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Experimental research on charging characteristics of a solar photovoltaic system by the pressure-control method

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Abstract: The charging characteristics of the valve-regulated lead acid (VRLA) battery driven by solar energy were experimentally studied through the pressure-control method in this paper. The aims of the research were to increase charging efficiency to make the most of solar energy and to improve charging quality to prolong life of battery. The charging process of a 12 V 12 A·h VRLA battery has been tested under the mode of a stand-alone photovoltaic (PV) system. Results show that the pressure-control method can effectively control PV charging of the VRLA battery and make the best of PV cells through the maximum power point tracking (MPPT). The damage of VRLA battery by excess oxygen accumulation can be avoided through the inner pressure control of VRLA battery. Parameters such as solar radiation intensity, charging power, inner pressure of the battery, and charging current and voltage during the charging process were measured and analyzed.

Key words: Solar photovoltaic (PV) system, Charging characteristics, Pressure-control method
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1 Introduction

The increasing demand of energy compels us to develop new technology of renewable clean energy such as solar energy. Energy storage is necessary for a stand-alone solar photovoltaic (PV) system because of intermittence and instability of solar rays. The benefit of such a system is determined mostly by charging methods as well as the life of batteries. Research on battery charging controller has recently focused on the electric-control method and the pressure-control method.

Two different kinds of battery charge controller for valve-regulated lead acid (VRLA) batteries for PV systems or wind turbine generators were developed (Yamazaki and Muramoto, 1998; Fernandez *et al.* 2001). Ross and Markvart (2000) proposed a battery model to investigate the effect of the charge controller strategy on the performance of a stand-alone PV system by using the circuit simulator a circuit simulator PSPICE. Gao (2008) introduced a type of switch circuit which can stabilize the output voltage of the solar cells in the optimum state, and steadily sustain charging current. Mishra *et al.* (1995) proposed a theoretical model of a PV system and analyzed the effect of temperature, battery voltage, and voltage-drop on the charging current of PV cells. Mahmoud (2006) studied the current and voltage characteristics experimentally by an equivalent circuit with a capacitor charging by PV cells through transient analysis. Sun *et al.* (2009) and Zheng *et al.* (2008) designed solar battery chargers of high charging efficiency by using perturb-observe method for maximum power point tracking (MPPT) and implementing the charging strategy with software. Hussein *et al.* (2009) proposed a new effective solar battery charging algorithm for NiCd, NiMH, lead-acid, and lithium-ion batteries in outdoor conditions with variable power in current mode and voltage mode. Zhou *et al.* (2009)

developed and simulated a simple battery charge and discharge protection programme for solar PV system. Huang *et al.* (2009) presented an intelligent solar charging system with a fuzzy logic control method to improve the efficiency of charging, suppress the abnormal battery temperature rise, lengthen the battery's life, and reduce the waste used. Huang *et al.* (2010) developed a charging control system based on a proportional plus integral (PI) algorithm using a pulse width modulation (PWM) charging technique, which can suppress the battery voltage overshoot within 0.1 V and is able to increase the charged energy by 78%. Gibson and Kelly (2010) tested the solar charging system for the iron phosphate type lithium-ion batteries with self-regulating design and MPPT. The conversion efficiency of the whole system reached 14.5% with the battery charging efficiency at nearly 100%.

Charging controllers of a PV system, based on the electric-control method, have been widely studied and improved. Electric-charging method, a method of regulating and limiting electric current and voltage during battery charging and discharging, does have many advantages, such as low cost, small size, and high efficiency. However, it cannot fully resolve the expansion problem caused by excessive gas produced during the over-charging process of the battery, and thermal failures occurring in battery charging process still exist. Zhu *et al*. (2009) and Tan (2010) studied on batteries such as VRLA batteries, which are widely used in the fields of telecommunications, electric power, and traffic systems, with the pressure-control method. The pressure-control method proposed by Xu *et al*. (1999) can solve thermal failures effectively through monitoring the inner pressure changes to control charging process based on the battery internal oxygen recycling theory. During the charging process of a VRLA battery, the internal-oxygen cycle and reaction may raise the electrolyte temperature, decrease inner resistance, and increase the charging current. Such a vicious circle results in thermal runaway and ultimately leads to the destruction of the cell especially in a high-temperature environment.

Battery charging characteristics driven by a photovoltaic system and based on the pressure-control method has been investigated experimentally in this paper. Several parameters including solar radiation intensity, charging current, voltage, and power during the charging process have been studied. The research mainly targets two aspects: to increase charging efficiency so as to make the most use of solar energy, and to improve charging quality in order to prolong the battery's life.

2 Experimental

The experimental system is shown in Fig. 1. The system consists of solar receptor, controller, charging system, and data collecting and processing system. Parameters, such as temperature, voltage, currents, and radiation intensity were measured. Amongst four temperature-measuring points, three T-type thermocouples were placed on the diagonal of the solar module, and another one was on the side of the battery. Environmental temperature was also measured. Hall voltage sensor and current sensor were used to measure the charging voltage and current of battery. All measured data were delivered to a computer via ADAM5000 series of data acquisition modules. A 12 V 12 A·h VRLA battery was driven by a solar PV receptor with the module model of CHSM-050M only and working in ambient temperature of 15–25 °C.

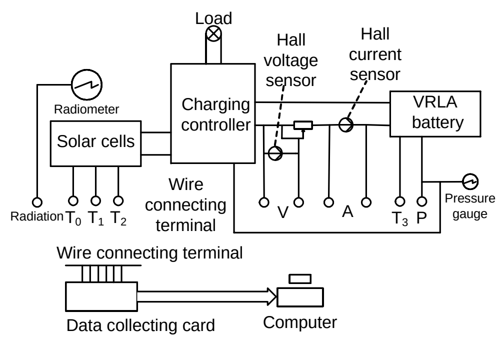

Fig. 1 Experimental setup

T_0, T_1, T_2, T_3: temperature controlled switches; V: voltage controlled switch; A: current controlled switch; P: pressure controlled switch

The pressure-controller is composed of a metallic membrane with a signal juncture and a chamber with an adjustable electrical connecting point. The pressure-controlled switch P is linked to the VRLA battery at the top via a short tube.

The pressure-control switch P will be activated, when the inner pressure of the VRLA battery is increased by accumulation of unabsorbed oxygen and reach a threshold value at the end of charging process.

The control module decreases the charging current and voltage as soon as the signal is received from the control switch P, and the battery subsequently turns to a floating charging process. The cell pressure also declines slowly to a safety range that avoids thermal runaway and the destruction of the cell.

3 Results and discussion

3.1 Inner pressure of the battery during charging

The threshold value of pressure-control unit was set at 0.02 MPa according to the battery's tolerance to inner pressure, which would increase as unabsorbed oxygen accumulates at the end of charging or over-charging process. Three inner pressure curves of the battery at the end of charging process are shown in Fig. 2, corresponding to environmental temperatures of 15, 20, and 25 °C, respectively. It can be observed that the inner pressure remains under 0.005 MPa for a long time during the charging period. When the inner pressure of the battery increases obviously within 25 min at the end of charging process, which means the charging battery is near completion, the pressure-controller will respond at the threshold value of 0.02 MPa. The reason for the inner pressure increasing is that the oxygen produced by the internal oxygen circulation in the anode cannot be completely absorbed in the cathode when charging is fulfilled and charging current exceeds the battery's receptivity. After the action of the pressure-control switch, charging current and voltage of the battery decrease suddenly and charging current remains in a small value for floating charge.

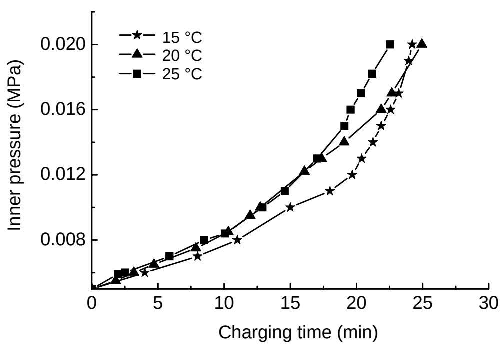

Fig. 2 Inner pressure of the battery at the end of charging

3.2 Charging current and voltage

Solar radiation intensity, charging current, voltage, and power of the VRLA battery are shown in Fig. 3. The battery is charged continuously using real sunlight for 610 min from the starting point A to the ending point E, and the pressure-control switch P is activated twice at points B and D during the charging process. Phase AB shows the main charging process with 74.9% charging capacity. Phase BE is in floating charging process. The charging current is decreased from 1.3 to 0.57 A while the charging voltage alters from 15.6 to 13.6 V after the first action of the switch P at point B in Fig. 3. The charging current decreased from 0.38 to 0.24 A and the charging voltage from 16 to 15.65 V after the second action at point D. The charging power during the floating charging process is as low as approximately 5 W. As shown in Fig. 4, the charging volume increases rapidly to 88.6% of its capacity at the beginning, while it increases slowly

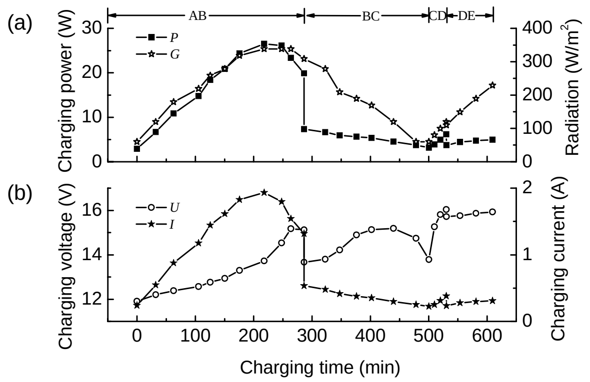

Fig. 3 Characteristic curves of the battery

(a) Charging power (*P*) and solar radiation intensity (*G*); (b) Charging voltage (*U*) and current (*I*)

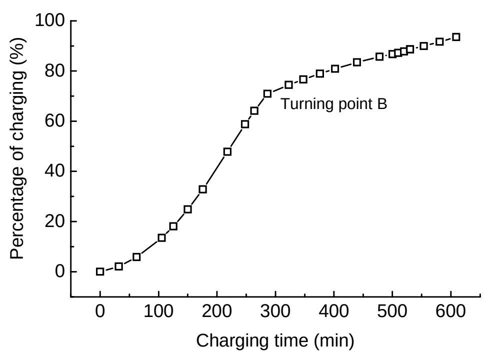

Fig. 4 State of charge (SOC) of the battery

after the turning point B, with an increment of only 4.59% in 79 min.

It can be inferred that the battery is well protected by the pressure-control switch in the whole process as the charging power of battery changed with the charging current and was independent of solar radiation intensity during the floating charging process.

3.3 Maximum power point tracking and the charging efficiency

There are many MPPT methods with simple structures and high performance such as perturbation and observation or incremental conductance. The MPPT method used in this paper is not complicated either. The core component obtaining the MPPT is just a pressure sensor and two current and voltage sensors in the experiment. When the inner pressure of the battery conducted to the pressure sensor reaches the preset value, the pressure-control switch will work and the MPPT is implemented by the control module.

According to the peak parameters provided by manufacturers of solar cell modules, such as voltage $V_{mp.stc}$ and current $I_{mp.stc}$ under the standard conditions with the radiation intensity G_{stc} of 1 kW/m^2 and battery temperature of 25 °C, current and voltage characteristic parameters such as V_{mp} and I_{mp} under any light intensity G and solar cell temperature can be calculated through the correlations proposed by Singer *et al.* (1984) as follows:

$$I_{mp}=I_{mp.stc}(1+a\Delta T)G/G_{stc}, \quad (1)$$

$$V_{mp}=V_{mp.stc}(1-c\Delta T)\ln(e+b\Delta G), \quad (2)$$

$$P_{mp}=I_{mp}V_{mp}, \quad (3)$$

where a=0.0025/°C; b=0.5; c=0.00288/°C; e is the natural logarithm base, and e=2.7183; ΔG is the difference between the standard radiation intensity (1 kW/m^2) and the actual light intensity; ΔT is the difference between the standard temperature (25 °C) and the actual temperature of the solar cells. P_{mp} is the solar module output. Curves ABCDE in Fig. 5a are the battery charging process in experiments. A theoretical curve of the peak power of PV modules varying with solar radiation intensity can be obtained from the above equations (Fig. 5b). Phase AB is the main part of charging, about 74.9% state of charge (SOC); its charging power is close to the maximum power point at all times. After a period of slow charging in phase BC, 91.1% SOC is maintained. The reason of the slowdown of charging rate in phase BC is the declining of the battery's charging ability at the end of the charging process. The pressure-controller was activated at point C, and the charging power fell to point D. Thereafter, in phase DE, the charging power remains low, about 5 W, as the battery is in floating charging process. It can be seen in Fig. 5b that experimental data fit well with the theoretical curve with a relative error of approximately 4% which indicates the pressure-controller can track the maximum power point very well during 90% of the charging time and help in the effective utilization of solar cells.

The charging volume of the battery by the pressure-control method and the electric-control method before the controller being activated is compared experimentally under different solar cell temperatures (from 20 to 34 °C). As shown in Table 1, the charging powers achieved by the pressure-control method are approximately 3.5%–25% above that of the electric-control method and the best charging effect is at a solar cell temperature of 25 °C.

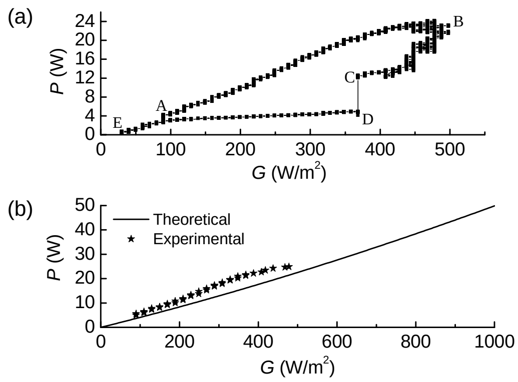

Fig. 5 Experimental and theoretical results of the power of battery and PV modules
(a) Battery charging process in experiments; (b) Comparison of experimental data and theoretical results

Table 1 Comparison of charging performance

T (°C)	Charging power (kW·h)		Increment rate (%)
	Pressure-control method	Electric-control method	
20	9.611×10^{-2}	8.643×10^{-2}	11.2
25	2.778×10^{-1}	2.207×10^{-1}	25.9
34	1.217×10^{-1}	1.176×10^{-1}	3.5

T: solar cell temperature

4 Conclusions

The charging characteristics of the battery driven by solar energy was studied and analyzed in this paper through the pressure-control method. Results showed that the pressure-control method could effectively control PV charging of the VRLA battery and prevent thermal failure. The pressure-controller is able to control the inner pressure of the VRLA battery in a safe pressure range that avoids the battery to be damaged by over charging or exploded by excess oxygen accumulation and prolongs the battery's life. Current-voltage characteristics of the battery and PV modules are well fitted through the MPPT that ensures the maximum use of the solar PV cells.

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