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An Experimental and Comparative Analysis of the Battery Charge Controllers in Off-Grid PV Systems

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ABSTRACT

The study of the battery charge process as the only power storage agent in off-grid systems is of significant importance. The battery charge process has different modes, and the battery in these modes is dependent on the amount of charge. In order to charge the battery in off-grid systems, two charge controllers including Pulse Width Modulation (PWM) and Maximum Power Point Tracker (MPPT) are commonly used. The charge rate (C-Rate) is different in these two models. Therefore, it is necessary to study the state of charge (SoC) in the PWM and MPPT models considerably. In this study, by using these two charge controller models, C-Rate is examined on portable and power plant scales. This research indicates that the PWM charge controller has better performance on the power plant scale than on the portable scale. The charging quality of the MPPT model is about 31 % and 7 % on portable and power plant scales, respectively, proved to be higher than that of the PWM charge controller. The PV panel performance has increased by 2 %-5 % through the application of the MPPT charge controller, compared with the PWM model. As the overall achievement of the experiment, according to the limitations of the MPPT charge controller, the PWM charge controller can be proposed on power plant scales, whereas the application of the MPPT model is appropriate for specific purposes.

1. INTRODUCTION

The application of renewable energy has significantly increased in the commercial, research, and high redundancy cases. Therefore, the use of solar energy deserves receiving particular consideration because of its availability and simple operation. Solar power outperforms other renewable energies due to the advantages such as low capital and current costs and being environmentally friendly (lowest greenhouse gas emissions). Photovoltaic systems have two models of operation: on-grid and off-grid systems. Both of the mentioned models have a backup system; however, the energy storage system (battery) is charged with supporting the grid in off-grid systems, which ensures meeting the energy supply requirement by the end-user when there is no radiation [1], [2]. Off-grid systems are advantageous in that there is no limitation concerning their installation place whatsoever. Therefore, they can be utilized in any case-place, including islands and highlands, where telecommunication and lighting systems are unavailable, or there is difficulty accessing the grid. The off-grid systems enjoy a greater number of economic benefits with evaluation indicators than on-grid systems such as greater net present value, lower annual energy production costs, and lower levelized costs [3]. Many studies have focused on the structure of off-grid power generation systems. In these systems, battery plays an important role as the storage system; therefore, the concept of energy storage is of special significance. Therefore, the definition of the battery charging algorithm is considered to achieve the required energy when solar radiation is not sufficiently adequate [4]. Pulse Width Modulation (PWM) and Maximum Power Point Tracker (MPPT) are the two models of battery charge controller sub-systems in solar energy systems. Both of these mentioned technologies are widely applied to off-grid systems. The ratio of stored energy to total capacity in a battery is defined by a parameter called State of Charge (SoC). SoC can be a real number in the range of zero (fully discharged) to one (the state of fully charged). Therefore, when the battery is in the mode of receiving energy from the grid, SoC registers a significant rise, and SoC declines when the battery loses energy. In this research, the battery SoC in the off-grid systems is examined by using PWM and MPPT charge controllers. In this respect, Ali et al. expanded an algorithm to generate an MPPT charge controller, which is considered to be a reliable method for charging sealed lead acid batteries [4]. At a higher level of the charging process and its probable errors, Hicks et al. studied the power quality of off-grid systems with low radiation intensity by optimizing the inverter and controlling current harmonics [5]. According to a series of studies, most of the research studies have been conducted on MPPT charge controllers, which are always used to increase the speed and quality of the battery charge process, especially in applications such as charging electric vehicles [6]. These studies often include an approach to amending the efficiency of these charge controllers, and they have been pursued to improve the performance of the whole system by changing the structure of the off-grid devices. However, PWM charge controllers are more applicable than the MPPT model due to lower prices and the absence of technical limitations concerning their use (such as no limitations of ambient temperature, system capacity, and noise).

In the discussion about the performance of the two charge controller systems, Carrar et al. reviewed SoC in sealed lead batteries by applying PWM and MPPT charge controllers so that the effect of the voltage drop on SoC can be monitored

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[1]. In addition, Laguado-Serrano et al. reviewed the performance of both charge controllers in charging and discharging processes by using a 30w solar panel and 12V/18 Ah battery. They found that the voltage increased to 14.7V and 13.7V in MPPT and PWM charge controllers, respectively [7]. Jafari et al. studied these two models of charge controllers by applying a 60W solar panel and 12V/12 Ah battery. They designed a small setup pilot and found that, in low capacities, the speed of charging in the PWM model was higher than MPPT and the MPPT charging quality was far better than the PWM model; however, they realized that the battery voltage boosted 12.7 and 13.55 in PWM and MPPT charge controllers [8]. Since the result of Laguado-Serrano appears to be overestimated and is different from the result of Jafari's study, the need for more study in this field is necessary. Hence, the purpose of this research is to develop and clarify the study, as previously carried out by Jafari et al. who evaluated the performance of these two models of charge controllers by power plant equipment including a panel and a battery with higher capacity.

Therefore, it is necessary to compare the behavior of these two charge controllers with respect to the battery charge on various scales with a more accurate theoretical and empirical approach that chooses a suitable user system, depending on different decision variables: economic, environmental, and system condition aspects. It is also essential to evaluate the performance of these two models in different capacities of power generation. This study (field of theory and model) focuses on the off-grid system of appropriate techniques for portable and power plant applications, whose following objectives are:

- Studying the battery SoC in the off-grid system for each of the PWM and MPPT charge controllers;
- Investigating the performance of these two models of charge controllers in different capacities of power generation;
- Providing a suitable model for the off-grid system in the geographic region of Iran.

The present research (experimental and measurement) has investigated the performance of the PWM and MPPT charge controllers operationally by constructing an off-grid experimental setup on different scales with different capacities of power generation. A qualitative achievement is anticipated to be obtained according to the advantages and disadvantages of the two-mentioned charge controllers in relation to each other, and a quantitative achievement will be obtained based on the connection between these systems and the pre-defined grid (off-grid).

2. THEORETICAL CONCEPTS AND SYSTEM DESCRIPTION

A theoretical summary of the battery charge process is as follows:

As shown in Figure 1, the battery-charge period can be used to elaborate on the relationship between voltage and current in a battery that performs as the charger, which returns the energy capacity to the battery. There is a three-state charging cycle for lead-acid batteries. The three-state charging cycle is the best and most efficient method for returning full capacity to the battery and extending battery life, as recommended by most lead-acid battery producers [9].

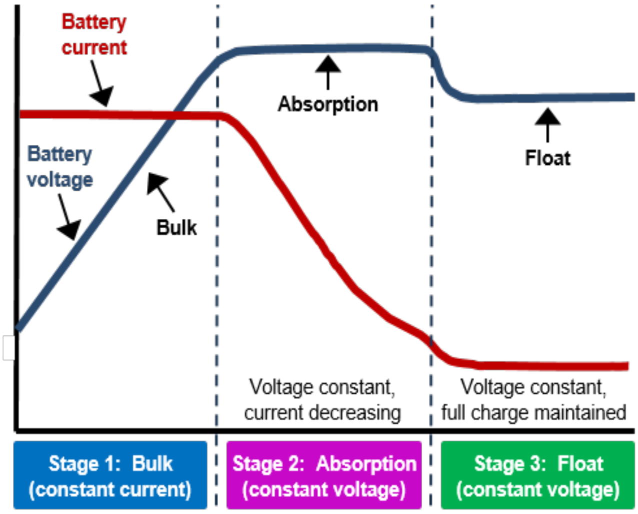

Figure 1. Voltage and current battery charge diagram in a three-stage charging cycle [9].

<u>Stage 1: Constant current charging or bulk charge mode</u>
In this stage, it is assumed that the battery starts in a discharged state and, then, the charger operates in the constant current mode, where the charger current stands steady and the battery voltage is permitted to grow while being recharged. Approximately 80 % of battery capacity is regressed at the same level of the current region.

<u>Stage 2: Absorption mode</u>
When the battery voltage reaches approximately 2.4 volts per cell or 14.6 volts for a 12V battery, the charger voltage remains stable at this level and the battery current is allowed to decline. It is in this region where the last 20 % of battery capacity is returned. This voltage level is maintained until the battery current reduces to approximately C/50-C/100, where C is the amp-hour rating of the battery. For instance, if it is a 100 amp-hour battery, the voltage should be retained at 2.5V per cell until the current decreases to 1-2 amps. The exact amount is not usually critical.

<u>Stage 3: Float mode</u>
At a point where the current undergoes a reduction to C/50-C/100, the battery charger enters the float mode. The float mode is a mode where the voltage on the battery is maintained at approximately 2.25 volts per cell, or 13.5 volts for a 12V battery. This voltage will retain the full charge condition in the battery without boiling electrolyte or overcharging the battery.

2.1. System description

In this research, some equipment was used to the necessary extent including 60 Watt and 320 Watt solar panels, a fixed stand with 35 degrees to the south for setting up the panel, 12 Ah and 65 Ah sealed lead-acid batteries, a PWM charge controller, an MPPT charge controller, two digital voltmeters, two digital Amp meters, and cables. Figure 2 shows the charging process; when the battery is charged by the PV panel, the amp meter A1 shows the output current of the panel and the amp meter A2 demonstrates the amount of the output current of the charge controller to the battery. Thus, voltmeter V1 represents the voltage of the panel, and voltmeter V2 illustrates the amount of the voltage on battery terminals. The solar radiation is measured by using a solar power meter at certain time intervals.

3. SYSTEM MEASUREMENT IN THE SoC

The time interval for measuring data is 15 minutes. The measurement data consist of irradiation intensity, PV panel output current, PV panel output voltage, the output current of the charge controller, output charge controller voltage, and the potential difference of the battery. In each step, the power and efficiency of the whole system were also calculated. The measurement was carried out in four scenarios for the two models of equipment. The first and second scenarios of measurement were performed for the portable scale equipment in July, and the third and fourth scenarios of the measurement were done for the power plant scale equipment in December under full sunlight conditions. The charging process is based on four scenarios as follows:

- First scenario: charge by the PWM charge controller, a 60 Watt solar panel, and a 12 Ah sealed lead acid battery,
- Second scenario: charge by the MPPT charge controller, a 60 Watt solar panel, and a 12 Ah sealed lead acid battery,
- Third scenario: charge by the PWM charge controller, a 320 Watt solar panel, and a 65 Ah sealed lead acid battery, and
- Fourth scenario: charge by the MPPT charge controller, a 320 Watt solar panel, and a 65 Ah sealed lead-acid battery.

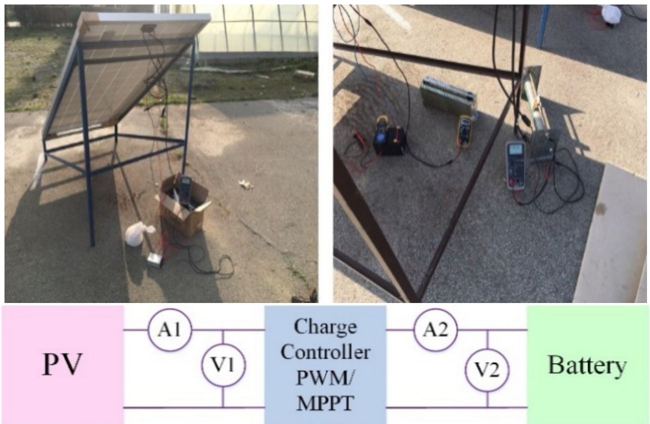

Figure 2. Experimental setup under study.

It should be noted that the technical analysis of the performance of both charge controllers is discussed after taking measuring steps.

Regarding the charge mode shown in Figure 2, the output of the PV panel is connected to the input of the charge controller. The charge controller has two DC outputs to charge the battery when connected to the load. In the first and second scenarios, measurements start at 10:30 AM with the solar irradiation of 681 (W/m^2) and continue until 15:00 PM with the solar irradiation of 690 (W/m^2). The results of measuring these scenarios are shown in Figures 3-6. Figure 3 demonstrates the battery charge process by the PWM charge controller on a portable scale, where the battery has been fully charged at 12.7 (V) and the subsequent fluctuations occur due to charge saturation current with no noticeable effects on the battery voltage and charge status. Therefore, the current of the battery is considerably reduced after charging (as shown in Figure 4). Figure 5 shows the battery charge process by the MPPT charge controller on a portable scale such that the battery has been fully charged at 13.55 (V), and the descending trend of the current diagram in Figure 6 confirms that the battery is charged.

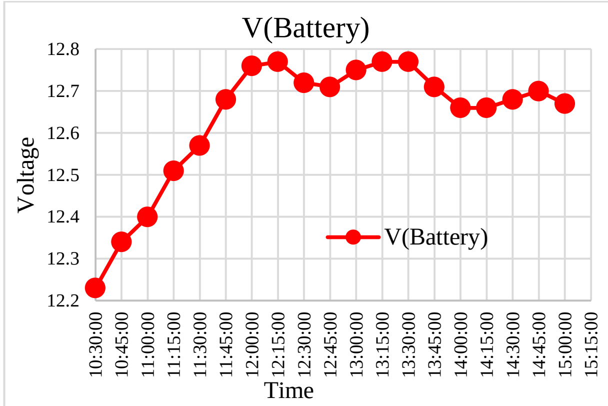

Figure 3. Voltage diagram of 12 Ah battery by using the PWM charge controller and 60 (W) PV panel VS time.

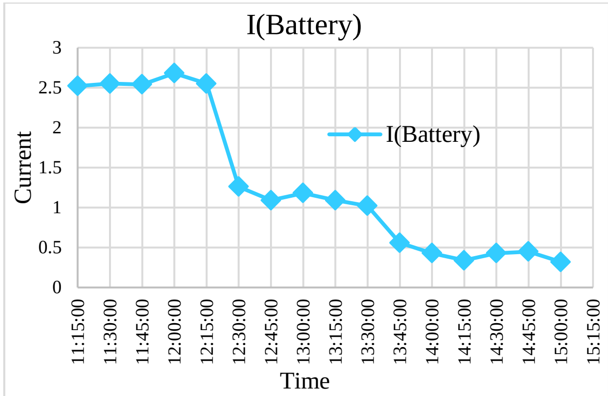

Figure 4. Current diagram of 12 Ah battery by using the PWM charge controller and 60 (W) PV panel VS time.

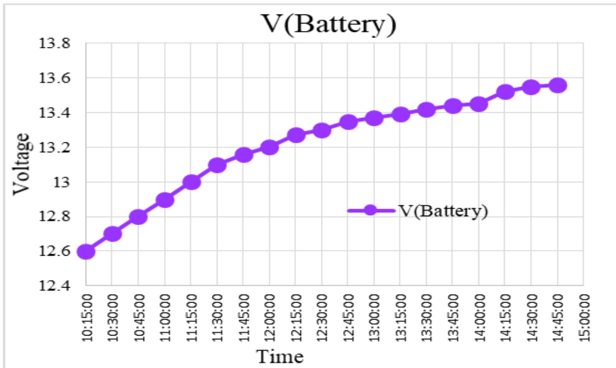

Figure 5. Voltage diagram of 12 Ah battery by using the MPPT charge controller and 60 (W) PV panel VS time.

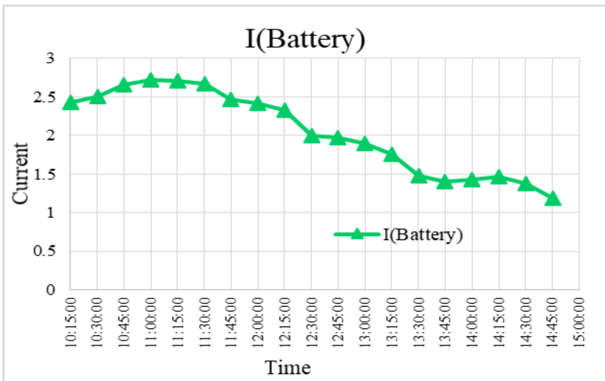

Figure 6. Current diagram of 12 Ah battery by using the MPPT charge controller and 60 (W) PV panel VS time.

In the third and fourth scenarios, measurements were carried out at 11:15 AM with the solar irradiation of 852 (W/m^2) and continue until 15:00 PM with the solar irradiation of 673 (W/m^2). The results of measuring these scenarios are shown in Figures 7-10, illustrating the correct charging process in both scenarios with respect to the input current and the battery voltage. As shown in Figures 7 and 9, the battery has been fully charged at 12.85 (V) by both of the charge controllers. The level of voltage at charging startup in the PWM mode is higher than that in the MPPT mode. Therefore, it should be concluded that the MPPT charge controller has a high Charge Rate (C-Rate), whereas, according to the current curve of the PWM charge controller, the charge quality on a power plant scale is better than that on the portable scale (Figure 8).

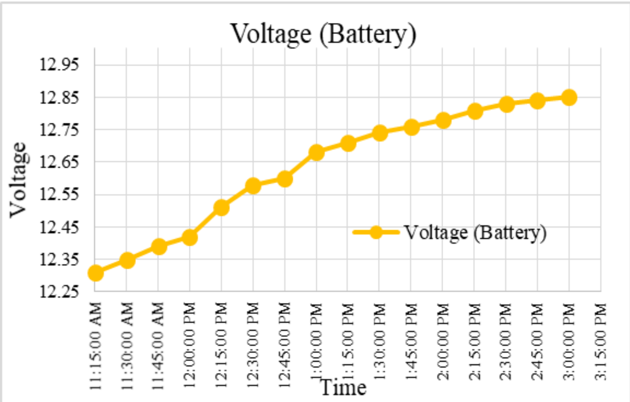

Figure 7. Voltage diagram of 65 Ah battery by using the PWM charge controller and 320 (W) PV panel VS time.

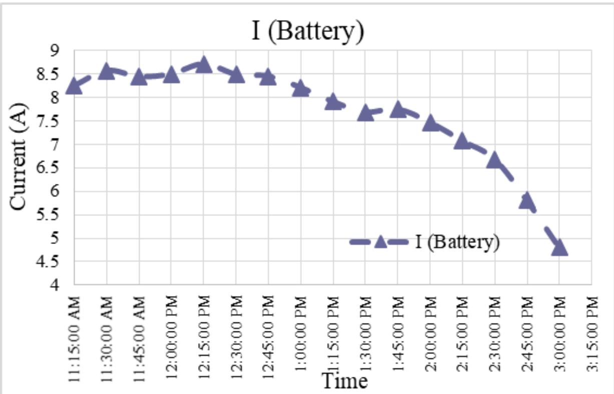

Figure 8. Current diagram of 65 Ah battery by using the PWM charge controller and 320 (W) PV panel VS time.

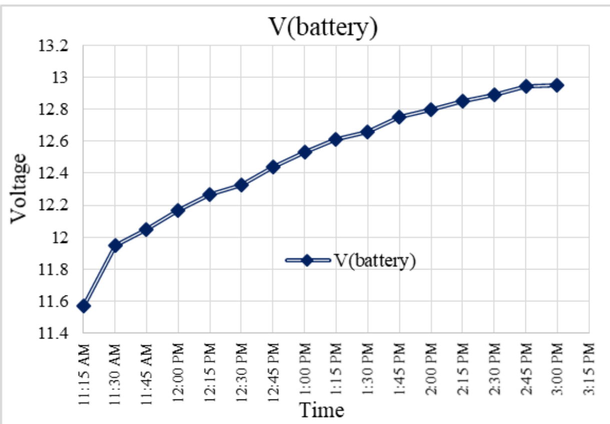

Figure 9. Voltage diagram of 65 Ah battery by using the MPPT charge controller and 320 (W) PV panel VS time.

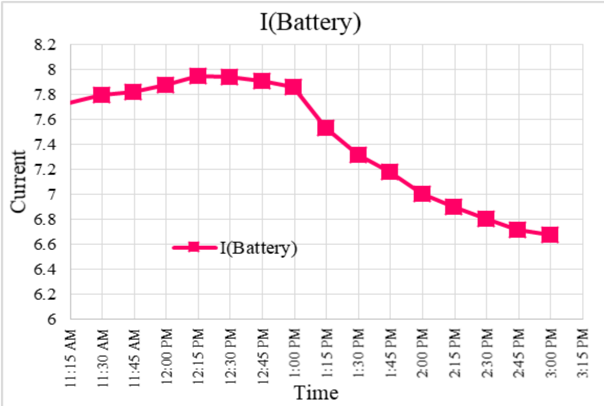

Figure 10. Current diagram of 65 Ah battery by using the MPPT charge controller and 320 (W) PV panel VS time.

4. TECHNICAL ANALYSIS

In this section, the charge current is initially compared and checked in both charge controllers. Then, by evaluating the performance of the two mentioned charge controllers, the performance of the PV panel will be analyzed. The charge current rate is expressed by C, which is the rate of capacity in the battery [10]. Since the used batteries are of 12 Ah and 65 Ah, the C-Rates are 12 A and 65 A, respectively. While the battery is charged with 1C, it will be charged for an hour. Thus, the battery is fully charged when the charging current attains 3 to 10 % of the battery capacity [11]. Figures 11 and 12 show the charge current diagram of the PWM and MPPT charge controllers on both of the considered scales. According to Figure 11, it is deduced that, compared to the MPPT mode, the charging process has reached 10 % of the battery capacity in a shorter amount of time in the PWM mode, which indicates a faster battery charge in the PWM charge controller. The slight slope in the current diagram of MPPT and the diagram of the battery charge voltage (as shown in Figure 5) indicates a higher charge capacity in the MPPT charge controller than that in the PWM. It is shown that the amount of SoC in the MPPT is more than that in the PWM. The results of Figure 12 are given below. The current trend indicates that the battery charge process has been tracked correctly, and the reduction of the current fluctuation shows that both of the charge controllers have acted in their full capacity. Meanwhile, the degree of fluctuation in the PWM charge controller is still higher than that in the MPPT model. However, the magnitude of this fluctuation has significantly decreased with respect to the battery charge curve, as compared to Figure 11.

In order to measure the initial voltage of the battery at the charge startup, the charging process in the MPPT model takes a shorter amount of time than that in the PWM model. In addition, considering the charge control process, it can be deduced that charging in the MPPT model has a higher quality than that in the PWM. As mentioned in Section 2, the battery charge process has three states, where the test in both charge controllers shows that charging in the PWM mode is processed only in the float mode. However, in the MPPT model, the battery charge process is carried out in the three mentioned states. This indicates that the power loss in the PWM model is more than that in the MPPT. In order to examine the two models of the charge controller more accurately, it is necessary to check the rate of charge, charge quality, and PV panel performance along with the performance of the charge controllers. Therefore, by studying the mathematical model of the two mentioned charge controllers, the expressed parameters will be calculated. Accordingly, it is necessary to plot the voltage-current and radiation diagram in two models of the PWM and MPPT charge controllers. Then, the charge rate of these two models of charge controllers should be compared. Figures 13-16 illustrate the voltage-current and irradiation diagram in the two mentioned charge controllers on portable and power plant scales.

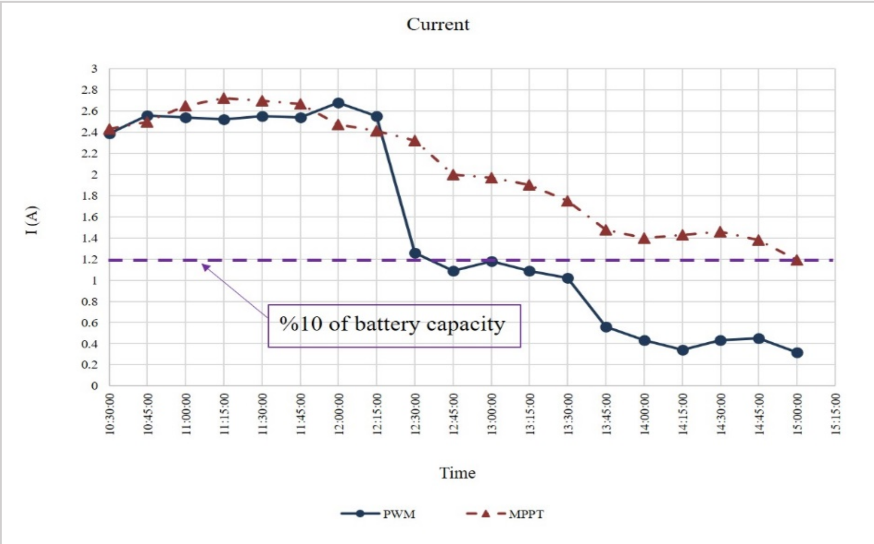

Figure 11. Comparison of the charge current in PWM and MPPT charge controllers on a portable scale.

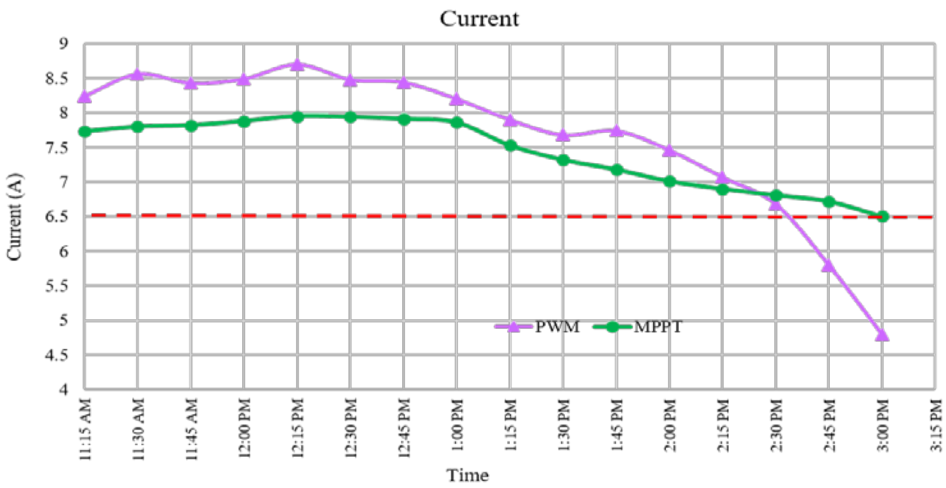

Figure 12. Comparison of the charge current in PWM and MPPT charge controllers on a power plant scale.

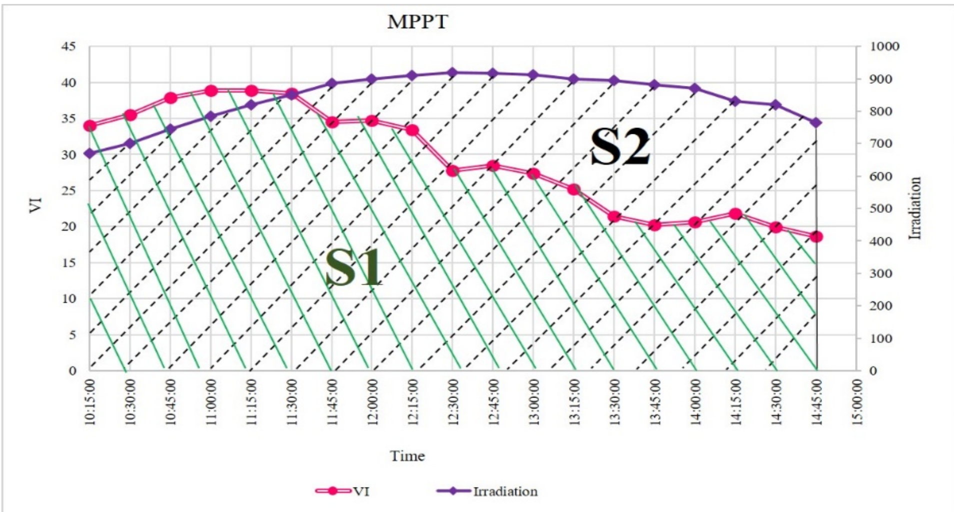

Figure 13. VI and solar irradiation diagram of the 12 Ah Battery by using the MPPT charge controller and 60 (Watt) PV panel VS time.

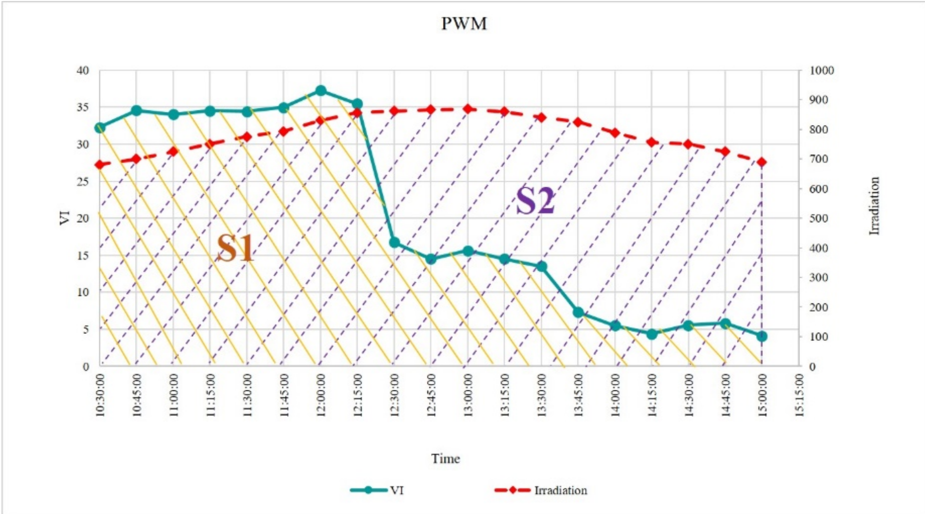

Figure 14. VI and solar irradiation diagram of the 12 Ah Battery by using the PWM charge controller and 60 (Watt) PV panel VS time.

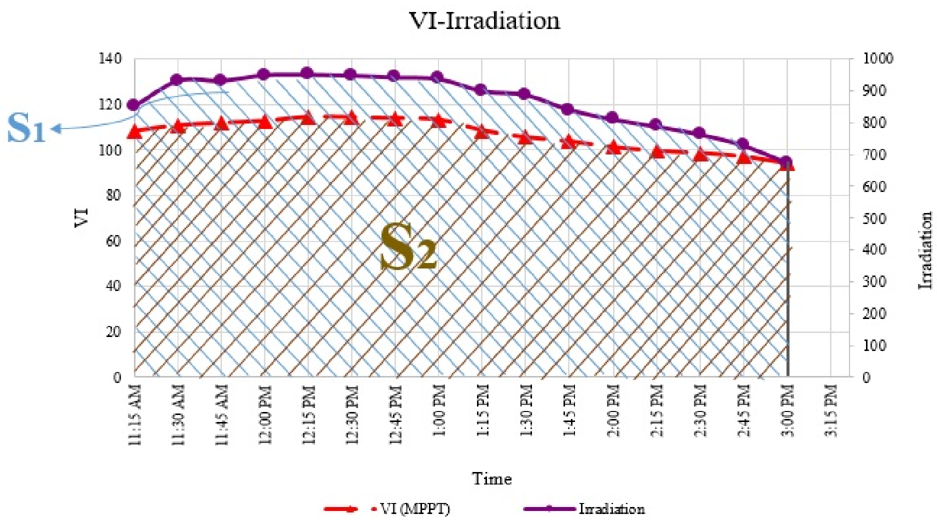

Figure 15. VI and solar irradiation diagram of the 65 Ah Battery by using the MPPT charge controller and 320 (Watt) PV panel VS time.

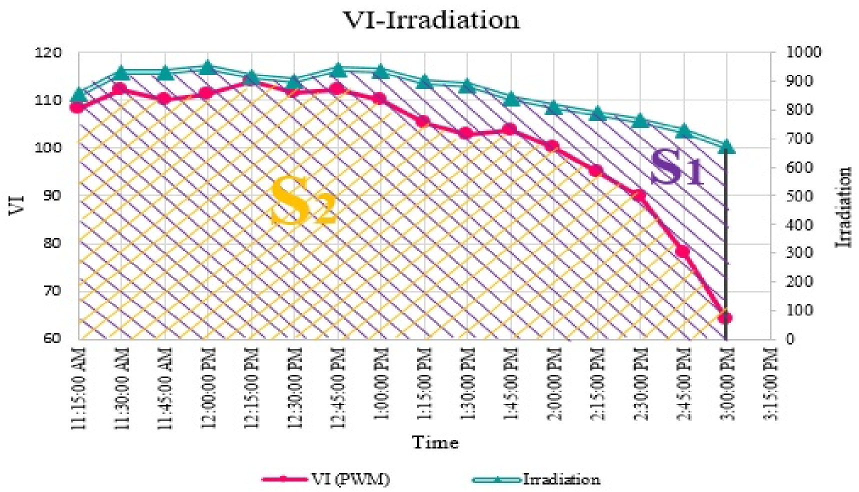

Figure 16. VI and solar irradiation diagram of the 65 Ah Battery by using the PWM charge controller and 320 (Watt) PV panel VS time.

In order to more accurately evaluate the charge quality and calculate its amount in the two mentioned charge controllers, it is necessary to compute the area under the curve of the VI diagram (as shown in Figures 13-16). Thus, by utilizing Equation (1) and Figures 13-16, the area under the curve (S) of the VI diagram will be achieved.

$$S = \int_{t_1}^{t_n} V.I.dt \tag{1}$$

According to Equation (2) and Figures 13 and 14, the battery charge qualities of the PWM and MPPT charge controllers in the first and second scenarios are 96 and 138.25 (Watt), respectively, during 4.5 hours. However, by considering Figures 15 and 16, the aforementioned values of the PWM and MPPT charge controllers in the third and fourth scenarios are 100 and 107 (Watt), respectively, during 4 hours. This subject indicates that the energy delivered to the battery in the MPPT model is about 31 % higher than that in the PWM model in the first and second scenarios and 7 % in the third and fourth scenarios. The results represent that the performance of the PWM charge controller has improved on power plant scales. Therefore, the voltage level has increased up to 0.9 (V) in the MPPT model compared to the PWM charge controller on portable scales. As shown in Figures 7 and 9, the voltage level in the MPPT charge controller stays constant in comparison with that in the PWM model on power plant scales. Although this review is appropriate, it is certainly not enough. Hence, it is necessary that the PV panel performance will be investigated according to the charge controller performance. To cover this issue, the performance of the PV panel in the battery charge according to the charge controller performance is achieved by the ratio of charge quality. The area under the curves (S) of the VI diagram is shown in Figures 13-16 with respect to the amount of the radiation produced (δ). In addition, the area under the curves of the irradiation diagram is shown in Figures 13-16. Equation (2) represents the PV panel performance (P) according to the charge controller performance as follows:

$$P = \frac{S}{\delta} \tag{2}$$

According to Equation (2), the PV Panel performance in charging the battery is calculated as 6 % and 8 % for the PWM and MPPT charge controllers, respectively, on portable scales. Moreover, it is 5 % and 10 % for the PWM and MPPT charge controllers on power plant scales, respectively. These values indicate that the performance of the PWM charge controller is lower than that in the MPPT charge controller, and the MPPT model can play a more effective role in increasing the PV panel performance in terms of quality and quantity compared to the PWM model.

5. CONCLUSIONS

In this research, two models of PWM and MPPT charge controllers were measured and evaluated technically and functionally, which helps the user to select these types of equipment in the off-grid systems. Therefore, the two mentioned charge controllers were applied to the battery charge under the same conditions; hence, the technical analysis of the quantitative and qualitative performance of the MPPT and PWM charge controllers was carried. The following results are achieved as follows. The current diagrams showed that the charge fluctuations in the PWM model were moderately high, which was improved by increasing power generation. However, the current diagrams showed slight fluctuations in the MPPT model and the battery charge process track correctly due to the current diagram (as shown in Figure 1). The area under the curve of VI diagram illustrates that the amount of energy delivered to the battery in the MPPT model was about 31 % and 7 % on portable and power plant scales, respectively, higher than that in the PWM model. The comparison of the PV panel performance according to the controller charging performance showed that the PV panel performance increased by 2 % to 5 % via the MPPT charge controller, indicating the better performance of this model of the charge controller. The charge diagrams of the PWM charge controller (in Figures 14 and 16) demonstrated that this type of charge controller had a better performance on the power plant scales than that on portable scales. Therefore, it is recommended using this charge controller with maximum operational power. As an overall achievement, of note, the MPPT model is superior to the PWM charge controller in terms of performance and charge quality. However, due to the MPPT mechanism, the temperature of this device increased to a greater degree than that in the PWM model when it was applied. This subject has a limited application in high capacities and the lack of the probability of implementation in the hot climate. This research indicated that the performance of the PWM charge controller was considerably weaker than that of the MPPT. However, according to the results, the performance of this charge controller was improved by increasing power generation. Therefore, it can be concluded that the PWM charge controller can be a great option on the power plant scales due to its affordable prices. While it is more appropriate to use the MPPT charge controller for special applications such as charging electric vehicles that require higher charge quality.

6. ACKNOWLEDGEMENT

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