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Quadratic Boost Converter with Proportional Integral Control in the Mini Photovoltaic System for Grid

***Abstract**. Power plants using Photovoltaics require a DC-DC converter to increase the DC voltage. The input voltage used is 12V DC with an expected output of 267 Volt DC, therefore a quadratic boost converter is used. To achieve set-point voltage the Integral Proportional Control is used. The results of this study, to reach a set-point voltage of 267 Volt, a resistance load of 1100 Ohm was used with a power capability of 64.8 Watt. In this study, this DC-DC converter was also tested on a PV system for normal and partially shaded conditions.*

Streszczenie.** Sieci fotowoltaiczne wymagają stosowania przekształtników DC-DC. Napięcie wejściowe jest zazwyczaj 12 V a wyjściowe powinno być około 260 V. W pracy przedstawiono przekształtnik typu boost stosowany do tego celu.* ***Przekształtnik typu boost ze sterowaniem PI do zastosowań w sieciach fotowoltaicznych

Keywords: DC-DC Converter, Quadratic Boost Converter, Proportional Integral, partially shaded
Słowa kluczowe: przekształtnik DC-DC, przekształtnik typu boost, sieci fotowoltaiczne.

Introduction

Electrical energy is one component that plays an important role in human life. The more electrical energy needs that are used, the more depleting sources of electrical energy such as petroleum, coal, and gas. Therefore renewable energy is needed to overcome this problem. Sunlight is the right solution to be used as a source of electrical energy. The utilization of sunlight is done by using photovoltaic which can convert solar energy into electrical energy [1-2]. Electric energy generated by photovoltaic will be stored in a battery that was previously connected to the charge controller to prevent charging when the battery is fully charged.

In Indonesia, the standard voltage used is 220 Volt AC, so it must be able to produce an output with a maximum voltage value. Therefore a converter is needed to produce maximum output. The voltage value of the battery is only 12 Volt, so to produce a DC voltage value of 267 Volt, a voltage booster circuit is needed, DC-DC Converter [3]. This type of DC-DC Converter is used to increase the voltage of the Quadratic Boost Converter which will be used as input for the inverter [4-6]. DC-DC Converter is a series of power electronics to convert an input dc voltage to an output dc voltage with a value greater or smaller than the input voltage. The input dc voltage from the dc-dc converter process is derived from a dc voltage source that usually has a fixed input voltage.

Basically, the dc output voltage to be achieved is an adjustment between the voltage at the output side and the input side of the same circuit. In its use, photovoltaics only produce low power and change periodically. This is caused by several factors such as light intensity, solar temperature, and geographical location (longitude and latitude). Also, the surrounding conditions that cover surfaces such as buildings, trees, or clouds that pass through it, also affect the strength of photovoltaic output. When viewed from its characteristics, photovoltaics have nonlinear characteristics and changes in radiation and surface temperature. The control system is needed to track the maximum photovoltaic power-point, this system is the Maximum Power Point Tracking (MPPT). This system is an electronic system, the search for maximum power is done by monitoring and controlling the voltage and current. When photovoltaic gets input from sunlight and temperature can produce currents. The large current produced by photovoltaics is directly proportional to the amount of sunlight entering the solar cell [7,8]. As in this study, simulation and implementation tests have been carried out to maintain the photovoltaic power at the optimal position by considering partially shaded factors by using an integral proportional control algorithm on Boost Converter Quadratic DC-DC. This study is a continuation of previous studies using the Hill-Climbing algorithm [9]. Quadratic Boost Converter with Proportional Integral Control in this Photovoltaic System is implemented as a mini power plant for mini photovoltaic system for grid.

In this study the design of a DC-DC converter using Quadratic Boost Converter will use a PI (Proportional Integral) controller that will be used to control so that the stable output voltage can reach the set-point.

Quadratic Boost Converter concept

Quadratic Boost Converter is a second phase DC-DC boost converter that functions to increase DC voltage. Quadratic Boost Converter has an output voltage that is always greater than the input voltage. The resulting output voltage can be calculated using equation (1).

$$V_{OUT} = \frac{V_{IN}}{(1-D)^2} \quad (1)$$

The Quadratic Boost Converter circuit, shown in Fig. 1, generally consists of MOSFETs (Q) as switches, inductors (L), diodes (D), capacitors (C), and resistors (R) as loads. The circuit operation is based on the assumption that the Q switch is ideal in operation and capacitors C_1 and C_2 are assumed to be large so that the voltage on the capacitors VC_1 and VC_2 is almost constant during the switching process.

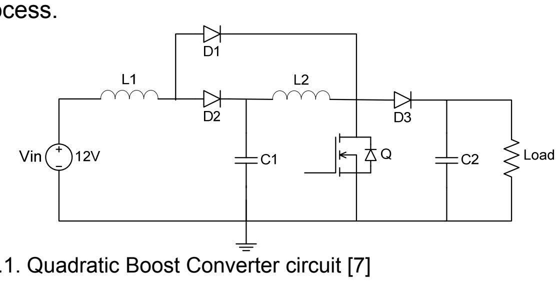

Fig.1. Quadratic Boost Converter circuit [7]

The gate current in the MOSFET is determined using equation (2), where P_G is the power at the gate which is determined by the oscillator frequency of 31 kHz (from the datasheet) and Capacitor 380 micro farads. Whereas V_{GS} is the voltage at the input (V_G) multiplied by the percentage of duty cycle (D).

(2) $$I_G = \frac{P_G}{V_G}$$
$$where, P_G = F_S Q_G V_{GS}; V_{GS} = V_G D$$

PI control in PV with and without partially shaded

PI Controller is a combined control system between proportional control and integral control. The block diagram is shown in Fig. 2.

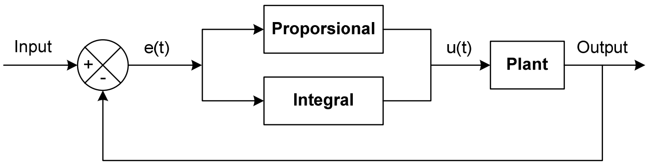

Fig.2. Block Diagram PI Controller [11]

In continuous time, the PI controller output signal is formulated in equation (3).

(3) $$\mu(t) = K_P\left(e(t) + \frac{1}{T_i}\int_0^t e(t)dt\right)$$

, with $\mu(t)$ = input signal control, K_P = proportional constant, T_I = integral time, K_I = integral constant, $e(t)$ = signal error and $e(t)$ = output plan reference.

The solar cell is basically a p-n junction semiconductor. When exposed to light, the current will be generated (DC current). Changes in current generated linearly with changes in intensity and temperature of sunlight. Fig. 3 shows the equivalent electrical circuit of a solar cell, where: I and V are the current (A) and output voltage (Volt) of solar cells, I_L is cell's photocurrent (A), R_S and R_{SH} are series resistance and shunt resistance (Ohm) of solar cell.

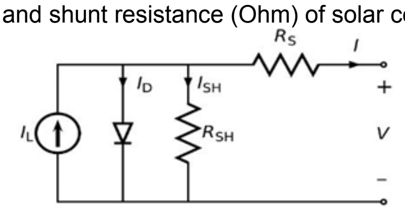

Fig.3. Equivalent circuit of photovoltaic [10]

I-V characteristics of the solar cell circuit shown mathematically in equation (4) [10, 11, 12], wherein: I_0 is the diode saturation current (A), q is the electron change (1.6×10^{-19} C), K is Boltzmann constant (1.38×10^{-23} J/K), the T cell temperature in Kelvin (K), and n is the ideal diode factor.

(4) $$I = I_D - I_0\left(e^{\frac{q(V+IR_s)}{nKT}} - 1\right) - \frac{V + R_s I}{R_{sh}}$$

Photovoltaic are usually shaded by disturbances such as branches of tree, passing clouds, high building, etc., which produces partially shaded on photovoltaic systems as shown in Fig. 4. During partially shaded, a small portion of PV cells that receive radiation still operate at optimal efficiency. Because the current flows through each cell in a series configuration constantly, the shaded cells need to operate with a reverse voltage to provide the same current as of the illuminated cells [13,14]. When shaded cells operate with reverse bias and produce reverse polarity electricity it will lead to a decrease in power and thus reduce the net power conversion efficiency [15 – 20].

A partially shaded module can be modeled by two groups of photovoltaic cells connected in series in the module. Each group receives a different level of irradiation.

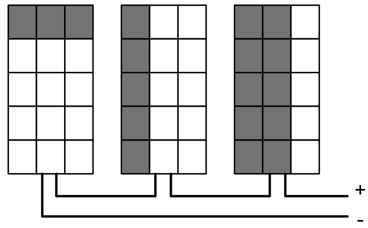

Fig.4. Photovoltaic when partially shaded

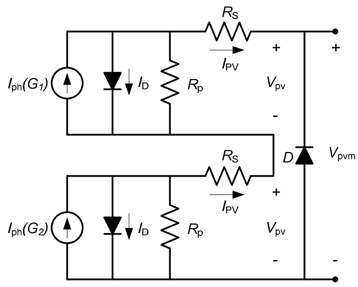

Fig.5. Partially shaded module circuit [15]

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Fig. 5 shows the circuit model for partially shaded modules, there is not a bypass diode for cells in the module. This module consists of r series of connected cells in which s shaded cell receives irradiance G_1 and (r-s) shaded cells receive irradiance G_2. Photovoltaic parameters can be represented in formula (5). [15]

(5) $$I_{ph1} = I_{ph}(G_1), I_{ph1} = I_{ph}(G_1),$$
$$N_{s1} = sN_{s1}, N_{s2} = (r-s)N_{s2}$$

where, the subscripts 1 and 2 refer to cells that receive irradiation from G_1 and G_2 respectively.

Method of Configuring Quadratic Boost Converter Systems in PV

The design of the Quadratic Boost Converter system is carried out in two stages. The first stage is simulation and the second stage is design and manufacture of the system hardware. For planning the system whose power source is from this photovoltaic, it aims to increase the voltage on the battery by 12 Volt DC to be increased to 267 Volt DC which will then be used as input on the inverter to 220 Volt AC voltage.

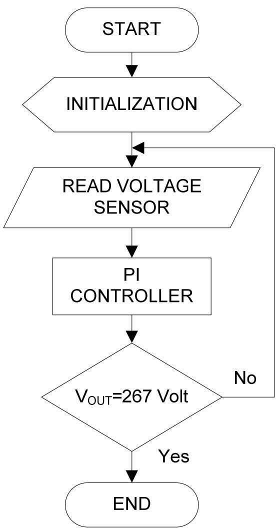


Fig..6. The work flow of the Quadratic Boost Converter system

The workflow of a simple Quadratic Converter system is shown in Fig. 6. The system work process starts with a photovoltaic cell that absorbs energy from the sun to be converted into electrical energy. The photovoltaic capacity used is 100WP. The electrical energy produced by photovoltaics will charge the battery through a charging controller which aims to stop charging when the battery is fully charged. The hardware system consists of a DC-DC converter type Quadratic Boost Converter as the main circuit, as well as voltage sensors and digital microcontroller circuits using Arduino. Quadratic Boost Converter circuit is used to increase the 12 Volt DC from the battery voltage to 267 Volt DC. The Quadratic Boost Converter circuit switching control system is controlled by MOSFET IRFPS40N50L which gets PWM signal input from the microcontroller. Driver control is needed between the Quadratic Boost Converter circuit and the microcontroller so that the microcontroller is not damaged due to the reverse flow from the main circuit to the microcontroller. This circuit is called a PWM driver circuit using TLP250 IC, where the power supply is sourced from the 12 Volt DC Battery itself. Furthermore, the Quadratic Converter circuit will use a PI (Proportional Integral) controller to control the Quadratic Boost Converter output voltage to reach the set point.

Simulation of Quadratic Boost Converter with PI control on PV

This simulation aims to see the ideal results of the output voltage pulse waveform in the Quadratic Boost Converter circuit. Fig. 7 shows the Quadratic Boost Converter circuit for simulation using simulation software.

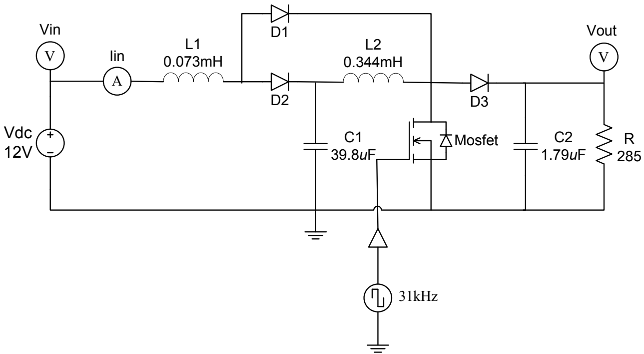


Fig.7. Quadratic Boost Converter simulation circuit

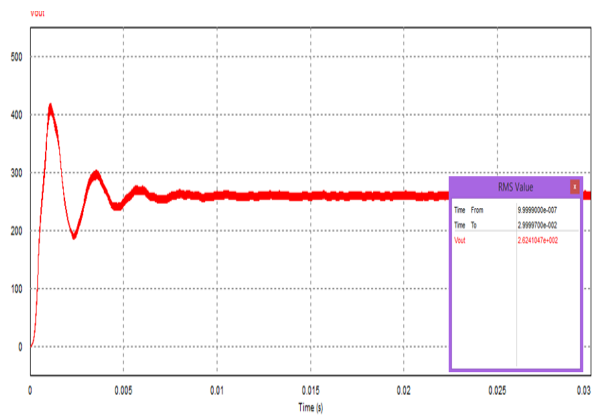


Fig. 8. Output voltage wave without PI control

The Quadratic Boost Converter circuit design in this simulation uses a 12 Volt DC input voltage according to the flow diagram in Fig. 6. The simulation results for this circuit are the output voltage signal waveform shown in Fig. 8. In the textbox in this figure, it can be seen that the Quadratic Boost Converter output voltage is only 262 Volt DC, and has not reached the 267 Volt DC output voltage.

The addition of PI (Proportional Integral) control in the circuit will function as a control system to control the output voltage of the circuit so that the output voltage of the Quadratic Boost Converter can be stable at 267 Volts. Quadratic Boost Converter circuit with PI control is shown in Figure 10.

Simulation results are shown in Figure 9, where the output voltage waveform of Quadratic Boost Converter using PI (Proportional Integral) controller output voltage can reach 267 Volts.

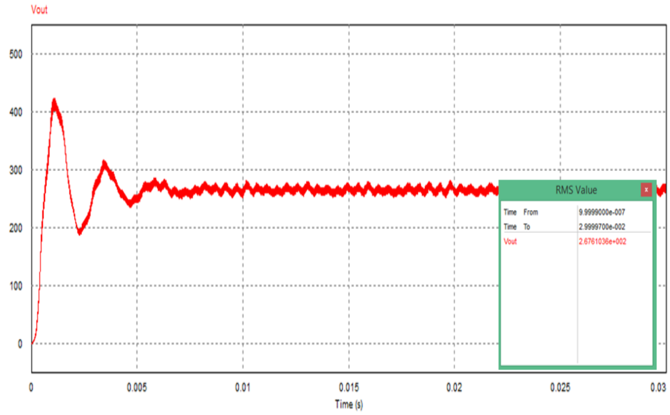


Fig.9. Output voltage wave with PI control

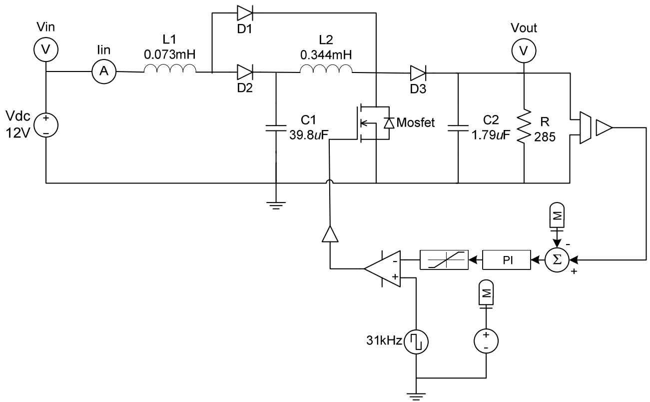


Fig.10. Quadratic Boost Converter simulation circuit with PI control

Data and Discussion

Fig. 11 a) shows the Quadratic Boost Converter hardware being tested, and Fig. 11 b) is hardware that has been packaged in a clear plastic box.

Hardware testing that has been done aims to get an evaluation of the output of the circuit and the system so that the performance of the tool can be known as expected. In hardware testing, the Quadratic Boost Converter system uses a rheostat load (variable resistor) and a voltage source from a 12 Volt DC battery. Table 1 shows the results of testing by measuring the input and output voltages, input and output currents, input and output power using 285 Ohm loads. V_{OUT} analysis in Table 1 column 6, calculated using the formula in equation (1). In the work cycle of 10%, the voltage increase should be 14.8 Volt, but the measured output voltage V_{OUT} is 14.2 Volt, so there is a difference (error) of 4.06%. While the current is 0.05 Amp so the power is 0.71 Watt. By changing the percentage of the work cycle, then in the work cycle of 78.8%, the increase in voltage should be 267 Volt, but the measured output voltage is 152 Volt, there is a difference (error) of 43.07%. While the current is 0.36A, so the power is 54.72 Watt. In this condition, the power efficiency reaches 54.3% which is calculated from the output power divided by the input power multiplied by 100%. So for a load of 285 Ohms the output voltage has not been able to reach 267 Volt.

Table 1. The test results Quadratic Boost Converter with 285Ω load

Duty Cycle (%)	V in (V)	I in (A)	V out (V)	I out (A)	V out analysis (V)	P in (W)	P out (W)	Power Efficiency (%)
10%	12	0,09	14,2	0,05	14,8	1,08	0,71	65,7
15%	12	0,14	16,1	0,07	16,6	1,68	1,13	67,3
20%	12	0,24	18,3	0,09	18,75	2,88	1,65	57,2
25%	12	0,33	20,6	0,11	21,4	3,96	2,27	57,3
30%	12	0,46	23,8	0,13	24,5	5,52	3,1	56
35%	12	0,61	27,3	0,15	28,4	7,32	4,1	56
40%	12	0,75	32,5	0,19	33,4	9	6,17	68,5
45%	12	0,92	38,4	0,21	39,7	11,04	8,06	73
50%	12	1,13	46,7	0,23	48	13,56	10,74	79,2
55%	12	1,33	57,4	0,25	59,3	15,96	14,35	89,9
60%	12	1,7	73,3	0,27	75	20,4	19,79	97
65%	12	2,74	92	0,3	98	32,88	27,6	83,9
70%	12	4,27	122	0,33	133	51,24	40,26	78,57
75%	12	6,2	143	0,35	192	74,4	50,05	67,27
78,8%	12	8,4	152	0,36	267	100,8	54,72	54,3

a)

b)

Fig.11. Quadratic Boost Converter simulation circuit with PI control

Spark testing and analysis are also carried out to find out how much current is flowing at the gate of the MOSFET, the results are shown in Table 2. I_G current is calculated using the formula in equation (2).

Table 3 shows the results of V_{OUT} measurements compared with V-Analysis when the Quadratic Boost Converter circuit is given a load of 1300 Ohms. At a work cycle of 10%, the V-Analysis voltage is 14.8 Volt and the measurement result on V_{OUT} is 29.14 Volt. Whereas in the work cycle of 78.8%, the V-Analysis voltage is 267 Volt and the measurement result on V_{OUT} is 267.2 Volt. From the data obtained, it can be seen that the calculated output voltage and the test output voltage have an error difference of only 0.07%. So for a load of 1300 Ohms the output voltage can reach 267 Volt.

In subsequent studies, the Quadratic Boost Converter circuit was tested using a PI (Proportional Integral) controller. PI Controller is used to control the Quadratic Boost Converter output voltage so that it can be stable at a voltage set point of 267 Volts.

Table 2. The MOSFET sparking analysis result

Duty Cycle (%)	V_{GS} (V)	P_G (W)	I_G (mA)
10%	1.2	0.014	1.167
15%	1.8	0.021	1.75
20%	2.4	0.028	2.33
25%	3	0.035	2.94
30%	3.6	0.042	3.53
35%	4.2	0.049	4.12
40%	4.8	0.056	4.71
45%	5.4	0.064	5.33
50%	6	0.071	5.89
55%	6.6	0.078	6.48
60%	7.2	0.085	7.07
65%	7.8	0.092	7.66
70%	8.4	0.099	8.25
75%	9	0.106	8.83
78,8%	9.456	0.1114	9.28

Table 3. Quadratic Boost Converter output voltage error with resistance load 1300Ω

Duty Cycle (%)	V_{OUT} Analysis (V)	V_{OUT} Testing (V)	Error (%)
10%	14.8	29.14	49.2%
15%	16.6	40.8	59.3%
20%	18.75	50	62.5%
25%	21.4	61.7	65.3%
30%	24.5	72.4	66.2%
35%	28.4	83.1	65.8%
40%	33.4	93.6	64.3%
45%	39.7	104	61.8%
50%	48	125.3	61.7%
55%	59.3	144.6	59%
60%	75	176.9	57.6%
65%	98	198,4	50.6%
70%	133	225.3	41%
75%	192	246.8	22.2%
78,8%	267	267.2	0.07%

From Fig. 12 the graph shows the response results by entering the value of K_P = 1 and K_I = 0.5 there is a rise time value = 5ms and settling time = 11ms and there is a steady-state error value = 36%. The output voltage cannot reach the set-point because the Quadratic Boost Converter is loaded with 285 Ohm resistance.

Fig. 13 shows the response results by entering the value of K_P = 1.5 and the value of K_I = 0.5 there is a rise time value = 10ms and settling time = 16ms and there is a steady state error value = 3%. The output voltage cannot reach the set-point because the Quadratic Boost Converter is loaded with 1000 Ohm resistance.

The results of the response in Fig. 14 by entering the value K_P = 2 and the value of K_I = 0.5 there is a rise time value = 10ms and settling time = 27ms and there is a steady state error value = 2%. The output voltage cannot reach the set-point because the Quadratic Boost Converter is loaded with 1000 Ohm resistance.

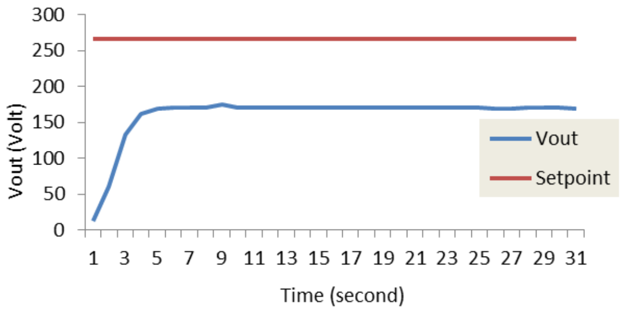


Fig.12. Response of Quadratic Boost Converter with PI Control for K_P = 1 and K_I = 0.5

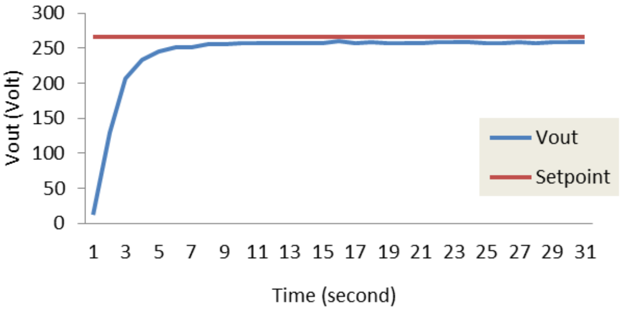


Fig.13. Response of Quadratic Boost Converter with PI Control for K_P = 1.5 and K_I = 0.5

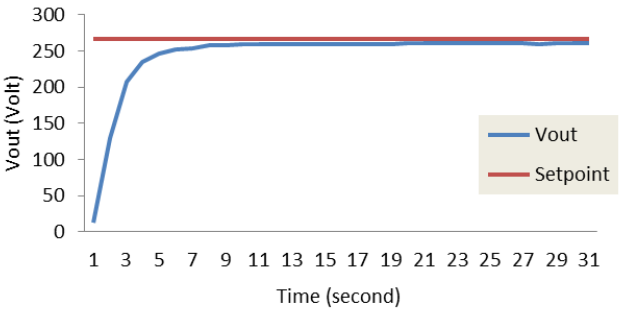


Fig.14. Response of Quadratic Boost Converter with PI Control for K_P = 2 and K_I = 0.5

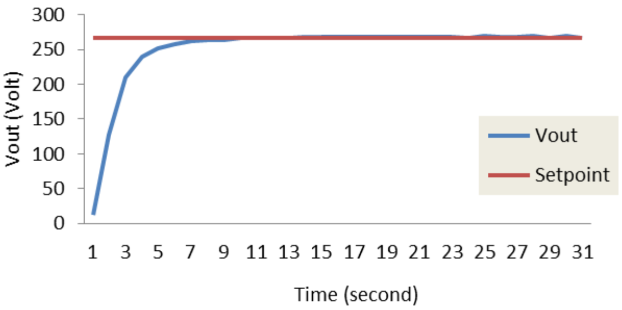


Fig.15. Response of Quadratic Boost Converter with PI Control for K_P = 1.7 and K_I = 0.5

From Fig. 15 the graph shows the response results by entering the value of K_P = 1.7 and the value of K_I = 0.5 there is a rise time value = 10ms and settling time = 23ms and there is a steady state error value = -0%. The output voltage can reach a set-point when loaded with 1100 Ohm resistance.

The results of the trial-error test of the PI controller obtained the response results to reach the set-point value by entering the value of K_P = 1.7 and the value of K_I = 0.5 obtained the output voltage Quadratic Boost Converter of 267 Volt DC using 1100 Ohm load resistance. So to know the ability of the power obtained by Quadratic Boost Converter can be seen through the calculation of $P_{OUT} = (V_{OUT})^2 / R = 2672 / 1100 = 64{,}8$ *Watt*. So the Quadratic Boost Converter's output power capability is 64.8 Watt.

Implementation Result Test

The tests carried out are measuring voltage and current for 2 system conditions, namely Quadratic Boost converter system without PI control and system with PI control. For systems with PI it is tested for 25% and 50% partially-shaded conditions. Fig. 16 shows testing techniques for implementation results.

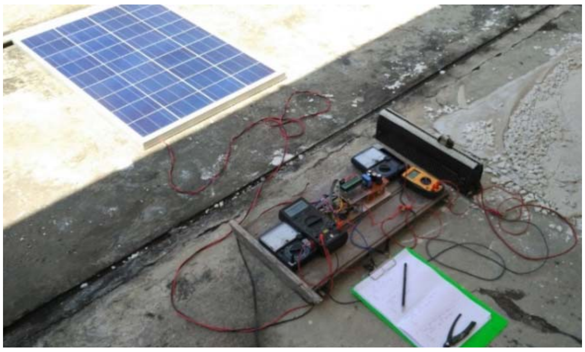


Fig.16. Testing techniques for implementation result

The measurement data set is the voltage and current values in the boost Quadratic Converter input. From the two values, it can be determined the electric power produced and the percentage of power increase between the two systems testing.

Tables 4, 5 and 6 show the results of system tests carried out for normal conditions, partially shaded 25% and partially shaded 50%, each tested without PI control and using PI control with several different loads 36 Ohm, 28.8 Ohm, and 11.3 Ohm. All measurement results are carried out when the weather is not in very bright conditions. From the table shows that the increase for testing without PI control compared with PI control, it can also be seen that the input voltage decreases but the current increase is very significant, affecting the increase in power. In Table 4, the power measured at load is 36 Ohm, without PI is 9.18 Watt and with PI is 54.04 Watt, this is significant with a power increase of 83.01%.

These results are close to conformity with the simulation results that is measured power at a load of 36 Ohms, without PI is 12.6 Watt and with PI is 55.55 Watt. Measured power changes that occur will be easier to see, for all conditions when presented in graphical form. Figs. 17, 18 and 19 show power changes between (a) without PI and (b) with PI for normal conditions, partially shaded 25% and partially shaded 50%. Measured power changes are influenced by the Quadratic Boost Converter and ignition of MOSFET which changes are set by coding algorithm on the microcontroller.

Conclusions

The Quadratic Boost Converter system research has been carried out and produced several conclusions as follows:

1. Testing without using PI control using a load with a resistance of 285 Ohms obtains an output voltage of 152 Volt DC when the working cycle is 78.8% and an error result of 43.07% is obtained. The output voltage has not reached 267 Volt DC because it uses a load with 285 Ohm resistance. The output voltage can reach 267 Volt DC because it uses a load with a resistance of 1300 Ohm.

Table 4. Testing result Quadratic Boost Converter without and with PI control under normal conditions

Hour	Load (Ω)	Without PI method			With PI method			Increase (%)	Weather
		Voltage (V)	Current (A)	Power (W)	Voltage (V)	Current (A)	Power (W)		
11.00	36	18	0,51	9,18	14	3,86	54.04	83,01	Bright spot
12.00		18	0,5	9	15	3,6	54	83,33	Bright
13.00		18	0,5	9	14	3,33	46.62	80,69	Cloudy
11.00	28.8	18	0,68	12,24	14	3,62	50.68	75,85	Bright spot
12.00		18	0,67	12,06	13	4,13	53.69	77,54	Bright
13.00		18,5	0,67	12,395	13	3,46	44.98	72,44	Cloudy
11.00	11.3	17	1,55	26,35	6	5,08	30.48	13,55	Bright spot
12.00		16,5	1,48	24,42	7	4,33	30.31	19,43	Bright
13.00		16,5	1,44	1`,44	7	3,76	26.32	9,73	Cloudy

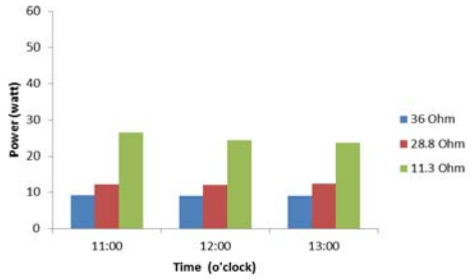
Table 5. Testing result when partially shaded 50%

Hour	Load (Ω)	Without PI method			With PI method			Increase (%)	Weather
		Voltage (V)	Current (A)	Power (W)	Voltage (V)	Current (A)	Power (W)		
11.00	36	8,5	0,24	2,040	8	1,39	11,12	81,65	Bright spot
12.00		8,5	0,23	1,955	8	1,23	9,84	80,13	Bright
13.00		8	0,21	1,680	7	1,10	7,7	78,18	Cloudy
11.00	28.8	8,5	0,23	1,955	7	2,23	15,61	87,48	Bright spot
12.00		8	0,31	2,480	7	1,81	12,67	80,43	Bright
13.00		8	0,28	2,240	7	1,32	9,24	75,76	Cloudy
11.00	11.3	8	0,72	5,760	7	2,02	14,14	59,26	Bright spot
12.00		8	0,68	5,440	5	2,88	14,4	62,22	Bright
13.00		8	0,65	5,200	5,5	2,56	14,08	63,07	Cloudy

Table 6. Testing result when partially shaded 25%

Hour	Load (Ω)	Without PI method			With PI method			Increase (%)	Weather
		Voltage (V)	Current (A)	Power (W)	Voltage (V)	Current (A)	Power (W)		
11.00	36	8.5	0.24	2.04	7	1,85	12,95	84,25	Bright spot
12.00		8.5	0.24	2.04	8,5	1,45	12,325	83,45	Bright
13.00		8	0.22	1.76	7	1,11	7,77	77,35	Cloudy
11.00	28.8	8.5	0.31	2.635	7	2,66	18,62	85,85	Bright spot
12.00		8.5	0.30	2.55	7	2,1	14,7	82,65	Bright
13.00		8	0.27	2.16	6	1,55	9,3	76,77	Cloudy
11.00	11.3	8	0.73	5.84	5	3,73	18,65	68,69	Bright spot
12.00		8	0.69	5.52	5,5	2,7	14,85	62,83	Bright
13.00		8	0.66	5.28	5,5	2,62	14,41	63,36	Cloudy

a). without PI control



b). with PI control

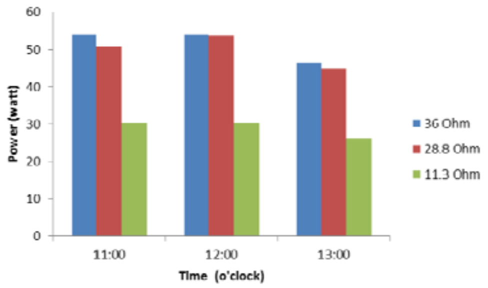
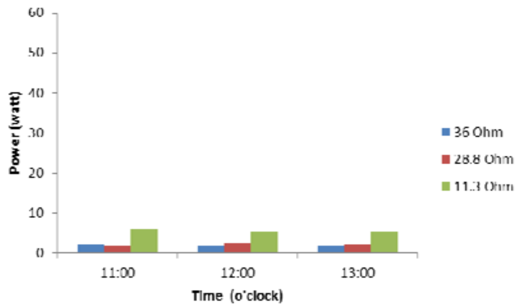


Fig.17. Rated power without and with the PI at normal conditions

a). without PI control



b). with PI control

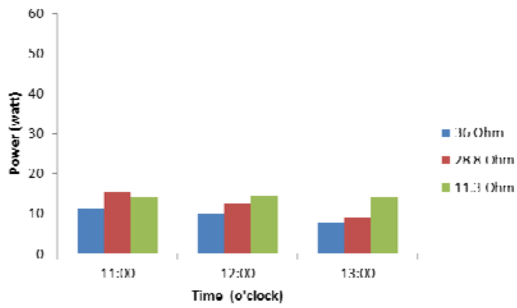
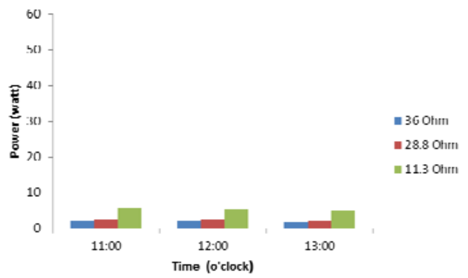


Fig.18. Rated power without and with the PI at partially shaded 50%
a). without PI control



a). with PI control

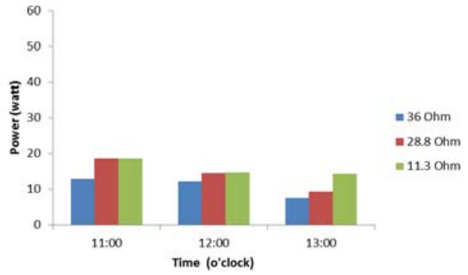


Fig.19. Rated power without and with the PI at partially shaded 25%dratic

3. The PI controller is used to control the Quadratic Boost Converter output voltage to reach the set point of 267 Volts. In the trial obtained K_P = 1.7 and K_I = 0.5 with a load resistance of 1100 Ohms so that the Quadratic Boost Converter output can reach a set point of 267 Volts with an output power of 64.8 Watts.

4. PWM regulator duty cycle settings show good work by providing changes in voltage and current on the Quadratic Boost Converter output. When the load on the rheostat is 28.8 Ohms, the highest Pin and Pout power is 55.80 and 43.55 Watt during the cycle. In system testing, there is an increase in power between systems without a PI control compared to a PI control with the percentage increase reaching more than 80%. The measured output power shows a difference compared to the time of the simulation, this is because the value of each component in the simulation is very different from the value of the component which actually has a tolerance value.

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