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Design of Maximum Power Point Tracking Photovoltaic System Based on Incremental Conductance Algorithm using Arduino Uno and Boost Converter

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Abstract

Fossil fuel reserves are limited while the growing demand for energy utilization. It leads to an acceleration of renewable energy use. One of the renewable energy resources is solar energy, called the photovoltaic system. This paper uses a photovoltaic solar system consisting of a solar panel module, DC-DC boost converter, voltage divider, ACS712 as a current sensor, Arduino Uno, and load resistor. Maximum Power Point Tracking (MPPT) controller is implemented to track the maximum power point of the solar panel system using a boost converter based on the Incremental Conductance algorithm embedded in Arduino UNO. The PV system with MPPT controller is designed with PV 20 W. The testing of the ACS712 current sensor and voltage sensor show error values of about 1.82% and 0.83%, respectively, which are acceptable limits. Besides, the DC-DC boost converter is also tested, and its performance shows an increase in the output voltage. The test result of the PV system with MPPT control based on the Incremental Conductance algorithm shows the average value of the PV power output with resistive load at 36 Ω is about 7.34 W, while the PV system without MPPT is about 6.07 W. Thus, the Photovoltaic system using MPPT controller based on the incremental conductance algorithm can control PV power output at the maximum power point.

I. INTRODUCTION

Electrical energy sources from fossil fuels are decreasing while demand increases significantly [1] [2]. The utilization of Renewable energy sources (RES) can substitute fossil fuels as an energy alternative to generate electricity. The RES use affects the reduction of emissions and an increase of energy self-sufficiency [3] [4] [5]. Achieving A sufficiency of energy supplies based on renewable energy sources would also reduce environmental pollution [6] [7] [8]. Therefore, renewable energy sources are needed to supply the demand for environmentally–friendly and low-cost energy sources. One of the renewable electricity resources used as alternative energy sources is Photovoltaic (PV) solar cell energy [9] [10] [11].

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PV Solar energy has many benefits, such as low-cost maintenance and no pollution, so that its benefits lead to an interesting issue in dealing with global warming problems [12]. Sunlight is converted into DC electrical energy using photovoltaic (PV) technology made of semiconductor materials called PV panels [13]. PV panel output varies due to nonlinear characteristics, which are affected by both solar temperature and radiation. Therefore, the PV output has to be controlled to reach the high efficiency of solar energy.

The maximum energy from the PV solar panels with the highest efficiency can be extracted known the Maximum Power Point Tracking (MPPT) Techniques [14]. These Maximum Power Point Tracking controller devices are implemented to set DC-DC Converter to extract the optimal solar energy from the solar panel module. The PV panel system has the curve of the power-voltage characteristic and current-voltage characteristic curve. Thus, voltage and current are the important variables used as a reference to control the boost Converter. The boost converter has the main role to increase the voltage and provide impedance between the PV solar system and load. The Incremental Conductance (IC) algorithm was chosen in this study to adjust the pulse width modulation (PWM) on the boost converter in order to obtain optimal energy output from the PV solar module. The conventional IC algorithm works when the change of power output and voltage output from PV occurs with the power-voltage characteristic consideration. IC algorithm categorized as the direct control method can show the high efficiency, and low cost compared to other conventional algorithms [15].

Many algorithms show complexity structure and implementation, for instance, the artificial intelligent algorithm control method has high complexity and also high cost. Besides, these control methods are difficult to hardware implementation. Nonlinear control methods, as intelligent control, also have medium to high complexity and high cost to implement hardware components. On the other hand, control methods based on the selection of parameter lead to low complexity yet its accuracy are low [15]. For example, CVT MPPT methods, that relation between the voltage at maximum power point and the voltage of the open circuit is formed as a linear function. This method, under temperature variations, cannot reach the perfect maximum power point tracking. Thus, MPPT needs an algorithm with low-medium complexity and easy hardware implementation in case of converter topology. The incremental conductance algorithm is the proposed method in this study to reach optimal power output from the photovoltaic module and easy hardware implementation using Arduino UNO. Besides, this paper also explains hardware components considering easy implementation and low cost.

II. METHODS

A. The System of PV

In this paper, the entire PV solar system is composed of PV solar panel, Arduino UNO (MPPT controller), voltage sensors, current sensors, loads and the power converter circuit. Its controller is applied in the Arduino Uno hardware to obtain duty cycle to control converter's MOSFET to get the maximum power. The IC algorithm codes are written and developed in the open-source Arduino software (IDE), and then the algorithm is sent to the Arduino UNO hardware. The photovoltaic panel used in this paper is a solar panel module model 156P-20 with a capacity of 20 W.

The equivalent circuit is the most implemented solar cell model. Its model consists of a current source, a diode as well as a shunt resistor R_{sh} connected in parallel, and the resistor R_s in series, as shown in Fig. 1. From this equivalent circuit, the equation of the output current is formulated as the following Equation 1 [16].

$$I_{out} = I_{ph} - I_{s,0}\left(\exp\left(\frac{V + IR_s}{aV_t}\right) - 1\right) - \frac{V + IR_s}{R_{sh}} \tag{1}$$

where:

I_{ph} : The photocurrent of the solar cell model (A)
$I_{s,0}$: The saturation of reverse current (A)

V : Represents the voltage output of the solar cell (V)
a : Represents the ideal diode factor of the solar cell
V_t : the thermal voltage

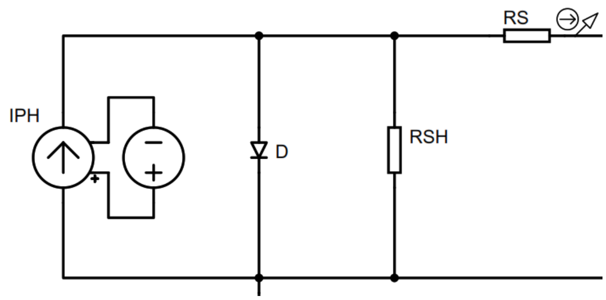

Figure 1. The PV equivalent model

Fig. 2 depicts the P-V characteristic curve obtained from the I-V characteristic curve as explained in Fig. 3. In this paper, The PV module 156P-20 has a characteristic output voltage of about 17.3 V and its current of about 1.17 A at standard temperature conditions (STC). The output voltage and current of the PV solar panel will be sensed by the sensor, and then these data are sent to Arduino UNO board in which algorithm varies the duty cycle Boost Converter in order to control PWM sent to MOSFET following the maximum power can be extracted from PV module.

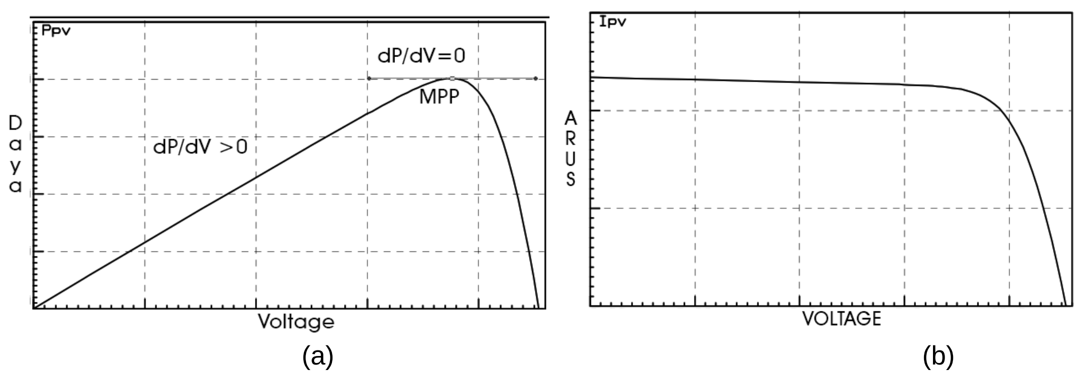

Figure 2. The P-V characteristic curve (a); The I-V characteristic curve (b)

Fig. 2 shows the I-V characteristic curve, which is based on the change of PV current (dI) and voltage (dV). The product of the voltage by the current obtains the P-V characteristic curve. Its PV curve shows the peak power namely the Maximum Power Point (MPP) [17]. The slope value of its curve is used as a reference track of the maximum power of the PV panel that can be reached.

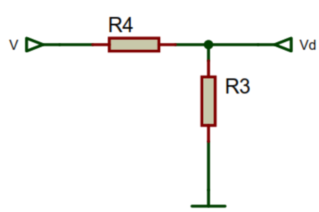

Figure 3. Voltage Divider (The Voltage Sensor)

The component shown in Fig. 3 is the voltage sensor using a voltage divider technique [18]. Its technique is used to reduce the output voltage of the PV panel to another voltage limit which is supported by Arduino, at 5 Volt. The resistor value, R, can be determined by implementing Equation 2, where V_d is the output voltage obtained. Arduino can read the voltage until 5 volts. For voltage value from the PV panel, V at 22 volts, the resistor values, R_3 and R_4 , selected to reach the voltage limit of Arduino are 25kΩ and 100kΩ respectively. These resistors are designed in high value to minimize energy losses. Therefore, the voltage divider technique is presented in Fig. 3.

$$V_d = \frac{R_3}{R_3 + R_4} V \quad (2)$$

Another component is the ACS712 current sensor module board as the current sensor used in this paper. The sensor has a current capacity at 20A to measure AC or DC current. The current sensor is connected in series with the circuit shown in Fig. 4. V_a and V_b are connected to the circuit which will be measured, while V_I is connected directly to the Arduino analog pin.

ACS712 module obtains the output analog voltage between 0 and 5 Volt from the current flowing through the circuit wire. Its output will be converted into digital value. After the output voltage is calculated, the value of current can be obtained using the below formulation [19]

$$I = \frac{V_{out} - 2500}{Sensitivity} \quad (3)$$

where V_{out}: the measured voltage; sensitivity: the scale factor at 100mV/Ampere for a 20A module.

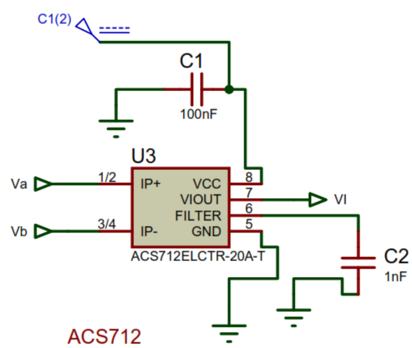

Figure 4. The Current Sensor ACS712 module

B. *The Boost DC-DC Converter*

A schematic of a boost converter is a basic component of a PV solar panel system with an MPPT system, which provides impedance between the load system and the PV solar panel. Fig. 5. shows the boost DC-DC converter circuit implemented in this paper. The boost DC to DC converter work in two switch conditions in MOSFET, on-state and off-state condition.

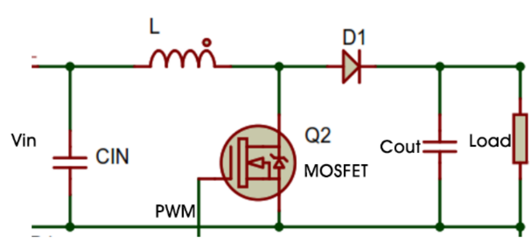

Figure 5. The Boost Converter Circuit

The first condition occurs when the switch is close condition. The current flows through the inductor generating a magnetic field following inductor storing some energy. The polarity is positive on the left side of the inductor. The output capacitor is therefore able to provide energy to the load side. During this condition, the reversing diode prevents the output capacitor from discharging through the MOSFET.

On the other hand, the current from the inductor will be reduced as its impedance is higher than the first condition when the switch is opened. The magnetic field previously obtained will be reduced in energy form to maintain the current flowing towards the load. Thus, the polarity of the left side of the inductor becomes negative. Its current flows through the diode, the output capacitor, and the load. The relationship of the input voltage V_{in} and the output voltage V_o can be formulated in the ideal transfer function, in following Equation. Where D is the duty cycle.

$$\frac{V_0}{V_{in}} = \frac{1}{1-D} \tag{4}$$

The next component is an inductor which is useful as a voltage amplifier after the switching process in the MOSFET. The minimum inductance can be calculated using Equation 5 where R is the load resistor and f_{min} is the minimum frequency [20].

$$L_{min} = \frac{D(1-D)^2 R_{max}}{2 f_{min}} \tag{5}$$

The output capacitance is one of the principal components of the boost converter that its value can be calculated using Equation 6. Where: R is the resistive load; D is duty cycle; $\%V_r$ is desired output voltage ripple; f_{min} is the minimum switching frequency of the boost converter. Besides, the input capacitor can be selected to stabilize the input voltage value due to the requirement of the peak current of a switching process [20].

$$C_{min} = \frac{D}{\%V_r . R . f_{min}} \tag{6}$$

C. The Maximum Power Point Tracking Controller

MPPT method types applied to the MPPT converter are explained by [21] [22]. The incremental conductance (IC) algorithm is the hill-climbing MPPT controller technique to track the maximum point of PV panel power generated. The IC algorithm written in the Arduino IDE program is uploaded in Arduino UNO hardware. Generally, The MPPT technique is to control the duty cycle value of the boost converter in order to obtain the optimum power [23]. The IC algorithm is based on the slope of the P-V characteristic curve in which the MPP point occurs. At this MPP, the change of the power with respect to the voltage equals to zero [24] [25]. The IC algorithm is described in Fig. 7.

The derivative of the PV power with respect to the output voltage is explained in Equation 7 and 8. The output voltage and current from the PV module is measured by sensor to calculate the instantaneous conductance (I_{PV}/V_{PV}) and the incremental conductance $(\frac{dI_{PV}}{dV_{PV}})$ [26] [27]. When the MPP occurs, the derivative PV power with respect to the voltage equals to zero. Thus, the sum of the incremental conductance and the instantaneous conductance equal to zero.

$$\frac{dP}{dV} = \frac{d(VxI)}{dV} = V\left(\frac{dI}{dV}\right) + I\left(\frac{dV}{dV}\right) \tag{7}$$

$$\frac{dP}{dV} = V\left(\frac{dI}{dV}\right) + I \tag{8}$$

$$-\frac{I}{V} = \left(\frac{dI}{dV}\right) \qquad when\ \frac{dP}{dV} = 0 \tag{9}$$

$$-\frac{I}{V} < \left(\frac{dI}{dV}\right) \qquad when\ \frac{dP}{dV} > 0 \tag{10}$$

$$-\frac{I}{V} > \frac{dI}{dV} \qquad when\ \frac{dP}{dV} < 0 \tag{11}$$

The principle behind the algorithm, Equation 9 to 11, is to compare incremental conductance and the instantaneous conductance to decide whether a decrease or an increase of the voltage to reach the MPP. When the power point is detected on the right side of the MPP, the sum of the incremental and the instantaneous conductance is positive which means that the incremental conductance is greater than the negative instantaneous conductance. Otherwise, When the Power Point is detected on the left side of the MPP, the sum of the incremental and the instantaneous conductance is negative which means that the incremental conductance is less than negative the instantaneous conductance.

II. RESULTS AND DISCUSSIONS

The designed PV system consists of the PV panel module, a DC-DC Boost converter circuit, Arduino UNO, and the load. When there is a variation of the input converter or output from the PV solar panel, the operating point of the PV module can be maintained at the optimum point by controlling the duty cycle. The current of the PV solar panel is detected by the ACS712 current sensor. A voltage divider is designed to detect the input and output voltages of the boost converter. Then the boost converter output is connected directly to the load. First of all, the current sensor, voltage sensor, and boost converter circuit will be tested. The MPPT controller circuit of the PV system using the boost converter is presented in Fig. 6.

A. Boost Converter

The boost converter can increase the output voltage by increasing the duty cycle value. To validate the functionality and the performance of the boost converter, the experiment of the converter is conducted with the generator source to provide the input voltage and duty cycle varied directly. The test results as presented in Table 1 show that there is an increase in the output voltage with a fixed input voltage of 17.8 V, as the duty cycle is increased significantly.

Fig. 9. shows the test result of the PWM signal from Arduino UNO, as the duty cycle, and MOSFET driver (TLP250). The value of the PWM signal based on the oscilloscope display with the $div = 1$ and $V / div = 5V$, then the voltage magnitude is:

$$V_{PWM} = 1\, x \frac{5V}{div}\, x1$$
$$V_{PWM} = 5\ V$$

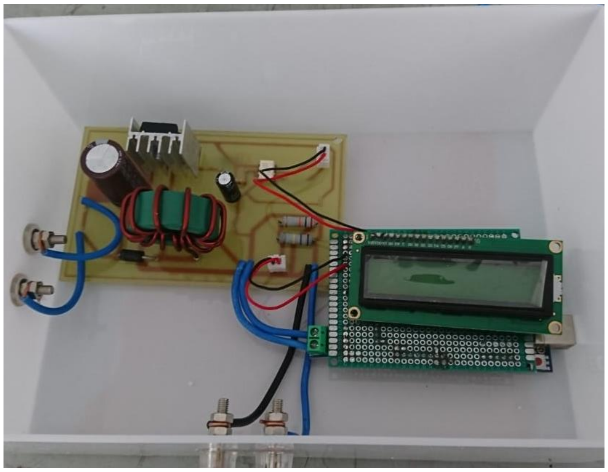

Figure 6. The PV MPPT Controller

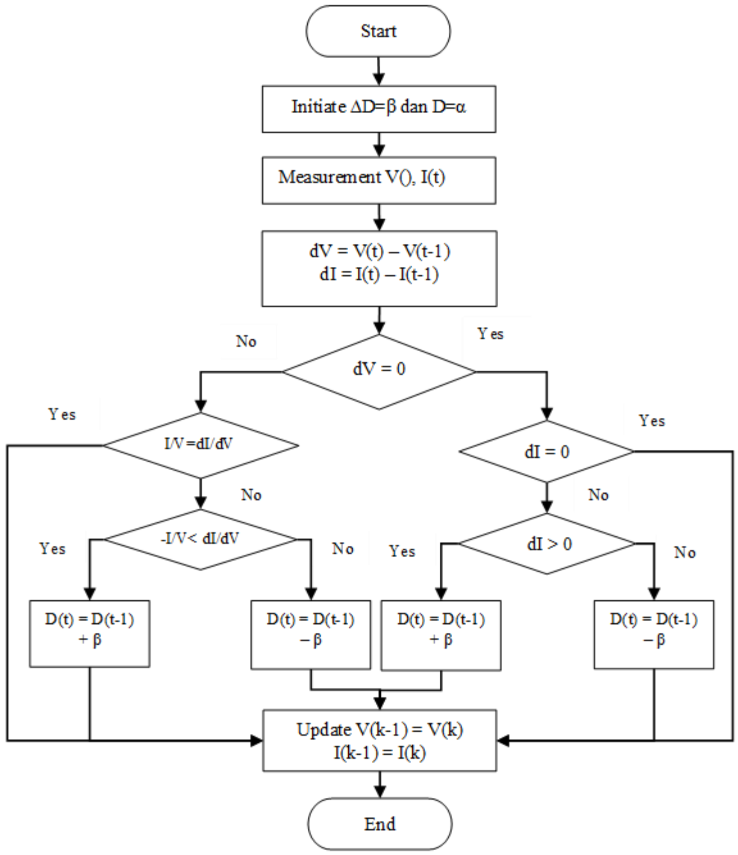

Fig. 7. The Incremental Conductance Algorithm Flowchart

To activate the MOSFET switch, the MOSFET driver increases the drive voltage. While interfacing to 5V, the MOSFET driver shift up to 15 volts as presented in the following calculation:

$$V_{MOSFET\ driver} = 15\,Volt$$

$$V_{MOSFET\ driver} = 15\,Volt$$

Table 1. The Performance of the Boost Converter

Duty Cycle	V input (Volt)	V output (Volt)
10	17,8	18,8
15	17,8	20
20	17,8	22
25	17,8	23,5
30	17,8	25,2
35	17,8	27
40	17,8	29
45	17,8	37
50	17,8	45
55	17,8	50
60	17,8	56

The current sensor and voltage sensor are implemented to provide the reference data to the Arduino UNO. The IC algorithm embedded in Arduino will use the current and voltage data to track the operating power point. The current sensor, ACS712, will be calibrated and validated whether ACS712 is working well. The voltage sensor test presented in Table 2 shows that the average error and the standard deviation are at 0.83% and 0.30, respectively. While the current sensor test ACS712, Table 3, shows an error value of 1.82% and a standard deviation of about 1.43. Thus, these results are an acceptable limit.

Table 2. The Performance of The Voltage Sensor

The voltmeter measurement (Volt)	**The voltage sensor (Voltage Divider)**	**Error (%)**
18,75	18,87	0,60
18,75	18,82	0,40
18,75	18,77	0,10
21,37	21,60	1,08
20,79	21,02	1,11
20,79	21,02	1,11
20,79	20,97	0,86
23,32	23,51	0,81
25,83	26,05	0,85
25,83	26,10	1,04
23,31	23,56	1,07
23,32	23,56	1,03
25,83	26,05	0,85
25,83	26,00	0,66
Average (%)		0,83
Deviation standard		0,30

Table 3. The Performance of The Current Sensor

Multimeter Digital (Ampere)	**Sensor ACS712 (Ampere)**	***Error* (%)**
1,7	1,69	0,59
1,7	1,64	3,53
1,66	1,64	1,20
1,66	1,64	1,20
1,66	1,59	4,22
1,64	1,59	3,05
1,24	1,20	3,23
1,49	1,49	0,00
2,15	2,13	0,93
2,06	2,03	1,46
2,16	2,08	3,70
2,08	2,08	0,00
2,15	2,13	0,93
2,06	2,03	1,46
Average (%)		1,82
Deviation standard		1,43

B. The PV MPPT Controller

The test was conducted in the power system laboratory, electrical engineering, University of Islam Malang. For testing the performance of the PV MPPT controller using the boost converter, this experiment uses the load resistor at 36 Ω. Its experiment is monitored to record the measurement result, especially measuring the voltage and current on the output side. Thus, the output power performance can be calculated as intended in Table 4.

The performance result of the PV system with MPPT controller based on the incremental conductance algorithm in Table 4 shows an expected performance improvement with regards to the output power compared to when the incremental conductance is not considered for the MPPT controller. This explains that the algorithm is able to maintain the maximum power point. On the other hand, the PV system without the MPPT controller using a fixed duty cycle cannot operate at the optimum power point. As shown in Table 5, the boost converter in the PV system without MPPT controller is capable of an increase of the output voltage about 14.63 V from the input voltage at 13V

Table 4. The PV MPPT Controller Performance

V_{out}(Volt)	I_{out}(Ampere)	P_{out} (Watt)
16.01	0.44	7.12
16.02	0.45	7.13
16.02	0.45	7.13
16.03	0.45	7.14
16.04	0.45	7.15
16.05	0.45	7.16
16.06	0.45	7.16
16.07	0.45	7.17
16.07	0.45	7.17
16.02	0.45	7.13
16.09	0.45	7.19
16.10	0.45	7.20
	Average	7.34

The performance result using the MPPT controller based on the IC algorithm in Table 4 shows the output power average of about 7.34 Watt using 36 Ω while the output power average for the PV system without using the MPPT controller is about 5.92 Watt, in Table 5. The PV panel system using the MPPT controller based on the incremental conductance with the boost converter show a good performance in case of tracking the operating power to the maximum power point.

Table 5. The PV System Performance

V_{out}(Volt)	I_{out}(Ampere)	P_{out} (Watt)
14.62	0.41	5.94
14.62	0.41	5.94
14.62	0.41	5.94
14.63	0.41	5.95
14.63	0.41	5.95
14.63	0.41	5.95
14.63	0.41	5.95
14.63	0.41	5.95
14.63	0.41	5.95
14.64	0.41	5.95
14.64	0.41	5.95
14.24	0.40	5.63
	Average	5.92

III. CONCLUSIONS AND RECOMMENDATIONS

This study uses a photovoltaic solar system consisting of a solar panel module, DC-DC boost converter, voltage divider, ACS712 as a current sensor, Arduino Uno, and load resistor.

The inclusion of an MPPT controller based on increased conductance using a boost converter resulted in the expected performance increase, the average output power as about 7.34 watts, compared to a PV system without an MPPT controller depicting lower performance than the proposed controller, around 6.07 watts. This proves that the system using MPPT controller based on IC algorithm can work better in maintaining the operating power at the maximum power point.

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