Performance of a 10 kWh Zinc-Bromine Flow Battery in Solar Power System

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ABSTRACT

Solar energy with solar cell technology is considered as clean energy. Due to intermittent solar radiation, its electrical production is affected. When solar panels are directly connected with grid, it results in electrical fluctuation in transmission lines. Energy storage is used to shift peak, regulate voltage, frequency, and power quality of solar power in the lines. The zinc bromide flow battery (ZBFB)is one type of flow battery employed in solar power system. In this study, the objective is to compare the performance of 10 kWh ZBFB during the charging process made according to electrical power produced by photovoltaic panels, with the performance of the same ZBFB during the discharging process with constant load. It was found that current and voltage of the ZBFB in charging and discharging processes depended on solar radiation and load consumption, respectively. Moreover, the PV power is higher than that of the charged battery because of solar charger efficiency. As comparing the battery performance between charging and discharging processes, it was found that the discharging efficiency of the battery was lower than that of the charging one due to PCS effiency of AC-DC converting.

1. INTRODUCTION

Nowadays, there is a yearly increasing electricity demand according to both population and economic growth. While controlling carbon dioxide emissions is a problem that all countries emphasize on reducing the problem of global warming occurrence, renewable energy sources are interesting to be utilized in place of fossil fuels.

Utilization of renewable energy such a solar energy with solar cell system is considered as clean energy being very popular in many countries due to easy installation and low cost with the small system. However, electrical production of the system is directly affected by the environment causing electrical instability. In addition to that, grid connection without electrical energy storage causes electrical fluctuation in transmission lines. Thus, the production is not estimated correctly resulting in being unable to decrease and increase the production during unstable solar energy. The energy storage causes the electrical production system more efficient and stable. With its basic principle, energy is stored during low electrical demand and released during high demand. Thus, it can decrease the peak power production and load in transmission lines as well. In addition to the peak shifting, the storage can be used to regulate voltage, frequency, and power quality [1].

There are several types of energy storage and can be classified as 5 main storages: mechanical energy storage such as compressed air energy storage; thermal energy storage such as sensible thermal storage; chemical energy storage such as hydrogen storage; electrochemical energy storage such as batteries; electrical energy storage as super-capacitors [2]-[3]. Energy storage, particularly electrochemical energy storage or battery is suitable for bulk storage and fast energy storage and discharge.

Redox flow battery (RFB) is one of the most promising batteries consisting of 2 electrolyte storages circulated by pump through electrochemical cells including cathode, anode, and membrane separator. Chemical energy is converted to electricity in the cells when 2-type electrolytes flow through. Electrolytes are separately stored in large tanks outside of electrochemical cells. Size of the tanks and quantity of the electrolytes determine the energy density of this battery. However, power density of RFB depends on the reaction rate at cathode and anode electrodes [4]. This type of flow batter is often called “Redox Flow Battery” because the reaction between electrolytes is reduction-oxidation. The advantage of RFB is high-power, long-time period, separated power rate and energy, simply changed electrolytes, fast response, no self-discharging because electrolytes can not react together due to separated storages.

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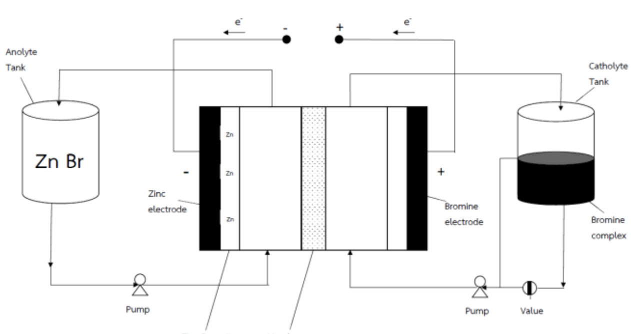
There are different types of existing RFB, depending on the composition of electrolyte: iron/chromium, iron/cadmium, quinone/bromide, vanadium/bromine, and all vanadium among others [5].

Nowadays, vanadium redox flow (VRFB) and zinc-bromine redox flow battery (ZBFB) can be clearly defined as state-of-the-art for the technology [6]. However, ZBFB has advantage over VRFB because the raw materials of electrolyte are cheaper as compared to VRFB [7]. The ZBFB generally consists of two separate electrolyte tanks containing an aqueous solution of zinc/bromide, membrane separator, and electrodes as shown in Fig.1. The stored electrolyte is circulated through each half cell. Membranes are used to prevent the crossover of bromide ions and bromine between zinc and bromine electrodes. During the charging process (Fig.1a), Zinc ions are reduced to Zinc deposited on the negative electrode as shown by Eq.(1)

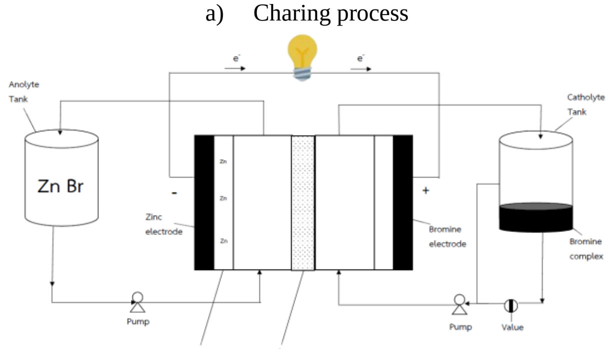
Negative electrode: $Zn^{2+}(aq) + 2e^{-} \rightarrow Zn(s)$ (1)

While bromide ions are converted to bromine at the positive electrode with free electrons as shown by Eq.(2)

Positive electrode : $2Br^{-}(aq) \rightarrow Br_2(aq) + 2e^{-}$ (2)



a) Charing process



b) Discharging process

Fig. 1. ZBFB flow battery

This bromine further forms a polybromide complex which is flushed from battery at the positive electrode by flowing electrolyte and settles to the bottom of the catholyte tank. During discharging process (Fig.1b), zinc is oxidized to zinc ions and bromine molecules are reduced to bromide. [6-9].

Moreover, the ZBFB has the practical energy density of 65 – 75 Wh/kg, which is much higher than that of VRFB (25-30 Wh/kg) [10]. However, its energy density is still lower than that of the theoretical one of 440 Wh/kg due to low conductivity of electrolytes, low reaction rate, conductivity, and high polarization of electrodes, and zinc dendrite [7,11,12]. Therefore, several previous research works have focused on developing positive electrode materials [13-16] as well as electrolytes [17-18]. The zinc dendrite is formed on zinc electrode by nature. It is a cause to not only decrease the battery performance, but also penetrate the membrane causing channel blockage and short-circuiting [6]. Its growth was found to be effectively suppressed by modifying electrolyte with methanesulfonic acid [10]. However, there are few works carried out to study on VRFB/ZBFB performance in photovoltaic systems [5,8,19].

In this study, the objective is to compare the performance of ZBFB during the charging process made according to electrical power produced by photovoltaic panels, with the performance of the same ZBFB during the discharging process with constant loads.

2. SYSTEM DESCRIPTION

To test the ZBFB performance of storing electricity generated by solar cell panels and releasing to loads, the testing system was set up at Faculty of Science, Naresuan University as shown in Fig.1-3.

Fig.1 presents system components: Zinc-Bromine Flow Battery (ZBFB), Hybrid Inverter, and Resistant Load.

In this system as shown in Fig.2, AC power from the grid is converted by a power conditioning system (PCS) to common system DC bus to which PV power is connected by maximum power point tracking solar charger (MPPT-SC) with 3.06 kWp of solar cell panels (Fig.3). Power flows in the system for both directions depending on whether it is charging or discharging. The temperature of electrolytes is controlled by air heat exchanger (cooling tubes with a fan). The two electrolyte pumps and an automatic fan are powered by the DC bus and are considered as auxiliary loads. Specification of the system is presented in Table 1. All parameters are recorded by the inverter for every 5 minutes and their list is summarized in Table 2.

3. METHODOLOGY

In this ZBFB testing, a commercial 10 kWh ZBFB was tested under the weather in Thailand. There are 3 tests carried out as described in Table 3.

In the first testing, the ZBFB was charged by solar cells without grid power and load. Current and voltage of solar charger (I_{sc},V_{sc}), battery (I_b,V_b), battery temperature (T_b), and state of charge (SOC) were recorded by the hybrid inverter. The charging efficiency of the ZBFB ($\eta_{ch\text{-}b}$) is calculated as the ratio of charged battery power ($P_{ch\text{-}b}$) and solar charger power (P_{sc}) as shown in Eq (3).

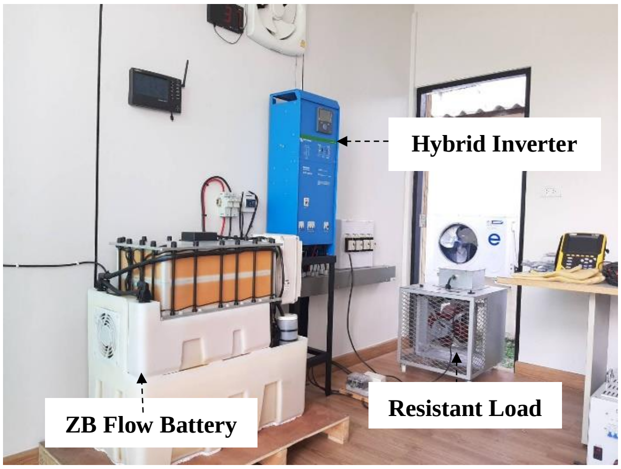


Fig. 2. Testing system of ZB flow battery.

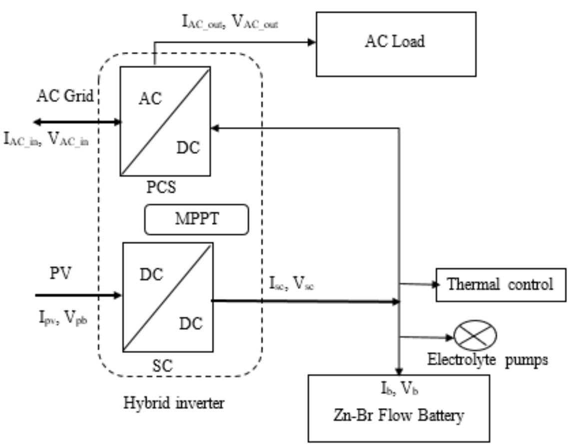


Fig. 3. Diagram of testing system.

Fig. 4. 3.06 kWp solar cell panels for testing system.

Table 1. Technical Specification of Testing System

List of components	Value
1. ZBFB (Redflow ZBM2 10 kWh)	
Voltage (V)	40-60
Rated energy (kWh)	10
Rated power (kW)	3
Operating temperature (°C)	15-50
2. Hybrid Inverter (Victron easy solar 5 kW)	150
Max. PV Voltage (V)	38-66
Input Voltage (V)	230
Output AC Voltage (V)	55.2 – 57.6
Battery Voltage (V)	
3. Resistant Load	
Max. Heating capacity (kW)	5
4. Solar cell panels (Q.PLUS L-G4.2 330)	340
Nominal power (W)	47.07
Open circuit voltage (V)	9.59
Short circuit current (A)	37.63
Voltage at MPP (V)	9.03
Current at MPP (A)	24
Weight (kg)	1994×1000×35
Dimension (mm)	

Table 2. List of recorded parameters by hybrid inverter

List of parameters	Description
$I_{AC\text{-}in}$,$I_{AC\text{-}out}$	AC input and output current
$V_{AC\text{-}in}$,$V_{AC\text{-}out}$	AC input and output voltage
I_{pv}, V_{pv}	PV current and voltage
I_{sc}, V_{sc}	Solar charger current and voltage
I_b, V_b	Battery current and voltage
T_b	Battery temperature
SOC	Battery state of charge, the level of charge of an electric battery relative to its capacity

$$\eta_{ch\text{-}b} = P_{ch\text{-}b}/P_{sc} \quad (3)$$

where $P_{ch\_b} = I_b \times V_b$; $P_{sc} = I_{sc} \times V_{sc}$;

For the second and third ones, the ZBFB was discharged at 0.2 kW and 0.4 kW of load for 5 hours when there is no PV power and grid power. Moreover, the discharging (η_{dis_b}) efficiency of the ZBFB is considered as the ratio of discharged battery power (P_{dis_b}),kW and consumption power of load (P_L), kW as shown in Eq (4).

$$\eta_{dis\_b} = P_{dis\_b}/P_L \quad (4)$$

The round-trip efficiency or the energy efficiency of the ZBFB is estimated as the ratio of battery energy discharged and charged as presented in Eq (5).

$$\eta_{E\_b} = (P_L \times t_L)/(SOC_{dis\_f} - SOC_{dis\_i}) \times E_b \quad (5)$$

where, t_L is time period (5 hours) for electrical load consumption, Eb is the rated energy of the battery (10 kWh). SOC_{dis_i} and SOC_{dis_f} are state of charge at initial and final discharging, respectively.

4. RESULTS & DISCUSSION

4.1 Voltage vs current profiles

The voltage and current profiles of the battery during charge/discharge testings are shown in Fig.4-6. In the charging testing, only PV was connected with inverter without grid power and load. The charging results was shown in Fig.4. As it can been seen from Fig.4, the battery was charged according to solar radiation from 6 a.m to 6 p.m on Jan 18, 2021. Its charging voltage and current variation were between 50 -55 V and 0-25 A, respectively due to intermittent solar radiation. For discharging testing, the load was supplied by the battery power from the inverter without PV and grid connection . The discharging results were shown in Fig.5 and 6. From the figures, the negative current represents discharging. As it can been seen from Fig.5-6, the battery was discharged at constant load of 0.2 kW and 0.4 kW for 5 hours, respectively. From the recorded current and voltage of the battery, it was observed that their voltage and current were constant at 57 V and variable depending of load demand, respectively.

Table 3. Tests carried out on the ZBFB system

No.	Description	Inverter setup
1	Charging battery by solar cells through solar charger	Disconnecting grid and load
2	Discharging battery at 0.2 kW	Disconnecting grid and solar cells
3	Discharging battery at 0.4 kW	Disconnecting grid and solar cells

4.2 Power vs efficiency profiles

The power vs effiency/SOC profiles for battery during charging and discharging cycles are shown in Fig.7-9. Fig.7 presents the power, charging efficiency and state of charge (SOC) of the battery during charging process. In this figure, the battery was charged from SOC of 24% (about 9 a.m) to 70 % (about 4 p.m) for 7 hours. With fluctuated charging power, the charging efficiency could reach 88% at 2 p.m. From the graph, it can be seen that the power of PV is slighly higher than that of the charged battery due to electrical resistant.

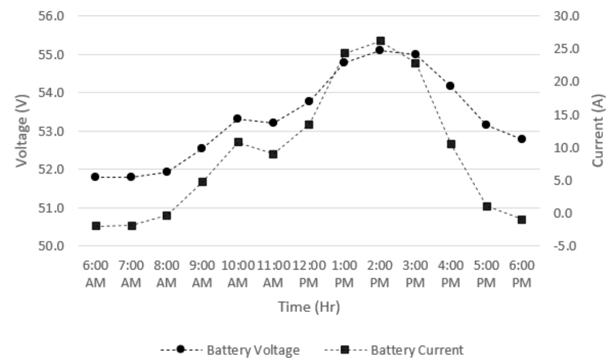


Fig 5. Charging voltage and current profiles on Jan 18, 2021.

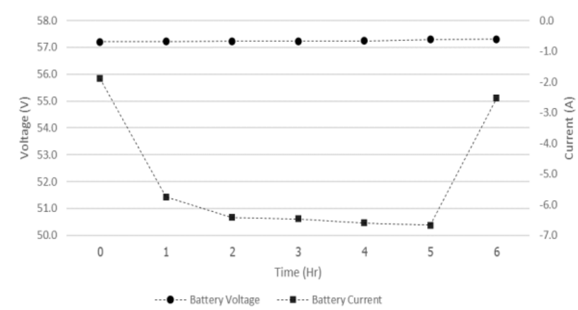


Fig. 6. Discharging voltage and current profiles at 0.2 kW on Jan 16, 2021.

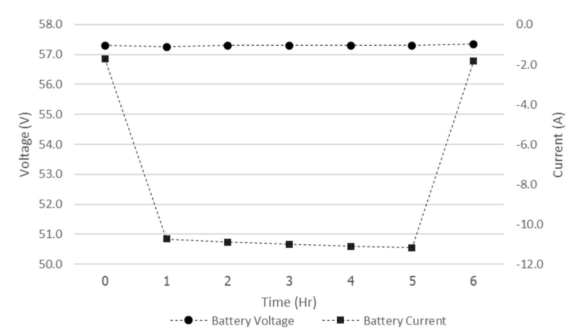


Fig. 7. Discharging voltage and current profiles at 0.4 kW on March 23, 2021.

Fig.8-9 shows the power, discharging efficiency and state of charge (SOC) of the battery during 5 hour discharging process. In Fig.8, the battery was discharged by 0.2 kW of constant load from SOC of 33% to 17 % with its discharging and round-trip efficiencies of 54% and 60% respectively. In Fig.9, the battery was discharged by 0.4 kW of constant load from SOC of 51% to 35% with its discharging and round-trip efficiencies of 64% and 77%, respectively. When comparing the battery performance between charging and discharging processes, it was found that the discharging efficiency of the battery was lower than that of the charging one due to PCS effiency of AC-DC converting. Moreover, the round-trip efficieny was found between 60 and 80 percentage according to [1]. It is slightly low because of auxiliary load consumption (fan and pumps).

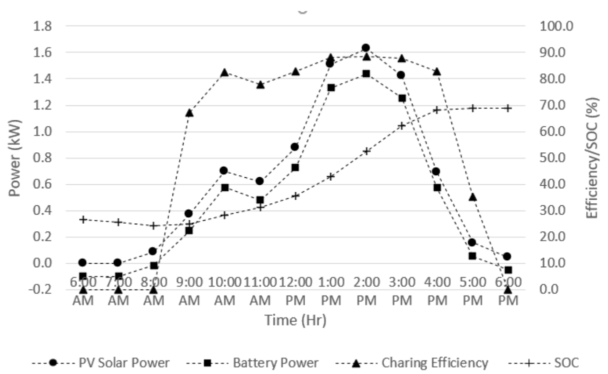


Fig 7. Charging power, efficiency and SOC profiles on Jan 18, 2021.

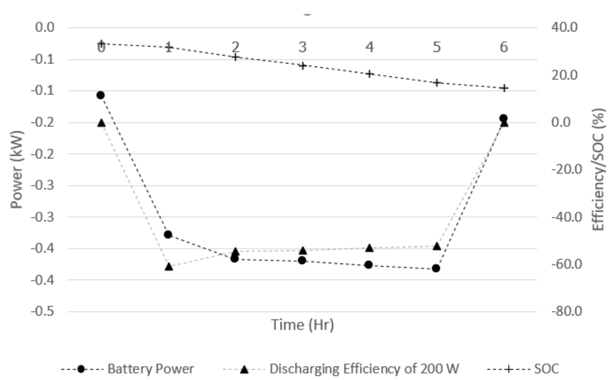


Fig 8. Discharging power, efficiency and SOC profiles at 0.2 kW on Jan 16, 2021.

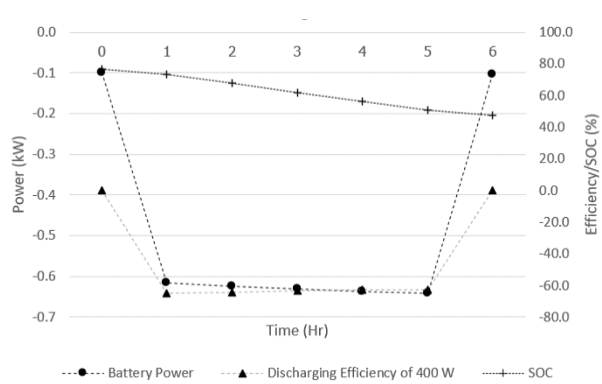


Fig 9. Discharging power, efficiency and SOC profiles at 0.4 kW on March 23, 2021.

4.3 Temperature vs efficiency profiles

Temperature vs battery power profiles during charging and discharging cycles are shown in Fig.10-12. In Fig.10, the battery was charged according to solar radiation resulting in increasing of battery temperature. However, during discharging the battery, it was found that the battery temperature increased as the discharging power increased as shown in Fig 11-12.

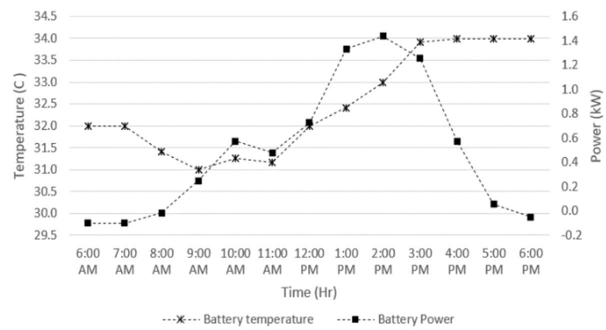


Fig 10. Charging temperature and battery power profiles on Jan 18, 2021.

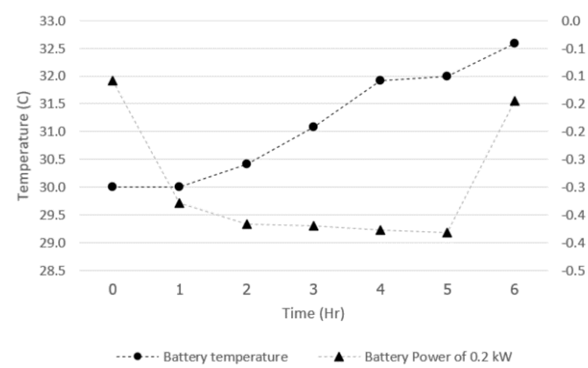


Fig 11. Discharging temperature and battery power profiles at 0.2 kW on Jan 16, 2021.

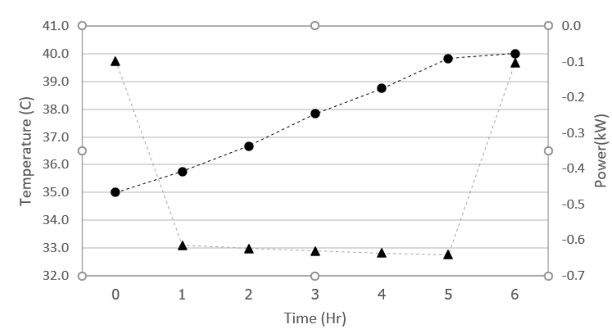


Fig 12. Discharging temperature and battery power profiles at 0.4 kW on March 23, 2021.

5. CONCLUSION

An assessment of ZBFB performance undergoing charging process made according to electrical power produced by photovoltaic panels and discharging process with constant loads was carried out.

In charging process, current and voltage of the ZBFB were varied according to amount of solar radiation but in discharging process, they depended on load consumption.

The power of PV is higher than that of the charged battery as predicted due to effect of solar charger efficiency.

When comparing the battery performance between charging and discharging processes, it was found that the discharging efficiency of the battery was lower than that of the charging one due to PCS effiency of AC-DC converting.

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