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Design and Implementation of a PI-MPPT Based Buck-Boost Converter

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***Abstract* – A Proportional-Integral (PI) based Maximum Power Point Tracking (MPPT) control algorithm is proposed in this study where it is applied to a Buck-Boost converter. It is aimed to combine regular PI control and MPPT technique to enhance the generated power from photovoltaic PV) panels. The perturb and observe (P&O) technique is used as the MPPT control algorithm. The study proposes to reduce converter output oscillation owing to implemented MPPT control technique with additional PI observer. Furthermore aims to optimize output power using PI voltage mode closed-loop structure.**

Keywords- PI based MPPT controller, Buck-Boost converter, solar energy, energy conversion, renewable energy.

I. INTRODUCTION

The energy is an indispensable requirement today. The 2014 annual report emphasizes that the energy needs are increasing day by day. The average energy demand is increasing 2% per year worldwide. To use only fossil fuels to meet this energy demand will lead to further contamination of the environment, which will further reduce its short lifetime [1]. This situation leads us to seek for alternative energy sources that are not only used in energy generation but are also used in transportation. There are many alternative energy sources on Earth such as solar power, wind power, biomass, geothermal etc. The wind and solar energy sources have the largest share in these resources. All over the world, wind and solar energy utilization is respectively 42% and 32% in alternative energy sources. The photovoltaic systems are preferred thanks to the absence of mechanical parts, directly electric energy generating, easy to use, low noise release and it is able to apply at every point in the world [3,4]. There are many type solar energy conversion systems are being used in the world. One of them that is called concentrated solar power plants are used to generate electricity from sun, and that power plants uses steam power at the same time. Another system known as PV panels are extensively used. The PV panels are composed of a combination of chemical P and N materials. PV panels can directly convert the solar energy into electricity. Nevertheless, there are many factors affecting the efficiency of PV panels such as air temperature, solar radiation and shadowing. In day these parameters constantly changes. Accordingly, PV panel output power is changed by parameters. Very different methods and techniques are used to eliminate this situation [5]. The Maximum Power Point Tracking (MPPT) controller is popular among the others techniques due to advantages such as suitable, good performance, and easy to apply [5,6]. In addition, converter structure to increase the availability of the solar panel is a key requirement. The Buck-boost converter is popular converter structure because of comprising two separate converter structure of Buck and Boost converters [7], high efficiency and requiring less component.

The reminder of the paper is organized by presenting the analytical structure of a buck-boost converter in the 2nd section, and its transfer function in the 3rd section. The PI assisted MPPT algorithm is explained in the 4th section that is implemented regarding to analytical theorems discussed in previous sections. The experimental results are given in the 5th section where the regular and proposed MPPT techniques are compared.

II. BUCK-BOOST CONVERTER TOPOLOGY

Basic circuit diagram of the Buck-Boost converter known as step-up/down is shown in Figure 1. The converter is a popular non-isolated, voltage inverting power stage topology where, S is switching component, L is inductance winding, D is fast diode, C is output capacitor and R is load resistance. The buck-boost converters comprise both buck converter and boost converter topology. Thus, buck-boost converter structure is able to decrease or increase the output voltage depends on input voltage level. Output voltage depends on switching frequency duty cycle (D). When D is less than 0.5, output voltage lower than input voltage like buck converter, otherwise D is greater than 0.5, output voltage higher than input voltage like boost converter, when D is equal to 0.5 input voltage and output voltage amplitude are equal. When the switch is turned to on state, diode voltage is reversed and the diode current (i_D) is obtained at zero value continuously, the source voltage is transferred to

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inductor and i_L increases as a function of time in conduction mode.

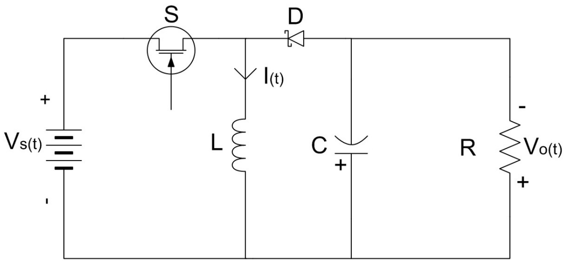


Figure 1. Circuit diagram of the Buck-Boost converter

The connection between the source and inductor is leaved when the switch is turned to off state. S_1 and i_D get equal to i_L at this state. The mentioned on and off states are used in steady state analysis as given in the following equation for each operation mode. The output voltage equation is obtained by equaling the variations of input voltage and duty cycle as given in (1).

$$Vc = \frac{D}{1-D} Vs \tag{1}$$

The converter operating modes are determined by inductor which are can be continuous conduction mode (CCM) or discontinuous conduction mode (DCM). In the CCM mode, the inductor value is selected high enough to avoid inductor current to decrease down to zero. However, in case of insufficient inductor values are used, the inductor current falls to zero for a while in each half-cycle that causes to operate in DCM. The limit of CCM and DCM operation modes is determined with respect to the value of inductor as seen in (2)

$$L = \frac{(1-D)^2 R}{2f} \tag{2}$$

III. Transfer Function of Buck Boost Converter

If it is examined as a small signal model of buck-boost converter topology, the analysis should be started with T_{on}. When the switch is turned on, the circuit structure is shown as seen in Figure 2. At this situation, the main current i(t) flows over the inductor and the input voltage as known inductor voltage Vs is expressed as in (3) and the capacitor current as in (4).

$$V_L(t) = L * \frac{di(t)}{dt} = Vs(t) \tag{3}$$

$$Ic(t) = C * \frac{dVo(t)}{dt} = -\frac{Vo(t)}{R} \tag{4}$$

As secondly the switch is turned off, the circuit structure is converter to one as shown in Figure 3. After the opening the switch, inductor voltage and capacitor current values are shown as in equation (5) and (6).

$$V_L(t) = L * \frac{di(t)}{dt} = Vs(t) \tag{5}$$

$$Ic(t) = C * \frac{dVo(t)}{dt} = -i(t)L - \frac{Vo(t)}{R} \tag{6}$$

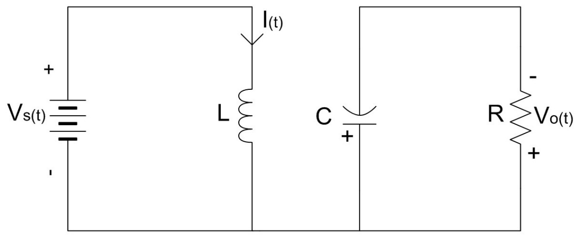


Figure 2. Circuit structure when the switch turned on

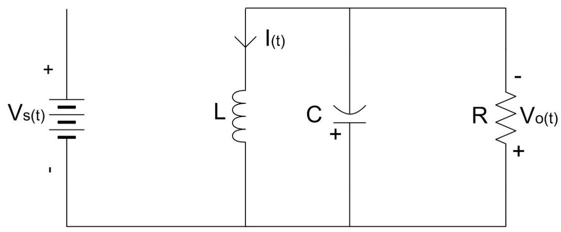


Figure 3. Circuit structure when the switch turned off

If all the equations are transferred to the S domain, then they can be written as follows;

$$sLi(s) = Dvs(s) + D'Vo(s) + (Vs - Vo)d(s) \tag{7}$$

$$sCv(s) = -D'i(s) - \frac{Vo(s)}{R} Id(s) \tag{8}$$

where $D' = (1-D)$

The output voltage is determined by two different variables. The first is the input voltage V_s(s), the second is the control input d(s). The output voltage of converter that on S domain is shown below;

$$Vo(s) = GV_s(s) * V_s(s) + GV_d(s) * d(s) \tag{9}$$

The output voltage equation, which is depending on duty cycle (D) is shown as follows.

$$\begin{aligned} Vs(s) &= \frac{-DD'}{D'^2 + s\frac{L}{R} + s^2 LC} * \\ Vs(s) &- \frac{D'(Vs - Vo) - sLI}{D'^2 + s\frac{L}{R} + s^2 LC} d(s) \end{aligned} \tag{10}$$

$$G_{Vs}(s) = G_{s0} \frac{1}{1 + \frac{s}{Q\omega_0} + (\frac{s}{\omega_0})^2} \tag{11}$$

wherein;

$$G_{s0} = -\frac{D}{D'},\ \frac{1}{\omega_0^2} = \frac{LC}{D'^2},\ \omega_0 = \frac{D2}{\sqrt{LC}},\ \frac{1}{Q\omega_0} = \frac{L}{D'^2 R}$$

The closed-loop control block, which is created from (9) is shown in Figure 4.

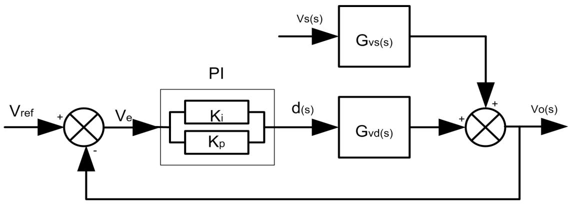


Figure 4. The closed-loop PI control block diagram

IV. MPPT CONTROL TECHNIQUE BASED ON PI

MPPT algorithm is the best way to optimally benefit from solar panels especially for the systems that are not tracking the solar angle. The MPPT techniques improve the efficiency of a PV system in order to maximize the PV array output power. There are many MPPT techniques for photovoltaic systems [9]. The perturb and observe (P&O) is one of the most widely used one Therefore, converter output voltage (V_{out}) and current (I_{out}) are measured by voltage and current sensors, respectively. Than output power (P_{out}) is calculated regarding to obtained values where the output power and output voltage are included to MPPT algorithm to evaluate and determine the PWM signal for switch. An 8-bit microcontroller executes all processes. The MPPT algorithm of this study is based on P&O algorithm I. Figure 5 shows the hardware diagram of MPPT algorithm while the flowchart is illustrated in Figure 6. The P&O algorithm can adjust duty cycle using PV array voltage and the power converter voltage difference by through observation. The power of PV array is calculated via measured voltage and current values. In order to determine duty ratio the latest observation of the obtained power is compared to the previous observation. afterwards, ensured difference is used to specify the next PWM duty cycle. The implemented PO algorithm looks for the increment of power perturbation and attempts to keep the duty cycle in the same way in order to achieve the MPP of PV array, also PI control is activated to reduce oscillation on the output voltage [8]. The algorithm can reverse the perturbation when there is a decrement occurs in the power observation. The algorithm repeats this process for reach to MPP of PV array, if the system reaches to the MPP, the algorithm produces steady duty cycle value.The oscillation at the MPP of PV array is demanded to be reduced in order to increase the stability.

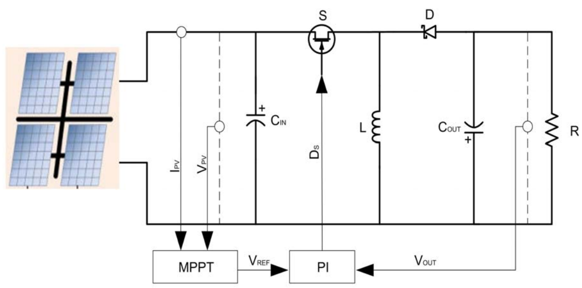


Figure 5. Hardware diagram of MPPT algorithm

The PI function, which is used to reduce oscillation on the output voltage, is shown in Figure 7.

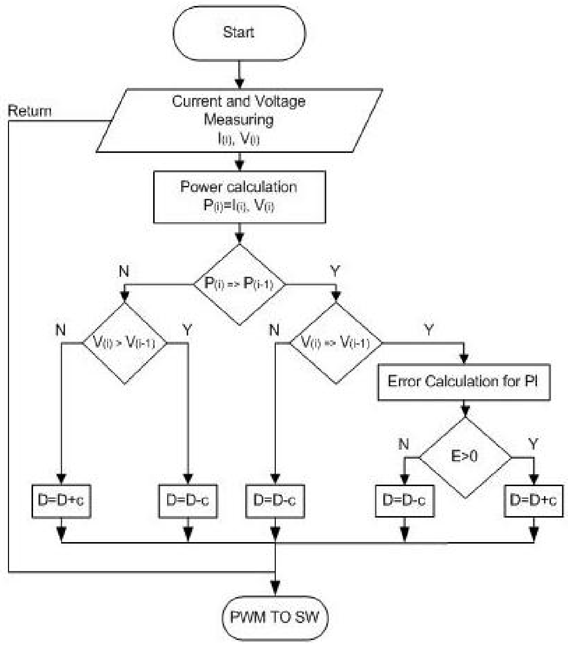


Figure 6. Flowchart of the PI based MPPT

$$
\begin{aligned}
&Void\ \_PI()\\
&\{\\
&Error\ = Vref\ - Vo;\\
&Error\ \_in = Error\ \_in + Error\ * dt;\\
&duty\ = Error\ * Kp + Error\ \_in * Ki;\\
&\}
\end{aligned}
$$

Figure 7. The short algorithm for error calculation

V. EXPERIMENTAL RESULT

This study attends to design of a buck-boost converter where it is simultaneously operated by a PI based P&O algorithm to regulate photovoltaic (PV) panel output voltage and power. The dc input voltages are programmed in order to emulate independent PV panels that has 200 Wp rated output power, 44 V open circuit voltage (V_{OC}), and 36.7V maximum power voltages (V_{PM}). The CCM mode parameters of the converter are given in Table 1.

Table.1 The buck-boost converter parameters

C_{in}	2200uF
C_{out}	800uF
L	1mH
f	22 kHz
R_{load}	25Ω
K_i	0.0005
K_p	0.5
d(t)	100ms
V_s	20-90V
V_o	60V

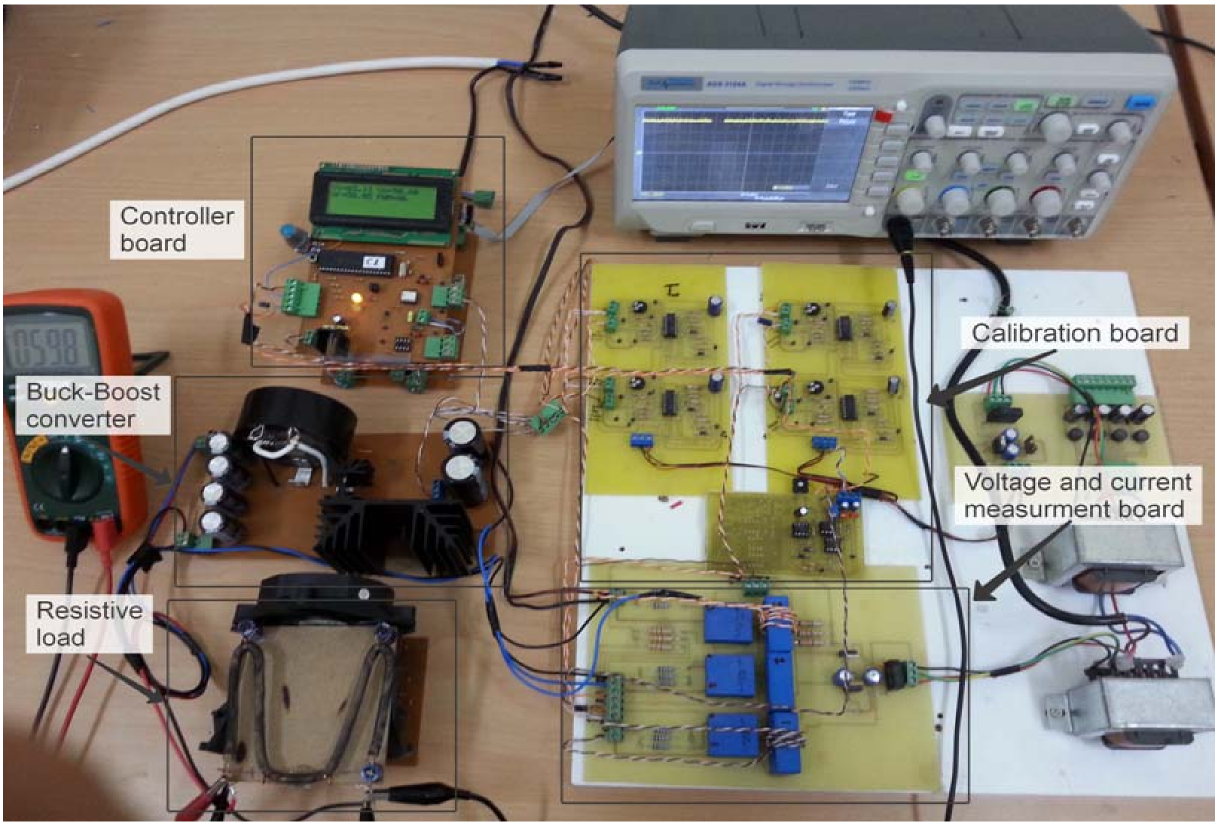


Figure 8. Full of study implementation and components

While the implemented converter system is shown in Figure 8 where the power stages and its components are depicted. In addition, Figure 8 also shows the microcontroller PCBs used to generate the driving signals and operating the PI based MPPT algorithm. The microcontroller evaluates all the data obtained from measurement and acquisition devices are called current and voltage measurement board, calibration board.

A. Current and Voltage Acquisition Circuit

The board consists of two sensor for each current and voltage measurement issues. The current acquisition circuit based on LA 55-P current sensor of LEM that has a conversion ratio at 1/1000 [10]. The voltage sensor that is known as LV 25-P operates according to the Hall-effect principle [11]. This sensor allows measurement of the voltage at 10-500 volts owing to its isolated inputs. Since the measurement values of current circuit will be quite low, the sensitivity of the data that will be transferred to the microcontroller (MCU) is also expected to be low. There is an active amplifier is designed to overcome this situation. The current data acquisition circuit is shown in Figure 9.a where the load current is obtained by the current sensor in a dc waveform and amplified with an operational amplifier (op-amp). Furthermore, a potentiometer and zener diode is used at the input side of the MCU to provide protection against overshoots. The voltage acquisition circuit designed for converter transforms the measured value to a dc waveform and then provides to the MCU by amplifying. The zener diode is also added to this circuit for protection issues where the complete circuit is seen in Figure 9.b.

The dc-dc converter includes switching noises on output signals as regularly seen in all switch mode power supplies. Therefore, the obtained voltage and current waveforms are expected with reduced noise and being filtered. The board including LM324 op-amp components is used to amplify and filter the acquired signal before calibration section. Each measurement channel is used to filter current and voltage signal at the same time [12,13].

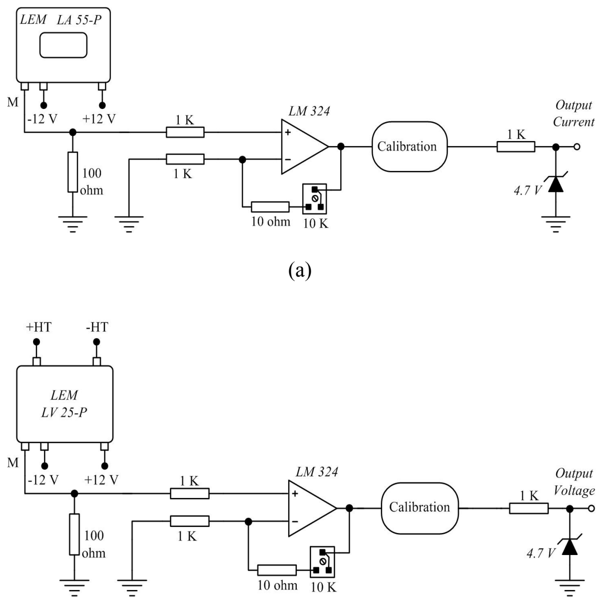


Figure 9. Data acquisition circuit, (a) current measurement section, (b) current measurement section

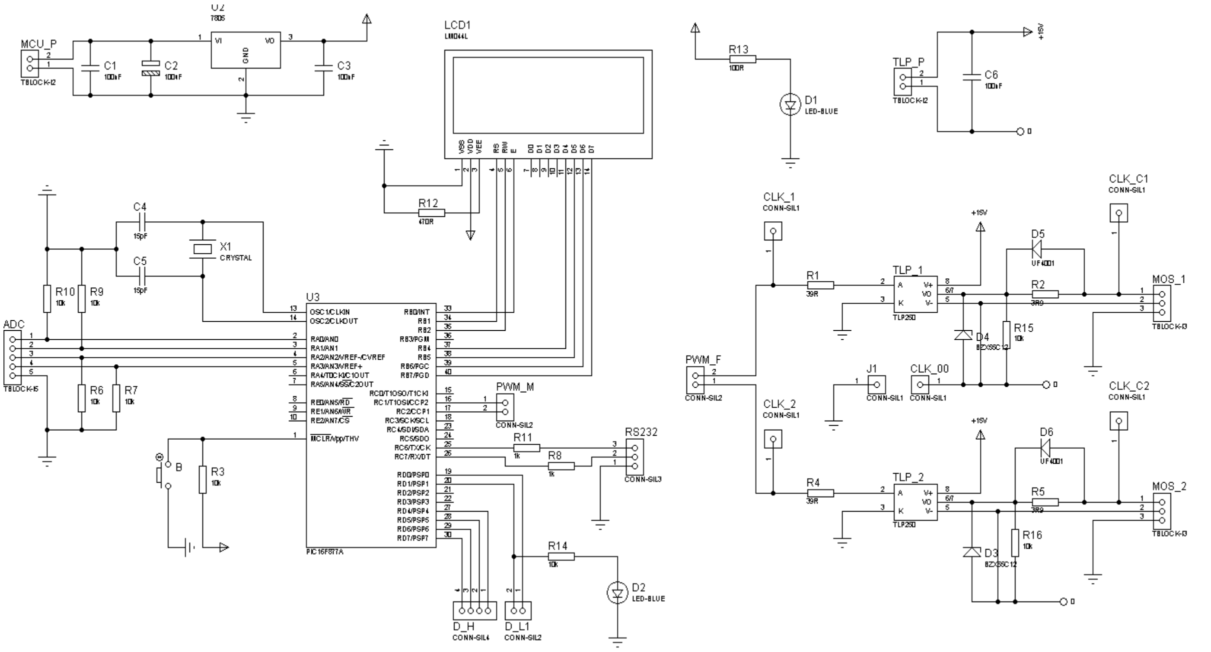


Figure 10. Schematic diagram of controller and driver boards

B. Controller Board and Driver

The controller board is comprised of a microcontroller and high-side mosfet driver. The microcontroller processes the feedback signals, which are obtained from current and voltage acquisition boards and it generates driving signals required for switching the mosfets. Microchip PIC16F877A MCU [14] is used in application while the mosfet drivers were TLP 250. The controller board design that is used in application is shown Figure 10 where the supply circuit and port connections of the MCU are illustrated on the left-hand side. The mosfet driving circuit that is controlled by the MCU and the mosfet connections are seen on the right-hand side of the same figure.

A sample switching signal that is generated by the microcontroller considering the acquired signals of load current and converter voltage is shown in Figure 11 where the duty cycle is at 42% and the switching frequency is at 22 kHz.

The inductor and capacitor cause the spike ripples during the high and low sides of generated pulse width modulation. These unstable transients subject the ripples seen on the converted output voltage. The proposed MPPT algorithm improved with PI assistance is compared to the regular MPPT algorithm with pure P&O control in order to validate the success of the proposed method. The regular MPPT controller with pure P&O algorithm generates the output voltage as seen in Figure 12.a where the tracking time and climbing shape of the output voltage are quite harsh comparing to Figure 12.b that is generated by the proposed method. The output voltage of converter that is depicted in Figure 12.b is based on search algorithm of the proposed PI-MPPT.

The PI control is operated when the input voltage increases the input power of the converter. In this case, error calculation function of PI algorithm is operated and duty cycle is increased or decreased proportional to the constant regulating value as previously shown in Figure 6 and Figure 7.

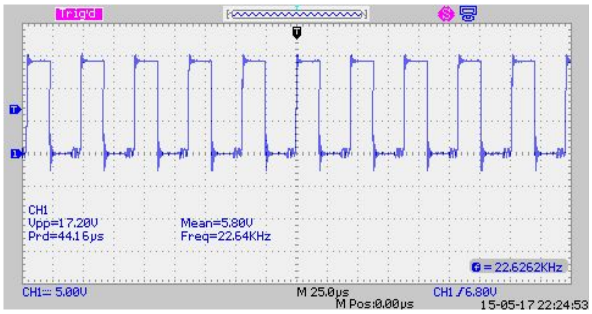
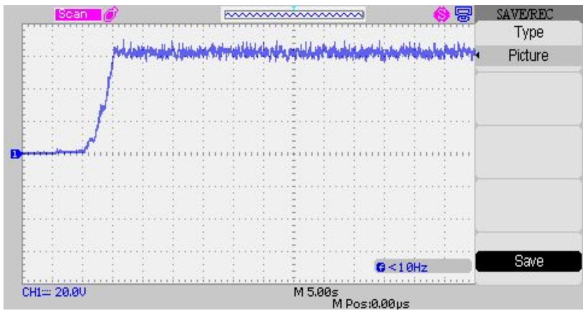
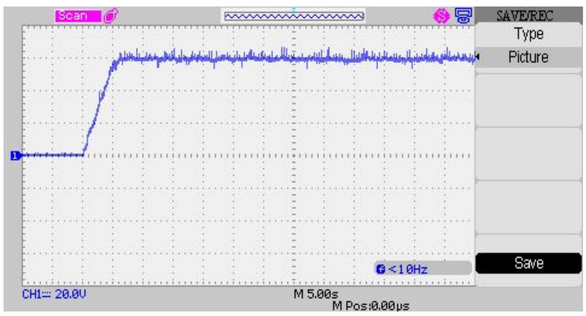


Figure 11. 22kHz switching frequency for driving the mosfet.



(a)



(b)

Figure 12. Output voltage of Buck-Boost converter, (a) pure P&O algorithm, (b) converted voltage of proposed PI and P&O algorithm.

VI. CONCLUSION

In this study, a method is proposed that is based on PI colligation with MPPT control in order to improve output voltage stability and to enhance output power efficiency. K_p and K_i values of control algorithm are determined by using Ziegler-Nichols method. The dc-dc converter is implemented in buck-boost converter topology to adjust output voltages at the desired V_{dc} voltage level. The programmed DC input voltages that is assumed to be generated by PV panels are shifted between 20V to 90V and the output voltage of converter is set to 60V.

The measured values verify that the proposed MPPT control based on PI and P&O algorithms tracks the reference values successfully. Furthermore, the comparison of the proposed method to regular MPPT shows that the output voltage rapidly reaches to desired reference value while the output voltage ripples are quire decreased. On the other hand, the converted power during the initial transient of output voltage is higher than regular MPPT output. The proposed study where the PI and P&O algorithms are combined in one control block allows achieving maximum power from PV using available MPPT techniques.

The proposed method will also be tested and improved at higher power ranges and interleaved converter topologies in future studies.

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