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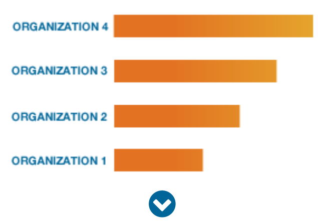

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Published in: 2019 16th International Conference on Quality in Research (QIR): International Symposium on Electrical and Computer Engineering

Date of Conference: 22-24 July 2019

Date Added to IEEE *Xplore*: 14 November 2019

ISBN Information:

INSPEC Accession Number: 19138852

DOI: 10.1109/QIR.2019.8898277

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2019 16th International Conference on Quality in Research, QIR 2019 - International Symposium on Electrical and Computer Engineering
July 2019, Article number 8898277
16th International Conference on Quality in Research, QIR 2019; Padang; Indonesia; 22 July 2019 through 24 July 2019; Category numberCFP19QIR-ART; Code 154240

Characteristics of lead-acid battery charging and discharging against residential load in tropical area (Conference Paper)

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Abstract

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Electrical system in remote areas that cannot be connected to national electricity networks can be served by installing solar based off grid system. The battery bank energy storage as an important part of off grid PV system still have challenges in renewable energy systems and hardly depend on weather conditions. This article will focus on the characteristics of lead-acid battery charging and discharging against residential loads. The research methodology used by testing the rooftop PV system for residential load useage which consists of 2 units 200 Ah battery, 1 unit off-grid inverter 1500 VA, 4 solar panels 260 Wp/unit, and vary residential AC load. The PV loading test was conducted to achieve battery average internal resistance as well as state of charge (SOC). The results of battery characteristics testing show that when clear sky during the day, the charging current is sufficient to charge batteries, so even high load such as air conditioner operated, PV generation still capable in serving loads without termination. The system will be interrupted only if the inverter current limit exceed. This battery usage characteristics can be used as a basis for further demand side management of residential load powered by PV system to improve continuity supply. © 2019 IEEE.

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And Residential load | Characteristic of charging and discharging | Lead-Acid Battery

Indexed keywords

Engineering controlled terms: Air conditioning | Battery management systems | Electric energy storage | Electric inverters | Electric utilities | Housing | Lead acid batteries | Photovoltaic cells | Renewable energy resources | Tropics

Engineering uncontrolled terms: Characteristic of charging and discharging | Charging current | Electrical systems | Electricity networks | Internal resistance | Renewable energy systems | Research methodologies | Residential loads

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Characteristics of Lead-Acid Battery Charging and Discharging Against Residential Load in Tropical Area

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Abstract*—Electrical system in remote areas that cannot be connected to national electricity networks can be served by installing solar based off grid system. The battery bank energy storage as an important part of off grid PV system still have challenges in renewable energy systems and hardly depend on weather conditions. This article will focus on the characteristics of lead-acid battery charging and discharging against residential loads. The research methodology used by testing the rooftop PV system for residential load useage which consists of 2 units 200 Ah battery, 1 unit off-grid inverter 1500 VA, 4 solar panels 260 Wp/unit, and vary residential AC load. The PV loading test was conducted to achieve battery average internal resistance as well as state of charge (SOC). The results of battery characteristics testing show that when clear sky during the day, the charging current is sufficient to charge batteries, so even high load such as air conditioner operated, PV generation still capable in serving loads without termination. The system will be interrupted only if the inverter current limit exceed. This battery usage characteristics can be used as a basis for further demand side management of residential load powered by PV system to improve continuity supply.

***Keywords*—Lead-Acid Battery, Characteristic of charging and discharging, and Residential load**

I. INTRODUCTION

Electrical systems in remote and rural areas which difficult for the national electricity utility to serve consumers in the area, because of the high operational and non-operational costs, the off grid generating system is the solution. Therefore, many off-grid communities have used diesel engines as the main source of energy to meet electricity needs, the government has also been involved in installing a series of self-renewable electrical energy with a battery energy storage system (BESS) [1]. However, energy storage systems are one of the biggest challenges for renewable energy systems, especially in stand-alone photovoltaic and windmills systems, where the battery's own energy storage system has proven to be very reliable because of its high-efficiency and response time [2]. Not only that, energy storage systems (ESS) in photovoltaic systems are a very economic system for the sale and purchase of electrical energy by using electricity on the network during the day and at night using electricity from photovoltaics [3].

Energy storage technology is classified according to the time needed to store energy in accordance with the application form; these categories are instantaneous (less than a few seconds), short-term (less than a few minutes), medium-term (less than a few hours), and long-term (days) [1, 4]. In addition, from BESS, there are various types of energy storage technologies [4-8]: pumped hydro energy storage (PHS), compressed air energy storage (CAES), energy storage that uses wheels to store kinetic energy (Flywheel) (FES), hydrogen-based energy storage systems (HES), energy flow battery storage (FBES), superconducting magnetic energy storage (SME), and thermal energy storage (TES). However, due to flexible placement, efficiency, scalability, and other interesting features [9], BESS is the preferred technology [10]. This is because, in terms of the level of technological development, BESS is superior to other energy storage systems, as shown in table 1 [5]. In table 1 below it can be concluded that the capital cost per kWh of CAES, PHS, and TES is very low compared to other energy storage technologies. Meanwhile, CAES has lower capital costs per kWh among developed technologies. Flywheel, Super capacitor, and SMEs have the highest efficiency and the fastest response time. Fuel cells and TES have low efficiency mainly due to large power losses. The age of use of the ESS system is based on electrical technology such as SMEs, capacitors and high super capacitors. PHS, CAES, Flywheel, and TES have a long service life. Battery life, battery flow, and fuel cells are not as high as other energy storage systems, because performance of chemicals slowly decreases during operating time.

In terms of environmental health criteria, PHS, CAES, batteries, flow batteries, and SMEs have a negative influence on environmental health because of several different reasons [5]:

- Construction of PHS can replace ecological systems, which may have high environmental consequences.

- CAES based on gas turbine technology is simple and involves the burning of fossil fuels, which causes emissions as a matter of concern for the environment.

- The battery has a toxic residue/disposal for a long time

- Battery flow has the same problem with batteries.

- The strength of the magnetic field of SMEs can be harmful to human health

Today, many types of battery energy storage systems are used for renewable energy storage system (RES), among others, such as Lead-Acid, lithium-ion (Li-Ion), nickel cadmium (Ni-Cd) batteries, and sodium sulfur (Na-S). Table 2 shows the main features of the battery type [5, 7, 11-16]. Regarding BESS used in photovoltaic systems, Lead-Acid is the most widely used technology [12], because the price is cheap, growing, high reliability, fast response, and the rate of slow chemical reactions that causes a decrease in battery capacity during the battery not used in low storage [17]. However, the battery charging process is not linear [18]. Because of the high economic costs generated by changing

BESS, a change in the control method and control strategy is needed to protect the battery from over charging and over discharging [19]. When designing a battery charging method, several parameters must be considered such as the storage conditions on the battery (SOC), battery life, and charging time [20].

Batteries are a widely used part and are increasingly important for a balanced energy system. Many different factors show superiority of Li-ion batteries compared to Lead-Acid batteries for balanced energy storage application Li-ion batteries have become the dominant resource in consumer electronics and vehicle applications [21] and Li-ion batteries have higher efficiency, longer durability, faster-charging ability, and lower added costs for energy supplied during its service life. For this reason, Li-Ion is considered better to be applied to balanced energy storage outside the network [22].

TABLE 1. COMPARISON OF CHARACTERISTICS OF TECHNOLOGY IN ENERGY STORAGE SYSTEMS [5].

ESS Type	Efficiency (%)	Capacity (MW)	Energy Ratio (Wh/kg)	Capital Cost ($/kW)	Capital Cost ($/kWh)	Time Respons	Lifetime (years)
TES	30-60	0-300	80-250	200-300	3-50	-	5-40
PHS	75-85	100-5000	0.5-1.5	600-2000	5-100	Fast (ms)	40-60
CAES	50-89	3-400	30-60	400-2000	2-100	Fast	20-60
Flywheel	93-95	0.25	10-30	350	5000	Very Fast(<ms)	~15
Baterai Pb-Asam	70-90	0-40	30-50	300	400	Fast	5-15
Baterai Ni-Cd	60-65	0-40	50-75	500-1500	800-1500	Fast	10-20
Baterai Na-S	80-90	0.05-8	150-240	1000-3000	300-500	Fast	10-15
Baterai Li-Ion	85-90	0.1	75-200	4000	2500	Fast	5-15
Fuel cells	20-50	0-50	800-10000	500-1500	10-20	Good (<1 s)	5-15
Baterai Aliran	75-85	0.3-15	10-50	600-1500	150-1000	Very fast	5-15
Kapasitor	60-65	0.05	0.05-5	400	1000	Very fast	~5
Superkapasitor	90-95	0.3	2.5-15	300	2000	Very fast	20+
SMES	95-98	0.1-10	0.5-5	300	10000	Very fast	20+

However, at present time, there are many of renewable facilities including Lead-Acid batteries and many requests for new control methods to increase service life on BESS. This article will only focus on the characteristics of lead-acid battery charging and discharging against residential load in tropical area.

TABLE 2. COMPARISON OF QUALITY CHARACTERISTICS OF BATTERIES [5, 7, 11-16]

BES Type	Cost ($/kWh)	Energi rate (MWh)	Energy Spec (Wh/kg)	DoD (%)	Life span	Eficiency (%)	Temperature Op (^{0}C)
Pb- Asam	50-150	0.001-40	35-50	70	5-15	70-80	-5 s/d 40
Na-S	200-600	0.4-244.8	100-175	100	10-20	75-89	325
Ni-Cd	400-2400	6.75	30-80	100	10-20	70	-40 s/d 50
Li-Ion	900-1300	0.001-50	100-200	80	14-16	75-95	-30 s/d 60
VRB	600	2-120	30-50	75	10-20	65-85	0 s/d 40
ZBB	500	0.1-4	60-85	-	8-10	65-85	0 s/d 40
PSB	300-1000	0.005-120	> 400	75	15	60-75	0 s/d 40

Nb: Pb-Acid: Lead-Acid; Na-S: Sodium-Sulfur; Ni-Cd: Nickel-Cadmium; Li-Ion: Lithium-Ion; VRB: Redox Vanadium flow battery; ZBB: Battery flow Zink Bromide; PSB: Battery flow of Polysulfide Bromide.

II. LEAD-ACID BATTERY

Currently, the most common type of battery used as energy storage is Lead-Acid batteries. This battery is most often used because the price is cheaper than other types of batteries. This battery has the characteristic of using lead (Pb) on both electrodes as its active material. In charged conditions, the positive electrode consists of lead dioxide (PbO2) while the negative electrode consists of pure lead (Pb). A membrane is attached to separate both electrodes. Sulfuric acid (H2SO4) is filled in the room between both electrodes as an electrolyte. A fully charged lead-acid battery has an acid density of about 1.24 kg/liter at 250C. This acid density changes according to the temperature and state of the battery charge. An acid density meter or voltmeter can state the state of charge from a battery [1].

All lead-acid batteries operate with the same basic reaction. When the battery unloads, the active material at the electrode reacts with the electrolyte forming lead sulfate (PbSO4) and water (H2O). When charging, lead sulfate changes back to lead dioxide at the positive electrode and lead to the negative electrode, and the sulfate ion (SO_4^{-2}) returns to the electrolyte solution that forms sulfuric acid. The following are reactions that occur in cells.

At positive electrode

$$PbO_2 + 3H^- + HSO_4^- + 2e^- \underset{charging}{\overset{discharging}{\rightleftarrows}} PbSO_4 + 2H_2O \ (1{,}685\ V) \quad (1)$$

At negative electrode

$$Pb + HSO_4^- \underset{charging}{\overset{discharging}{\rightleftarrows}} PbSO_4 + H^+ + 2e^- \ (0{,}356\ V) \quad (2)$$

Whole cell reaction

$$PbO_2 + Pb + 2H_2SO_4 \underset{charging}{\overset{discharging}{\rightleftarrows}} 2PbSO_4 + 2H_2O \ (2{,}041\ V) \quad (3)$$

From this reaction, there will be a greatest potential difference of 2,041 volts in the open-circuit. Reactions on lead-acid batteries can be seen in Fig. 1.

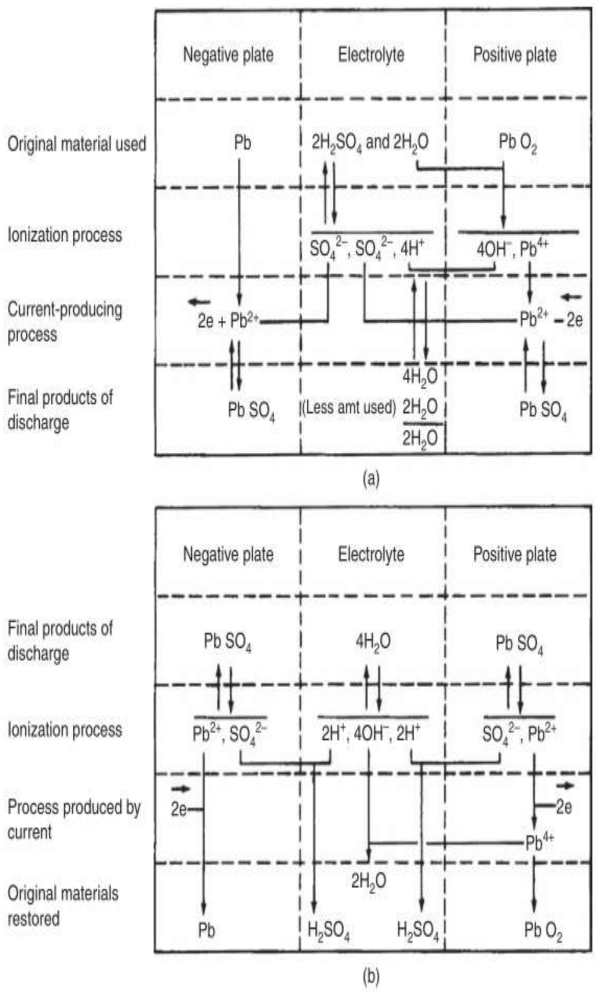

Fig. 1. Discharging and Charging Reaction on Lead-Acid batteries (a) Discharging. (b) Charging [23]

III. Method

The research methodology used is by testing the rooftop PV system for residential load which consists of 2 units 200 Ah battery, 1 unit off-grid inverter 1500 VA, 4 solar panels 260 Wp/unit, and vary residential load alternating current (AC). The test circuit is as shown in Fig. 2.

Fig. 2. Residetial rooftop PV system 1000 kW

Whereas the load current is measured using the Multi-Function DIN-Rail D52-2047 Digital Meter as show in the following Fig. 3.

Fig. 3. AC bus measurement PV off-grid output for various loads

IV. Result and Discussion

The PV output power and charging current for four units 260 Wp solar panel is shown in Fig. 4. In order to estimate available battery capacity remaining, the PV loading test was conducted and the achieved result as shown in Table 3.

TABLE 3 PV LOADING TEST RESULT

No	V (Volt)	I (A)	Pload (W)	Rin (Ohm)
0	24,3	0	0	NA
1	24	0,42	92,40	0,08
2	23,7	0,85	187,00	0,08
3	23,3	1,27	279,40	0,08
4	22,9	1,71	376,20	0,09
5	22,7	2,14	470,80	0,08
6	22,6	2,57	565,40	0,07
7	22,4	3	660,00	0,06
8	22,2	3,41	750,20	0,06

The average internal resistance 0.07 Volt was used to estimate the battery state of charge (SOC). The estimation of available battery capacity remaining is as shown in Table 4 during charging voltage or solar panel was switch on.

TABLE 4 LUMINOUS PV BATTERIES CAPACITY

Vbat	SOC (%)
22,2	0
23,1	25
24	50
24,9	75
25,8	100

The test results of battery discharging against residential loads can be seen in Fig. 5, Fig. 6 and Fig. 7. Where in Fig. 5 shows the comparison of load voltage and charging voltage of the battery, so that the average voltage generated by solar panels is 25.8 volt as charging voltage and load voltage 25.6

volt. This shows that to use the power from the battery is needed a battery voltage that is higher than the voltage required by the load. While in Fig. 6 there is a graph of the comparison of the charging current and load current on the battery, where the test data is taken during the sunny sky conditions and hot weather at 11.05 a.m up to 11.53 a.m with an average current produced by battery charging and consumed by load are 17.21 amperes and 2.15 amperes respectively.

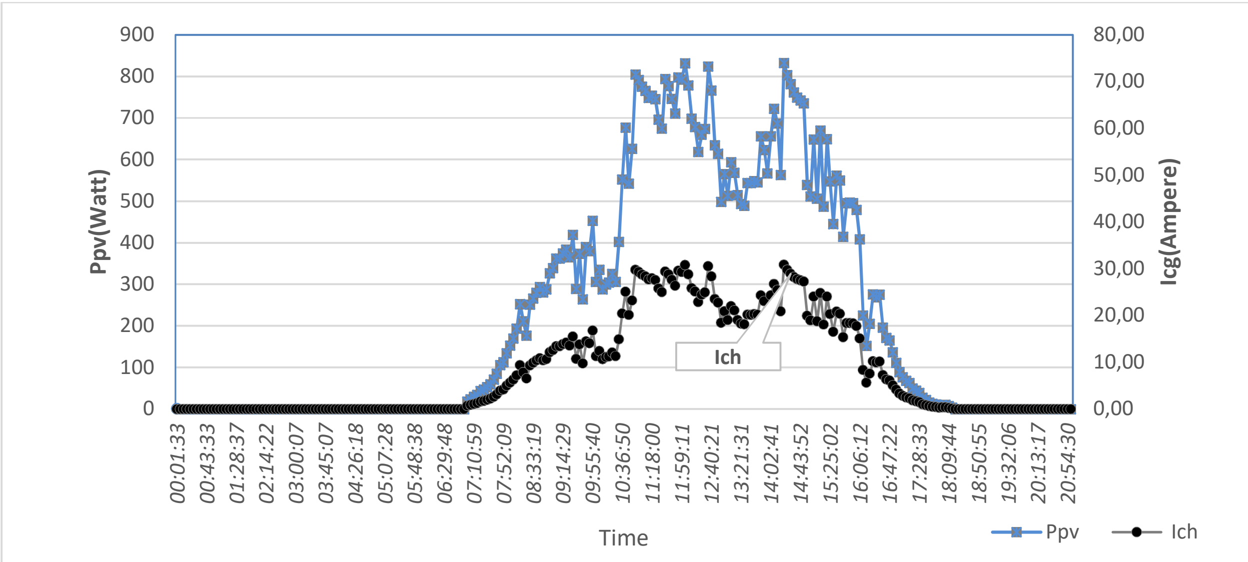

Fig. 4. PV power and charching current

From the Fig. 6 can be seen that maximum battery charging current i.e. 19.22 Ampere at 11.21 a.m, then the large battery discharging current to the load at the same time is 3.9 Amperes with terms the Air Conditioner and the fan is on-simultaneously as residential load.This shows that when the battery charging current is high, the battery discharging current handle large load. However at 11.22 a.m when residential load increase with water pump turn on, there was overload with the battery charging value of 17.33 Ampere, this happened because the battery charging current produced was not balanced with the battery discharging current to the load used. Under clear sunshine, the charging current value between 15 Amperes to 20 Amperes. Therefore, battery discharge current can still serve large loads such as the AC is turned on as shown in Fig. 6 from 11.35 am to 11.53 am.

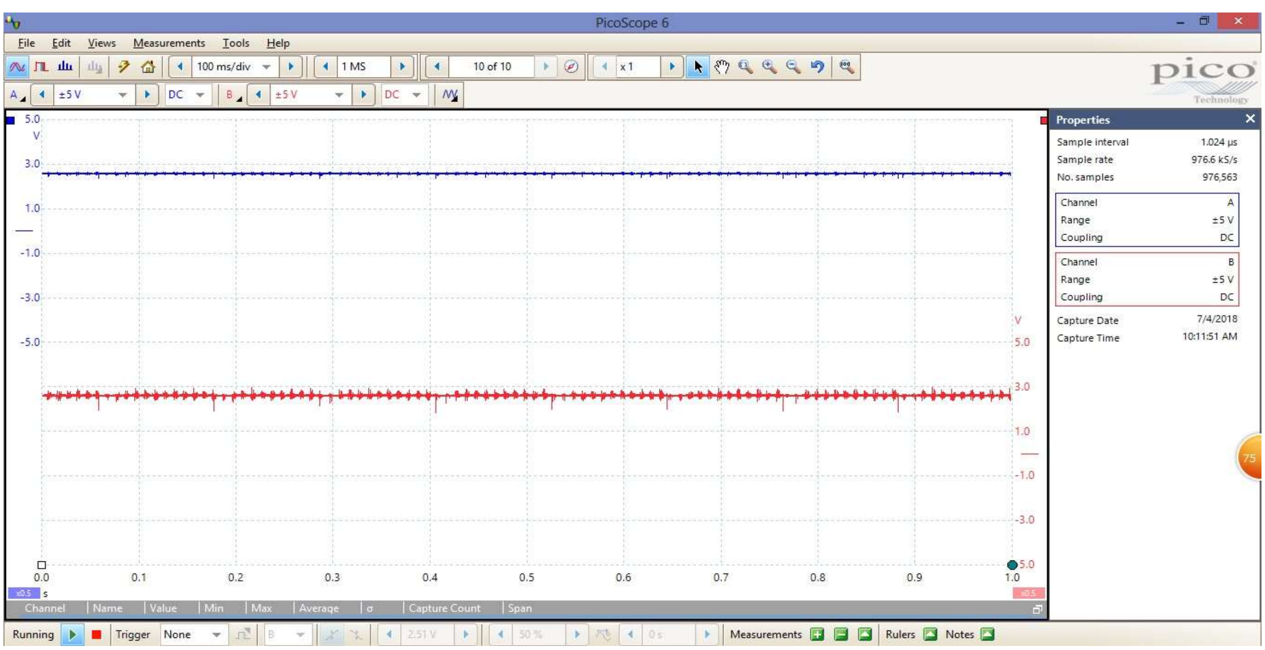

Fig. 5. Picoscope display of charging voltage and battery voltage without air conditioner load

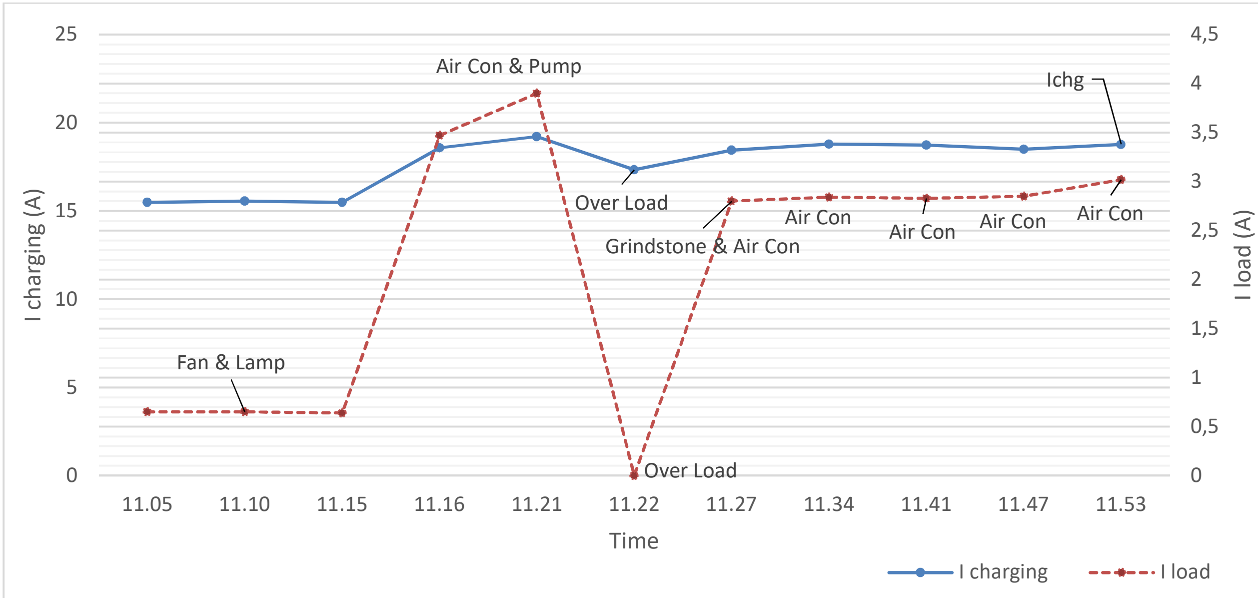

Fig. 6. Comparison of charging current and load current for various types of loads

The Fig. 7 also shows the relation of load power and load current for several hours under various type of load. The basic load are lamp and fan consumed 0.73 Ampere. When the AC is turned on the load current increases to 3.03 amperes and the battery can still work normally. At 01.16 pm there was an overload when battery discharge current to the load was reach 4.34 Ampere with terms the air conditioner and the high lamp load turn on simultaneously as a residential load. As well at 1:18 p.m. , there was an overload where the battery discharging current to the load was reach 4.5 Ampere with the air conditioner and grindstone on simultaneously as residential load used.

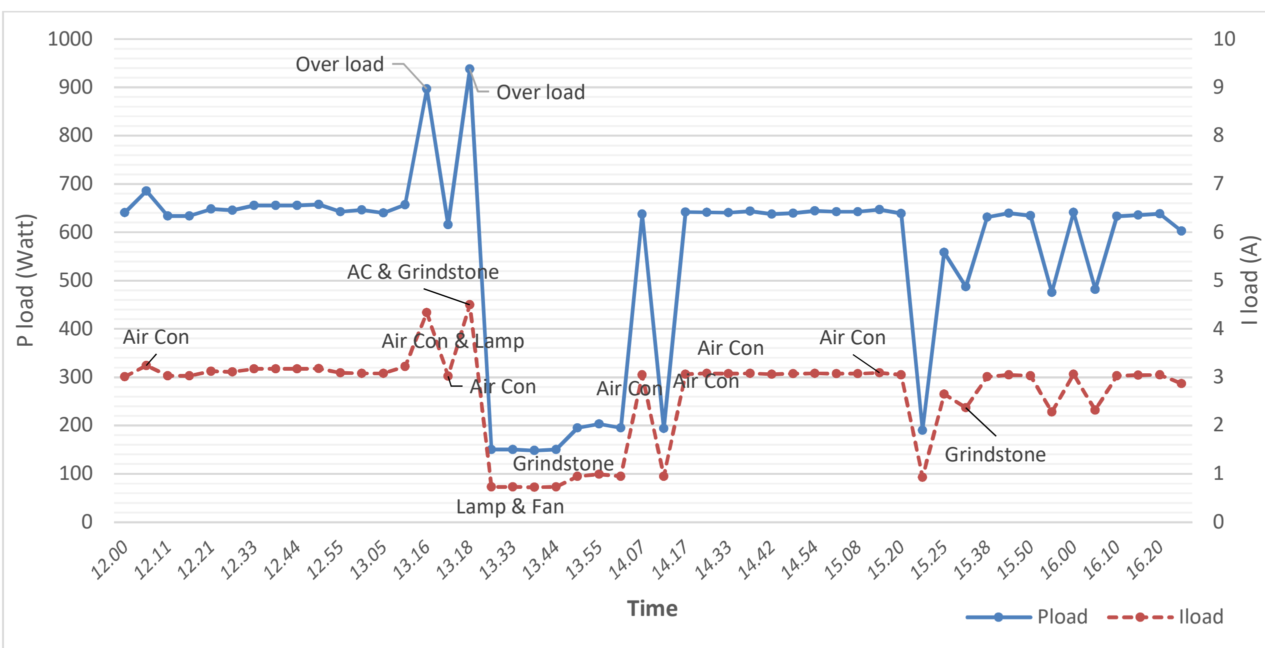

Fig. 7. Load power and current under various types of loads

And from the graph in Fig. 7, it can be concluded that the overload will occur when the value of the battery discharging to the residential load above of 4.3 Ampere.

From above analysis of the characteristics of lead acid batteries usage against various load conditions the right load management is needed to improve service continuity. In charging current conditions high or daylight with clear sky, a high load scheme can be applied, whereas in conditions of low charging or overcast conditions, a medium load scheme should be applied. However when the charging current is not available or at night, a lower load or lighting load scheme should be applied. By regulating the loading side, it is expected that there will be an increase in the continuity and and life length of PV system storage.

V. Conclusion

The characteristics of lead-acid battery charging and discharging against residential load in tropical area have been done and reported in this paper. The results show that during clear sky and good weather, the charging current rate between 15 Ampere to 20 Ampere, and load current can be served even AC load is on. However, in cloudy conditions or in the afternoon before sunset, the charging current will decrease. If given a high load, the battery discharging current can support only for 2 hours. The battery will overload when loaded with currents over 4.3 Ampere. To get complete and accurate result, thus online data retrieval system is needed to record data automaticaly. Furthermore, demand side load management technique is neededs for residential powered by PV system to extend battery operation time continuity supply.

Acnowledgment

The authors would like to thank for the research funding support from the Directorate General of Higher Education Ministry of Research, Technology and Higher Education under Penelitian Tesis Magister research scheme.

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For acceptance, fully registration, and presentation of the paper with the title of

Characteristics of Lead-Acid Battery Charging and Discharging Against Residential Load in Tropical Area

In The 16th International Conference on Quality in Research (QiR) held on 22-24 July 2019 at Padang, West Sumatra.

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