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# Control of the Output Voltage of the PV System Based DC-DC Boost Converter Using Arduino microcontroller

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***Abstract-*** The main object of this paper is to design and implement a DC-to-DC boost converter that regulates output voltage to a desired value and can be used in Photovoltaic system appliances or other unregulated sources. To regulate the output voltage of the boost, a feedback loop with Proportional-Integral-Differentiator (PID) controller is employed. The duty cycle is controlled to produce constant output voltage using voltage mode control technique. A simulation of the boost converter is done in MATLAB/Simulink. Also a practical implementation with the help of Arduino microcontroller is confirmed the validity of the control algorithm. Simulation and practical results have been proven that the proposed design is able to produce a regulated output voltage successfully against variation of input voltage and load.

***Index Terms-*** **Photovoltaic (PV) cell, boost converter, voltage control mode, PID controller, microcontroller and digital PWM generation.**

## I. INTRODUCTION

The world trend nowadays is to use sustainable and renewable energy sources such as PV cells which require power electronic devices. The output voltage of the solar panels is relatively low and considerably unregulated since it is depending on sun insolation and temperature. Therefore, the low and fluctuating PV system voltage is required to be boosted to a higher and regulated voltage. A DC to DC boost converter with feedback control loop is commonly employed to control the voltage of the PV system to the desired and constant level suitable for several domestic applications [1].

The objectives of this paper can be summarized by:

i) Analyzing the continuous conduction mode (CCM) of DC-DC boost converter and designing their components under this operating mode at 10 kHz switching frequency for a PV system having a maximum power rating of 2 kW.

ii) Testing the response of the boost converter with and without PID controller using MATLAB/ Simulink under various operating conditions.

iii) Implementing digital PID controller system using Arduino UNO microcontroller and examine the hardware implementation under the same simulation conditions for comparison study.

## II. BASIC OPERATION OF A DC-DC BOOST CONVERTER

A DC-DC boost converter is a type of power converter with an output voltage greater than its input voltage. Generally, the basic operation of the boost converter is performed by a combination of four elements which includes inductor (L), controlled electronic switch (usually MOSFET or IGBT), diode, and an output capacitor (C). The basic schematic circuit of a boost converter is given in Fig. 1[2].

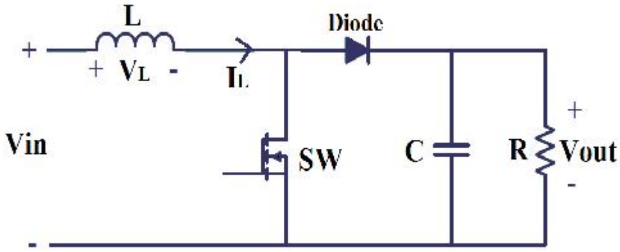
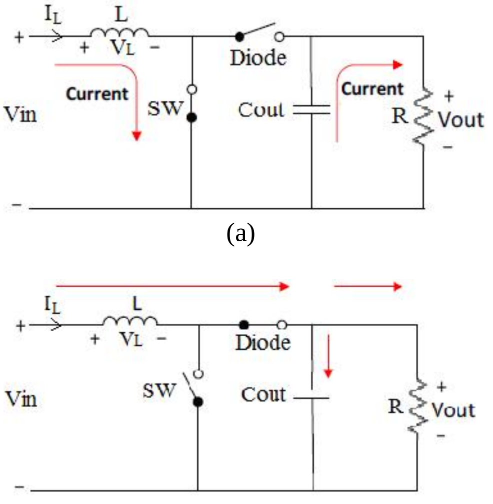


Fig. 1: Basic circuit of the boost converter

In the boost converter, the output voltage is stepped up and controlled by adjusting the ON/OFF time durations of the control signal which is applied to the controlled switch (SW). The boost converter runs in two distinct states [3].

- *State 1:* in this state, SW is in ON-state (closed). The boost circuit will be divided into two loops as shown in Fig. 2-a. At the first loop (left), the input current flows through the inductor and the SW. During this state, the inductor current ($I_L$) will rise and the energy stored in it and not supplied to the load. The inductor voltage ($V_L$) represents input voltage ($V_{in}$). Under this state, the diode is OFF (reverse biased) and the capacitor is in discharging mode to supply current to the load (right loop).
- *State 2:* here the SW is in OFF state (Open). The current flows to the capacitor and load through the diode as depicted in Fig. 2-b. The energy stored in the inductor

during state1 is now transferred to the load together with that from the input source. The current of the inductor continues in decay up till the MOSFET is fired again in the following period. During this period, ($V_L = V_{in} - V_{out}$).



(a)

(b)

Fig. 2: Two circuit states of the boost converter
(a) ON state MOSFET , (b) OFF state MOSFET

## III. OPERATION MODES OF THE BOOST CONVERTER

There are two modes of operation for the boost converters. These modes are continuous conduction mode (CCM) and discontinuous conduction mode (DCM) [3]. Only CCM mode is described and adopted in this work because it has best performance and easy design. Analysis of the circuit under CCM has been carried out assuming ideal boost converter. Also the capacitor and inductor are assumed to be lossless.

In CCM mode, $I_L$ flows continuously and dose not reach to zero as given in Fig. 3.

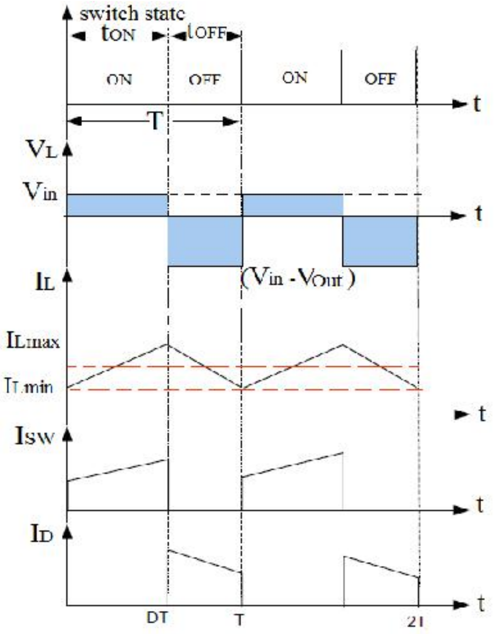


Fig. 3: Current and voltage waveforms of the boost converter (CCM)

The relation that relates the output voltage ($V_{out}$) and input voltage ($V_{in}$) in CCM is given by following equation [4]:

$$V_{out} = \frac{1}{1-D} V_{in} \tag{1}$$

Where, $D$ represents duty cycle which refers to the ratio of ON-time of the MOSFET to the total switching time *(T)*. The D takes values between *zero* and *one* (*zero* refers to the MOSFET is always OFF and *one* refers to the MOSFET is always ON). Thus, Eq. (1) shows that $V_{out}$ is always greater than $V_{in}$ and it increases with an increase of $D$. Theoretically, $V_{out}$ goes into infinity as $D$ approaches to *one* but practically goes to *zero*. In the practical boost converter, the duty cycle cannot equal to *one* because the inductor would become saturated and the input voltage would be shorted [5]. As mentioned in [6], an approximate practical limits for boost converter duty cycle in CCM ranges from *20%* to *80%*.

## IV. PROPOSED SYSTEM AND COMPONENTS SELECTION

Before choosing the components of the DC-DC boost converter, The PV system specifications that required to stepped up and regulating its voltage must be studied. The PV system is consisting of *eight* SOLIMPEKS PV modules which are connected in series as depicted in Fig. 4.

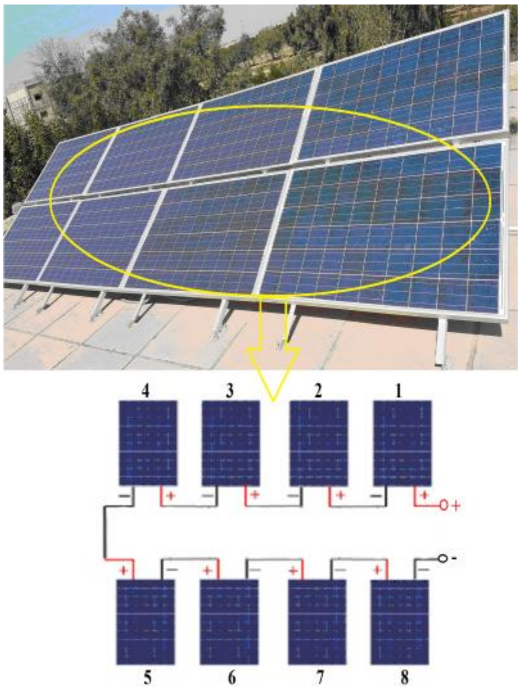
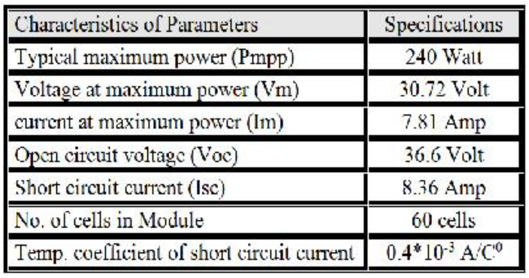


Fig. 4: Pictorial image of eight series SOLIMPEKS PV modules

The specifications of the SOLIMPEKS PV module at STC (1kW/m$^2$, 25˚C) are given in Table1.

Table 1: SOLIMPEKS PV Module Specifications at STC (1kW/m$^2$, 25$^0$C)



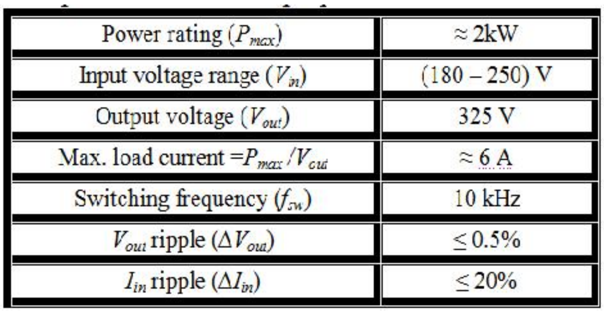
| Characteristics of Parameters | Specifications |
|---|---|
| Typical maximum power (Pmpp) | 240 Watt |
| Voltage at maximum power (Vm) | 30.72 Volt |
| current at maximum power (Im) | 7.81 Amp |
| Open circuit voltage (Voc) | 36.6 Volt |
| Short circuit current (Isc) | 8.36 Amp |
| No. of cells in Module | 60 cells |
| Temp. coefficient of short circuit current | $0.4*10^{-3}$ A/C$^0$ |

Thus, the whole PV system which will be studied in this paper has the following specifications at STC:

- Maximum Power ($P_{max}$) = 240 × 8 = 1920 W,
- $V_m$ = 30.72 × 8= 245.76 V and $V_{OC}$ = 36.6 × 8 = 292.8 V,
- $I_m$= 7.81 A and $I_{SC}$ = 8.36 A

All components of the DC-DC boost converter should meet the specifications of the PV system mentioned above and the parameters tabulated in Table 2.

Table 2: Specifications of the proposed DC-DC boost converter



| | |
|---|---|
| Power rating ($P_{max}$) | ≈ 2kW |
| Input voltage range ($V_{in}$) | (180 – 250) V |
| Output voltage ($V_{out}$) | 325 V |
| Max. load current =$P_{max}/V_{out}$ | ≈ 6 A |
| Switching frequency ($f_{sw}$) | 10 kHz |
| $V_{out}$ ripple ($\Delta V_{out}$) | ≤ 0.5% |
| $I_{in}$ ripple ($\Delta I_{in}$) | ≤ 20% |

The following subsections provide an outline of the considerations for designing boost converter components.

*A. Power MOSFET and Diode Switches Selection*

The appropriate power MOSFET and diode rating selection are based on the specifications of the PV system. The main considerations for the selection are [2]:

i- The reverse breakdown voltage rating must be greater than the maximum input and output voltages.

ii- The rated average forward current of the MOSFET should be greater than the boost input current while the rated average forward current of the diode must greater than the load current.

iii- For better efficiency, choose the diode with quick switching characteristic, low parasitic capacitance and low forward voltage drop ($V_F$). A Schottky diode is recommended because of its low forward drop.

*B. Duty Cycle (D)*

The duty cycle depends on the $V_{in}$ and $V_{out}$ of the boost converter and can be obtained from equation (1) as:

$$D = 1 - \frac{V_{in}}{V_{out}}$$

(2)

Since $V_{out}$ is constant at desired voltage of 325V, a duty cycle changes with the value of its input voltage as follows:

- The minimum duty cycle ($D_{min}$) at maximum input voltage ($V_{in\text{-}max} \approx 250V$),

$$D_{\min} = 1 - \frac{V_{in-\max}}{V_{out}} = 1 - \frac{250}{325} \approx 0.23$$

(3)

- The maximum duty cycle ($D_{max}$) at minimum input voltage ($V_{in\text{-}min} \approx 180V$),

$$D_{\max} = 1 - \frac{V_{in-\min}}{V_{out}} = 1 - \frac{180}{325} \approx 0.45$$

(4)

*C. Switching Frequency Selection*

In order to minimize the inductor size and reduce distortion, switching frequency ($f_{sw}$) selection must be high sufficiency, in the range of 2 kHz-100 kHz. However higher switching frequencies lead to high switching losses [4]. Compromising between the two factors must be considered when choosing an operating frequency and inductor for a DC-DC converter. The value of $f_{sw}$ has been selected as 10 kHz.

*D. Inductor Selection*

The inductor selection is the most important factor because it determines the inductor current ripple ($\Delta I_L$). This ripple is proportional inversely with the value of $L$ and is presented by [3]:

$$\Delta I_L = \frac{V_{in} D T}{L} = \frac{V_{in} D}{f_{sw} L}$$

(5)

To operate the boost converter in CCM, the critical inductance value ($L_{crit}$) is given by:

$$L_{crit} = \frac{V_{in} D}{f_{sw} \Delta I_L}$$

(6)

The selection of $L_{crit}$ must be greater than the calculated value. Any value less than $L_{crit}$ will lead to operate the boost converter in DCM.

The average inductor current ($I_L$) is given by:

$$I_L = \frac{I_{out}}{(1 - D)}$$

(7)

$I_L$ is at maximum value when the input voltage is minimum (i.e. when $D_{max}$=0.45), and the maximum output current ($I_{out}$) is about 6A. Thus the maximum r.m.s. value of $I_L$ is:

$$I_L = \frac{6}{(1-0.45)} \approx 11A$$

For CCM operation, the peak inductor current ($I_{Lpeak}$) can be given by

$$I_{Lpeak} = I_L + \frac{\Delta I_L}{2}$$

(8)

The approximate value of $\Delta I_L$ is 2.2A based on the assumption of 20% ripple input current. Therefore, $I_{Lpeak} \approx 12.1A$.

Substitute all values in equation (6) to find $L_{crit}$, which is equal to (*3.7 mH* ).

The practical design of the inductor is based on the value of critical inductance that is calculated and maximum amount of current that is carried. A toroidal ferrite core is suitable selection for the design.

### *E. Output Capacitor Selection*

The output boost converter capacitor ($C_{out}$) is greatly affected by the output voltage ripple ($\Delta V_{out}$). The output voltage peak-to-peak ripple can be determined by [2]:

$$\Delta V_{out} = \frac{I_{out} D}{f_{sw} C_{out}}$$

(9)

The capacitor value can be determined from:

$$C_{out} = \frac{I_{out} D}{f_{sw} \Delta V_{out}}$$

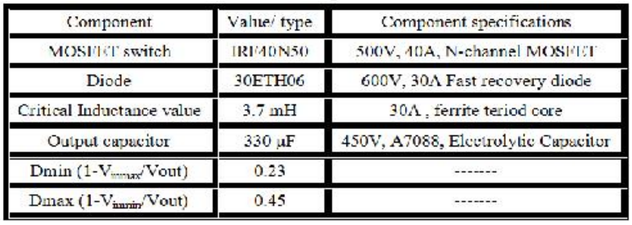
(10)

The selection of $C_{out}$ must be higher than the calculated value to make sure that the converter's output voltage ripple remains within the specific range and its equivalent series resistance (ESR) should be low. ESR can be minimized by connecting a number of capacitors in parallel.

Substitute the values of $I_{out}$, $f_{sw}$, and $\Delta V_{out}$ into Equation (10), the capacitance value is about 166 uF. An appropriate standard capacitor is chosen greater than this calculated value.

Table 3 summarized the calculated parameters and selected components of the proposed boost converter based on the equations and considerations mentioned previously.

Table 3: Boost converter calculated parameters and selected components

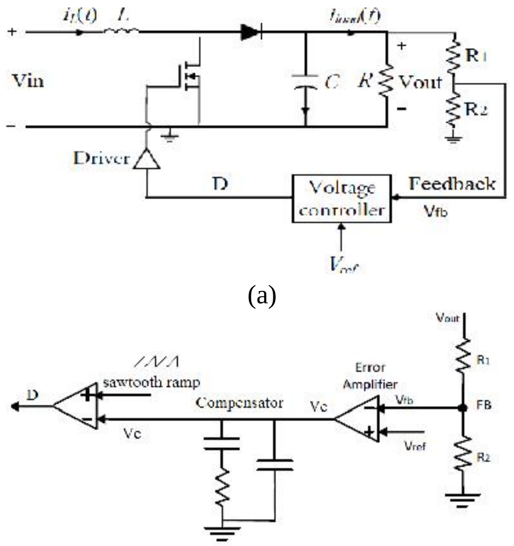


| Component | Value/ type | Component specifications |
|---|---|---|
| MOSFET switch | IRF40N50 | 500V, 40A, N-channel MOSFET |
| Diode | 30ETH06 | 600V, 30A Fast recovery diode |
| Critical Inductance value | 3.7 mH | 30A , ferrite teriod core |
| Output capacitor | 330 µF | 450V, A7088, Electrolytic Capacitor |
| Dmin (1-$V_{inmax}$/Vout) | 0.23 | ------- |
| Dmax (1-$V_{inmin}$/Vout) | 0.45 | ------- |

## V. CONTROL SCHEMES OF DC-DC CONVERTERS

To regulate the output voltage of the DC-to-DC converters, feedback loop is employed for adjusting duty cycle and obtained the desired voltage output. The most common control schemes are: Voltage Mode Control (VMC) and Current Mode Control (CMC) [3,6,7]. Other hybrid designs are deduced from combinations of these controls. Here, VMC control strategy has been adopted because CMC has a certain complexities.

The schematic diagram of a VMC is shown in Fig. 5 [3]. $V_{out}$ of the boost converter is observed through a voltage divider ($R_1$ and $R_2$) that feeds a fraction of the output voltage back and creating a closed-loop system. The feedback voltage ($V_{fb}$) and the reference voltage ($V_{ref}$) are entered into the error amplifier to generate the error signal ($V_e$). The generated signal ($V_e$) is then fed to the compensator (such as PID controller) to produce control voltage ($V_c$). This control voltage signal is compared with a saw-tooth wave to produce a controllable duty cycle which is called pulse width modulation (PWM) signal, that drives the MOSFET[4, 6].



(a)

(b)

Fig. 5: VMC of the boost converter
(a) Boost converter and Control block
(b) Voltage control block

When $V_{out}$ of the converter is increased, $V_c$ is also increased which causes the duty cycle of the MOSFET to decrease (less pulse width) as shown in Fig. 6. The changing in duty cycle will adjust $V_{out}$ of the boost converter by reducing error to zero and make the output voltage follow the reference value.

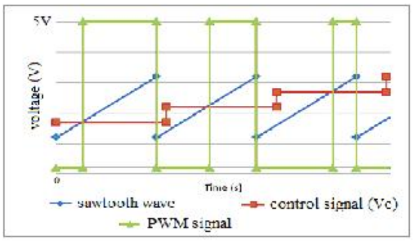


Fig. 6: Generation of PWM signal

## VI. PID CONTROLLERS

The PID controllers are feed-back control loop technique that is generally employed in controlling the industrial equipments. It consists of three terms (proportional "$K_p$", integral "$K_i$" and derivative "$K_d$"). The block-diagram of the PID controller is shown in Fig. 7.

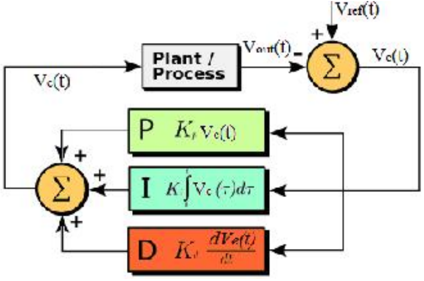


Fig. 7: PID controller block diagram

The aim of the PID controller is to make the actual output ,$V_{out}(t)$, of the plant (boost converter), follows the reference signal, $V_{ref}(t)$, by its attempting to reduce the error signal, $V_e(t)$, where:

$$V_e(t) = V_{ref}(t) - V_{out}(t)$$

(11)

The controlled output variable, $\boldsymbol{V_c(t)}$, is adjusted to the new value according to the following expression:

$$V_c(t) = K_p V_e(t) + K_i \int_0^t V_e(^2)d^2 + K_d \frac{dV_e(t)}{dt}$$

(12)

Where:

$t$: Current time, and $^2$ : Integration variable; its value from time zero to the current $t$ [8].

Although there are only three parameters associated with the PID controller, but the tuning of them to the optimal value is a complex problem. There are different methods are adopted to find the values of these parameters, called PID tuning. If the PID controller parameters are selected incorrectly, the controlled process will become unsatisfactory or unstable.

The Ziegler-Nichols method [9] is widely used to tune the parameters of the PID controller experimentally. First, set $K_i$ and $K_d$ to zero and the gain $K_p$ increase until the system reaches to a stationary oscillation. After that $K_p$, $K_i$ and $K_d$ parameters will calculated through determining the gain ($K_u$) and the time of the oscillation ($T_u$). The parameters are calculated depending on the controller type, and can be found in the Table 4.

Table 4: Ziegler-Nichols method [9]

| Control type | $K_p$ | $K_i$ | $K_d$ |
|---|---|---|---|
| P | $0.5\,K_u$ | - | - |
| PI | $0.45K_u$ | $0.8T_u$ | - |
| PID | $0.6K_u$ | $0.5T_u$ | $0.125T_u$ |

A PID controller block has been introduced in MATLAB Simulink library as described in Fig. 8. The block parameters can be tuned automatically using PID tuner to achieve an acceptable response for the simulink control design. In Some applications, only one or two terms of the PID controller are used to get the proper control for the system. This is done by making the other terms to zero. In this case, a PID controller is calling (PI, PD, P or I) controller.

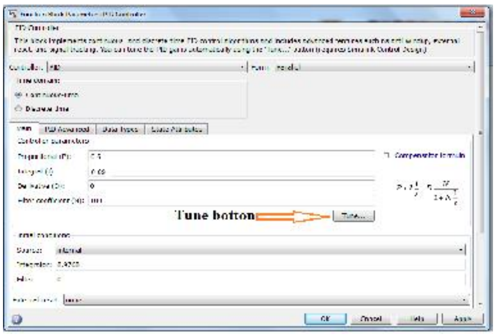


Fig. 8: PID MATLAB Simulink block

## VII. BOOST CONVERTER SIMULATION

The DC-DC boost model has been simulated in MATLAB (illustrated in Fig. 9) based on the specifications and calculated values listed in the Tables (1-3).

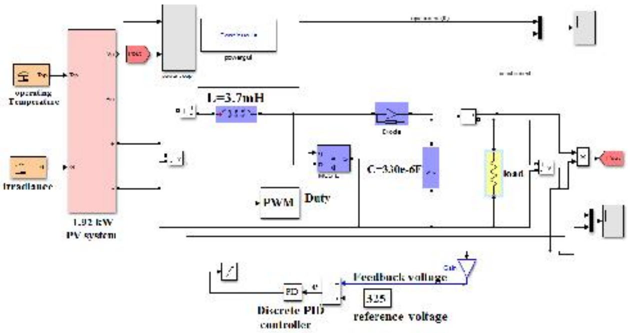


Fig. 9: Complete simulink model of the boost converters

The boost circuit has been connected to a PV system which is pictured in details in the mathematical simulink model of Fig 10.

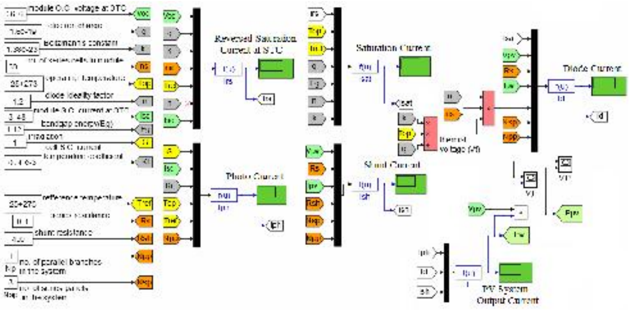


Fig. 10: Simulink mathematical model of PV system

In order to verify the performance of this model, many cases have been tested such as load changes and input voltage changes, with and without PID controller.

### *A. Open Loop System Model (Without Controller)*

Open-loop system can not be used in practical applications. It has been simulated to test the correct selection of the system components and satisfy the boost characteristics that have been calculated previously, more than anything else. The system has been studied when a 325V/1900 W resistive load was applied on it. The PV system voltage at STC is about 250V. To produce 325V, duty ratio of the PWM signal applied to the MOSFET switch gate is (0.23).

The simulation results of the PV system voltage ($V_{in}$) and output voltage of the boost converter ($V_{out}$) are cleared in Fig. 11. The output voltage ripple ($\Delta V_{out}$) of the converter is (0.4V) which falls within the allowable range (≤ 0.5% $V_{out}$). This gives an indication that the capacitor that has been selected is suitable for the system.

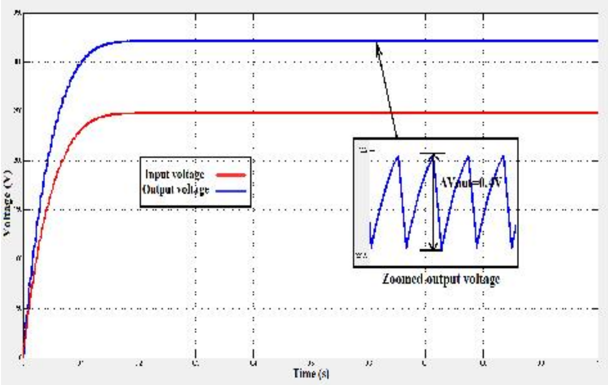


Fig. 11: Boost converter input and output voltages at D=0.23

The inductor current ($I_L$) and output current ($I_{out}$) are shown in Fig. 12. The inductor current ripple ($\Delta I_L$) of the converter is (1.9 A) which falls within the requirements range, (≤ 20% $I_L$). This means that the inductor value selection was correct.

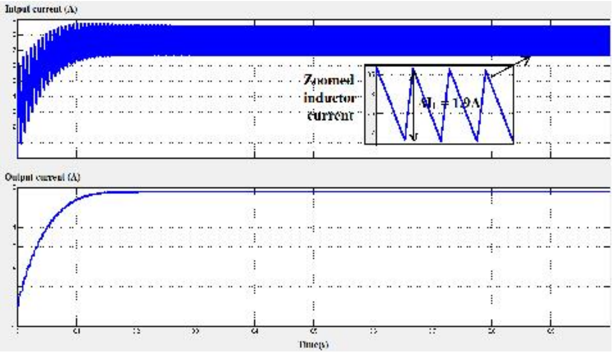


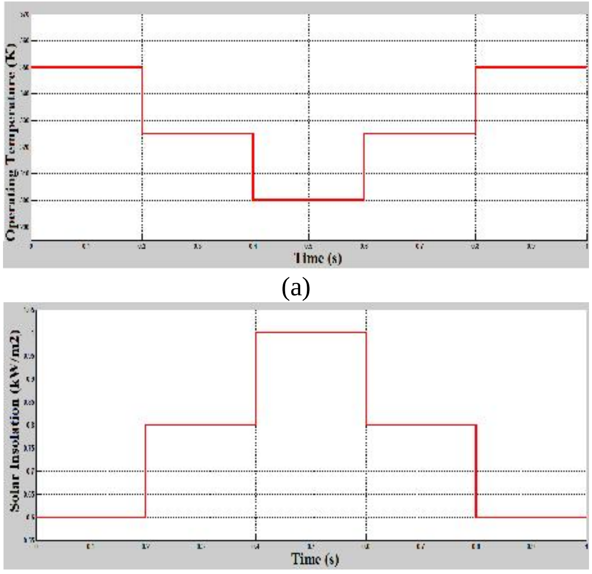
Fig. 12: Boost converter Input and output current at D=0.23

### *B. Closed Loop System*

In practical applications a closed-loop system is used. The system is tested to examine the design and provide a constant output voltage with the help of PID controller. The system has been studied for the following cases:

*i- Variable input voltage and constant load*

The response of the closed loop system has been tested, first, at the constant load and variable input voltage (the input voltage variation is intended to reflect the effect of temperature and insolation variations (Fig. 13a & b) on the output voltage of the solar system).



(a)

(b)

Fig. 13: Step changes in weather conditions
a) Operating temperature, b) Solar insolation

The output voltage response and the changes in the input voltage have been pictured in Fig. 14. The figure shows that the output voltage is to some extent constant and equals 325V. After each disturbance in the input voltage (increase or decrease), the controller senses these changes and respond to them after comparing them with the reference voltage. The output voltage quickly reaches the steady state value (after 0.1s from the instant of disturbance creation). This means that the PID controller has an effectiveness response during the adopted changes.

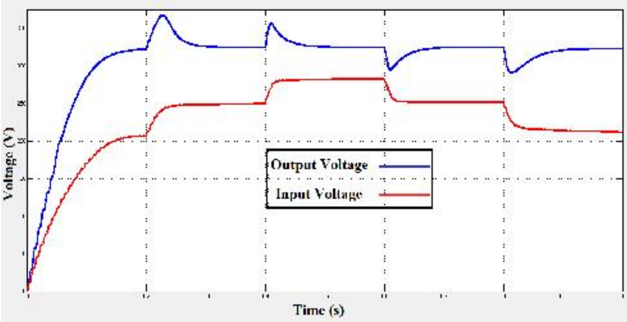


Fig. 14: Response of $V_{out}$ of closed loop system at constant load and Variable $V_{in}$

*ii- Constant input voltage and variable load*

The designed closed loop PID controller also has been tested under load step changes while the PV system voltage remains constant at STC. As it is clear from Fig. 15, the load changes have been issued at 0.2s interval. It is obvious that the PID controller response depends on the amount of changes in the load and the output voltage almost matches the desired value of 325V.

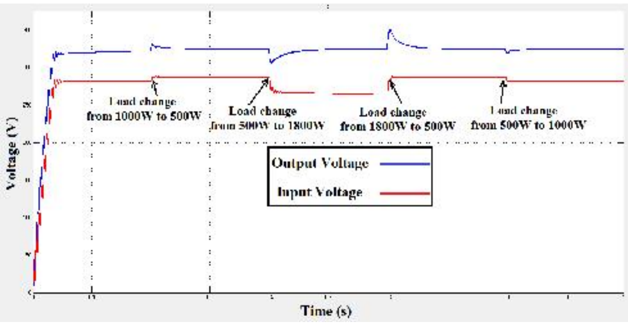


Fig. 15: Response of $V_{out}$ of closed loop system at different loads

## VIII. BOOST CONVERTER HARDWARE IMPLEMENTATION

After being verified the required DC-to-DC boost converter by the MATLAB program, it has been implemented practically. To obtain a constant output voltage of the boost converter, voltage and/or current feedback loops must be used. The duty cycle is increased or decreased according to the state of the input voltage using PWM method. Modern controllable equipments use microcontroller to achieve PWM although simple analog circuit can be used. Digital controllers have numerous preferable features as compared to the analog controllers. These positive features include programability, adaptive, less sensitivity to the environment variations, capable to achieve complex control techniques and require few extra components. Beside that, the changing in the gain in analog control circuit is performed by adjusting the hardware components which is considered hard solution.

In order to implement a PWM signal generator for controlling the duty cycle of the MOSFET switch using a microcontroller, the following items should be covered.

- PWM concept and how can be generated using Arduino microcontroller.
- How to measure DC voltage by microcontroller.

### A. PWM Generation Using Microcontroller

A PWM is a well known technique to control the output voltage by adjusting on-time of the pulse width (duty cycle) of analog signal. The frequency of PWM represents the amount of time taken by PWM to complete one cycle. In order to produce variable analog values, the pulse width can be changed from 0% to 100%. Figure 16 displays the PWM output for different duty cycle. The distance between any two successive red lines represent the time of one cycle and the reciprocal this time interval gives the switching frequency of the PWM output. To effectively use the PWM function of the Arduino, its timer function should be concerned.

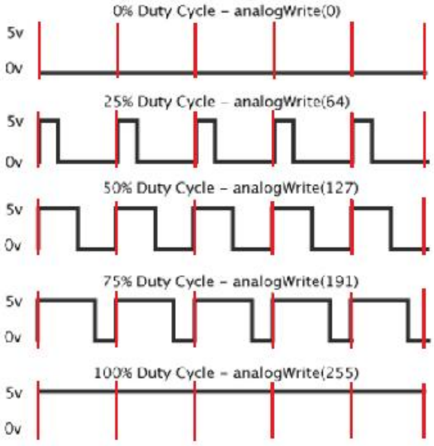


Fig. 16: Various PWM (Various duty cycles)

The ATmega328P datasheet gives a detailed description of the PWM timers [10]. Here, a simple explanation for the use of timers.

There are three timers in the ATmega328P chip, and they can be configured in a different ways to perform different purpose. They are described as follow:

i- Timer 0: this timer is used for PWM outputs on pins 5 and 6. It has 8-bit size and its maximum counting time is 255.

ii- Timer 1: this timer is used for PWM outputs on pins 9 and 10. This timer has additional modes to supports timing results up to 16 bits. Thus, it can reach a maximum value of 65535.

iii- Timer 2: this timer is used for PWM outputs on pins 3 and 11. The size of this timer is the same of timer 0 but has different pre-scale values from the Timer 0 and Timer 1.

The two outputs of each timer have the same frequency but differ in duty cycles (depending on the respective output compare register). If the timer current count reaches ad exceeds the compare register set value, the corresponding output is toggled. Each timer has pre-scale factors (such as 1, 8, 64, 256, or 1024) to set the time intervals between successive counting. The timer clock frequency represents the ratio of Arduino clock frequency (16 MHz) and pre-scale factor.

Two registers are used to adjust the output of each timer. They are called Timer/Counter Control Registers, written acronym TCCRnA and TCCRnB, and the value of ***x*** is the timer number (0,1,2). These two registers hold the following groups of bits that control the operation of the registers, frequency, and also pre-scalar values:

- Waveform Generation Mode bits (WGM): These bits control the supported mode of the timer. These bits are split between the Registers TCCRxA and TCCRxB.
- Clock Select bits (CS): These bits control pre-scale value.
- Compare Match Output Mode bits (COMxA and COMxB): These bits enable/disable/invert outputs A and B.

There two PWM modes of the operation for the timer (fast mode and phase correct mode). In this work, fast PWM mode is used so it will be explained briefly here only.

In the fast mode PWM mode this PWM mode, the timer repeatedly counts from 0 to 255. The output turns ON (HIGH) when the timer is at 0, and turns OFF (LOW) when the timer reaches the output compare register value (OCRxX). Higher OCRxX value means the higher duty cycle. The diagram given in Fig. 17 shows the outputs values for the two registers OCRxA and OCRxB. Note that both outputs, OCxA and OCxB, have the same frequency with different duty cycle.

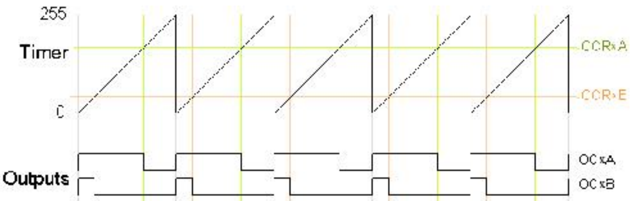


Fig. 17: Outputs values for the two registers OCRxA and OCRxB (Fast PWM Mode)

### B. DC Voltage Measurement

As the microcontroller's analog input pin is restricted to 5V maximum, a voltage divider is required to step down the voltage to the range of the microcontroller's analog inputs as given in Fig. 18. The values of resistors are selected so that the current flowing through them is small and cause small power losses ($P_{loss}= I^2R$).

The suitable resistors values of the voltage divider that used to step down a 325 V voltage are; R1 = 1MΩ and R2= 12 kΩ. Thus, the calculated voltage value that stepped by voltage divider is 3.85 V which is appropriate for microcontroller analog input pins (ATmega328P chip has six analog input pins "A0-A5"). These pins convert analog voltage to suitable digital value (0-1023). The analog value of voltage is read by Arduino microcontroller using (analogRead) function that covers the range 0 to 1023.

The step increment can be found as:

step increment=1ADC = 5/1024 = 0.00488 V

Vin = Vout*(R1+R2)/R2

= ADC reading * 0.00488 * (1012kΩ/12kΩ)

This marks that a 1023 reading corresponds to an input voltage of 5V. In practical, 5V may not obtain always from the Arduino, so the voltage between the 5V pin and ground pin of Arduino must be measured first during calibration by using a voltmeter, and use 1ADC=measured voltage/1024 instead of (5/1024).

The microcontroller changes the duty cycle according to the reading of analog value of the feedback voltage (at its analog input pins). The modification of the duty cycle follows the relation derived in CCM (D=1- $V_{in}$/ $V_{out}$).

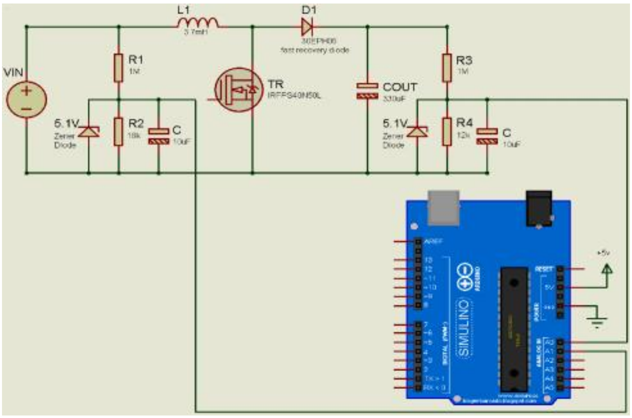


Fig. 18: The boost converter circuit and its control

## IX. BOOST CONVERTER HARDWARE IMPLEMENTATION

Figure 19 shows a photographic image of a practical boost converter circuit including control stage. The control stage contains *Arduino UNO* microcontroller (ATmega328P), optocoupler, IR2110 driver, current sensor, and voltage divider.

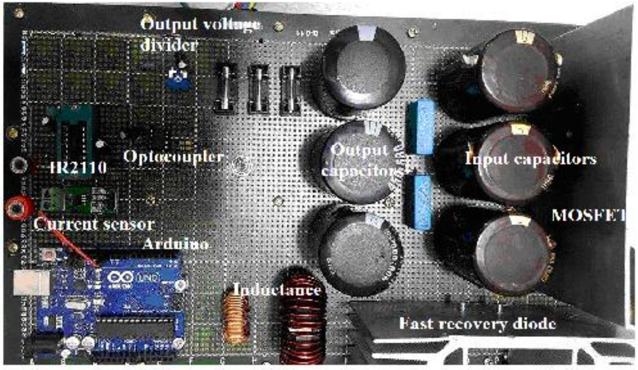


Fig. 19: Pictorial image of the experimental DC-DC boost converter circuit

Optocoupler offers electrical isolation between the microcontroller and the power circuit. It also protects the microcontroller from any reverse currents flowing from the power circuit. Figure 20 shows the schematic diagram of the 6N137 optocoupler.

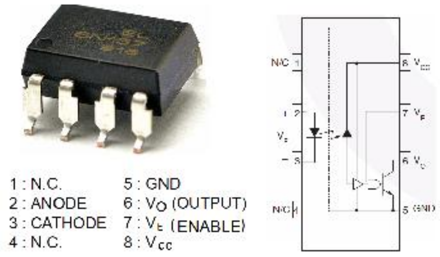


Fig. 20: 6N137 optocoupler schematic diagram

The output PWM signal of the 6N137 optocoupler is applied to the power MOSFET switches in the boost power stage via an IR2110 gate driver. The PWM signal will be fed to the $L_{IN}$ pin (pin 12) as depicted in circuit of Fig. 18 which has been given obviously. When the internal logic detects logic high at pin 12, the Lo pin (pin 1) will be driven.

Moreover, the converter circuits have some protection features. The zener diodes at the analog inputs are used for over voltage protection. They ensure that the feedback voltage does not exceed their breakdown voltage of 5 V. The small ceramic capacitors are putted in parallel with the large electrolytics that have a relatively high resistance to reduce the SER and hence improve the efficiency and performance of the circuit.

## X. DIGITAL IMPLEMENTATION OF PID CONTROLLER

The program boost control code is written use Arduino software and loaded into the microcontroller directly. ATmega328P executes calculation based on the PID control algorithm and generate a PWM control signal using Timer 2 and working in fast PWM Mode. Figure 21 shows the flowchart of the proposed digital PID algorithm.

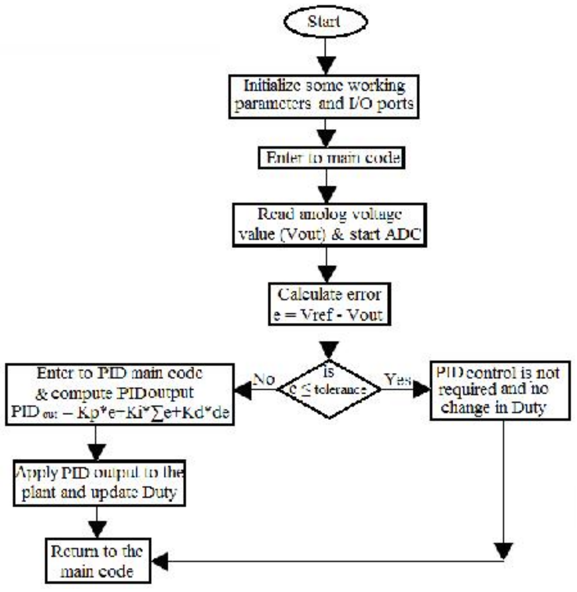


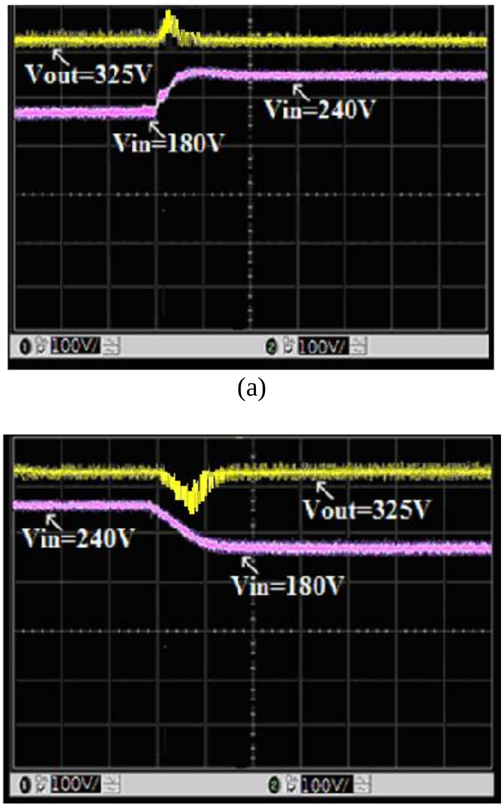
Fig. 21: Flowchart of the digital PID algorithm

## XI. EXPERIMENTAL RESULTS AND ANALYSIS

The boost converter system is tested with a closed loop only using digital PID controller under the same states introduced in closed loop simulation subsection in order to establish the circuit operation and emphasize the simulation results.

*i- Variable input voltage and constant load*

The input voltage is supplied from rectified variable AC source. It increased and decreased is steps (increased from 180V to 240V then return to 180V). The load is constant and has power of 1kW. The output voltage response is appeared in Fig. 22 where it is close to 325V during two changes in the input voltage. The practical results offer that the output voltage is approximately match the simulation result and thereby confirms the controller design. The positive and negative overshoots are about 45V and 60V respectively. The positive overshoot is due by the rise in the input voltage while negative overshoot due to the drop in the input voltage. The settling time is approximately 1s and is higher than simulated time (0.1 ms) due to the parasitic impact of the practical boost components circuit.



(a)

(b)

Fig. 22: Output voltage response at during step change input voltage
a) when $V_{in}$ step up from 180 to 240V,
b) when $V_{in}$ step down from 240 to 180

*ii- Constant input voltage and variable load*

The experimental circuit is tested under load step changes from 400W to 1200W then to 400W for 200 V input. Figure 23 gives the response of the output voltage during step changes in the load. The output voltage is settled at 325V under load variation after time interval depends on the changing in the load. The results give that the overshoot is approximately 25V and the voltage is settled after 0.5s. The positive overshoot is due to the drop in the load and negative overshoot due to the rise in the load.

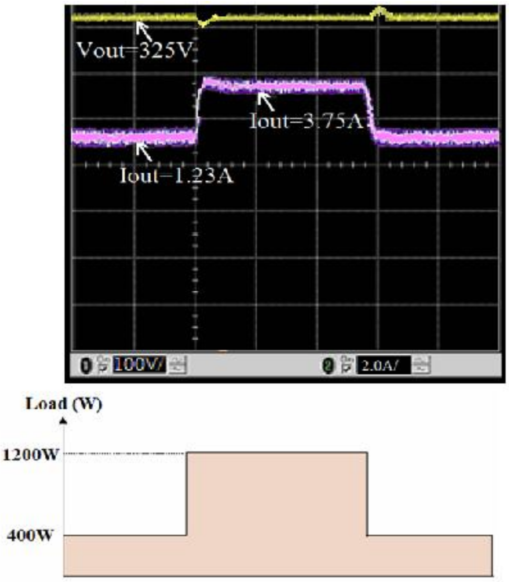


Fig. 23: Output voltage during load variation

## XII. CONCLUSION

This paper presented the design, simulation, and implementation of the DC-DC boost converter with PID controller. First, the system has been simulated in MATLAB software and gives efficient results when the sudden changes in the input voltage as well as in the load are made. After that, a practical design has been constructed and tested for the same simulation conditions. The digital PID controller was executed using *Arduino* microcontroller that has several on board advantages. Experimental results exhibit a good regulation performance for the output voltage under all test conditions. Thus the designed DC-DC Boost converter can be used in PV system applications or other fluctuations sources.

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