15V	46%	100%
2	10V	15V	33%	100%
3	15V	15V	0%	100%
4	20V	15V	0%	75%
5	25V	15V	0%	60%



(a)



(b)



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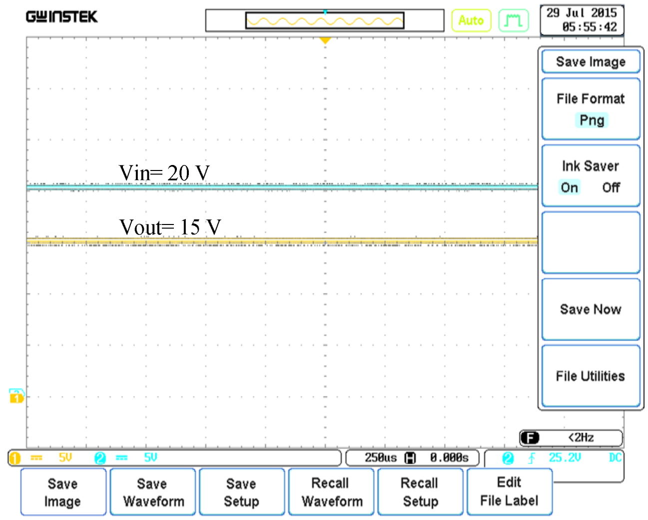
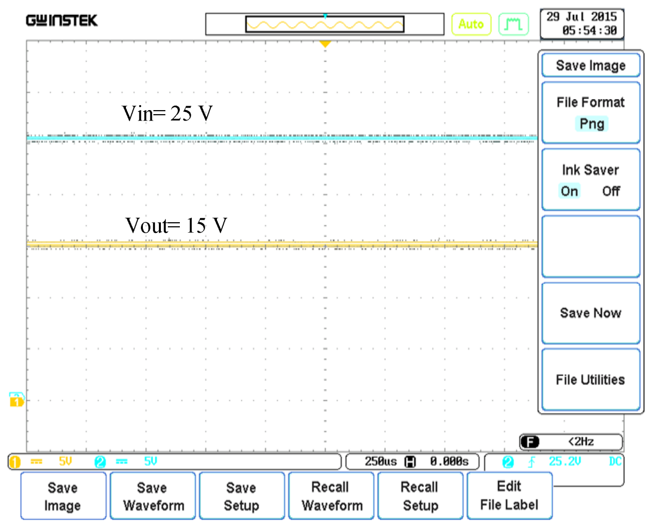


(d)



(e)

Fig. 14: Results on the laboratory`s oscilloscope for different values of input voltage at constant Output Voltage. (a), (b), (c), (d) and (e) are the oscilloscope views of input and output voltage for buck-boost non-inverting converter

VI. Conclusion

A non-inverting buck-boost converter has been designed and implemented to stabilize the output voltage within unregulated range of the input voltage. A microcontroller has been used to implement the control scheme for both buck and boost operation modes of power switches SW_1 and SW_2. It is based on microcontroller which permits flexibility for modifications of controlling program. The simulation of non-inverting DC/DC buck-boost converter using microcontroller atmega8 is done in Proteus suite and is implemented in the environmental of experimental testing. The simulation and experimental results show that the proposed non-inverting buck- boost DC/DC converter has the ability to produce a constant output voltage of 15V within a variable input voltage range from 8 to 25V. The system is useful for stabilizing output voltage for unregulated input voltage which is varying up to 3 times of its smallest value.

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