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Performance analysis of solar electric scooters with different charger controllers

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ABSTRACT

This study investigates the impact of solar charge controller (SCC) type on battery charging in solar-powered electric scooters (e-scooters). The research compared maximum power point tracking (MPPT) and pulse width modulation (PWM) controllers by monitoring average output power, current, and voltage every 10 minutes. Results showed that under stationary conditions, MPPT controllers delivered higher efficiency, generating 5.87 W of power compared to PWM's 5.05 W. This advantage persisted even during scooter operation, with MPPT controllers producing 4.91 W versus PWM's 4.31 W. Overall, the findings demonstrate that MPPT SCCs offer a more efficient solution for charging e-scooter batteries.

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1. INTRODUCTION

Energy is essential for human survival. Fossil energy is the most common energy source used to meet human needs, and it is used in almost all human activities. However, excessive use of fossil energy can lead to energy problems, such as energy crises. The main cause of energy crises is the excessive consumption of resources, such as fossil fuels like oil, gas, and coal. To reduce our dependence on petroleum, we are turning to solar energy. Solar power, a clean and renewable energy source, is harnessed to power vehicles and drive the transition towards a more environmentally friendly transportation landscape. The transportation industry is undergoing a significant change with the widespread adoption of electric technology across various modes of transport, including cars, motorcycles, and bicycles. Electric vehicles provide a compelling alternative to traditional vehicles, offering lower operating costs, reduced emissions for cleaner air, and improved fuel efficiency. With fuel supplies dwindling, electric vehicles provide a sustainable and eco-friendly alternative for transportation, effectively minimizing air pollution caused by exhaust emissions.

Electric vehicles represent a significant breakthrough in reducing exhaust emissions from conventional oil-fueled vehicles. This shift towards electric vehicles is driven not only by environmental concerns but also by the depletion of fossil fuel reserves. The global trend towards electric vehicles has spurred significant investments in the technology, including in Indonesia. This surge in funding is fueling research and innovation, leading to breakthroughs in battery technology, charging infrastructure, and overall vehicle performance. Additionally, electric technology is transforming various modes of transportation, making them more sustainable and eco-friendlier. Electric scooters, in particular, have emerged as a popular choice for short-distance commutes, offering an alternative to conventional vehicles.

According to Ministry of Energy and Mineral Resources (MEMR) data [1], fossil fuels remain the dominant energy source in Indonesia. In 2021, petroleum (27.80%), coal (10.35%), and natural gas (10.55%) comprised a combined 48.70% of the energy mix. Electricity (19.84%), biogas oil (22.86%), and liquefied petroleum gas (LPG) (8.59%) contributed to the remaining share. Notably, conventional sources (oil, coal, and gas) accounted for a significant 87.84%, while new and renewable energy (hydropower, solar, wind, and geothermal) only reached 12.16%. The transportation sector is the biggest energy consumer, accounting for 45.76% of total consumption in 2021. Industry (31.11%), households (16.89%), commercial (4.97%), and other sectors (1.27%) followed. Indonesia boasts a substantial solar energy potential, estimated between 4.5 and 5.1 kWh/m^2/day [2]. Despite this abundance, solar energy utilization remains significantly low, representing only 0.05% of the total primary energy supply as of 2021. This highlights the need to develop and implement solar panel technology across various applications [3], [4]. Looking ahead, solar panels have the potential to extend beyond household needs (solar rooftops) and serve as a viable energy source for electric vehicles, potentially positioning solar-powered electric vehicles as a leading alternative [5], [6].

Environmental concerns have become a major global priority, driving the urgent need for sustainable transportation solutions [7], [8]. This has led to a recent surge in the development and adoption of electric vehicle technology, encompassing both private vehicles (cars, bicycles) and public transportation systems [9], [10]. The evolution of vehicle models reflects this shift, with electric scooters transitioning from children's toys to viable alternatives for short-distance travel [11]–[14]. Since the 2000s, researchers have extensively studied micro-mobility modes, focusing on design, performance, production feasibility, and safety considerations [15]–[20].

Iyer *et al.* [21] introduced a solar-powered electric scooter design using solar panels as the primary energy source for its hub motor. The scooter operates by harnessing solar energy, storing it in a dedicated 48 V/20 Ah battery via a charging circuit, and then delivering it to the 48 V/200 W DC hub motor through the accelerator and gate switch. This switch ensures safety by automatically disconnecting the brushless direct current motor (BLDC) from the throttle when braking, as the hub motor is embedded directly into the wheel for efficient propulsion. Patel *et al.* [22] developed a safe and robust three-wheeled campus vehicle based on an electric scooter design. Their simulations showed the frame could withstand significant weight, with a maximum observed stress of 92 MPa, well below the safe limit of 174.5 MPa.

Expanding on the concept of solar-powered electric vehicles, Masud *et al.* [23] further explored its potential by building a prototype tricycle. This design utilized key components like photovoltaic (PV) panels, permanent magnet DC (PMDC) motors, controllers, and batteries. The tricycle's power transmission system demonstrated both simplicity and efficiency, with test results revealing that the integrated solar panels could provide an additional 24% of the operational energy needs. Furthermore, the estimated manufacturing cost of $240 and near-zero carbon emissions highlight its economic and environmental advantages, positioning it as a promising eco-friendly transportation option.

This electric vehicle research highlights promising advances such as safe designs and solar power integration that can reduce reliance on fossil fuels and potentially lower operating costs. In addition, the efficient power transfer systems presented offer environmental and economic benefits. However, further research is critical to address limitations in charging times, battery performance, and the optimal use of solar panels to maximize range.

In the past five years, many researchers have been actively exploring the potential of solar-powered hybrid electric bicycles, with promising results and prototypes demonstrating their feasibility for future sustainable transportation [24]–[27]. Researchers have made many innovations to replace conventional public transportation. Baghel *et al.* [28] proposed a novel approach to public transportation by developing a solar-powered hybrid e-rickshaw. Their design incorporated a 315 Wp PV module, capacitor banks, and Arduino circuits. This modification resulted in a significant performance boost compared to conventional e-rickshaws. The hybrid rickshaw achieved a range increase of up to 50.76% using solar power, while the starting current dropped from 57 to 41 A at full load, extending battery life. Overall, this project demonstrates the potential of solar-powered e-rickshaws to improve vehicle efficiency and sustainability.

Meanwhile, Hamoodi *et al*. [29] investigated the effectiveness of a solar-powered hybrid e-bike system. Their research found that the integration of a PV module increased the bicycles' range by up to 0.755 km/hour and increased the top speed by 6.88 km/hour compared to using the battery alone. This system combines solar energy for battery charging with a high-torque motor, promoting environmentally friendly transportation and reducing dependence on fossil fuels.

Furthermore, Asrori *et al.* [30] conducted a study to evaluate the charging efficiency of a 100 Wp solar panel on an electric bicycle. Their research showed that the panel achieved a maximum voltage of 17.49 V and a current of 3.37 A under ideal conditions of 1,008 W/m² irradiation. This resulted in a battery charging efficiency of 58.94%. When integrated with a bicycle, the panel improved battery storage by 33.33% during a one-hour test under average irradiation. These results suggest that solar-powered electric bicycles have the potential to enhance the performance of electric vehicles in the future.

Previous research has attempted to combine renewable energy sources, especially solar energy, with electric vehicles. However, there is still a lack of information on the performance of solar panels and their integration with electric vehicles ergonomically. Some studies also do not specifically discuss the effect of solar radiation, the type of solar panel, and the improvement of battery charging efficiency.

In this study, researchers focused on solar electric scooters and aimed to identify the effect of solar radiation on battery charging and the effectiveness of solar panels through the use of solar charger controller types. This research aims to improve the performance of electric vehicles and introduce new features that increase the comfort and safety of electric vehicle users.

2. RESEARCH METHOD

The research, conducted outdoors at the State Polytechnic of Malang's solar and renewable energy laboratory (Indonesia, 7.94356°S, 112.61381°E), investigated the impact of solar charger controller type (pulse width modulation (PWM) or maximum power point tracking (MPPT)) on electric scooter battery charging output power. The solar irradiation data was collected on a sunny day, in April 2024 between 8:00 AM and 3:00 PM using a Lutron SPM-1116SD solar power meter. The study employed the type of solar charger controller as the independent variable, with electric scooter battery output power as the dependent variable. The state of the electric scooter (Stationary or moving) was a controlled variable.

2.1. Experimental set-up

Figure 1 illustrates the research setup. A solar power meter automatically recorded and logged solar radiation data on a secure digital (SD) card. Additionally, an Arduino microcontroller, programmed to function as the central processing unit, collected and saved current and voltage data from the solar charger controller output during battery charging. This data was also stored on an SD card. The Arduino's versatility facilitates diverse functionalities, allowing it to receive sensor inputs, analyze data, and execute commands [31], [32].

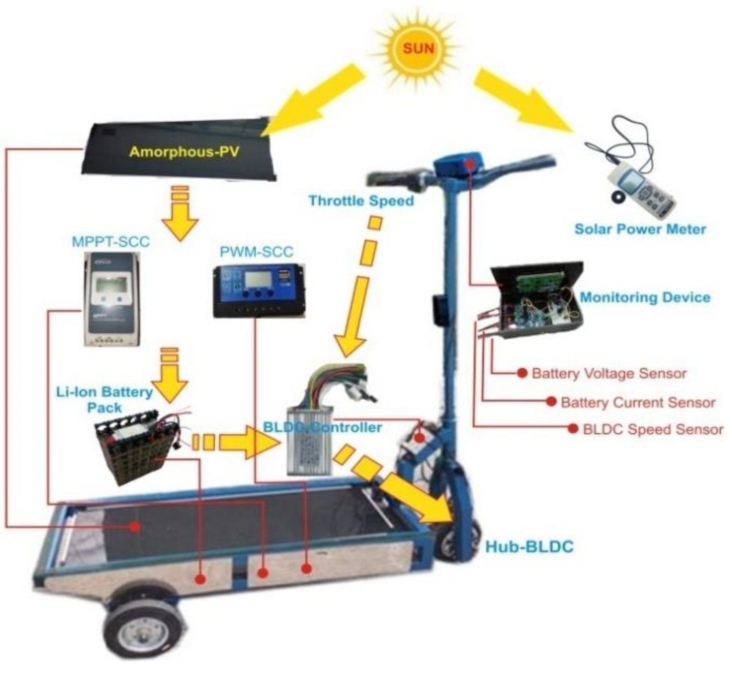

Figure 1. Experimental setup for comparing solar charger controller (SCC) types on E-scooter battery charging

2.2. Monitoring design of electronic device

The monitoring tool uses an Arduino Uno microcontroller to process the data from the sensors, and the other components are shown in Figure 2. These components include voltage sensors, ACS712 current sensors, real-time clock (RTC) modules (serving as timers), liquid crystal displays (LCDs) for displaying recorded data, and SD card data logger modules for storing recorded data during testing. The Arduino integrated development environment (IDE) provides the software used to program the tool. The components used in the design of Figure 2 consist of i) Arduino Uno, a microcontroller that acts as a processor of the data collected by the sensors; ii) SD card data logger module that functions to store the data processed by the Arduino Uno; iii) LCD20x4, functions as a real-time data display to facilitate periodic checks; iv) The DS321 RTC module, functions to find out the time in real-time; v)Voltage sensor, functions to detect battery voltage to determine battery voltage during testing; vi) ACS712 current sensor, functions to detect battery current consumption on electric scooters; and vii) Breadboard, functions as a terminal for connecting sensors, microcontrollers, and actuators.

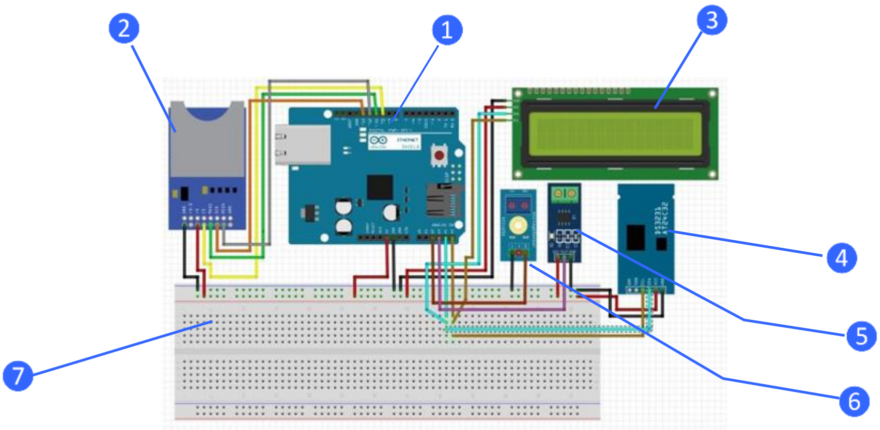

Figure 2. The circuit design of the monitoring device

2.3. Prototype of solar e-scooter

The hybrid electric scooter prototype with a 15 Wp amorphous solar panel is shown in Figure 3 [33]. The frame, propulsion system, and charging system are the three main parts of the scooter. The dimensions of the frame are 1,060 mm in length, 380 mm in width, and 1,500 mm in height. Its ground clearance is 70 mm.

Figure 3. The prototype solar-powered three-wheel electric scooter [33]

The electric scooter (Figure 3) features an electric drive system powered by a 29.4 V 12 Ah lithium-ion battery, BLDC controller, and 24 V-250 W BLDC wheel motor. A speed throttle and electrical wiring complete the system. For charging, a 15 Wp amorphous solar panel, protected with 10 mm acrylic, is integrated into the frame. The research compared the effectiveness of two solar charging controllers: MPPT and PWM.

3. RESULTS AND DISCUSSION

The data collected from the solar panels during the observation period, including voltage, current, and electrical power, were compiled into Tables 1-6. In addition, the influence of these variables was analyzed by converting this tabular data into graphs and performing further analysis.

3.1. PWM solar charger type testing

Table 1 presents the results of a 7-hour (8:00 AM to 3:00 PM) battery charging test on a stationary e-scooter using a SCC-PWM. The descriptive statistics presented in Table 2 offer a succinct and informative overview of the collected data. This statistical analysis proves crucial for the preliminary examination, enabling the scrutiny of fundamental characteristics, detection of outliers, and initial interpretation.

Table 1. E-scooter battery charging with PWM controller

Local Time (hh:mm)	Solar Irradiance (W/m^2)	Voltage (V)	Current (A)	Power (W)
08:00	663.20	27.09	0.07	1.90
08:30	710.40	27.09	0.07	1.90
08:50	733.30	27.18	0.15	4.08
09:00	778.30	27.18	0.16	4.35
09:30	768.70	27.18	0.16	4.35
09:40	793.60	27.13	0.17	4.61
10:00	867.10	27.22	0.22	5.99
10:30	862.40	27.22	0.22	5.99
10:50	850.20	27.25	0.22	6.00
11:00	836.70	27.32	0.25	6.83
11:30	996.60	27.43	0.33	9.05
12:00	993.20	27.42	0.30	8.23
12:30	992.10	27.20	0.24	6.53
12:50	979.90	27.25	0.23	6.27
13:00	896.90	27.25	0.22	6.00
13:30	896.90	27.24	0.21	5.72
13:50	829.30	27.24	0.22	5.99
14:00	731.20	27.22	0.17	4.63
14:30	738.70	27.22	0.15	4.08
14:50	579.90	27.18	0.06	1.80
15:00	554.70	27.18	0.06	1.80

Table 2. Summary statistics of battery charging with PWM controller on stationary e-scooter

Parameters	Solar Irradiance	Volt	Current	Power
Desc.Statistic	(W/m2)	(V)	(A)	(W)
Mean	812.06	27.22	0.18	5.05
Standard Error	27.77	0.02	0.02	0.44
Median	829.30	27.22	0.21	5.72
Mode	896.90	27.18	0.22	1.90
Stnd.Deviation	127.26	0.09	0.07	2.03
Sample Variance	16,193.99	0.01	0.01	4.10
Kurtosis	-0.36	1.61	-0.29	-0.29
Skewness	-0.30	1.00	-0.22	-0.15
Range	441.90	0.34	0.27	7.25
Minimum	554.70	27.09	0.06	1.80
Maximum	996.60	27.43	0.33	9.05

Table 2 summarizes the battery charging characteristics using the PWM controller. Average voltage during the test was 27.22 V, with a current averaging 0.18 A and a resulting average power output of 5.05 W. Current fluctuated between 0.06 and 0.33 A, while voltage remained relatively stable, ranging from 27.09 to 27.43 V. Consequently, battery charging power varied between 1.80 and 9.05 W. Solar irradiance also exhibited a range, with values measured from 554.70 to 996.60 W/m². averaging 812.06 W/m². Peak solar irradiance occurred at 11:40 AM, while the lowest value was recorded at 3:00 PM.

Table 3 shows the test results of the electric scooter using SCC-PWM while driving on the road. The scooter was driven at a speed of 10 km/h for the flat road test. Table 3 presents the data for the running e-scooter equipped with a PWM controller. The maximum recorded voltage was 27.24 V, with a current of 0.22 A and a resulting power output of 5.99 W. These values are lower compared to the stationary test results (Table 1) due to the rider's body partially shading the solar panel. This shading reduces the amount of sunlight reaching the panel, limiting energy conversion and consequently impacting charging performance.

Table 3. Battery charging data for running e-scooter with PWM controller

Local Time (hh:mm)	Solar Irradiance (W/m²)	Voltage (V)	Current (A)	Power (W)
08:00	700.4	27.11	0.07	1.91
08:20	695.9	27.10	0.07	1.90
08:30	701.8	27.10	0.07	1.90
08:40	706.5	27.11	0.07	1.90
08:50	750.6	27.17	0.15	4.08
09:00	821.8	27.20	0.20	5.44
09:10	824.9	27.21	0.20	5.44
09:20	826.5	27.21	0.21	5.71
09:30	830.7	27.22	0.21	5.72
09:40	839.6	27.22	0.21	5.72
09:50	841.2	27.22	0.22	5.99
10:00	856.8	27.24	0.22	5.99

3.2. MPPT solar charger type testing

The test results of the electric scooter battery charging system using the MPPT solar charge controller under stationary conditions are shown in Table 4. In addition to the raw data in Tables 4 and 5 presents a statistical summary of the battery charging test results for a stationary scooter using the SCC-PPT controller. The average values for voltage, current, power, and solar irradiance were 27.25 V, 0.20 A, 5.87 W, and 774.21 W/m², respectively.

Meanwhile, Table 6 is the result of the SCC MPPT test conducted on a running electric scooter between 08:00 and 10:00. These tests captured maximum values of 27.24 V for voltage, 0.24 A for current, and 6.54 W for power. The charging tests on the running scooter were conducted for a shorter time than the stationary scooter tests (presented in Table 4) due to the limited capacity of the battery, which cannot sustain operation for a full day.

Table 4. Stationary e-scooter battery charging data with SCC-MPPT

Local Time (hh:mm)	Solar Irradiance (W/m^2)	Voltage (V)	Current (A)	Power (W)
08:00	501.30	27.08	0.07	1.90
08:30	621.90	27.07	0.15	4.06
08:50	686.60	27.08	0.07	1.90
09:00	738.70	27.18	0.15	4.08
09:30	803.80	27.28	0.22	6.00
09:40	812.60	27.18	0.22	5.98
10:00	832.20	27.18	0.23	6.25
10:30	865.80	27.24	0.24	6.54
10:50	872.00	27.25	0.26	7.09
11:00	897.50	27.41	0.3	8.22
11:30	943.20	27.44	0.34	9.33
12:00	937.90	27.44	0.34	9.33
12:30	869.70	27.44	0.34	9.60
12:50	869.50	27.44	0.29	7.96
13:00	845.60	27.28	0.27	7.37
13:30	859.90	27.28	0.27	7.37
13:50	811.10	27.22	0.24	6.53
14:00	747.00	27.22	0.20	5.44
14:30	607.50	27.18	0.17	4.62
14:50	579.90	27.18	0.07	1.90
15:00	554.70	27.18	0.07	1.90

Table 5. Summary statistics of battery charging using MPPT on a stationary e-scooter

Parameters Desc.Statistic	Solar Irradiance (W/m^2)	Volt (V)	Current (A)	Power (W)
Mean	774.21	27.25	0.21	5.87
Stnd. Error	28.76	0.03	0.02	0.55
Median	812.60	27.22	0.23	6.25
Mode	#N/A	27.18	0.07	1.90
Stnd. Dev.	131.78	0.12	0.09	2.51
Sample Var.	17,365.16	0.01	0.01	6.31
Kurtosis	-0.63	-0.78	-0.86	-0.85
Skewness	-0.76	0.43	-0.40	-0.35
Range	441.90	0.37	0.27	7.71
Minimum	501.30	27.07	0.07	1.90
Maximum	943.20	27.44	0.34	9.60

Table 6. Battery charging data with SCC-MPPT on running e-scooter

Local Time (hh:mm)	Solar Irradiance (W/m²)	Voltage (V)	Current (A)	Power (W)
08:00	698.5	27.10	0.07	1.90
08:10	700.5	27.10	0.08	1.93
08:20	700.3	27.12	0.07	1.90
08:30	749.9	27.17	0.15	4.08
08:40	752.6	27.17	0.15	4.08
08:50	823.8	27.21	0.22	5.99
09:00	841.6	27.21	0.22	5.99
09:10	836.7	27.22	0.22	5.99
09:20	851.0	27.22	0.22	6.19
09:30	840.6	27.22	0.23	6.46
09:40	836.0	27.23	0.23	6.26
09:50	856.0	27.22	0.24	6.53
10:00	858.9	27.24	0.24	6.54

3.3. Comparison of SCC performance on stationary scooters

Figure 4 illustrates the relationship between solar irradiance and charge power over time for MPPT and PWM solar charge controllers under stationary conditions. Solar irradiance (red circles, left Y-axis) starts around 300 W/m² at 8:00 AM and peaks over 900 W/m² at noon before gradually decreasing to 300 W/m² by 3:00 PM. Meanwhile charging power, measured in watts (W), is plotted on the right Y-axis. The lines on the graph, shown as orange boxes and blue triangles, represent the performance comparison of SCC-MPPT and SCC-PWM, respectively. As expected, SCC-MPPT consistently delivers higher charging power than SCC-PWM. Its peak of around 9.5 W at noon coincides with the peak solar irradiance. SCC-PWM's peak, around 5.5 W at 11:00 AM, follows a similar pattern as SCC-MPPT but with consistently lower values. Both methods show a decrease in charging power as solar radiation weakens in the afternoon.

The results show that the SCC-MPPT is more effective in converting solar energy into charging power than the SCC-PWM, particularly during peak solar irradiance periods. It suggests that using an MPPT controller can enhance the efficiency and effectiveness of solar charging systems.

In addition, Figure 4 demonstrates that amorphous solar panels can capture a notable amount of energy even in low solar radiation conditions. This amount is equivalent to roughly 13.33% of the installed capacity in an e-scooter. The results emphasize the efficiency of amorphous solar modules in utilizing lower light levels in comparison to crystalline modules [9], [33]. The MPPT-type SCC graph is very identical to the solar radiation curve, which shows that the MPPT SCC effectively extracts the maximum power produced by the solar panel. In contrast, the PWM charge power is consistently lower than the MPPT charge power at all time intervals, which is especially noticeable during periods of reduced solar irradiance. These observations underscore the superior efficiency of MPPT charge controllers in harvesting solar energy compared to PWM charging over a wide range of irradiance conditions [34].

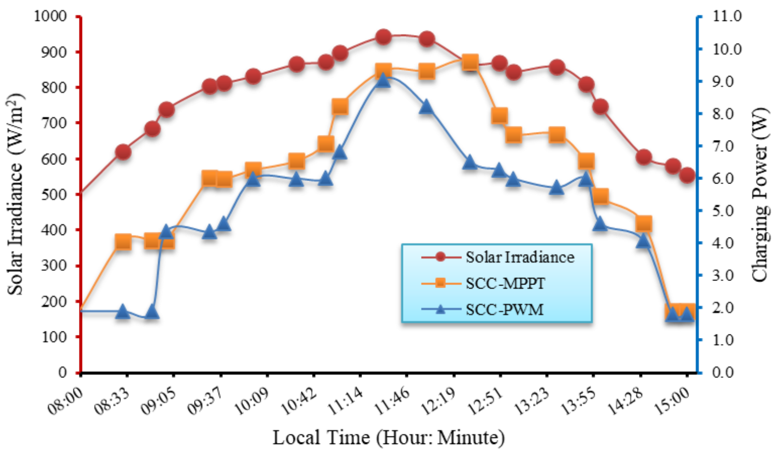

Figure 4. The relationship between solar irradiance and battery power charging for MPPT and PWM solar charge controllers on stationary conditions

3.4. Comparison of SCC performance on moving scooters

Figure 5 shows the charging power generated by MPPT and PWM solar controllers on a moving scooter. Figure 5 shows a comparative analysis of the charging performance between MPPT and PWM controllers installed on a running/moving scooter. It can be seen from the graph that the MPPT controller consistently performs better than the PWM controller, especially during periods of lower solar irradiance. This discrepancy can be attributed to the higher efficiency of the MPPT controller in extracting maximum power from the solar panel. As a result, the MPPT controller proves to be more adept at optimizing charging output under varying solar conditions, thereby increasing the overall effectiveness of the charging system installed on the scooter [15], [35].

In addition, the correlation shown in Figure 5 between the charging power of both solar charger controllers and the intensity of solar irradiance suggests a proportional relationship. It means that as the solar irradiance increases, the charging power of both controllers increases accordingly. However, it's important to emphasize the clear advantage of the MPPT controller in recharging the battery quickly and effectively compared to the PWM controller. For example, at 10:00 A.M., the MPPT controller achieves a charge rate of 6.54 W, surpassing the PWM controller's slightly lower rate of 5.99 W. This discrepancy emphasizes the higher efficiency of the MPPT controller in optimizing the charging processes, thus allowing more efficient use of solar energy resources for battery recharging purposes.

The MPPT controller for charging a battery on an e-scooter proves advantageous due to its increased efficiency and ability to accelerate battery charging, surpassing the capabilities of PWM controllers. This advantage is maintained even under conditions of reduced solar irradiation. Therefore, the MPPT controller emerges as the preferred choice to effectively manage the battery charging requirements of an electric scooter, ensuring optimal utilization of the available solar energy resources and maintaining efficient operation under varying environmental conditions.

Solar e-scooters, combining the benefits of electric scooters with solar power, offer a compelling eco-friendly transportation option. They boast several advantages. Firstly, they produce zero tailpipe emissions, contributing to a cleaner environment. Secondly, by utilizing solar power for charging, they reduce reliance on the electricity grid, potentially leading to lower running costs. Thirdly, like all-electric vehicles, they operate quietly, minimizing noise pollution in urban areas. Finally, under ideal conditions, solar electric scooters have the potential for self-sufficiency, recharging themselves through integrated solar panels.

However, there are some limitations to consider. The operating range of solar electric scooters is limited by the size of their integrated solar panels. These panels can only collect a relatively small amount of solar energy, resulting in a shorter range compared to electric scooters that rely solely on grid charging. In addition, solar electric scooters are weather-dependent. Charging relies heavily on sunlight, so cloudy or dark days will significantly hinder charging. Finally, charging speed is an issue. Even in ideal sunlight, solar panels will take longer to charge the battery than plugging into a conventional power source.

Despite their limitations, solar electric scooters remain an intriguing concept for reducing emissions and promoting renewable energy. However, further research is crucial to address current shortcomings. This includes exploring new solar panel types, optimizing solar charger technology, and developing more efficient, higher-capacity batteries to extend range and charging speed. Additionally, research into lighter, weather-resistant scooter designs will be key to achieving seamless and ergonomic integration of solar panels.

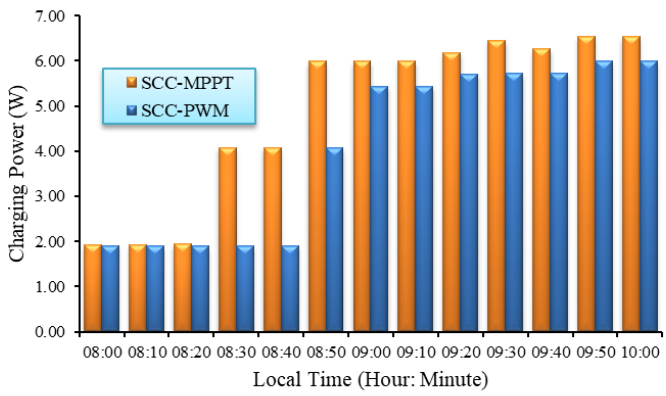

Figure 5. Performance comparison of MPPT and PWM controllers for moving e-scooters

4. CONCLUSION

The MPPT controller for charging a battery on an e-scooter proves advantageous due to its increased efficiency and ability to accelerate battery charging, surpassing the capabilities of PWM controllers. This advantage is maintained even under conditions of reduced solar irradiation. Therefore, the MPPT controller emerges as the preferred choice to effectively manage the battery charging requirements of an electric scooter, ensuring optimal utilization of the available solar energy resources and maintaining efficient operation under varying environmental conditions.

Despite their exciting potential for eco-friendly transportation and reduced running costs, solar electric scooters currently face limitations in range and charging efficiency. These limitations stem from the size of the solar panels and their dependence on sunlight. Further research on solar panel technology, battery capacity, and scooter design is necessary to unlock the full potential of solar electric scooters as a sustainable transportation option.

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