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ScienceDirect

Energy Procedia 115 (2017) 102–113

Energy Procedia

www.elsevier.com/locate/procedia

International Conference – Alternative and Renewable Energy Quest, AREQ 2017, 1-3 February 2017, Spain

Simulation of Buck-Boost Converter for Solar Panels using PID Controller

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Abstract

Currently, there are plenty of technological applications that utilize natural, environmental-friendly sources of energy. However, a disadvantage often found in natural energy sources is that the intensity produced is uncertain. This occurence is also found in solar panels, wherein the light intensity that enters is not always equal. Light intensity may be affected by various factors such as ones on gloomy or sunny weathers. This irregularity on light intensity leads to deviation of voltage output produced by the solar panel. With the use of buck-boost converters, the amount of output voltage may be set to higher or lower than the input voltage, enabling us to maintain the desired output voltage. The amount of output voltage produced is controlled by a microcontroller program which regulates pulse widths produced by PWM signals. This paper discusses about designing a buck-boost converter for solar panels, with a voltage input range of 10 to 50 V. The regulation of output voltage is the main aim in analyzing the success of the design created. The design is simulated with Proteus 8.4, and yields a voltage output with an efficiency of 90 to 99%.

Keywords: buck-boost converter; PWM; duty cycle; solar panel; solar energyIntroduction

1. Introduction

Solar panels are widely used as an environmentally-friendly electricity supply. It is very popular since it simple to install and relatively cost-effective. Unfortunately, a problem is often found, wherein the voltage output produced is

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10.1016/j.egypro.2017.05.011

not constant. A buck-boost converter is a component found in solar panels which is used to regulate the voltage output produced by these solar panels. This converter can be adjusted to produce voltage with a larger or smaller value than the initial voltage. This experiment aims to create a voltage output at a constant value of 12 V, with a range of voltage input of 10 to 50 V. The voltage value produced by the converter is controlled by the pulse width produced by the PWM (Pulse Width Modulation) generator. The pulse width produced by the PWM generator is controlled by a microcontroller. The microcontroller is programmed to control the pulse width and frequency produced. According to the problem stated above, the author creates a circuit architecture as well as a controller scheme for buck-boost converters which may produce a constant voltage output, which is not affected by sunlight intensity. The controller scheme used is the PID (Proportional Integral Derivative). The converter circuit is connected to the arduino microcontroller, and simulated in Proteus 8.4.

1.1 Pulse Width Modulation (PWM)

Pulse width modulation is a method used to adjust the width of a signal. This signal width is represented as a pulse width for one period of time. Commonly, a PWM signal has an equal basic amplitude and frequency, but with a varying pulse width. With the PWM technique, several *on* and *off* pulses will be formed. The percentage of *on* pulses are represented in duty cycles. A duty cycle has a range of 0 to 100%. From the calculation of duty cycle, the resulting voltage output will be known. This is herein stated

$$V_{in(min)} = -V_{out} \times \frac{(1-D)}{D} \tag{1}$$

Wherein:

$V_{in(min)}$ = minimum voltage input
V_{out} = maximum voltage output
D = *duty cycle*

1.2 PWM buck-boost converter circuit on continous current mode (CCM)

A buck-boost converter is a type of converter which has the ability to convert a voltage output into a larger or smaller output than the voltage input. The polarity of voltage output will be the opposite of the voltage input's polarity. The PWM buck-boost converter circuit is shown in Figure 1.a. The circuit consists of a MOSFET as a controlled switch, inductor L, filter capacitor C, and load resistor R_L. The switch is turned *on* and *off* on the switching frequency (F_s) = 1/T with a duty cycle ratio (D) = t_{on}/T, wherein t_{on} is a time interval when the switch *on*. Figure 2.b. shows a buck-boost converter equivalent circuit for CCM when the switch is *on* and the diode is *off*, and when the switch is *off* and the diode is *on*.

During time interval $0 < t \leq DT$, the switch turns *on* and the diode turns *off*, as indicated in Figure 2.b. The diode voltage is $-(V_i+V_o)$ and this keeps the diode *off*. The inductor voltage is V_i and adds the linear increase on the inductor current with a steepness of V_i/L. During the $DT < t \leq T$ time interval, the switch *off* and the diode *on*, as shown in Figure 2.c. The inductor voltage is $-V_o$ and causes the inductor current to decrease linearly with a steepness of $-V_o/L$. The switch voltage is $V_i + V_o$. When t = T, the switch turns *on*, and a new cycle begins.

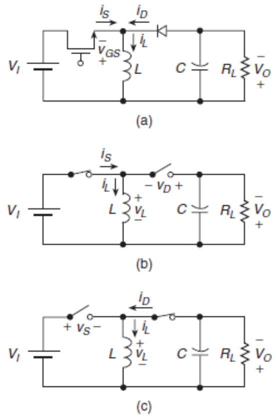


Fig. 1. PWM buck-boost converter and it's ideal equivalent circuit for CCM mode. (a) Buck-boost converter circuit. (b) Equivalent circuit during on switch and off diode. (c) Equivalent circuit during off switch and on diode. [1]

2. Methodology

The designing of the buck-boost converter is done with first determining the types of component, component's value, as well as aligning the component's values with the ones available on market. Then, a programming is done on the Arduino microcontroller by referring to a previously made flowchart. This virtual circuit is then assembled on Proteus 8.4, and simulated by inserting the completed program.

2.1 Calculation of Components

Before component-calculating, the desired parameters are set, which are:

1) Parameters

Table 1. List of parameters

Legend	Parameter	Value
$V_{i(min)}$	minumum voltage input	10 V
$V_{i(max)}$	maximum voltage input	50 V
V_o	voltage output	12 V
$I_{o(min)}$	minimum output current	2 A
$I_{o(max)}$	maximum output current	5 A
$P_{o(min)}$	minimum output power	50 W
$P_{o(max)}$	maximum output power	100 W
F_s	switching frequency	7812.5 Hz
	ripple	< 1%
D_{min}	minimum duty cycle	0.193
D_{max}	maximum duty cycle	0.545

1) Output current (I_o), output power (P_o) and output voltage (V_o)

The value of minimum power desired is 50 W. The initial voltage that enters is assumed as 25 V. Hence, the output current is 50 W / 25 V = 2 A. The input voltage is regulated, becoming 12 V. With the decrease in voltage, the current increases to 5 A. With this, the power is $12\ V \times 5A$ = 60 W. For accuracy in calculation, the current value set is into 3 A.

2) Load resistance (R_L)

The equation used is,

$$R_L = {V_o}/{I_o} \tag{2}$$

$$R_L = {12}/{3} = 4\ \Omega$$

3) Voltage Transfer (M_{VDC})

M_{VDC} is a voltage transfer function in converters. The DC voltage transfer function is classified into minimum voltage transfer ($M_{VDC(min)}$), and maximum voltage transfer ($M_{VDC(max)}$). The equation used is,

$$M_{VDC} = {V_o}/{V_i} \tag{3}$$

Hence,

$\mathbf{M_{VDC(min)}} = {12}/{50} = 0.24$, and $\mathbf{M_{VDC(max)}} = {12}/{10} = 1{,}2$

4) Minimum Inductance (L_{min})

The minimum inductance value is gained by the equation $L_{min} = {R_L(1 - D_{min})^2}/{2F_s}$ (4)

L_{min} = 167 µH. For the circuit to work well, the inductor value must be at least 25% larger than the chosen L_{min}. The inductor has a value of 220 µH [2]. With a value of 220 µH, the values of I_o, P_o and R_L are recalculated.

1. $R_L = 5.2783\ \Omega$
2. $I_o = 2.2734$ A
3. $P_o = 56.8350$ W

I_o and $P_{o(min)}$ lies in the range of 2 to 5A and 50 to 100 W, hence inductor 220 µH can be used in the circuit. To determine the suitable MOSFET and diode, a calculation is done with these parameters:

2) Peak-to-peak inductor current ($\Delta_{iL(min)}$)

The peak-to-peak inductor current is,

$$(\Delta_{iL(min)}) = {V_o(1 - D_{max})}/{F_s x L} \tag{5}$$

$\Delta_{iL(min)} = 3.1767$ A.

3) Maximum input current ($I_{i(max)}$)

$I_{i(max)}$ is an input current which flows in the circuit, expressed by

$$I_{i(max)} = M_{VDC(max)} \times I_{o(\max)} \quad (6)$$

$I_{i(max)} = 6$ A.

4) Current stress ($I_{SM(max)}$)

Current stress is the current value that is able to be detained by the MOSFET switch and the diode in an *on* condition. The current stress value is calculated with the equation,

$$I_{SM(max)} = I_{DM(max)} = I_{i(max)} + I_{o(\max)} + {}^{\Delta\ \mathrm{iL(min)}}/_{2}\ I_{SM(max)} \quad (7)$$

$I_{SM(max)} = I_{DM(max)} = 12.5884$ A.

5) Voltage stress ($V_{SM(max)}$)

Voltage stress is the voltage value which is able to be detained by the MOSFET and diode in an *on* condition. The voltage stress value is calculated with the equation,

$$V_{SM(max)} = V_{i(max)} + V_o.\ V_{SM(max)} \quad (8)$$

$V_{DM(max)} = 62$ V.

From the calculation results above, the IRF5210S MOSFET is used, with a $V_{DSS} = -100$ V and $I_{SM} = -140$ A. The diode used is 75LQ150 with $I_{F(A)} = 75$ A, $V_{RRM} = 150$ V and $V_F = 0.78$ V. The negative value on the V_{DSS} and I_{SM} MOSFET is caused by the voltage-polarity-reversing MOSFET.

6) Output capacitor (C_{out})

The C_{out} value is used to minimize the voltage ripple produced by the circuit. The voltage ripple can also be minimized by calculating the ESR (Equivalent Series Resistance) value. ESR is the value of series resistance on the capacitor, with a unit in ohm (Ω).

1. Voltage ripple (V_r) = 0.12 V
2. Peal-to-peak voltage ripple (V_{rpp}) = 0.1 V
3. ESR = 7.9438 mΩ

The voltage ripple on the capacitor ripple (V_{cpp}) is 0.02 V

7) Minimum capacitor (C_{min})

This is the minimum capacitor value for the circuit work as desired. The calculation used is,

$$C_{min} = \left({D_{max}}/{F_s \times R_L}\right) \times \left({V_o}/{V_{cpp}}\right) \quad (9)$$

C_{min} = 7929 µF

By calculating the capacitor value available on market, a capacitor with a value 8200 µF [3] i utilized. With a capacitor value of 8200 µF, I_o, P_o and R_L are recalculated:

1. R_L = 5.1044 Ω
2. I_o = 2.3509 A
3. P_o = 58.7725 W

$I_{o(min)}$ and $P_{o(min)}$ are in a range of 2 to 5 A and 50 to 100 W, hence the 8200 µF capacitor may be used in the circuit. The R_L component is adjusted with the resistor value that is market-available. The R_L used is 5.1 Ω ± 5%.

A buck-boost converter is aimed for battery-charging, hence an additional resistor is added with a total resistance of 5 Ω, as the load. After it is simulated, the current produced ranges between 2.35 to 2.4 A.

The amount of diodes given are 2 to 3 diodes. This is to prevent heat from the real, implemented circuit. From the simulaton result, the maximum current produced is 129 A. Meanwhile, one 75LQ150 diode can only withstand if passed by a current ($I_{F(A)}$) to 75 A. In this circuit, 2 diodes are arranged in parallel so that the circuit may withstand a current of maximum 150 A.

2.2 Design of PWM MOSFET driver

The PWM driver acts as a switching pengatur of a MOSFET. Without the PWM driver, a MOSFET may not be able to change from the on to off state, or the opposite. This will cause a circuit failure.

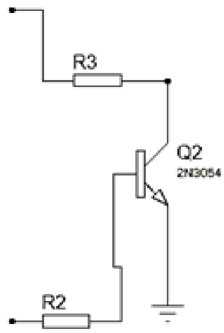


Fig. 2. The designed PWM MOSFET driver

The Q2 transistor used is type 2N3054.

V_{cc} = 12 V

R_3 = 1000 Ω (value have been set)

$$I_c = {(V_{cc} - V_{CE(SAT)})}/{R_3} = {(12 - 1)}/{1000} \quad (10)$$

$I_c = 0.011$ A

The 2N3054 transistor has these specifications, as mentioned in the *datasheet* [4]:

$hfe_{(min)} = \beta = 25$; $Ic_{(max)} = 4$ A
The equation for I_β is,

$$I_\beta = {I_c}/{\beta} = {0,011}/{25} \tag{11}$$

$I_\beta = 4.4 \times 10^{-4}\ A$

Vb = 5 V
The equation for R_2 is,

$$R_2 = {(V_B - V_{BE})}/{I_B} \tag{12}$$

$R_2 = {(5 - 1,7)}/{4,4 \times 10^{-4}} = 7500\ \Omega$

2.3 Design of voltage divider circuit

The voltage divider circuit is used to make the voltage output of the buck-boost converter possible to be converter into a 0-5 V scale (a voltage range readable by the Arduino). The output voltage equation used is [5],

$$V_o = V_{i(Arduino)} \times {R_5}/{R_4 + R_5} \tag{13}$$

V_o is the maximum output voltage readable by the Arduino, that is 5 V. $V_{i(Arduino)}$ is the maximum desired input voltage, that is 50 V.

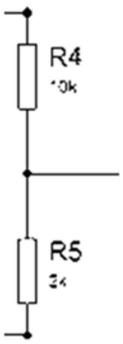


Fig. 3. Voltage divider circuit configuration

R_4 is set to be 10 kΩ. The above equation will calculate the value of R_5. From the calculation result, the R_5 obtained is 2 kΩ.

2.4 Design of operational amplifier (op-amp) circuit

The op-amp circuit is arranged to reverse the output voltage into an opposite polarity from the input voltage. With this, the output voltage with a negative (-) value will be changed to positive (+), enabling the Arduino microcontroller to read it.

The calculation of the gain given by the op-amp is:

Gain = $-{R_F}/{R_{in}}$ = ${-130\ k\Omega}/{130\ k\Omega}$ = -1; so that, the output voltage only changes by it's polarity. The op-amp circuit does not affect the value of output voltage.

2.5 Program flowchart

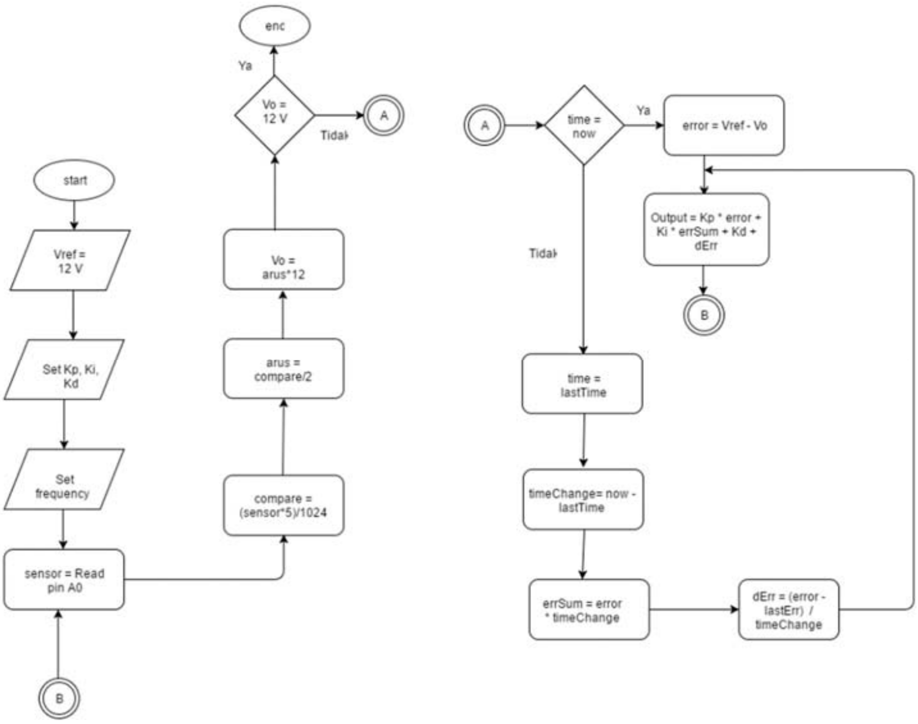


Fig. 4. Program flowchart

The system works by setting a desired voltage referemce (V_{ref}), that is 12 V. Then, an initial value of K_p, K_i and K_d are set. The limit value for PWM is obtained from a manual calculation of duty cycle required for every input voltage. The voltage input through the inductor, capacitor and resistor, then passes through the voltage divider to convert its value into a voltage range of 0-5 V. After that, the voltage passes the op-amp circuit to reverse it's polarity into positive. The voltage output (V_o) will be compared against V_{ref}, to obtain the error value. This error value then will be brought back into the system, to re-adjust the P,I and D parameters in the system. The frequency used in the Arduino microcontroller is 7812.5 Hz. The frequency-setting is explained in the program,

```
setPwmFrequency(6, 8);
```

which means that it manages the frequency on pin 6, then that frequency value is divided by 8. The frequency value on pin 6 is 62500 Hz, which is later divided by 8; yielding 7812.5 Hz.

Then, sensor reads the voltage from pin A0. This is written in the command:

```
sensor= analogRead(A0);
```

To convert the value prom analog to digital reading, the number read will be divided by 1024. Then, it is multiplied by 5 to convert it into a 0-5 V scale, as follows:

```
compare= (sensor*5)/1024;
```

On these two command lines, a calculation is done when voltage passes through the voltage divider circuit. Current is calculated by dividing the comparison value by 2, then the voltage is obtained by the current (in the flowchart diagram, current is represented by *arus*) value, multiplied by 12. 2 and 12 are obtained from the voltage divider sensors:

```
current=compare/2;
volt=current*12;
```

Then a time calculation is done, to know the difference in the voltage produced, as well as to calculate various error parameter required to adjust the output voltage. This is done in,

```
unsigned long now = millis();
double timeChange = (double)(now - lastTime);
```

and

```
lastErr = error;
lastTime = now;
```

The error parameter is done in,

```
error= Setpoint - volt;
errSum += (error * timeChange);
double dErr = (error - lastErr) / timeChange;
```

The values of error, errSum, and dErr is used for the output value computation,

```
Output = kp * error + ki * errSum + kd * dErr;
```

2.6 Circuit Scheme

According to the design employed as well as the calculation of components by considering market availability, this circuit is proposed. The circuit components are arraanged with Proteus 8.4, by using the prepared library.

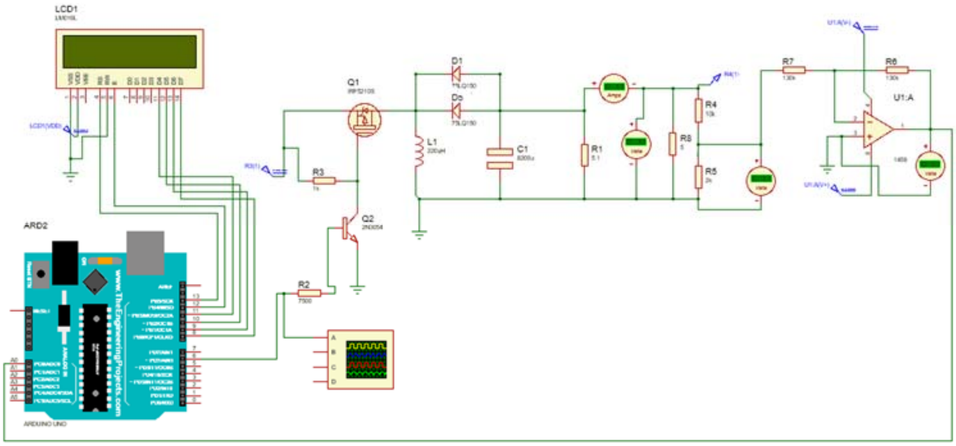


Fig. 5. The circuit scheme on Proteus 8.4

The components used are:

Table 2. List of components

Type	Value	Amount
IRF5210S MOSFET	-	1
75LQ150 Diode	-	2
2N3054 Transistor	-	1
Capacitor	8200 µF	1
Inductor	220 µH	1
Resistor	1 kΩ; 7,5 kΩ; 5,1 Ω; 5 Ω; 10 kΩ; 2 kΩ; 130 kΩ (2)	8
LM1458 Op-amp	-	1
16x2 LCD	-	1

3. Analysis

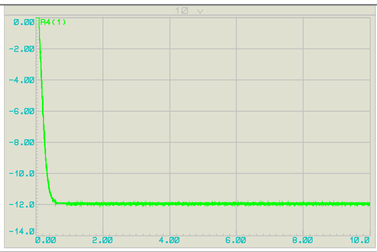
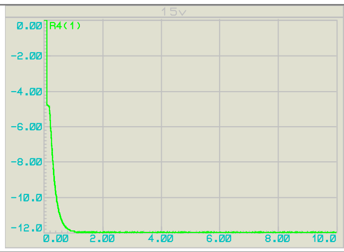
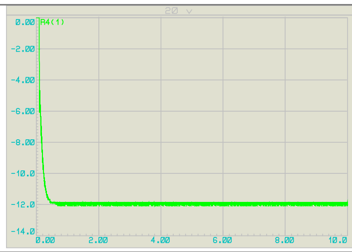
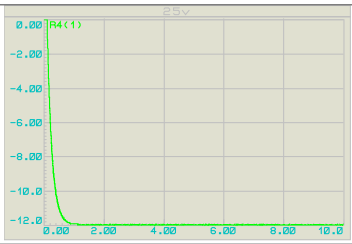
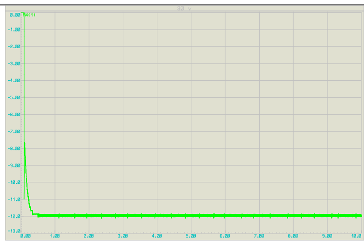
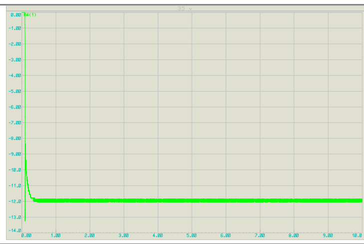
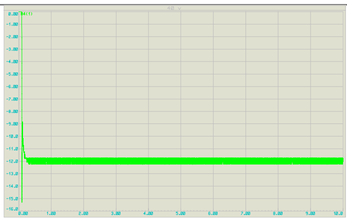
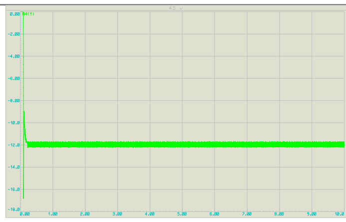
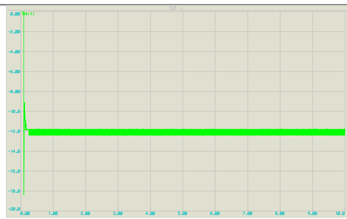
In this section, few analysis has been made, based on the simulations done.

3.1 Simulation on voltage range of 10 to 50 V

A simulation is done from the voltage of 10, 15, 20 and so on until 50 V. A combination of K_p, K_i and K_d values are applies on the test. K_p is tested first; after the system oscillates, K_i is given on the system untul it reaches 12 V; after that, a K_d value is given to stabilize the system. After tested with a few values, a most optimim value of K~~p~~, K_i and K_d are obtained. The graph shows a comparison of voltage (vertical line) against time (horizontal line). The output voltage simulation is done for 10 seconds. The results are therefore:

$K_p = 1$; $K_i = 0.01$; $K_d = 0.1$

Table 3. Graphs from V_i of 10 to 50 V

$V_i = 10$ V	$V_i = 15$ V	$V_i = 20$ V
		
$V_i = 25$ V	$V_i = 30$ V	$V_i = 35$ V
		
$V_i = 40$ V	$V_i = 45$ V	$V_i = 50$ V
		

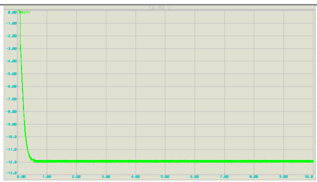
When $K_p = 1$; $K_i = 0.01$ and $K_d = 0.1$, the output voltage was able to be stabilized until it reaches a range of 11.9 to 12.2 V. The graph shows a negative number for each of the results. This will not be a problem, simce the negative sign is only a voltage polarity. The measured voltages have a negative sign since the measuring probes are arranges in the end of the voltage divider, wherein the output voltage is still in a negative value and has not passed the inverting op-amp yet. The largest settling time (T_s) value is in the input voltage of 10 V, that is 1s. T_s is getting lesser as the input voltage increases, with a smallest value of 0.3 s. The highest accuracy obtained on the test results is 90%.

3.2 Field test

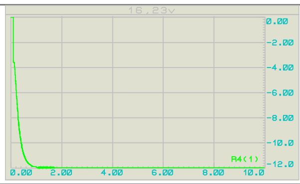
Datas have been obtained on solar panels before a PID controller is given. V_{in} datas are obtained for one day, for 10 hours. A test is done with $K_p = 1$; $K_i = 0.01$; and $K_d = 0.1$. The results of the field tests are:

Table 4. Field test graphs

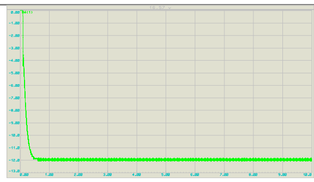
$V_i = 13{,}93$ V



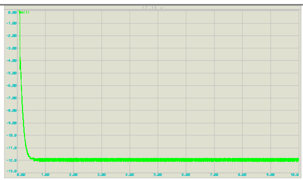
$V_i = 16{,}23$ V



$V_i = 16{,}57$ V

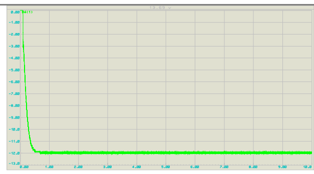


$V_i = 17{,}14$ V

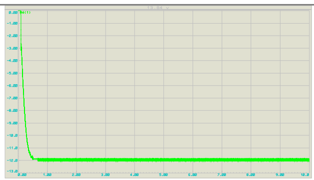


$V_i = 12{,}81$ V

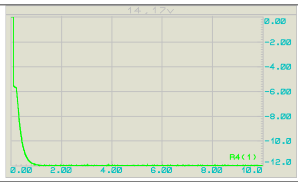
$V_i = 13{,}69$ V



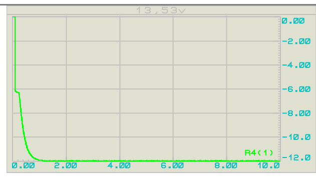
$V_i = 13{,}84$ V



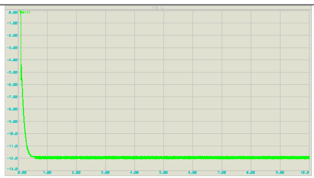
$V_i = 14{,}17$ V



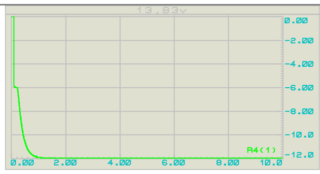
$V_i = 13{,}53$ V



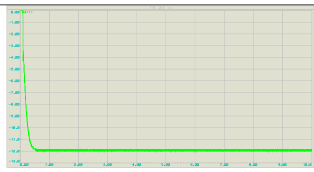
$V_i = 19$ V



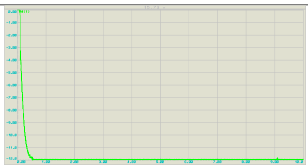
$V_i = 13{,}83$ V



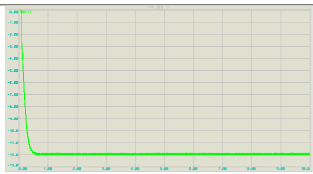
$V_i = 16{,}31$ V



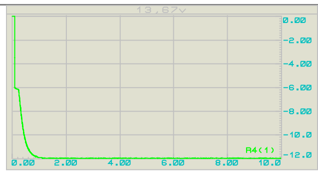
$V_i = 15{,}73$ V



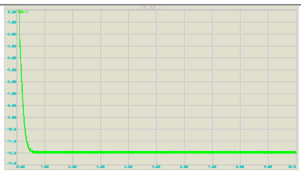
$V_i = 14{,}08$ V



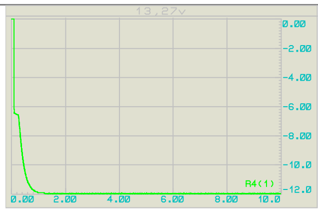
$V_i = 13{,}67$ V



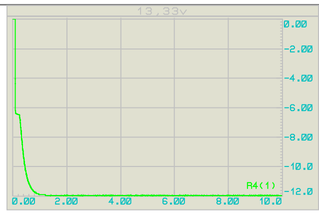
$V_i = 13{,}32$ V



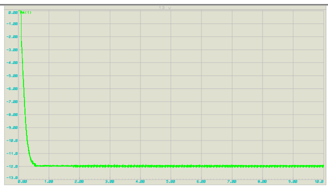
$V_i = 13{,}27$ V



$V_i = 13{,}33$ V



Untuk $V_i = 13$ V



A field test is done as well, to prove the success of the buck-boost converter. The test results shows that the voltage ranges produced are 11.9 to 12 V. The value of 12 V is obtained on the input voltage of 13; 13.32; 15.73; 14.08; 16.31 and 19 V. Ts ranges from 0.6 to 1 s. The graphs also show a negative number for result. Just like the same test, the negative sign is a voltage's polarity. The masured voltages has a negative sign since the measuring probes are put in the voltage divider, where the output voltage still has a negative value and has not passed the inverting op-amp yet. The highest accuracy obtained in this testing is 99%.

References

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