The Performance Comparison of Battery Charging Using MPPT and PWM Controllers on Amorphous Solar Panel-Based E-Scooters

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Abstract

Solar Panel-Based Electric Scooter (E-Scooter) is an electric vehicle in the form of a scooter that uses solar panels as a source of electrical energy for charging batteries and a BLDC motor as a wheel drive. With the development of the E-Scooter, it is necessary to know how to charge the battery. This research aims to determine the type of Solar Charge Controller (SCC) that can maximize battery charging on the E-Scooter. The research method is to compare SCC MPPT and SCC PWM. The research was conducted by monitoring the output current and voltage of the solar charger controller generated by the solar panels every 10 minutes. After that, the recorded data will be stored in the monitoring device's memory for further processing. The results of the data that have been obtained on the e-scooter using the SCC MPPT type are capable of producing a power of 9.05 W with a current value of 0.33 A and a voltage of 27.47 V. Meanwhile, the PWM type SCC is capable of producing 8.22 W of power with a current value of 0.30 A and a voltage of 27.42 V. So that the MPPT type SCC is more economical than PWM for charging when the e-scooter is not moving. For the running conditions of the MPPT type SCC e-scooter is capable of producing 7.36 W of power with a current value of 0.27 A and a voltage of 27.26 V. Meanwhile, the PWM type SCC is capable of producing a current of 6.81 W with a value of 0.25 A and a voltage 27.24 V. So that the MPPT type SCC is more efficient than PWM for charging when the e-scooter is running.

Keywords: *Electric Scooter, Solar Charger Controller, PWM, MPPT, Battery charging*

I. INTRODUCTION

Based on Minister of Energy and Mineral Resources (MEMR) data [1], most of the energy sources used in Indonesia still come from fossils, namely petroleum at 27.80%, coal at 10.35%, natural gas at 10.55%, electricity at 19.84 %, biogas oil at 22.86% and LPG at 8.59%. The highest percentage of energy sources produced in 2021, still comes from conventional energy consisting of oil, coal and gas, amounting to 87.84%. Meanwhile, sources of new and renewable energy (hydropower, solar, wind & geothermal) are only around 12.16%. Meanwhile, the largest energy consumption during 2021 is still dominated by the transportation sector, amounting to 45.76%. Furthermore, the industrial sector (31.11%), household (16.89%), commercial (4.97%), and other needs (1.27%).

The potential for solar energy in Indonesia is between 4.5 and 5.1 kWh/m^2/day [2]. When compared to other energy sources, solar energy's enormous potential has not been utilized to its fullest extent. Until 2021 the utilization of solar energy in Indonesia is only around 0.05% of the total primary energy supply [2]. Therefore, it is necessary to develop solar panel technology for various applications [3-4]. In the future, solar panels are not only for household energy needs (solar rooftop), but have great potential as an energy source for electric vehicles. Thus solar-based electric vehicles can be the best alternative [5-6].

Globally, there is a considerable worry about the problem of creating ecologically friendly ways of transportation in the present period [7]. Consequently, the transition to electric power technology for both private vehicles (such as cars and bicycles) and public transportation has begun recently [8-9]. The modifications and developments were also seen in the evolution of vehicle models. Such as electric scooters, which were formerly only toys for kids, are now starting to develop into alternative modes of short-distance transportation [10-13]. Several studies on micro-mobility modes, especially regarding design and performance, have been massively carried out since the 2000s. Likewise, the analysis of production feasibility to safety has also been studied by many researchers [14-19].

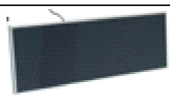
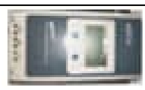
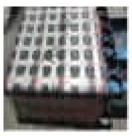
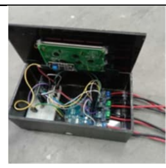
Patel et al (2016), designed and developed a three-wheeled campus vehicle based on the E-Scooter. The results of the simulation testing of the frame show that the strength of the frame is safe because the observed von Mises stress is 92 MPa which is far below the allowable stress limit of 174.5 MPa. The results of Stress and Strength can reach above the weight of 200 kg, so the design of this e-scooter is safe under these load conditions [20].

II. MATERIALS AND METHODS

The research was conducted outdoors at the solar and renewable energy laboratory of the State Polytechnic of Malang, Indonesia, at latitude 7.94356 °S and longitude 112.61381°E. Solar radiation data was retrieved using the Lutron SPM-1116SD solar power meter on a sunny day between 08:00 a.m. and 03:00 p.m. in August 2023. In this study, the independent variable is the type of solar charger controller (PWM or MPPT), and the dependent variable is the output power for charging the electric scooter battery. The controlled variables are the state of the electric scooter (stationary or running).

The materials and measuring tools used in this research are listed in Table 1.

Table 1. The materials and device instrument of research

Materials	Specifications	Picture
Electric Scooter	BLDC Hub Type 24V/250 W	
PV Module	Amorphous Silicon 15 Wp	
Solar Charger Controller	MPPT 10 A	
Solar Charger Controller	PWM 10 A	
Battery	Lithium-Ion 29,4 Volt 12 AH	
Monitoring Devices	▪ Arduino Uno ▪ Voltage sensor ▪ Current Sensor ▪ Speed Sensor ▪ RTC Module ▪ SD Card Module ▪ LCD	

The research equipment settings for the solar charge controller comparison are shown in Figure 1.

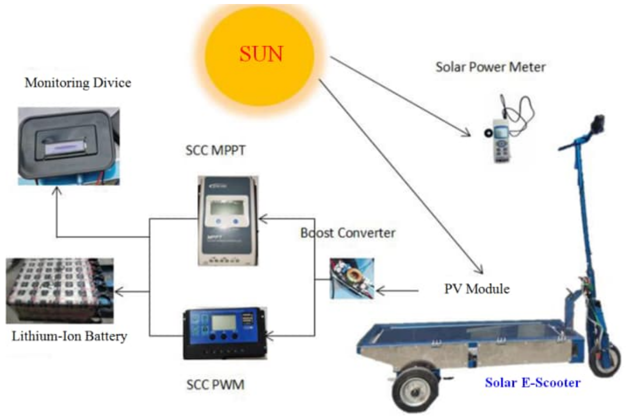


Figure 1. Experimental setup for comparing solar chargers on E-Scooter

Figure 1 shows the equipment settings for the research. The data collected includes the level of solar radiation on the surface of the solar panel, using a solar power meter that automatically records and saves the data to an SD card data logger. Additionally, current and voltage data are collected from the solar charger controller output produced by the solar panel during the battery charging process, using an ACS712 current sensor and voltage sensor assembled and integrated with an Arduino microcontroller that automatically saves the data to the SD card data logger [21].

Figure 2 shows a prototype of a hybrid electric scooter with a 15 Wp amorphous solar panel. The electric scooter consists of a frame, drive system, and charging system. The electric scooter frame has dimensions of 1060 mm in length, 380 mm in width, and 1500 mm in height, with a ground clearance of 70 mm.

Figure 2. Prototype of a solar-powered electric scooter

The drive system uses electrical components, as listed in Table 1, including a 29.4 V 12 AH lithium-ion battery, BLDC controller, 24V-250W BLDC wheel, speed throttle, and electrical wiring. A 15 WP amorphous solar panel protected with 10 mm thick acrylic is integrated into the scooter frame. Two charging systems using solar charging controllers, Maximum Power Point Tracking (MPPT), and Pulse Width Modulation (PWM), were compared.

III. Results and Discussions

Data processing in this research involved converting the tabular data collected into graphs. The graphs were then analyzed to determine the influence of the independent and dependent variables. Data on observation time and solar charger controller output (voltage, current, and electrical power) obtained by the solar panels were entered into tables (Tables 2-7).

A. *MPPT Solar charging Test*

Table 2 shows the test results of the e-scooter battery charging system using the MPPT solar charge controller under stationary conditions.

Tabel 2. Battery charging data from a stationary scooter using an MPPT solar charge controller

Maximum Power Point Tracking (MPPT)				
Local Time (hh:mm)	Voltage (V)	Current (A)	Power (W)	Sol. Rad (W/m^2)
08:00	27.08	0.07	1.895	501.3
08:20	27.08	0.07	1.895	592.0
08:30	27.07	0.15	4.060	621.9
08:50	27.08	0.07	1.895	686.6
09:00	27.18	0.15	4.077	738.7
09:30	27.28	0.22	6.001	803.8
09:40	27.18	0.22	5.979	812.6
10:00	27.18	0.23	6.251	832.2
10:20	27.25	0.24	6.540	857.3
10:30	27.24	0.24	6.537	865.8
10:50	27.25	0.26	7.085	872.0
11:00	27.41	0.30	8.223	897.5
11:30	27.43	0.33	9.051	943.2
12:00	27.42	0.3	8.226	937.9
12:10	27.23	0.25	6.8075	867.9
12:20	27.22	0.24	6.5328	860.4
12:30	27.2	0.24	6.528	869.7
12:40	27.21	0.22	5.9862	846.9
12:50	27.25	0.23	6.2675	869.5
13:00	27.25	0.22	5.995	845.6
13:30	27.24	0.21	5.7204	859.9
13:50	27.24	0.22	5.9928	811.1
14:00	27.22	0.17	4.6274	747
14:20	27.22	0.15	4.083	687.4
14:30	27.22	0.15	4.083	607.5
14:50	27.18	0.07	1.9026	579.9
15:00	27.18	0.07	1.9026	554.7

Furthermore, the test results presented in Table 2 can be further processed and summarized statistically, as indicated in Table 3.

Tabel 3. Descriptive statistics of MPPT Solar charging on stationary scooter

Desc. Statistic \ Parameters	Volt (V)	Current (A)	Power (W)	Sol. Rad (W/m^2)
Mean	27.23	0.20	5.54	784.70
Standard Error	0.02	0.01	0.32	19.21
Median	27.22	0.22	5.98	832.20
Mode	27.18	0.15	1.90	#N/A
Stnd.Deviation	0.10	0.08	2.09	125.95
Sample Variance	0.01	0.01	4.38	15864.18
Kurtosis	0.16	-0.54	-0.54	-0.63
Skewness	0.60	-0.21	-0.18	-0.72
Range	0.40	0.26	7.17	450.80
Minimum	27.07	0.07	1.89	501.30
Maximum	27.47	0.33	9.07	952.10
Count	43.00	43.00	43.00	43.00

The average test results for voltage, current, power, and solar radiation are 27.23 V, 0.20 A, 5.54 W, and 784.7 W/m^2, respectively.

Table 4 shows the results of the SCC MPPT test on an e-scooter in running conditions, conducted between 8:20 AM and 10:00 AM.

Tabel 4. MPPT-Battery charging data on running scooter

Maximum Power Point Tracking (MPPT)				
Local Time (hh:mm)	Voltage (V)	Current (A)	Power (W)	Sol. Rad (W/m^2)
8:20	27.10	0.07	1.90	698.5
8:30	27.12	0.07	1.90	700.3

8:40	27.17	0.15	4.08	749.9
8:50	27.17	0.15	4.08	752.6
9:00	27.21	0.22	5.99	823.8
9:10	27.22	0.22	5.99	831.2
9:20	27.21	0.22	5.99	836.3
9:30	27.22	0.22	5.99	836.7
9:40	27.22	0.23	6.26	840.6
9:50	27.22	0.24	6.53	856.0
10:00	27.24	0.24	6.54	858.9

The maximum data results obtained were a voltage of 27.26 V at 10:00 AM, a current of 0.24 A, and a power of 7.36 W. The running e-scooter test was conducted in a shorter time than the stationary e-scooter test because the battery power is limited and cannot be used from morning to evening.

B. PWM Solar charging Test

Battery charging test on a stationary e-scooter using SCC-PWM was conducted for 7 hours (8:00 am to 3:00 pm). The results are shown in Table 5.

Table 5. Battery charging data for a stationary scooter with SCC-PWM

Pulse Width Modulation (PWM)				
Local Time (hh:mm)	Voltage (V)	Current (A)	Power (W)	Sol. Rad (W/m^2)
08:00	27.08	0.07	1.90	501.3
08:10	27.08	0.07	1.90	518.2
08:20	27.08	0.07	1.90	549.4
08:30	27.08	0.07	1.90	619.4
08:40	27.08	0.15	4.06	637.0
08:50	27.08	0.07	1.90	686.2
09:00	27.18	0.15	4.08	733.3
09:10	27.18	0.15	4.08	773.0
09:20	27.13	0.17	4.61	798.3
09:30	27.13	0.17	4.61	793.6
09:40	27.18	0.22	5.98	812.9
09:50	27.18	0.22	5.98	824.7
10:00	27.18	0.22	5.98	867.9
10:10	27.33	0.23	6.29	842.9
10:20	27.23	0.23	6.26	855.4
10:30	27.25	0.22	6.00	850.2
10:40	27.25	0.24	6.54	857.3
10:50	27.25	0.24	6.54	878.9
11:00	27.32	0.25	6.83	836.7
11:10	27.34	0.25	6.84	846.9
11:20	27.42	0.30	8.23	941.6
11:30	27.42	0.30	8.23	943.2
11:40	27.42	0.30	8.23	949.5
11:50	27.42	0.30	8.23	934.6
12:00	27.41	0.30	8.22	927.8
12:10	27.34	0.25	6.84	857.3
12:20	27.38	0.25	6.85	846.6
12:30	27.2	0.17	4.62	776.9
12:40	27.2	0.17	4.62	759.4
12:50	27.22	0.23	6.26	844.5
13:00	27.22	0.23	6.26	842.1
13:10	27.22	0.23	6.26	864.3
13:20	27.23	0.22	5.99	876.9
13:30	27.21	0.22	5.99	869.5
13:40	27.21	0.22	5.99	830.9
13:50	27.22	0.22	5.99	807.1
14:00	27.18	0.17	4.62	738.7
14:10	27.18	0.15	4.08	667.8
14:20	27.18	0.15	4.08	601.0
14:30	27.18	0.07	1.90	579.4
14:40	27.18	0.07	1.90	530.7
14:50	27.08	0.01	0.27	405.9
15:00	27.08	0.01	0.27	398.4

Descriptive statistics, shown in Table 6, were used to create a concise and informative summary of the data collection. This statistical information is important for initial data exploration, as it allows for the analysis of basic characteristics, identification of outliers, and initial interpretations.

Table 6. Descriptive statistics of SCC-PWM on stationary scooter

Parameters / Desc. Statistic	Volt (V)	Current (A)	Power (W)	Sol. Rad (W/m^2)
Mean	27.22	0.19	5.07	764.60
Standard Error	0.02	0.01	0.34	22.37
Median	27.20	0.22	5.98	824.70
Mode	27.18	0.22	1.90	857.30
Stnd.Deviation	0.11	0.08	2.20	146.71
Sample Variance	0.01	0.01	4.83	21524.10
Kurtosis	-0.46	-0.47	-0.48	0.14
Skewness	0.56	-0.61	-0.59	-1.02
Range	0.34	0.29	7.96	551.10
Minimum	27.08	0.01	0.27	398.40
Maximum	27.42	0.30	8.23	949.50
Count	43.00	43.00	43.00	43.00

Table 6 shows the characteristics of battery charging by the PWM controller, with average values of 27.22 V for voltage, 0.19 A for current, and 5.07 W for power during testing. The current ranged from 0.01 A to 0.3 A, while the voltage was relatively stable between 27.02 V and 27.42 V. Therefore, the battery charging power ranged from 0.27 W to 8.23 W. The tests also showed a range of solar radiation from 398.40 W/m^2 to 949.50 W/m^2, with an average of 764.6 W/m^2. The peak solar radiation occurred at 11:40 am, and the lowest solar radiation occurred at 3:00 pm.

Table 7 shows data from the SCC-PWM e-scooter test while running.

Tabel 7. PWM-Battery charging data on running scooter

Pulse Width Modulation (PWM)				
Local Time (hh:mm)	Voltage (V)	Current (A)	Power (W)	Sol. Rad (W/m^2)
8:20	27.10	0.07	1.90	695.9
8:30	27.10	0.07	1.90	701.8
8:40	27.11	0.07	1.90	706.5
8:50	27.17	0.15	4.08	750.6
9:00	27.20	0.20	5.44	821.8
9:10	27.21	0.20	5.44	824.9
9:20	27.21	0.21	5.71	826.5
9:30	27.22	0.21	5.72	830.7
9:40	27.22	0.21	5.72	839.6
9:50	27.22	0.22	5.99	841.2
10:00	27.24	0.22	5.99	856.8

The results of the SCC PWM e-scooter test when running, which showed a highest voltage of 27.24 V with a current of 0.22 A and a power of 6.81 W, are shown in Table 7. The e-scooter test results in running conditions were lower than in stationary conditions because the solar cell was blocked by the e-scooter rider.

C. Comparison of charging performance of MPPT and PWM controllers on stationary scooters

Based on the test results in Tables 2 and 5, a battery charging power graph was generated. Figure 3 compares the charging power produced by the MPPT and PWM solar charge controllers.

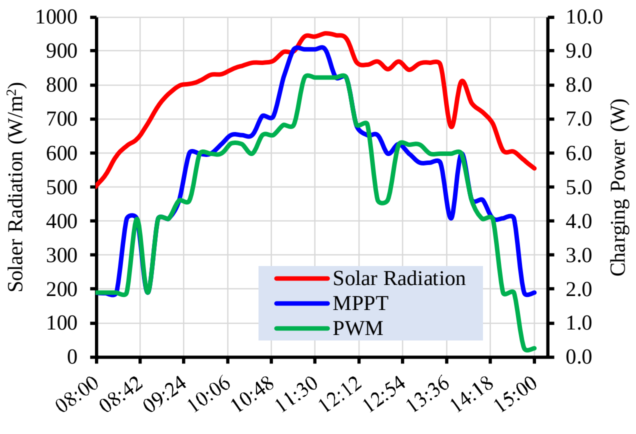


Figure 3. A graph comparing MPPT and PWM charging power over local time in stationary e-scooter conditions

Figure 3 shows a graph of the solar radiation, MPPT, and PWM charging power of a stationary e-scooter battery over 7 hours (8:00 a.m. to 3:00 p.m.). The graph shows that solar radiation is highest at midday and decreases towards the evening. The MPPT charging power closely follows the solar radiation curve, indicating that the MPPT charge controller can efficiently extract the maximum power from the solar panel. The PWM charging power is lower than the MPPT charging power at all times, especially at lower solar radiation levels.

D. Comparison of charging performance of MPPT and PWM controllers on running scooter

Figure 4 presents a graph of the charging power produced by the MPPT and PWM solar charge controllers on a running e-scooter.

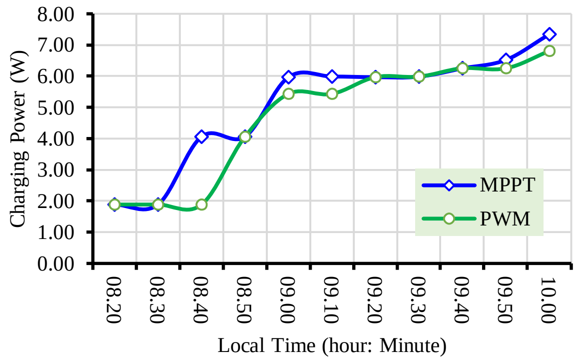


Figure 4. Comparison of MPPT and PWM controllers on running e-scooters.

The graph compares the charging performance of MPPT and PWM controllers on a running scooter, showing that the MPPT controller outperforms the PWM controller at all times, especially at lower solar radiation levels, due to its greater efficiency in extracting maximum power from the solar panel [15-16].

The graph also shows that the charging power of both controllers increases as the solar radiation increases. However, the MPPT controller charges the battery more quickly and efficiently than the PWM controller. For example, at 10:00 AM, the MPPT controller is charging the battery at 6.54 W, while the PWM controller is charging the battery at 5.99 W.

Therefore, the MPPT controller is a better choice for charging a battery on a running scooter because it is more efficient and can charge batteries more quickly and efficiently than PWM controllers, even when solar radiation is low.

IV. CONCLUSIONS

Test results show that the MPPT charge controller is a better choice for charging the e-scooter battery, regardless of whether the e-scooter is stationary or running. It's because the MPPT charge controller continuously adjusts the charging voltage to maximize power output, while PWM charge controllers use a fixed charging voltage, which can lead to fluctuations in charging power. As a result, the MPPT charge controller is more efficient and can charge the battery faster and at a higher charge rate.

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