Modeling and experimental analysis of battery charge controllers for comparing three off-grid photovoltaic power plants

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ARTICLE INFO

Keywords:
Photovoltaics
Off-grid system
Battery system
Charge controller
Charge and discharge

ABSTRACT

The study of battery charge algorithm as a sole power storage agent in off-grid systems is essential. The battery charge algorithm has various methods, and the battery in these methods relies on the quantity of charges. Hence, a charge controller is used to safeguard and regulate battery charge and discharge for off-grid photovoltaic (PV) systems. This study presents the 11.4 kWp power plant analysis comprising three 3.8 kWp each of off-grid, hybrid and grid-assisted systems with battery capacities of 900 Ah, 1235 Ah and 910 Ah, respectively, where all the systems were reconfigured to function as off-grids. The battery charge controller charges the lead-acid battery using a three-stage charging strategy, including constant current, constant voltage and float charge stage. A DT800 data logger was installed to simultaneously record the electrical parameters of the systems, while Kipp & Zonen CMP 11 pyranometer was selected to measure solar radiation data. Experimentation with three electric bar heaters, each with fan and humidifier, were used as loads to draw constant power of 1.2 kW from batteries of each system on charging and discharging on an overcast and clear sky days for a week. The useful study is performed in the following ways; MPPT tracking performance, battery charging and discharging performance and charge controller efficiency. The performance results reveal that the MPPT can track the PV module maximum point at solar irradiance from 07h15 to around 12h00 maximum power tracking efficiency. An irradiance of illumination fluctuates from 5 W/m² to 850 W/m² while the electrical energy consumed by the loads in off-grid, hybrid and grid-assisted systems are 456.12, 568.87 and 80.00 Wh, respectively. It is estimated that individual owners could charge electric appliances from residential and commercial buildings of solar arrays of clean, renewable solar energy.

1. Introduction

The use of renewable energy has considerably improved in the research and commercial sectors in recent times. Thus, solar energy, being one of the renewable energies, needs to be accorded with priorities since it is readily available and straightforward to operate. Moreover, solar energy beats other renewable energies owing to different benefits, including being environmentally friendly and low prices. The solar PV system has two modes of configuration; off-grid and grid-connected PV systems. The off-grid system has a storage system that charges and supplies power to the loads when there is no radiation [1, 2]. Off-grid systems are beneficial because there is no restriction regarding the areas of installations, such as highlands and islands, where electricity and telecommunication are absent, or places that struggle for grid connections comprising rural electrification and street lighting [3].

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https://doi.org/10.1016/j.heliyon.2021.e08331

Received 24 July 2021; Received in revised form 4 October 2021; Accepted 4 November 2021

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potential dependable. Moreover, the benefits of energy storage are not limited to balancing the variations in ever-rising energy crises in the electricity sector and meeting long-term demand and stable power [7]. Thus, battery use as a storage facility can enhance power production as they can be used to generate stored energy during off-peak periods.

Nevertheless, the sporadic nature of PV power is its utmost difficulty in establishing off-grid PV power plants. In the isolated communities of lesser developed nations, at night and in cloudy weather when the available solar radiation is relatively low, obtaining electricity from the power grid at a reasonably high amount is unavoidable. In sunny weather conditions, however, when PV produces substantial electricity, the surplus power is wasted since the native electrical loads, and the consumption capacity of the power grid is limited.

Consequently, much of the efforts in the PV industry have been dedicated to developing sophisticated PV components, including battery and charge controllers for proper power distributions. To this effect, devising effective and dependable system components assists the solar system to function proficiently in both power production and load management. This made charge controllers and the battery storage system more prominent today due to the rapid growth for solar energy [8].

In this situation, designing a more reliable electricity system and developing advanced PV components for the off-grid and grid-connected PV systems become indispensable. On the other hand, energy storage has remained a complex and most tasking issue encountered in the solar energy application in the absence of charge and discharge of the battery system by the charge controller [9].

With the fact that backup storages make the system more dependable in the period of little production, charge controllers help control the charging and discharging process and assure the system’s reliability. The charge controllers can charge the batteries during the excess of power production from the PV arrays, while the stored power from the battery bank supplies the required amount of energy to the load during the period of little or no generation. However, to appreciate the necessities of bank supplies the required amount of energy to the load during the production from the PV arrays, while the stored power from the battery charge controllers can charge the batteries during the excess of power charging and discharging process and assure the system’s reliability. The in the period of little production, charge controllers help control the system to function proficiently.

Modeling an off-grid PV system is an intermediate step that must pave the way for system sizing and applications. Modeling needs a set of equations characterising all components of the measuring system. Such a system comprises a PV generator, charge controller and an energy storage device.

2. Materials and methods

2.1. System components modeling

Modeling an off-grid PV system is an intermediate step that must pave the way for system sizing and applications. Modeling needs a set of equations characterising all components of the measuring system. Such a system comprises a PV generator, charge controller and an energy storage device.

2.1.1. Modeling of photovoltaic generator

The daily power output produced by a PV array can be measured through Eq. (1) [18].

\[
P_{p(t)} = \left( \frac{G(t)}{G_{in}} - \mu_{T(t)}(T_{c} - T_{a}) \right) \times \eta_{in} \times \eta_{w}
\]

where \( G_{in} \) and \( T_{a} \) are the solar radiation and the ambient temperature respectively at STC, \( \mu_{T(t)} \) is the temperature coefficient of the PV module power; \( \eta_{in} \) and \( \eta_{w} \) are the efficiencies of inverter and wires, respectively;

2.1.2. Maximum power point tracking charge controller efficiency model

The tracking efficiency of MPPT charge controller can be calculated as follows in Eq. (2) [19]:

\[
\eta_{tracking} = \frac{P_{prev,average}}{P_{available}} \times 100
\]

In which \( P_{pv, average} \) \( P_{available} \) are output power and output power of solar PV, respectively.

2.1.3. Modeling of battery bank

Lead-acid batteries are frequently used in energy storage systems. The selection of the appropriate size of battery bank for the solar energy applications needs a broad knowledge of the battery’s charge and discharge conditions, such as operating temperature, load demand, solar radiation pattern, the efficiency of the charge controller and other components [20]. Usually, losses in energy arise when charging the battery bank, and the efficiency falls when the battery gets old and misused. The total battery storage capacity of size C with the charge and discharge rate termed as \( C_{rate} \), the time for charging/discharging the battery, \( T_{cd} \) is given by Eq. (3).

\[
T_{cd} = C/C_{rate}
\]

However, the discharging mechanism of a lead-acid battery follows a famous Peukert’s law [21] of Eq. (4).
\[ C = I^k \Delta t \]  

where \( \Delta t \) is the duration or discharging time while \( I \) represent discharge current and \( k \) is the Peukert constant. The accountability of the battery’s age and the discharge temperature are not considered in the Peukert constant since they negatively affect the battery’s capacity [21]. Also, using Eq. (5), the relationship between current, charge capacity and time can be expressly applied to control the overcharge protections.

\[ I = Ae^{-t} \]  

where \( I \) stand for charging current, \( A \) represents ampere-hour initially discharged from the battery while \( t \) is the time. The quantity of energy conveyed to a battery during charge \( (E_{ch}) \) or supplied by a battery during discharge \( (E_d) \) under the constant-current state is presented by Eqs. (6) and (7), respectively.

\[ E_{ch} = I_a V_{ch} k_{ch} \]  

\[ E_d = I_d V_d t_d \]  

where \( V_{ch} \) and \( V_d \) are the mean voltages, these Equations reveal that the current and the energy supply in a battery are in direct proportionality.

### 2.2. Data acquisition system descriptions

The electrical data acquisition system performance measurements cover the PV module, charge controller, battery, and inverter current [22]. All the measurements sensors and devices were connected to a DT80 dataTaker accompanied by a CEM 20 channel expansion module, where data are stored and retrieved periodically. The PV systems electrical parameters data acquisition system are presented in Figure 1. In the off-grid system, 80 A shunt resistors with a voltage drop of 50 mV were used for the current measurements. The grid-assisted and hybrid systems use 100 A shunt with a corresponding voltage drop of 60 mV for the same measurements. The current flowing through the shunt resistors is proportional to the drop voltage, and it is logged using a defined voltage to the current multiplier in the dataTaker. On the other hand, Kipp & Zonen CMP 11 pyranometer was selected to measure solar radiation data. It has a response time of <500 ns and working temperature from –40 °C to +80 °C [23]. The HMP60 temperature and relative humidity probe measure the outdoor air temperature and relative humidity using a platinum resistance temperature (PRT) detector to measure air temperature [24] and a capacitive relative humidity sensor to measure relative humidity. Tables 1, 2, and 3 present the specifications of the PV module, charge controllers and battery systems, respectively.

### 2.3. Experimental procedure

Three electric bar heaters, each with fan and humidifier, Model: SBFH-2000, were used as loads to draw constant power of 1.2 kW respectively, from batteries of each system on charging and discharging on an overcast and clear sky days. The selected batteries include 6 V M-Molar, Trojan L16RE-2V and Hoppecke 6 OPzS with capacities of 900 Ah, 1235 Ah and 910 Ah discharge time, respectively. They are deep

### Table 1. Module specifications for the three systems at standard test conditions.

| Parameters | Off-grid system | Hybrid system | Grid-assisted system |
|------------|----------------|---------------|---------------------|
| Materials | HIT module | Polycrystalline | Polycrystalline |
| No. of PV modules | 20.0 | 15.0 | 15.0 |
| P_{max} (W) | 190.0 | 250.0 | 250.0 |
| V_{mpc} (Volts) | 37.6 | 29.6 | 30.1 |
| I_{mpc} (Amps) | 5.05 | 8.23 | 8.31 |
| V_{oc} (Volts) | 46.6 | 37.63 | 37.4 |
| I_{sc} (Amps) | 5.57 | 8.67 | 8.84 |
| Power (kW) | 3.80 | 3.75 | 3.75 |

Figure 1. The PV systems electrical parameters data acquisition system indicating the (a) hybrid (b) grid-assisted and (c) off-grid systems’ voltage scaling devices and other measuring instruments.
dischargeable lead-acid batteries mainly designed for renewable energy applications accounting for 75% of PV/wind power systems [16]. To completely protect the battery and guarantee efficiency, a three-charging technique was adopted for the experiments. Figure 2 presents the flow chart of the charging algorithm performed.

However, the battery current is configured so that when the value is negative, it means that the charging process is undergoing while the positive values indicate discharging operations. Each charge controller has an inbuilt MPPT tracking algorithm in which it places a variable load and tracks the maximum power point of the load. Two shunt resistors are also aligned, each at the input of the battery bank and the inverter to measure the current flowing into and out of the battery bank and as well as into the inverters, respectively. The DC power output that emanates from the batteries are fed directly into the inverter for conversion into AC power at a frequency of 50 Hz and voltage of 230 V. The output current, voltage and power from the inverter are measured using the IEM3155 for the off-grid, whereas IEM 2150 for the hybrid and grid-assisted energy meters. The measured parameters were logged by the DT80 data taker at thirty minutes’ intervals and collected using a personal computer via Wi-Fi wireless connections throughout the entire experimental cycle. The battery voltage and current variations measured under constant charging and discharging load power with no external load (charging period) or power supply (discharging period) are studied for further analysis.

Figure 3 shows the experimental set-ups for the three systems.

The experiment was set up to execute a test where the batteries and charge controllers were applied together. This is useful to analyse the influence of the respective charge controllers in the corresponding batteries. The PV generator was used as the current source with a voltage limitation corresponding to open-circuit voltage (Voc). The batteries were initially discharged, irrespective of the loads, until the MPPT charge controllers switched off the loads. This point was considered as the low-voltage disconnect point (cut-off voltage). After this, the batteries were then charged without load connections. It was observed that the batteries could charge indefinitely with no load connections because of the absence of chemical reactions taking place in the batteries. Once again, the batteries were all discharged until the cut-off voltages were reached. The recharging was repeated at this point, but constant loads of 1.2 kW each was used to draw power from each system. The charging was maintained for at least 5 h while all the loads were connected until the three batteries attained float charging. At this point, the charging currents (PV) were put off at the circuit breakers while the equivalent loads were still in connection.

| Parameters                      | Off-grid system | Hybrid system | Grid-assisted system |
|--------------------------------|-----------------|---------------|---------------------|
| Model                          | FLEX Max 80     | Microcare     | Microcare           |
| Equalization voltage (V)       | 14.4            | 12–15         | 12–15               |
| Flat voltage (V)               | 13.6            | 12.5          | 12.5                |
| Frequency (Hz)                 | 20–80           | 20–80         |                     |
| Efficiency (%)                 | 98              | 96            | 96                  |
| Boost voltage (V)              | 14.5            | 14.5          |                     |
| Switch current (A)             |                 | <10/hr        |                     |
| Operating temperature range (°C)| -40 to 60       | 0–40          | 0–40                |

**Table 2. Charge controller specifications for the three systems.**

**Table 3. The technical data of the battery bank.**

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**Figure 2. Flow chart of charging algorithm.**

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**Table 3.** The technical data of the battery bank.
3. Results and discussion

3.1. Long term performance analysis

Generally, the battery current in the three systems was observed to be maximum from January up to April, with the highest peak in January and February, the typical months of summer. The negative values of battery current show the charging of the battery, hence the downward curves of all the systems, whereas the battery voltage is the upward curves with positive values. About 10% of the data was lost due to components failures. The monthly variations of battery current and voltages are presented in Figure 4.

The average battery current monitored for the period in Figure 4 were measured to be -1.203 A for the M-Molar in (a) while for the Hoppecke and Trojan in (b) and (c) are -1.03 and -0.23 A, respectively. Nevertheless, the battery voltage for the Hoppecke remains high and stable in the range of 51–55 V for about 3–5 days, irrespective of the weather conditions. Thus, even early in the morning and at night when there was low solar radiation, this battery system still powers a load of more than 1.2 kW between 5 to 6 h off-peak. Figure 5 presents the average temperature as well as the mean global solar radiation measured for one year. The minimum mean monthly solar radiation of 3.03 kWh/m²/day was recorded in June, the peak of the winter season, whereas the maximum 7.34 kWh/m²/day was recorded in December, the peak of the summer season.

The average radiation for the typical year was 4.98 kWh/m²/day, and the average temperature was 16.88 °C. Similar values were reported in [17] in Durban, South Africa, where average daily irradiance varies from...
the least value of 110 kWh/m² in June to 190 kWh/m² in January, while the lowest monthly average daily temperatures being 15 and 16 °C were recorded in June and July respectively.

3.2. Effect of charging with constant load

The experimental work was done at a constant load of 1.2 kW. Each of the systems started powering from the lowest cut-off voltages. The first stage among the three charge cycle is a constant current that drives the battery voltage up to around 07h15 at sunrise. At this point, the output power for each PV array increases gradually, and the battery voltages respond accordingly. This is in accordance with the findings [25, 26]. However, on perceiving non-uniformity in discharging, the MPPT goes into an equalised mode to restore battery bank balance before switching to boost mode as its main charge mode. Usually, this stage leaves the battery 75–90% of its capacities depending on irradiance conditions [27]. The PV power produced at this stage was fed to the load directly instead of charging the battery. Nevertheless, the MPPT started charging the batteries at a voltage of 49.9, 45.3 and 47.2 V for M-Molar, Hoppecke and Trojan battery systems, respectively, at 11h45. During this stage, most of the power from the PV array feeds the batteries while the rest goes to the load, as presented in Figure 6.

On the other hand, the performance of each of the battery current and voltage in Figure 6 could be described in three phases. Phase A represents the boost charging stage. In this stage, MPPT is triggered, and the charge controller attempts to deliver the power requirement of the battery by charging it at the maximum power point of the PV array. It is performed at a great battery current and battery voltage until the set point for absorption voltage is reached at the value of 55.4 V in each system.

The next charging stage, phase B, is the equalisation stage, and it is considered constant voltage performed to normalise the battery voltage of all the cells. The charging current decreases gradually from 27.7 to 18.5 A for the M-Molar while Hoppecke and Trojan decreased from 15 to 10 A and 23 to 13 A, respectively at the end of each phase by charging it at the maximum power point of the PV array. However, according to research conducted by [28], the battery voltage descents from 2.05 V before sustaining at a discharge plateau value of 1.85 V and supplies a discharge current of 0.03 mA to the solar cell and maintains over 80% of its charged capacity after more than 2h. It is noticed that during the absorption charging stage, the Trojan battery voltage is more stable, the voltage doesn't exceed 56 V as compared to the M-Molar and Hoppecke battery systems. Since the charging time is more than the boost charging stage, the charge voltage was kept moderately high so as to recharge the battery fully with reasonable time.

Phase C is described as float charging. Here, the charge controllers maintained the high voltage 53.9, 51.5 and 49.2 V for the M-Molar, Hoppecke and Trojan batteries, respectively, while their corresponding

Figure 5. The average temperature and mean global solar radiation measured for one year.

Figure 6. A day profile graph of current/voltage against charging time for (a) M-Molar (b) Trojan (c) Hoppecke batteries to describe the three-stage MPPT charging algorithm.
charging current declined. This ensures that the battery state of charge is fully maintained. In the same way, the daily charge and discharge graphs for the current with and without electrical load connections are shown in Figure 7. The battery charging is preceded by a rise in voltage, as explained in Figure 6.

However, high voltage enhances gas sulphating as well as shedding of paste that bring about a shorter lifespan of the batteries and capacity loss. Meanwhile, the battery capacity increases gradually over the charging time, attaining up to 230 mAh/cm² in the solar to-battery charging efficiency presented by [29] for charging with a load integrated while the efficiency is mostly lesser than the solar module efficiency with the non-loaded. Hence, using Eq. (5), the ampere-hour relationship reveals that the M-Molar battery current with load connection has the highest charges of -27.75 A at 13h30, whereas, for Hoppecke and Trojan systems, 12h00 were -18.51 and -25.23 A, respectively. Solar radiation and module temperature are the main influencing factors affecting PV power production [22]. PV current curve does not always follow the irradiance curve directly throughout the day as expected since the photo-generated current is directly proportional to solar irradiance [6]. However, the connected load also determine the amount of current released by the PV module. PV open circuit voltage tends to decrease with an increase in the module temperature. The current and voltage distribution of the PV, charge controller and battery for the one week reporting period are presented in Figure 8.

In Figure 8, the negative battery current depicts charging, whereas load supply (discharging) was represented with the positive current. Comparing Figure 8 (a-c) indicates that the PV voltage increases with solar irradiance in all the systems. At midday which corresponds with peak module temperature, a slight dip of the systems' voltages was also observed. Furthermore, the PV current appeared to have increased with the solar radiation but dropped by approximately half around midday, as seen in Figure 9, where a day data is presented to depicts the PV output power, battery power and power ratio.

The changes between operating energies before and after the charge controllers signify the charge conversion losses. Hence, it is noticed in Figure 9 that a very high level of efficiency, featured by the power ratio, is attained virtually in all the charge cycles for the three systems, excluding the final stage of the cycle, when the charge controller begins float mode, as well as the stage changes. At a given time during the experimental test (about 2:58 PM), a decrease in current is noticeable owing to the passage of clouds above the test position. At this point, the PV module is unable to provide sufficient power to the electrical load. Based on the typical operation of MPPT charge controllers, the systems' charge controllers continuously monitor the PV power level and batteries state of charge, as shown in Figure 6.

### 3.3. Energy and power of lead-acid battery systems

Two essential strategic conditions for battery systems are power requirement, both for storage capacity as well as for charge and discharge current, as seen in Eqs. (6) and (7), respectively. The discharging process in Figure 10 started immediately after the PV circuit breakers were put off, which made the solar array output power drops. The battery systems were only responsible for feeding the loads. The graph depicts a constant power discharge profile of the three systems, in which the loads are constantly controlled at 1.2 kW. It was observed that the battery voltages began to drop slowly in response to increased demand during the current change in the opposite way. Eventually, the battery voltages were reduced to the low voltage cut-off as the loads drew power from the batteries. This behaviour is in line with the findings [30].
However, from the experiment, the cut-off voltage for the M-Molar, Trojan and Hoppecke systems are 39.1, 29.9 and 45.5 V, respectively. It is expected that the sudden drop in the battery current and voltage of the M-Molar system that lasts for only about one and half hours means that the battery system does not hold charges long enough due to weak battery capacity, unlike the Hoppecke and Trojan systems that last for about five hours each. Near the end of discharge, the current is significantly increased in each system to compensate for the voltage drops, increasing ohm polarisation and progressing the end of discharge. The AC load power measurements obtained show that the three systems fluctuate differently with respect to time, as presented in Figure 11.

The load power for the grid-assisted system is more stable and has more useful power as compared to off-grid and hybrid systems. The fluctuations are more significant for the grid-assisted system with excess power losses. This could be due to its slower discharging rate, as can be observe in Figure 11. Also, the spikes on the power curves at the beginning and at the end of charging correspond to periods when there is a sudden increase and decrease in demand of the battery bank. The power in the battery has to be discharged for a while until the demand is met before returning to its initial charging level. However, Figure 12 shows a graph of PV power production and AC constant load with respect to time in each of the systems. Generally, each of the systems begins generating power from 07h30, with the highest power being generated at noon. Based on the measurements, the power fluctuates maximum in Figure 12 (a) around 2.1–2.5 kW around noon.

Figure 8. The effect of solar irradiance on the current and voltage output in PV systems in (a) off-grid system (b) hybrid system (c) grid-assisted system.

These fluctuations might be caused by damages at the first cell string on the PV array’s east side, thereby causing hot spots. This justifies the multiple steps observed at higher irradiance. The smooth spikes found in Figure 12 (b) and (c), respectively, were results of evidence of no hot spots at the modules or strings of the arrays. The constant AC load observed in Figure 12 (c) shows a stable capacity of the battery. Even at night or in the morning, when the PV is not generating, the system still delivers the same power to the load. However, the AC power for the off-grid can only deliver a constant load from 07h30 to 20h00. It can be seen that the system can only last for about 2 h after the sunset at 18h00, and the AC load goes to zero showing that the capacity of the battery has almost reached to its lifespan. The system’s battery capacity in Figure 12(b) is relatively stable since the AC load to about 20% during the off-peak period. On the other hand, to attain the maximum power of the battery, the external resistance of the circuit should be the same as the battery’s internal resistance [31]. Figure 13 demonstrates the power against current requirements for different capacities of the three systems. Figure 13 shows the relationship between power and current. When the power increases, the current also rises, unlike the energy of the battery. Thus, batteries have to be discharged at high currents to supply high power to the PV systems. The frequency distribution of the battery voltage in each system is shown in Figure 14. Except for hybrid, off-grid, and grid-assisted battery voltages, there were more than 150 distributions; while the peak is at class 50–54 in all three systems, the off-grid is the highest of up to 250 distributions.
It is evident that battery voltage is distributed between 40-44 to 60–64 in all three systems. The dominating battery voltage of the off-grid system is detailed elsewhere [6, 32]. The power in the battery bank can be lost either in use or idle mode. Hence, slight self-discharge amounts affect the whole system efficiency. Thus, self-discharge turns out to be an essential matter in discussions, as depicted in Figure 15.

The reactive power generated is strongly dependent on the AC power, as observed in Figure 12, which depends on solar irradiance, as seen in Figure 15. The reactive power for the three systems fluctuates around 0.58–0.61 W. PV and battery work in pairs to make sure that they generate the needed power to the load. The weather data, including ambient temperatures, cleanness index, and solar irradiance in Alice, South Africa, are supported in the findings [33, 34, 35]. The loads were centred on normal residential and commercial practical activities, as depicted in Figure 16, which shows rises in power consumption during the morning from 08h00 and highest at mid-day, especially hybrid systems that involve commercial activities by the workers. Little energy is being consumed at night from 17h00–20h00 for off-grid and hybrid systems.

Among the three systems, the highest consumptions are found at 12h00 for hybrid systems. In addition, the load behaviour depicted over an entire day showed that off-grid, hybrid and grid-assisted systems are highest at 456.12, 568.87 and 80.00 Wh, respectively, at a peak irradiance of 823.45 W/m².

The measured and predicted charge controller efficiency were plotted against time as shown in Figure 17. As expected, higher efficiency was noticed at solar noon of favourable weather conditions.
Figure 12. PV generated power and AC constant load against the time of the day for (a) off-grid (b) hybrid and (c) grid-assisted systems.

Figure 13. PV power against PV current reliance for a 48-V at (a) 900 Ah for off-grid (b) 910 Ah for the hybrid system and (c) 1235 Ah for grid assisted system.
The regression analysis displays a well-fitted correlation for the three charge controllers. The measured and predicted charge controller efficiency is different from those delivered by the STC technical specifications [36, 37]. The maximum measured efficiency for FlexMax in off-grid, Microcare in hybrid and Microcare in grid-assisted are 95.98%, 95.21% and 98.21%, respectively, which are lower than the manufacturers’ specifications. The average values for both measured and predicted efficiency are presented in Table 4.

The observed differences between measured and predicted values are the results of power losses in the subsystems.

4. Conclusion

This paper presents the charging and discharging mechanism of battery performances for PV energy storage. The study utilised a three-stage charging mechanism where constant current, constant voltage, and floating charging were studied. The proposed design was validated through experimental results. The performance measured efficiency results in off-grid, hybrid and grid-assisted are 95.98%, 95.21% and 98.21%, respectively. The battery capacities of Hoppecke and Trojan systems are respectively more stable when deployed with a load of more than 1.2 kW. This is justified by being able to last up to four to five days.
during off-peak periods. The reactive power for the three systems was found to revolve around 0.58–0.61 W. The results from the experiment show that the charging mechanism is reliable with the planned three-stage charging control mechanism. The PV voltages in all three systems were found to increase with the increase in solar irradiance, whereas the subjected load influenced the PV currents distribution. The difference between average measured and average predicted charge controller efficiency is not more than 0.5%. All the off-grid systems were closely monitored in various weather conditions. Hence, it can be reliably used for PV performance monitoring for all parameters with a high degree of precision, attractive, environmentally system of low maintenance requirements that can meaningfully fulfill the normal isolated community’s electricity consumption desires.

Declarations

Author contribution statement

Edson L. Meyer: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data.

Oliver O. Apeh: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Ochuko K. Overen: Performed the experiments; Contributed reagents, materials, analysis tools or data.

Funding statement

Oliver O Apeh was supported by the National Research Foundation (NRF), South Africa (129641).

Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

Acknowledgements

Special thanks to the members of staff and the students of Fort Hare Institute of Technology (FHIT) for their technical support of this research.

References

[1] W. Cai, et al., Optimal sizing and location based on economic parameters for an off-grid application of a hybrid system with photovoltaic, battery and diesel technology, Energy 201 (2020) 117480.
