



Tracking solar panel maximum power point using IoT-based mamdani fuzzy logic control

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Abstract

Renewable energy is an important solution to overcome the limitations of conventional non-renewable energy. The role and breakthroughs in using renewable energy are one of the research priorities that need to be developed and get more attention. Solar panels are one of the technologies for utilizing this energy source. However, with all the benefits of solar panels, the biggest challenge currently faced is the energy conversion system, which still experiences fluctuations in output power due to unpredictable changes in solar irradiance, especially when covered by clouds. To overcome this problem, an effective Maximum Power Point Tracker (MPPT) system is required and has been developed. MPPT has feature limitations based on price, which is what drives the creation of an MPPT that is easy to develop. This study proposes the use of fuzzy logic methods in MPPT to determine the maximum point that needs to be achieved by solar panels. All acquired data is transmitted using IoT to the cloud for further data analysis. The IoT system is built by sending data from the DHT22 and INA 226 sensors to transmit temperature, current, and voltage data to the ESP32. This data will be sent to the MQTT broker. The broker will forward the received data to the subscriber. This study applies the INA226 sensor, which is used to take data from solar panels by reading the current passing through the shunt resistor. The result is then processed into input to control MPPT by considering fuzzy conditions to maintain optimal power output. This research produces the final result in the form of a constant voltage required by the battery to fulfill the core function of SCC, where the output is optimal through adjustment of the work cycle, so this research is expected to make data on solar panels easy to obtain and analyze with MPPT, which can be developed in the future. The research is novel due to the implementation of fuzzy logic to determine control parameters.

Keywords:

Solar panel, MPPT, fuzzy control, tracking efficiency.

1 Introduction

Renewable energy is energy produced from natural resources that are unlimited and will never run out. In the future, renewable energy will play a big role because non-renewable energy will run out as it is used. One solution to answer the need for renewable energy is the use of solar energy [1]. The use of solar cells for household needs has been researched by comparing their use with using electricity from the grid, especially in terms of the investment that has been spent; it will be more economical to use solar energy [2]. Apart from that, the use of solar cells is also increasingly

widespread, not only for lighting [3] but also for drying food, driving rice threshing machines [4], and even for use in baby incubators [5].

In recent technological research, the mechanism for harnessing solar energy has advanced rapidly to meet various needs through solar panel technology. The development of a solar panel system will be effective if it can convert solar energy into electricity stably and optimally [6]. The use of Maximum Power Point Tracking (MPPT) can keep the condition of the solar panel system stable, by adjusting the power that can be drawn according to solar radiation and temperature conditions. This feature can extend the lifespan of components in the solar panel system, starting from the solar panels to the batteries used [7].

Efforts to utilize solar energy as much as possible include dynamic MPPT, which is mechanical tracking of the sun's position, where the angle of the surface of the solar panel will move according to the movement of the sun [8][9][10]. However, mechanical movement requires energy to run the motor, so we are looking for an alternative to static MPPT that does not require additional energy but uses several algorithm methods, including the Perturb and Observe (P&O) method. This method involves 2 stages, perturbation for changing and observation for adjusting. This method has the advantage of high accuracy values. It is not influenced by the characteristics of the solar panel, but the weakness is that data processing takes a long time. In steady state conditions, there will be a loss of voltage and current due to oscillations [11][38][41]. The incremental conductive algorithm method by regulates changes in terminal voltage on solar panels based on incremental and instantaneous conductance. This method is good for rapidly changing environments but is less efficient than P&O [12]. Another maximum point search method uses fuzzy logic and artificial neural networks [13]. The fuzzy logic method uses the current value entering the sensor to become input to the membership function [14]. The advantage of using the fuzzy method is simpler programming [15]. MPPT research so far has been carried out, among other things, by creating microcontroller-based adaptive control with a resulting voltage in the range of 3.28 – 9.27 V with an input voltage of 3.4 – 9.67 V [16]. Other research compares SCC using PWM and SCC using MPPT, which is already on the market [17][18][19][41][42][43].

Fuzzy technology is widely applied in computer vision [20] [21], image processing [22][23][24], natural language processing [25][26], and data mining science in general [27][28][44][45]. Other relevant research shows the energy efficiency between MPPT and PWM-type charge controllers under various solar irradiation conditions and seasonal variations. The results show that MPPT controllers offer better energy efficiency than PWM controllers [29]. Research comparison shows that the MPPT controller has a charging current of 8.5A and 7A, while the PW controller produces 7.5A and 6A current to the battery under no-load and load conditions, respectively [30]. The PWM controller is an option with acceptable efficiency and a lower price in relation to the MPPT controller. In the implementation of both controllers, we calculated similar periods of autonomy [31]. Another research analyzes the performance comparison between MPPT and PWM charge controllers in charging batteries using MATLAB Simulink simulations, showing higher efficiency for MPPT under various current and voltage input conditions [32]. Another research comparing four MPPT approaches, and their classification based on nine factors, has been presented. The result is in terms of tracking speed and stability, conventional methods have a higher response time compared to the intelligent, optimization, and hybrid techniques [33]. P&O solution gave 94% performance when configured. P&O controller has a better time response process. As compared to the P&O method of tracking, the incremental conductance response rate was significantly slower [34].

This research was carried out with the aim of creating an MPPT prototype using a fuzzy algorithm combined with a solar charge

controller that controls the incoming voltage and current from the solar panel to the battery. The voltage and current are adjusted to the values required by the battery with the aim of maintaining the battery in the highest possible state of charge, protecting the battery from overcharging and over-discharging, and can be monitored via mobile phone. The research is innovative because of the use of fuzzy logic for identifying control parameters.

2 Research methodology

2.1 Research method

The method used in this research is experimental. This method is needed to determine the variable objects that will be searched for comparison and analysis. Variables are determined to assist in forming the design needed to obtain the desired results. The results

of the design will be tested and tried to obtain variable values that have been determined in the design [35].

The method, as it is shown in Fig. 1, will begin by explaining the literature study and designing the SCC MPPT. The first design will start from a fuzzy modeling design, and after being modeled, the algorithm will be tested. If it is still not suitable, then it will be modeled again. When testing is appropriate, it will start with SCC MPPT construction, followed by adding monitoring features. Performance testing will be carried out when the feature has passed completion and will be reconstructed if the performance still does not meet the formulation and objectives. When you have answered the formulation and objectives, the results will be reviewed. A decision can be made when the review has been completed.

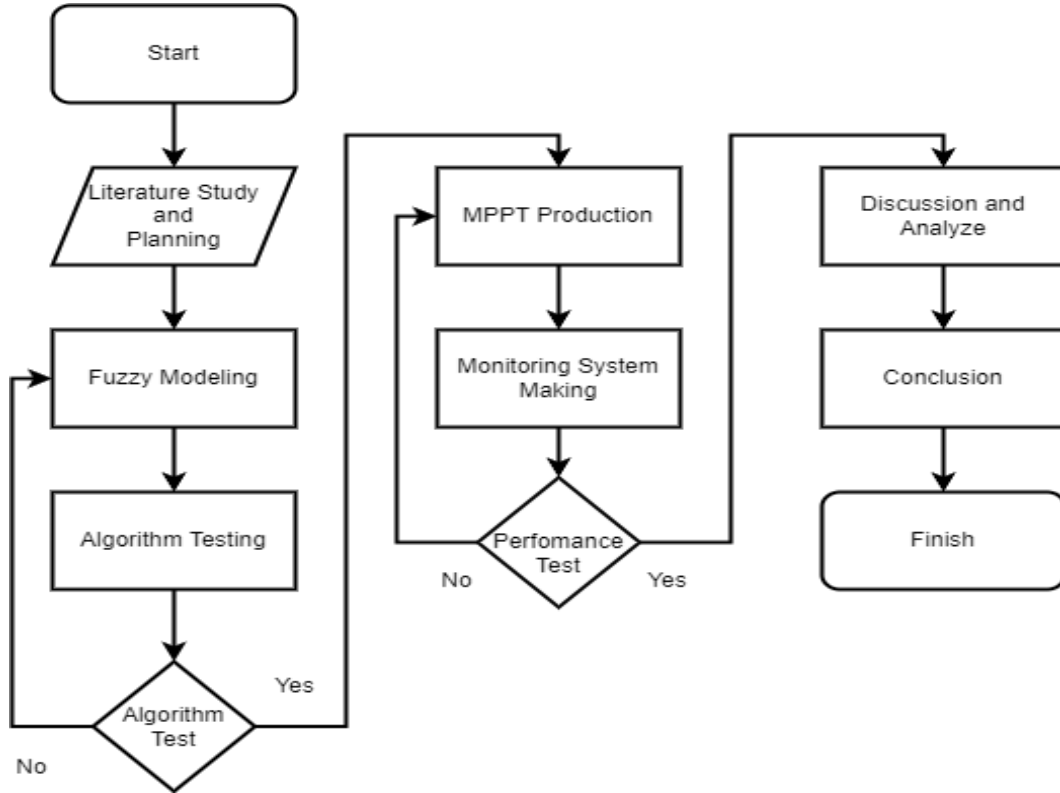


Fig. 1. Experimental flow.

The developed device is shown in Fig. 2. The consists of a solar panel and an SCC MPPT panel box.



Fig. 2. Solar panel and SCC MPPT box.

2.2 Buck boost model

In this research, a buck-boost component with IC LTC3780 is used, which can help provide PWM and duty cycle simulations needed to produce the desired output voltage. This research uses a 12 V 5 AH battery as a place to store the power produced by solar panels. It requires a voltage in the range of 13 V to 15 V to charge a 12 V battery.

This range is included in the constant voltage category, which is a function of SCC [36]. The LTC3780 buck-boost IC will be programmed with ESP32 to carry out operations according to the algorithm. The algorithm will provide PWM and duty cycle simulations five times, with a scale of 20% for each simulation. The MPPT value can be taken after it has been simulated and has produced the constant voltage required by the battery. The simulation will have a tolerance of 10% if each simulation produces an output voltage value that is far away, but cannot produce a constant voltage value.

2.3 MPPT SCC design

The design of the MPPT SCC is shown in Fig. 3. SCC MPPT will use ESP 32 as a controller whose function is to manage the results of sensor data readings and carry out algorithm programs. INA226 as a voltage and current sensor total 2 are installed from the solar panel output and input before going to the battery functions to track the power produced and released. The LTC3780 IC is a buck-boost component that regulates voltage and current.

IRF530S MOSFETs are used at each input and output of the LTC3780 with the aim of protection to prevent reverse current to the ESP32.

The solar panel as a voltage input will be forwarded to the INA226 to measure the voltage and current. ESP 32 will regulate

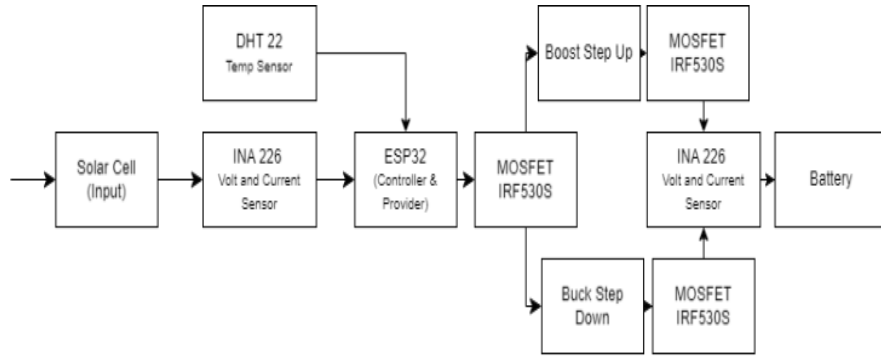


Fig. 3. MPPT SCC design.

2.4 Tracking power algorithm

A principle of the MPPT equation is to optimize power when the derivative of power with respect to voltage (dP/dV) equals zero. This is represented as in Eq. (1) and Eq. (2).

$$\frac{dP}{dV} = 0 \quad (1)$$

$$V * \frac{dI}{dV} + I = 0 \quad (2)$$

This mathematical criterion pinpoints the Maximum Power Point (MPP) on a solar panel's Power-Voltage (P-V) curve, enabling a converter to modify the electrical load to harness the maximum achievable power amid fluctuating environmental conditions.

Photovoltaic (PV) cells do not produce their maximum power at every operating point. The maximum power is produced at a specific voltage and current combination, known as the MPP [39][40].

The MPP algorithm uses the principle [37]: (1) tracking the Curve, MPPT algorithms use the $dP/dV = 0$ principle to find the MPP; (2) dynamic adjustment, they continuously monitor the PV system's voltage and current and adjust a control element (like a buck converter) to keep the operating point at the MPP, even when conditions like sunlight and temperature change; (3) algorithms, common MPPT algorithms, such as P&O [38][41], use this concept to perturb the voltage slightly and observe the change in power to find the direction that leads to maximum power, then adjust the voltage to stay there.

2.5 Fuzzy algorithm

The fuzzy logic process involves four main steps as it is shown in Fig. 4: reading input values, fuzzification, where crisp input data is converted into fuzzy sets with degrees of membership (e.g., "warm" or "hot"); inference, where "if-then" rules are applied to these fuzzy inputs to produce fuzzy outputs; and defuzzification, which converts the combined fuzzy output back into a single, precise crisp value. This process allows fuzzy logic systems to handle uncertainty and make decisions based on human-like reasoning, using intermediate values between absolute truth (1) and absolute falsehood (0). The last step is writing the control parameter.

The input for processing fuzzy values is the current value (A) and the voltage value (V). Both inputs are calculated to power input (Pi) and power output (Po). After the data is collected by fuzzification, the data will be processed in a rule base or inference process. After processing, the execution of conclusions occurs in the defuzzification process, which produces fuzzy output values in the form of a digital control parameter.

the input from INA226, DHT22 for command input on the first IRF530S MOSFET. The input from the solar panel will be increased or decreased based on the active MOSFET. The voltage entering the accumulator is in accordance with the specified output.

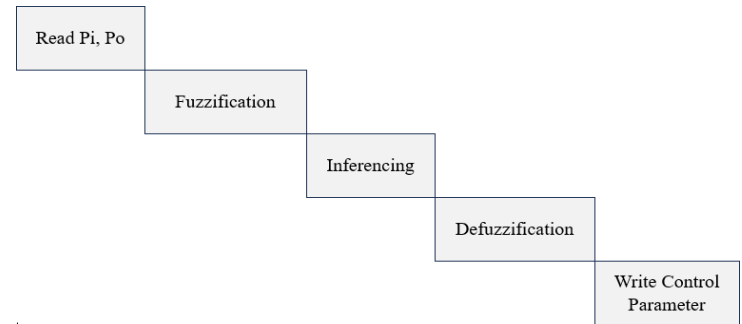


Fig. 4. Fuzzy flow diagram.

The fuzzy set design has 4 conditions that are distinguished from variations in the input voltage value received by the system. It is shown in Table 1.

Table 1. Fuzzy rule table

Fuzzy rule	Input voltage value (Vi)	Output voltage value (Vo)
Condition 1	$\geq 14 \text{ V}$	15 V – 13V
Condition 2	$\leq 13.99 \text{ V} \ \& \ \geq 10 \text{ V}$	15 V – 13V
Condition 3	$\leq 9.99 \text{ V}$	15 V – 13V
Condition 4	1 V – 0 V	1 V – 0 V

The mentioned table results in the fuzzy rules:

IF (Vi > 14V) AND (Vo = 13 to 15V) THEN Cond-1
IF (Vi =10 to 13.9V) AND (Vo = 13 to 15V) THEN Cond-2
IF (Vi < 9.99V) AND (Vo = 13 to 15V) THEN Cond-3
IF (Vi =0 to 1V 14V) AND (Vo = 0 to 1V) THEN Cond-4

Condition 4 is a condition where the solar panel is no longer able to produce current and voltage, so that the output is in the same range as the input. The algorithm will not decide the condition if the duty cycle simulation has not been completed, and will produce the appropriate voltage and maximum power. When the simulation has finished, the algorithm can decide on the optimal conditions at that time at the same time as the simulation starts again in a new sequence

2.6 System testing

The first test plan will be carried out by comparing the SCC MPPT prototype with the MPPT on the market (commercial MPPT SCC type SP 666). Testing to see whether the SCC MPPT resulting from research development can follow the function of the MPPT SCC type SP 666, and what MPPT efficiency value is produced.

3 Results and discussion

3.1 First test of SCC MPPT and MPPT SCC type SP 666

Data was acquired in the first test between July 20 to 28, 2024, at 15:00 with a radiance value of 700 (W/m^2) obtained from the

BMKG website. The solar panels are in a condition without partial shading. The solar panels are installed at 30° facing east. This data shows that the input voltage produced by the solar panels is above 14 V and the output voltage value is constant at 13.80 V. These results show that condition 1 occurred in the algorithm during data retrieval. The highest input voltage value is at 15:10, namely 21.92 V with a current value of 69.51 mA. The lowest input voltage value is at 15:20, namely 21.10 V with a current value of 56.77 mA. The result is shown in Table 2.

Table 2. Testing SCC MPPT MS-100-39

Time	Vin sensor (V)	I sensor (mA)	Vout sensor (V)	Iout sensor (mA)
15:00	21.91	69.51	13.80	93.00
15:05	21.87	69.7	13.80	90.00
15:10	21.92	65.7	13.80	67.00
15:15	21.56	62.17	13.80	63.00
15:20	21.10	56.77	13.80	67.00

The input voltage and current values are read by the system via the first INA226 sensor. There is a difference with the largest voltage error value being 2% and the largest current error value being 12.7%. It is shown in Table 3.

Table 3. Validity of input current and voltage values

Vin sensor (V)	I sensor (mA)	Vin actual (V)	I actual (mA)	Vin error (%)	I error (%)
21.91	69.51	21.4	72.70	2%	4%
21.87	69.7	21.4	72.90	2%	4.3%
21.92	65.7	21.4	70.30	2%	6.5%
21.56	62.17	21.7	69.15	1%	10%
21.10	56.77	21.20	65.10	0.4%	12.7%

The output voltage and current values read by the system via the second INA226 sensor have differences, with the largest voltage error value being 1.4% and the largest current error value being 12%. It is shown in Table 4.

Table 4. Validity of output current and voltage values

Vout (V)	Iout (mA)	Vout actual (V)	I out actual (mA)	Vout error (%)	Iout error (%)
13.8	93.00	14.00	98.00	1.4%	5%
13.8	90.00	13.90	96.60	0.7%	6.8%
13.8	67.00	13.80	75.60	0%	11%
13.8	63.00	14.00	72.30	1.4%	12%
13.8	67.00	14.00	70.20	1.4%	4%

This data is the efficiency result of SCC MPPT to see how much SCC MPPT can maintain the power value and reduce the amount of power lost, as it is shown in Table 5.

Table 5. SCC MPPT efficiency results

Input			Output			Eff (%)
V	I (mA)	P (W)	V	I (mA)	P (W)	
21.91	69.51	1.523	13.8	93.00	1.28	84%
21.87	69.70	1.524	13.8	90.00	1.24	81%
21.92	65.70	1.44	13.8	67.00	0.92	64%
21.56	62.17	1.34	13.8	63.00	0.87	65%
21.1	56.77	1.20	13.8	67.00	0.92	77%

MPPT SP666 is an MPPT SCC Type SP 666, which has maximum voltage specifications (Vm) of 24 V and maximum current (Im) of 10 A. Data was taken during the day on the first test between July 20 to 28, 2024, at 15:00 with a radiance value of 700 (W/m²). The solar panels are in a condition without partial shading. The solar panels are installed at 30° facing east. The conditions are the same as test 2, but the radiance value that is received by the solar panels is different due to differences in time lag and cloud

conditions. The highest input voltage value is at 15:35 with a result of 18.90 V, and the lowest voltage value is at 15:55 with a result of 17.90 V. It is shown in Table 6.

Table 6. Testing SP66 MS-100-39

Time	Vin sensor (V)	I sensor (mA)	Vout sensor (V)	Iout sensor (mA)
15:35	18.90	14.40	14.10	160.00
15:40	18.20	14.30	14.10	104.00
15:45	18.20	14.40	14.10	101.00
15:50	18.60	14.30	14.10	155.00
15:55	17.90	14.40	14.10	161.00

This data shows the efficiency of the SP 666. It depicts how much the SP666 can maintain the power value and reduce the amount of power lost. In this second test, it was found that the highest efficiency figure from the MPPT was in the fifth shot at 80% which is produced by the highest output power of 2.32 W. The highest incoming power was in the first shot, with a value of 3.02 W. It is shown in Table 7.

Table 7. SP666 efficiency results

Input			Output			Eff (%)
V	I (mA)	P (W)	V	I (mA)	P (W)	
18.9	160.0	3.02	14.4	160.0	2.30	76%
18.2	104.0	1.89	14.3	104.0	1.49	79%
18.2	101.0	1.84	14.4	101.0	1.45	79%
18.6	155.0	2.88	14.3	155.0	2.22	77%
17.9	161.0	2.88	14.4	161.0	2.32	80%

SCC MPPT system testing and daytime SP666 testing were carried out for comparison. The test was carried out under conditions that were not ideal but had the same radiance value. The same radiance value does not completely occur due to differences in test times in the same radiance value time range. SCC MPPT can properly follow the function of the SP666 by proving that it can maintain the output voltage required by the battery in accordance with the constant voltage range. SCC MPPT can well maintain power loss, but the efficiency results of SP666 are much more stable than SCC MPPT. The solar panel efficiency results when using SCC MPPT are 0.43% and the solar panel efficiency results when using SP666 are 0.85%. The solar panel efficiency results produced are higher if the solar panels use SP666.

This difference shows that SCC MPPT can functionally follow SP666, but SP666 can show better performance than SCC MPPT. Note that you need to pay attention to the fact that these results cannot be used as a complete conclusion because the solar panels are not in ideal conditions and the test time is different.

3.2 Second test of SCC MPPT on differences in radiance

The test was carried out between July 20 to 28, 2024. The SCC MPPT was tested at different radiance values at 10:00 – 15:00. The solar radiance value is obtained from the BMKG website. The solar panels are in a condition without partial shading. The solar panels are installed at 30° facing east. It is shown in Table 8

Table 8. SCC MPPT Testing With Level Radiation Parameter

Time	Vin sensor (V)	I sensor (mA)	Vout (V)	Iout (mA)	Ir (W/m ²)
10:00	21.78	75.78	13.4	82.30	400
11:00	22.60	78.60	13.4	85.24	550
12:00	24.20	90.70	13.9	96.60	750
13:00	23.36	86.00	13.7	92.35	750
14:00	21.10	72.40	13.5	72.10	600
15:00	16.46	56.00	13.2	56.40	300
16:00	14.40	49.40	13.2	50.70	150

This test was carried out to see the effect of the radiance value on the power produced by the solar panel. It shows that at 10:00 the

radiance value is 400 (W/m^2), which results in an input voltage value of 21.78 V and an incoming current of 75.78 mA. At 11:00, it shows a radiance value of 550 (W/m^2), which produces an input voltage value of 22.60 V and an input current of 78.60 mA. At midday at 12:00, it shows a radiance value of 750 (W/m^2), which produces an input voltage value of 24.20 V and an incoming current of 90.70 mA. The radiance value is still the same at 13:00, namely 750 (W/m^2), which produces an input voltage value of 23.36 V and an input current of 72.10 mA. There was a decrease in the radiance value to 600 (W/m^2) at 14:00, which resulted in an input voltage value of 21.10 V and an input current of 72.40 mA. At 15:00, the radiance value drops by half from before to 300 (W/m^2), which results in an input voltage value of 16.46 V and an input current of 56.00 mA. At the end of data collection at 16:00, the radiance value was 150 (W/m^2), which resulted in an input voltage value of 14.40 V and an input current of 49.40 mA. There is an increase and a decrease in the value of the incoming voltage and incoming current following the radiance value.

The curve of Fig. 5 shows that the greater the value of solar radiance, the greater the value of the input voltage, closer to the maximum voltage, and the smaller the value of solar radiance, the value of the input voltage will be smaller, away from the maximum voltage. The same applies to currents; the smaller the solar radiance value, the smaller the incoming current, and the greater the solar radiance value, the greater the incoming current. This conclusion is not absolute in this test. There is a large radiance value, but it produces small input voltage and current values from a smaller radiance value. At 550 (W/m^2) and 400 (W/m^2) it is done in the morning with cloudless conditions so that the solar panels can fully receive radiation, compared to when the radiance value is 600 (W/m^2), which is done in the afternoon with conditions that will transition down to 300 (W/m^2). This decreasing condition was caused by the number of cloud particles being different from the morning test, so that the radiation received by the solar panels was not optimal. SCC MPPT proves that in transition conditions, where the radiance value changes, it can maintain the output voltage value well. It is shown in Table 9.

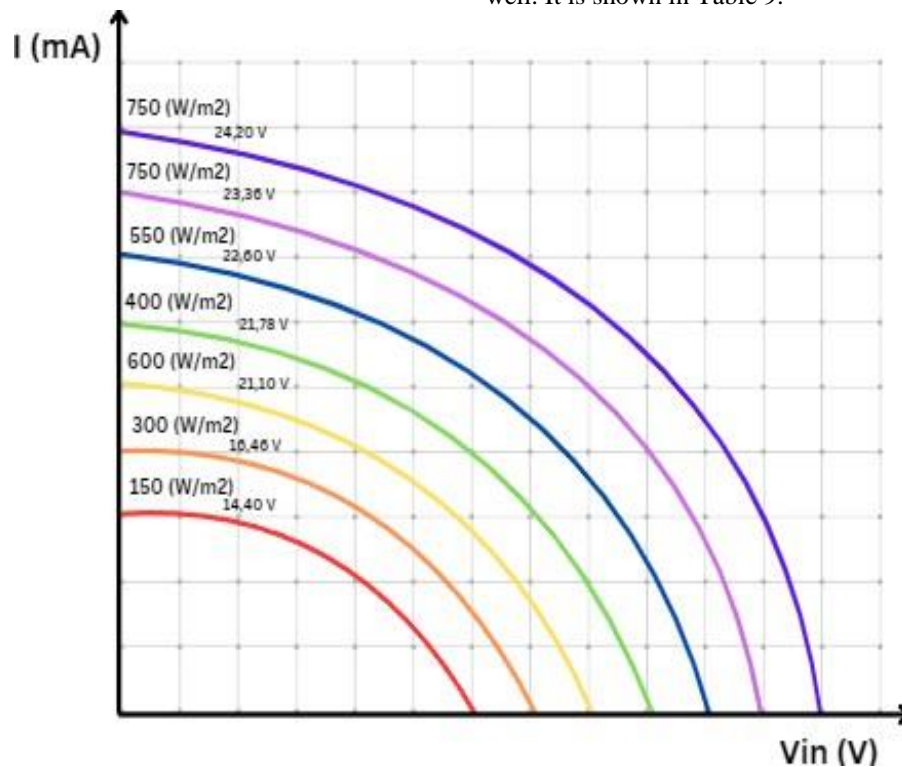


Fig. 5. Curve against level radiation.

Table 9. Validity of input current and voltage values

Vin sensor (V)	I sensor (mA)	Vin actual (V)	I actual (mA)	Vin error (%)	I error (%)
21.78	75.78	21.60	80.20	0.8%	5.5%
22.60	78.60	23.00	83.30	1.7%	5.6%
24.20	90.70	23.85	95.40	1.4%	4.9%
23.36	86.00	22.90	90.25	2%	4.7%
21.10	72.40	21.30	75.60	0.9%	4.2%
16.46	56.00	16.90	60.00	2.6%	6.0%
14.40	49.40	15.00	51.30	4%	3.7%

The input voltage and current values are read by the system via the first INA226 sensor, as it is shown in Table 10. There is a difference between the largest voltage error value being 2.6% and the largest current error value being 6%.

There are differences in the output voltage and current values read by the system via the second INA226 sensor, with the largest voltage error value being 2.8% and the largest current error value being 7%.

The solar panel can produce the highest input power at 12:00 with a radiance value of 750 (W/m^2), namely 2.19 W, as it is shown in Table 11 and Fig. 6. It can be observed that the power output from the solar panel increases and decreases according to the

radiance value. However, this statement is not absolute due to differences in conditions at radiance values of 550 (W/m^2) and 400 (W/m^2) with radiance values of 600 (W/m^2). Radiance of 600 (W/m^2) produces a smaller input power value of 1.53 W. SCC MPPT can produce the highest output power value of 1.37 W, the same as conditions where the highest value of input power is 2.19 W. SCC MPPT can produce power well and reduce power loss by more than 50%. There is a high efficiency value at 16:00 with a radiance value of 150 (W/m^2), namely 94%. These results show that SCC MPPT can produce maximum power while maintaining low power loss.

Table 10. Validity of output current and voltage values

Vout (V)	Iout (mA)	Vout actual (V)	Iout actual (mA)	Vout error (%)	Iout error (%)
13.4	82.30	13.45	85.45	0.3%	3.6%
13.4	85.24	13.80	90.25	2.8%	5.5%
13.9	96.60	14.00	98.35	0.7%	1.7%
13.7	92.35	14.00	94.70	2%	2.4%
13.5	72.10	13.70	76.00	1.4%	5.1%
13.2	56.40	13.50	61.30	2.2%	7.0%
13.2	50.70	13.50	52.90	2.2%	3.9%

Table 11. SCC MPPT efficiency results against radiation

Input			Output			Eff (%)
V	I (mA)	P (W)	V	I (mA)	P (W)	
21.78	75.78	1.65	13.4	82.30	1.10	67%
22.60	78.60	1.78	13.4	85.24	1.14	64%
24.20	90.70	2.19	13.9	96.60	1.34	61%
23.36	86.00	2.01	13.7	92.35	1.27	63%
21.10	72.40	1.53	13.5	72.10	0.97	64%
16.46	56.00	0.92	13.2	56.40	0.74	81%
14.40	49.40	0.71	13.2	50.70	0.67	94%

Power and Efficiency Againsts Radiance

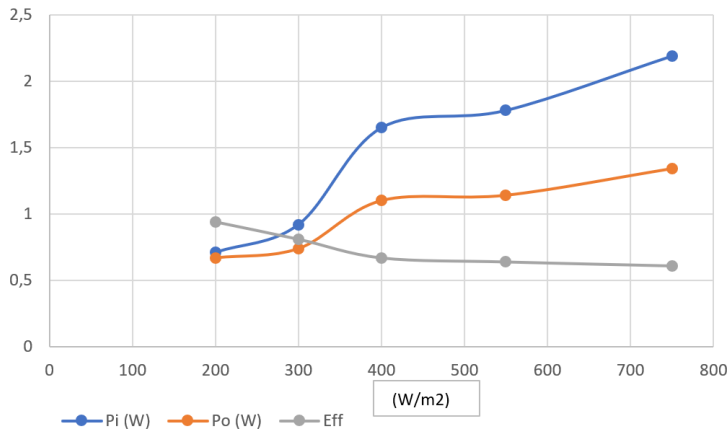


Fig. 6. SCC MPPT efficiency results.

3.3 Solar panel power monitoring display on handphone

To make it easier to monitor the condition of solar panels and the energy produced based on IoT, information on current, voltage, power, and temperature can be seen on mobile phones. As it is shown in Fig. 7.

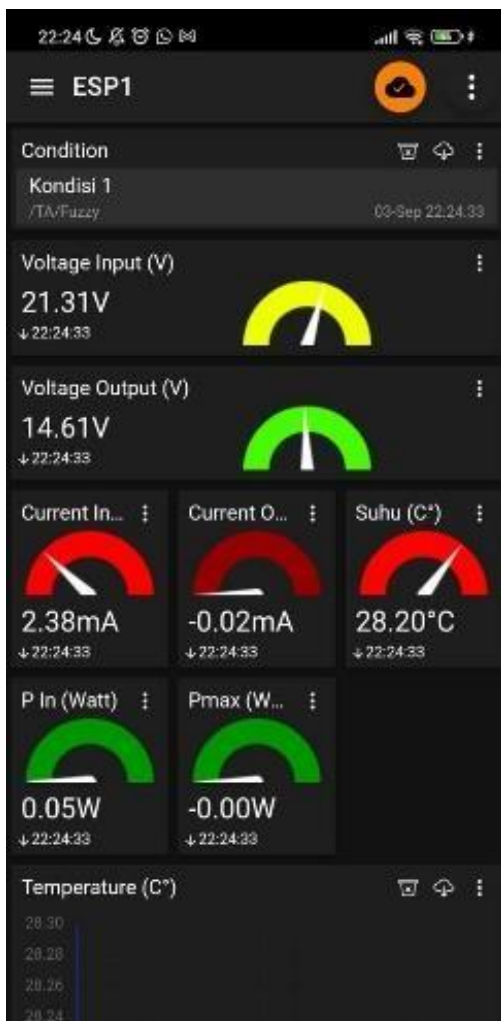


Fig. 7. Interface application.

4 Conclusions

The MPPT SCC prototype successfully generated the constant voltage required by the battery, fulfilling a core function of an SCC. It effectively produced optimal output power conditions through simulated duty cycle adjustments, a fundamental aspect of MPPT operation. When compared to a commercial SP 666 MPPT SCC, the prototype demonstrated comparable functionality, albeit with a different efficiency rating. The use of an ESP32 microcontroller enables future development and customization of this MPPT SCC prototype. The use of fuzzy logic that applies to the P&O algorithm has been able to identify the point where the maximum power occurs.

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