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Application of valve-regulated lead-acid batteries for storage of solar electricity in stand-alone photovoltaic systems in the northwest areas of China

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Abstract

Photovoltaic (PV) installations for solar electric power generation are being established rapidly in the northwest areas of China, and it is increasingly important for these power systems to have reliable and cost effective energy storage. The lead-acid battery is the more commonly used storage technology for PV systems due to its low cost and its wide availability. However, analysis shows that it is the weakest component of PV power systems. Because the batteries can be over discharged, or operated under partial state of charge (PSOC), their service life in PV systems is shorter than could be expected. The working conditions of batteries in remote area installations are worse than those in situations where technical support is readily available. Capacity-loss in lead-acid batteries operated in remote locations often occurs through sulfation of electrodes and stratification of electrolyte.

In northwest China, Shandong Sacred Sun Power Sources Industry Co. Ltd. type GFMU valve-regulated lead-acid (VRLA) batteries are being used in PV power stations. These batteries have an advanced grid structure, superior leady paste, and are manufactured using improved plate formation methods. Their characteristics, and their performance in PV systems, are discussed in this paper. The testing results of GFMU VRLA batteries in the laboratory have shown that the batteries could satisfy the demands of the International Electrotechnical Commission (IEC) standards for PV systems.

Keywords: Valve-regulated lead-acid battery; Cycling tests; Photovoltaic power station

1. Introduction

Solar energy is a green and renewable power source and the solar photovoltaic industry is developing very quickly in the world. The resource of solar energy of China is abundant, particularly in the northwest areas [1]. For example, on the Qinghai-Tibet Plateau (I region in Fig. 1) the total annual solar insolation is about 8000 MJ m^{-2}, and the annual average hours of sunshine more than 3000 h. There is a shortage of electricity in such remote areas because of their geography, the regions being a long way from established electricity grids. Setting up solar photovoltaic installations in these areas provides an effective solution to this problem. No other power generation system can match the reliability of an expertly designed stand-alone solar power station in these areas. They have no moving parts, very little maintenance is needed, and solar power systems can be designed to match the load requirement. Furthermore, a solar power system consists of small, light-weight components which are easy to transport and assemble at the site, and it can be expanded in a modular fashion later as power demands grow. In addition, the impact of a solar power system on the environment is almost negligible.

The applications of solar energy and other renewable energy systems will develop quickly in the next decades in China. Prediction of the utilization of renewable energy resources in China from 1998 to 2050 is shown in Figs. 2 and 3. From these figures, we can see that the expansion of the utilization of solar energy is faster than that of other kinds of renewable energy, particularly for China's ecology development (ED) project.

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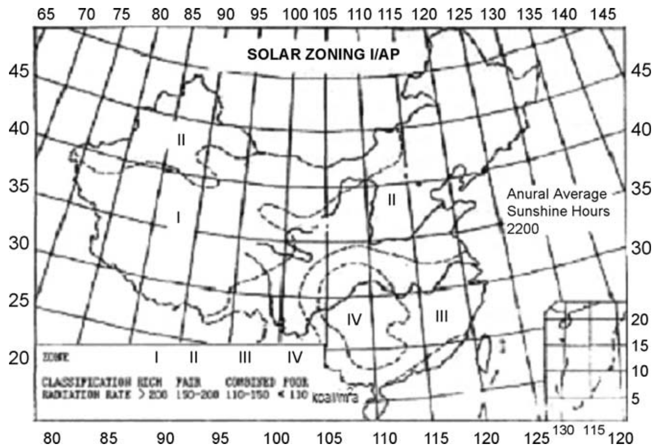

Fig. 1. The solar zoning map of China and the radiation rate of different regions.

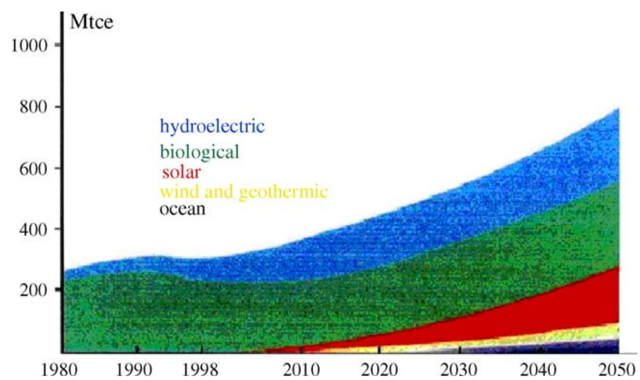

Fig. 2. Prediction of utilization of renewable energy resources in China from 1998 to 2050, as BAU project.

There are a number of projects being carried out at the present time on the utilization of solar energy in China. According to "The Brightness Project of China", use of photovoltaic and wind energy technologies could solve the problem of the deficiency of electricity for the 23 million people in remote areas by 2010. The Chinese Government will contribute 10 billion Chinese Yuan for promotion of PV techniques and the total capacity of PV systems will reach 300 MW by the end of 2005.

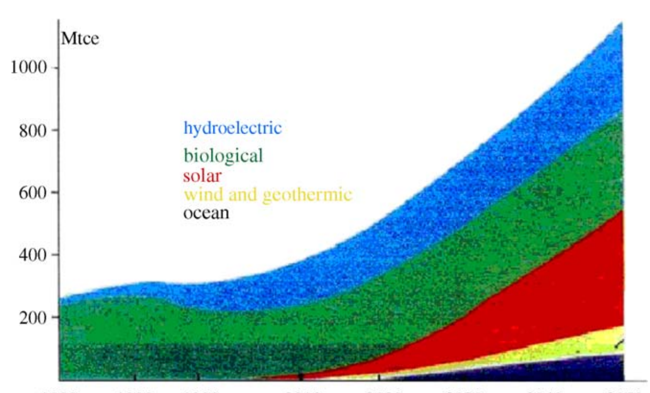

Fig. 3. Prediction of utilization of renewable energy resources in China from 1998 to 2050, as ED project.

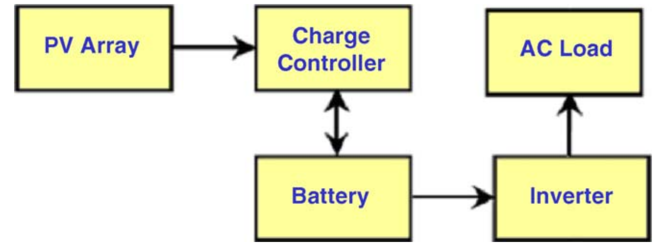

Fig. 4. Diagram of stand-alone PV system.

Most of China's PV power stations are presently built in the northwest areas where electricity grids are hard to reach, and these stations are almost all stand-alone PV systems. Typical diagrams of a stand-alone PV system and a PV-wind energy hybrid system are shown in Figs. 4 and 5. The geographic features of the northwest areas are: high elevation, large temperature difference between day and night, diminished atmospheric pressure, significant seismic activity, and difficulty of access. The requirements for batteries in PV systems in such locations are: long cycle life; wide operating temperature range; low self-discharge rate; good sealing to prevent the escape of water vapor and acid from the battery; resistance to earthquakes with intensity up to 7 on the Mercalli scale.

Due to the strong development of photovoltaic installations in the northwest areas of China, it is increasingly important for these systems to be reliable and cost effective. In this application, the lead-acid battery is the more commonly used technology for power storage due to its low cost and its wide availability. However, analysis shows that it is the weakest component of PV power systems. Because the batteries can be over discharged or operated under partial state of charge (PSOC), their service life in PV systems is shorter than could be expected and the working conditions of batteries in remote area installations are worse than those in situations where technical support is readily available. Capacity-loss in lead-acid batteries operated in remote locations often occurs through sulfation of electrodes and stratification of electrolyte. Large sulfate crystals can form in the lower section of the electrodes under deep discharging or low rate charging conditions of the battery in the operation cycles of a PV system. The large crystals of sulfate are difficult to reduce from $PbSO_4$ to Pb, and limit battery life.

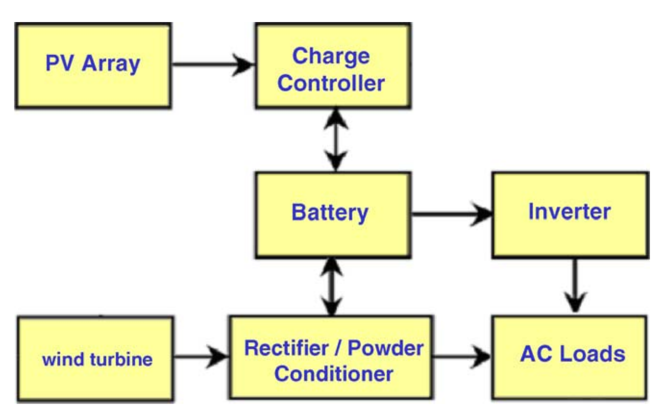

Fig. 5. Diagram of PV and wind energy hybrid system.

2. The design and manufacturing features of Shandong Sacred Sun Power Sources Industry Co. Ltd. type GFMU VRLA battery for PV systems

The discharge rate of batteries in PV systems is low, being between $0.01C_{10}$ and $0.05C_{10}$. The batteries are often cycling in a different state of charge (SOC) and depth of discharge (DOD) than in other lead-acid battery applications. The batteries can be overcharged in strong sunshine during the day, or over discharged during periods of bad weather. The plate grids and the active materials should be designed specially to accommodate such variations. The elements of the batteries should be assembled tightly to reduce shedding of active materials and stratification of the electrolyte. The following technical measures are taken in the production of the VRLA battery named as GFMU for PV systems [2,3]:

(1) Increased grid thickness of the positive electrode; the pattern of the grid is designed in a flat rectangular shape to increase its ability to support the active materials and to prolong the float charge life of the battery.
(2) Addition of the appropriate amount of humic acid to the negative active material to improve cycling capacity at low temperature and to increase the charge acceptance of the battery.
(3) Increased curing temperature of the positive plate in order to increase the quantity of tetra-basic lead sulfate (4BS) in the plate and to improve the cycling life of the positive electrode in the long term.
(4) Increased pressure of assembly of the components of the battery to reduce shedding and to increase the cycle life of the battery.
(5) Increased quantity of electrolyte in the battery to prevent dry-out of electrolyte occurring.
(6) The release pressure of the safety valve of battery adjusted to the appropriate value for use in elevated plateau areas to avoid the valve opening too often.

3. The test methods used for evaluation of VRLA batteries for PV applications and the test results [4,5]

Due to specific constraints and operating conditions in photovoltaic operation, conventional battery tests are not appropriate. In China, three test methods are used for testing the cycling properties of VRLA batteries for PV systems. Results are often only available after a year or two of battery testing.

3.1. IEC 61427 standard cycling test

This test procedure is based on the principle of performing cycles at two different states of charge. Cycles are carried out successively around a low state of charge (∼20%), then around a high state of charge (∼80%) so as to reproduce the typical operating conditions of a battery exposed to seasonal variation. The test tends to characterize fault conditions when the battery capacity is not appropriate for the PV system or the weather has extended periods when it is very bad and/or very good.

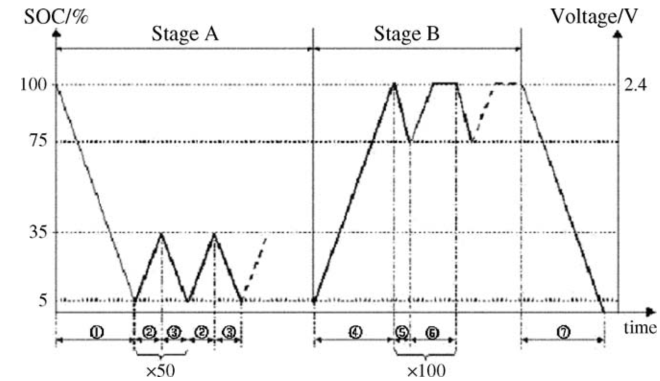

Fig. 6. IEC 61427 standard cycling test procedure: (1) 95% discharge at I_{10} (9 h30 min); (2) 30% recharge at I_{10} (3 h); (3) 30% discharge at I_{10} (3 h); (4) full recharge at I_{10} during 24 h (cut-off 2.4 V_{pc}); (5) 25% discharge at 1.25 I_{10} (2 h); (6) recharge at I_{10} during 6 h (cut-off 2.4 V_{pc}); (7) discharge at I_{10} with cut-off 1.75 V_{pc}, then capacity measurement at I_{10}.

The test conditions are as follows:

- Fifty cycles of 30% DOD are carried out between 5 and 35% SOC, and then a hundred cycles are carried out between 75 and 100% SOC. These 150 cycles are immediately followed by a capacity measurement and form a test sequence.
- The testing period lasts about 50 days. Several test sequences are repeated until an end of test criterion is reached.
- The temperature of the battery is maintained in a bath at 40 °C (the high temperature at which the test takes place aims at accelerating the degradation and thus reducing the time necessary to reach the end of life criterion).

A period of this test procedure is presented in Fig. 6.

The results of tests of the GFMU 2 V 500 Ah VRLA batteries using the IEC 61427 standard cycling test are presented in Fig. 7. The abscissa is the number of the test sequence, the ordinate is the discharge capacity. The results in the figure show that GFMU 2 V 500 Ah VRLA batteries have good cycling ability; after seven sequences (1050 cycles), the discharge capacity is still higher than the rated capacity. The battery test has lasted for 350 days up to now. The IEC test results (350 days) of GFMU

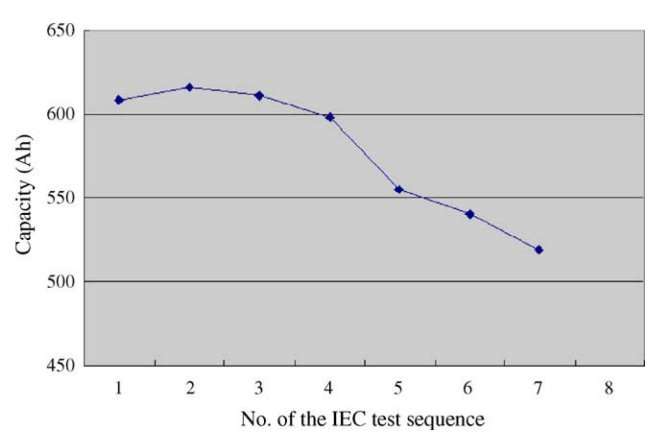

Fig. 7. The discharge capacity curve of GFMU 2 V 500 Ah VRLA battery for IEC cycling test.

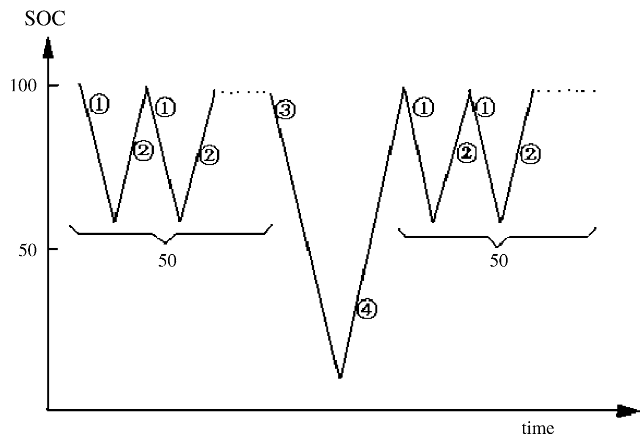

Fig. 8. Standard GB cycling test procedure: (1) discharge at $0.2C_{10}$ A for 2 h; (2) charge at $0.2C_{10}$ A to 2.25 V_{pc}; (3) full discharge at $0.1C_{10}$ A to 1.8 V_{pc} for capacity measurement; (4) recharged at $0.1C_{10}$ A to 2.35 V_{pc}.

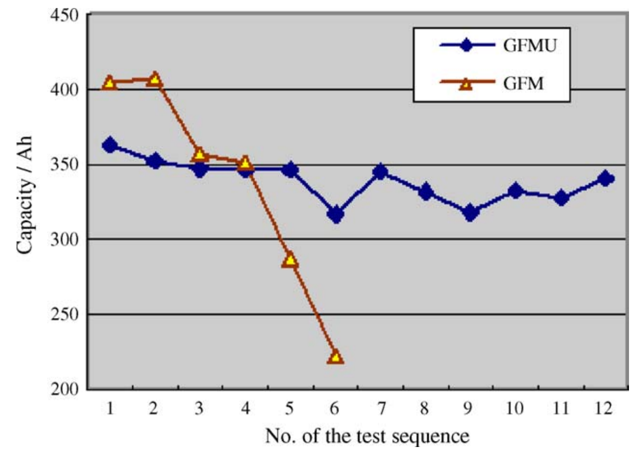

Fig. 9. The discharge capacity curves of GFMU and GFM 2 V 300 Ah VRLA battery in the standard GB cycling test.

2 V 500 Ah VRLA batteries are better than results (150 days) reported in literature [4] for pasted plate VRLA batteries. The tests of these GFMU batteries are continuing.

3.2. Chinese standard Guo Biao (GB) (National Standard) cycling test

In order to test the cycling durability of the batteries, they are cycled at a $0.2C_{10}$ A discharge current and at a $0.2C_{10}$ A charge current for 50 cycles. Every 50 cycles of the battery test and a following capacity measurement form a test sequence. The DOD of the batteries is 40%. The change of the SOC of batteries is between 60 and 100% in the course of each cycling test. After 50 cycles (forming a sequence) a full discharge at $0.1C_{10}$ A is taken as a capacity measurement. Then the batteries are recharged at $0.1C_{10}$ A and cycled at a $0.2C_{10}$ A discharge current and at a $0.2C_{10}$ A charge current continuously. The test procedure is described as follows and shown in Fig. 8:

- Step (1): Discharge at $0.2C_{10}$ A for 2 h.
- Step (2): Charge at $0.2C_{10}$ A to 2.25 V per cell and maintain this voltage for 22 h.
  The batteries are repeatedly cycled going through Steps (1) and (2) 50 times.
- Step (3): After 50 cycles, a full discharge at $0.1C_{10}$ A to 1.8 V per cell is carried out to measure the capacity of the batteries.
- Step (4): The batteries are recharged at $0.1C_{10}$ A to 2.35 V per cell, and the voltage of the battery is held at 2.35 V per cell for 3 h.

After that the batteries are continuously cycled following Steps (1), (2), (1), (2), . . ., (3), (3).

The test results of GFMU and GFM 2 V 300 Ah VRLA batteries using the Chinese standard GB cycling test are presented in Fig. 9. The positive grid of GFMU batteries is thicker than that of GFM. After 12 sequences (650 cycles), the capacity of the GFMU batteries are still higher than the rated capacity. But the capacity of GFM batteries drops quickly during cycling. The lifetime of GFM batteries is less than half that of GFMU. The charge and discharge current are higher than that of IEC cycling test in this procedure. The test results show that the GMFU VRLA battery, with thick positive grids, has a long life at high current density cycling.

3.3. Test of cycling at low discharge rate

In order to test the cycling durability of the batteries at low charge and discharge rate, the following test procedure is taken and shown in Fig. 10:

- Step (1): Discharge at $0.05C_{10}$ A for 3 h.
- Step (2): Charge at $0.05C_{10}$ A to 2.35 V per cell for 6 h.
  The batteries are repeatedly cycled going through Steps (1) and (2) 50 times.
- Step (3): After 50 cycles (a sequence) a full discharge at $0.05C_{10}$ A to 1.8 V per cell is taken to measure the capacity of the batteries.

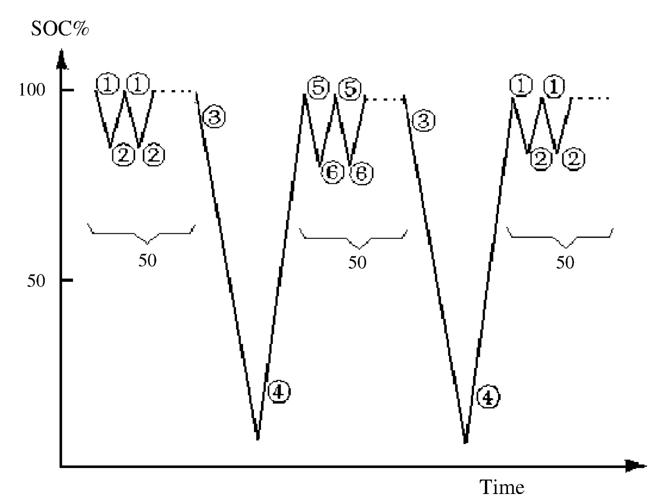

Fig. 10. Test procedure of cycling at low discharge rate: (1) discharge at $0.05C_{10}$ A (3 h); (2) charge at $0.05C_{10}$ A to 2.35 V_{pc} (6 h); (3) full discharge at $0.05C_{10}$ A to 1.8 V_{pc}; (4) recharged at $0.1C_{10}$ A to 2.35 V_{pc}; (5) discharge at $0.05C_{10}$ A (4 h); (6) charge at $0.05C_{10}$ A to 2.35 V_{pc} (6 h).

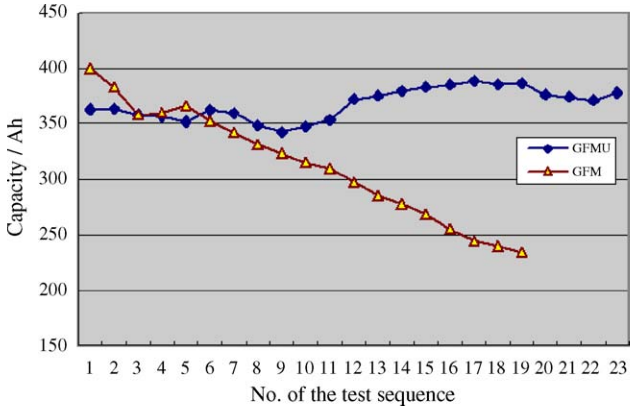

Fig. 11. The discharge capacity curves of 2 V 300 Ah VRLA batteries in low discharge rate cycling.

- Step (4): The batteries are recharged at $0.1C_{10}$ A to 2.35 V per cell, and the voltage of the battery is maintained at this value for 3 h.
- Step (5): Discharge is carried out at $0.05C_{10}$ A for 4 h.
- Step (6): Then charge at $0.05C_{10}$ A to 2.35 V per cell for 6 h.

After that, the batteries are continuously cycled following Steps (1), (2), . . ., (3), (4); (5), (6), . . ., (3), (4).

The discharge capacity curves from GFMU 2 V 300 Ah and GFM VRLA batteries at a low discharge rate ($0.05C_{10}$ A or I_{20} A), using the above test procedure, are shown in Fig. 11. The DOD of the batteries is from 15 to 20% and the SOC after charging is 100%. Every 50 cycles of the battery test form a test sequence. After 21 sequences (1100 cycles) the discharge capacity of the GFMU batteries is still higher than the rated capacity. But the capacity of the GFM battery decays quickly in the course of cycling despite having a high initial discharge capacity. This shows that it is important that the thickness of positive plates should be above a definite value. The low discharge rate test of batteries has lasted for 3 years up to now. Testing of the GFMU batteries is continuing.

4. Application of VRLA batteries to stand-alone PV systems in practice [6–8]

Electricity from solar cells is available only during day–light hours and the battery becomes discharged at night: there is no continuous float charge on the battery. Under such circumstances, batteries undergo three different kinds of cycling.

Daily cycling. After being fully recharged during a sunny day, the battery will start discharging as the sun goes down. In the following morning the solar array is capable of recharging the battery again.

Seasonal cycling. The ideal situation for a battery would be to have a solar array large enough to keep the batteries fully charged each day all year round. In practice, the system can be designed to cover some of the seasonal variations by allowing the battery to be discharged in winter more deeply than normally.

Autonomy cycling. During an unusually long period of bad weather, or as a result of system malfunction, the battery can become deeply discharged. To ensure that the battery capacity can recover, the system controller normally cuts off the load when at least 20% of the battery capacity still remains.

4.1. Testing PV systems with VRLA batteries in the laboratory

Tests of PV systems with VRLA batteries are performed in our laboratory. The system consists of a PV array, charge controller, inverter, batteries and ac load. A sketch of this system is shown in Fig. 4. The working voltage of the PV array is 34 V and the working current is 22 A with power output 750 W. The 24 V, 600 Ah battery bank consists of two parallel strings of 12 GFMU 2 V 300 Ah VRLA batteries. The output of the batteries is connected to an inverter with a 220 V (ac) 250 W load. The batteries are charged by the PV array during the day and are discharged at night for 5 or 6 h (alternatively every 7 days) through the load. The cut-off voltage of the battery bank is 28.8 V (2.40 V per cell) during charge; the voltage on discharge is limited to 21.6 V (1.80 V per cell) and above to protect the batteries. The profile of charge and discharge of the laboratory PV system is shown in Fig. 12. The typical charge current of batteries from the solar panels on a sunny day is shown in Fig. 13. After every 60 days of charge-discharge (a sequence) the battery bank is discharged at $0.05C_{10}$ A to 1.85 V per cell for capacity measurement. The capacity of the battery bank in laboratory operation of the PV system as a function of time is shown in Fig. 14. This cycling test of the PV system has lasted more than 2 years up to now, and the battery bank is still operating well.

4.2. An example of a stand-alone PV power station in the Tibet Autonomous Region of China

There are a number of stand-alone PV power stations built in the remote Counties of Tibet for household electricity generation. The installed capacity of PV stations ranges from 15 to 100 kW. These PV stations exclusively use VRLA batteries for electrical energy storage. For example, Zheng Qi County

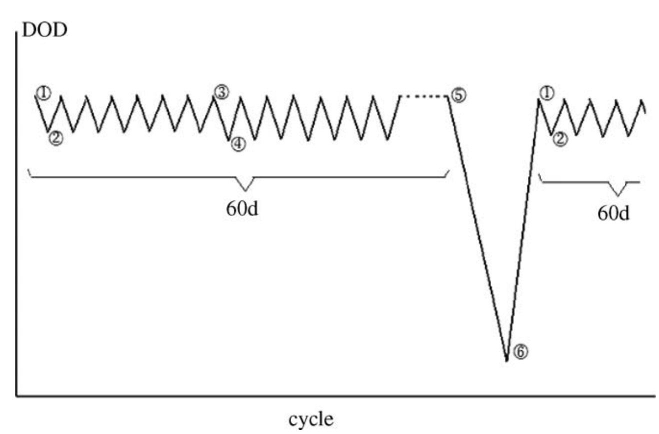

Fig. 12. The operation mode of laboratory PV system: (1) discharge at night for 5 h at $0.022C$; (2) charge by PV array in day time; (3) discharge at night for 6 h at $0.022C$; (4) charge by PV array in day time; (5) full discharge at $0.05C_{10}$ A to 1.85 V_{pc} for every 60 days; (6) recharge at $0.05C_{10}$ A to 2.38 V_{pc}.

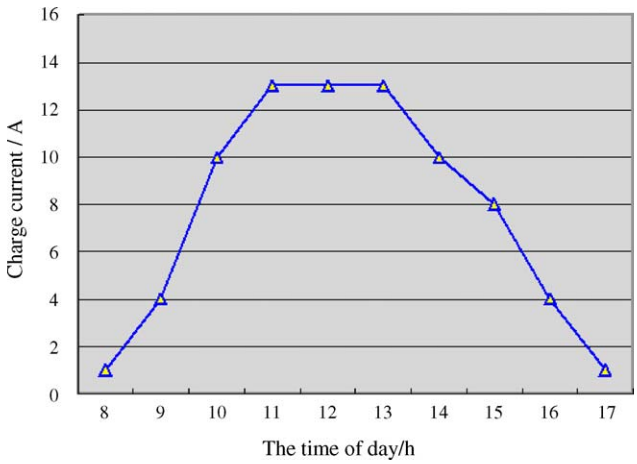

Fig. 13. The typical charge current of batteries from the solar panels in a sunny day.

PV power station (designed capacity 20 kW, started operation in October 2002) contains a battery bank with four strings of 110 units of GFMU 2 V 600 Ah VRLA batteries in parallel, a solar array, and a set of control equipment. This system is same as that illustrated in Fig. 4. When the charge voltage of battery strings reaches 257 V (2.34 V per cell), charging is stopped; at that point the batteries could be near fully charged, and halting charging should reduce water loss that would result from gassing of the batteries. The batteries supply electricity at night for about 5 h for residents. The DOD of the batteries is controlled between 5 and 10%. Sunshine is very strong in Tibet at most times and there is almost no periods of cloudy days. A photograph of the solar array of the 20 kW PV system is shown in Fig. 15. The VRLA batteries (Fig. 16) are housed in a battery room with solar wall heating, and the room temperature does not drop below zero degrees in winter even though the outdoor temperature can be −35 °C.

The discharge data records of the batteries from 19 January 2003 to 6 November 2003 in the Zheng Qi PV power station is shown in Fig. 17. The batteries are discharged every day for about 5 h and supply average electrical power of 23.9 kWh every day; the DOD of the VRLA batteries is about 5%. From the curves in Fig. 17 we can see that, in the later part of the period, the electricity supplied by the batteries increased slightly. The DOD of the batteries increased a little too. And the SOC of the batteries

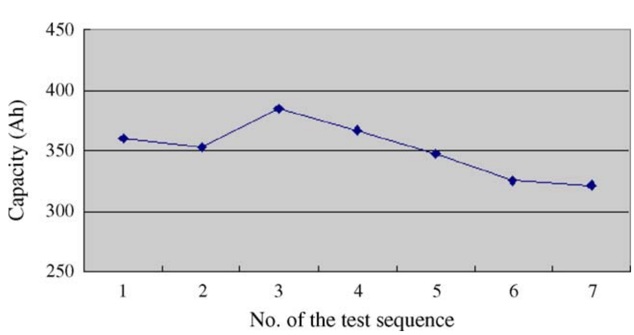

Fig. 14. The capacity change curve of the GFMU batteries in operation of laboratory PV system.

Fig. 15. Twenty kilowats PV power station in Zeng Qi County, Tibet.

Fig. 16. GFMU 2 V 600 Ah VRLA in battery room.

decreased a little. There were 21 cloudy days in this period, and the batteries still supplied electricity. The average charge voltage at 11:30 a.m. was 2.285 V per cell. The average open circuit voltage (OCV) was 2.191 V per cell after charge. The PV power

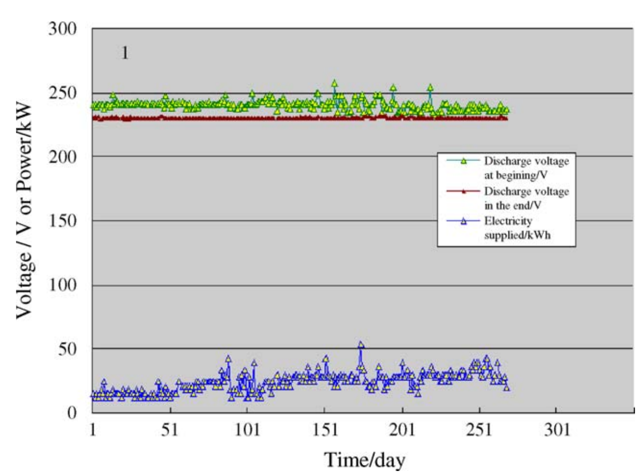

Fig. 17. The discharge behaviour of the GFMU batteries in near 1 year at Zheng Qi PV power station.

Table 1
The operation parameters Jiang An PV and wind energy hybrid power station on 19 October 2003

Time (h)	Wind turbine output (kW)	Solar array output (kW)	Both output[a] (kW)	Average battery voltage (V_{pc})	Load power[b] (kW)
7:00	0.57		0.57	2.056	3.84
8:00	0.55		0.55	2.047	6.52
9:00	2.60	2.34	4.94	2.048	7.39
10:00	5.47	1.43	6.90	2.060	6.70
11:00	6.01	1.56	7.57	2.086	6.88
12:00	9.40	1.56	10.96	2.109	4.54
13:00	6.90	3.64	10.54	2.132	3.94
14:00	8.53	4.29	12.82	2.135	4.37
15:00	8.06	2.99	11.05	2.131	3.94
16:00	7.61	9.23	16.84	2.161	3.94
17:00	7.28	1.56	8.84	2.109	6.60
18:00	7.50		7.50	2.106	5.87
19:00	1.75		1.75	2.045	13.60
20:00	3.25		3.25	2.036	15.10
21:00	7.00		7.00	2.034	15.16
22:00	7.65		7.65	2.039	10.60
23:00	7.30		7.30	2.083	2.55
24:00	3.45		3.45	2.071	1.76

[a] Total output electric energy = 126.6 kWh.
[b] Total output electric energy = 121.3 kWh.

station stopped working for a few days, because the solar cells became covered by sand. When the sand was removed, operation of the station was restored. The batteries are working in high SOC, because they can be charged adequately by the solar cells almost every day. The Zheng Qi PV power station has worked successfully. According to the present operational state of the VRLA batteries in the PV power station, these batteries could be used for more than another 5 years. The battery life reflects the battery SOC during cycling and affirms that an adequate PV array-to-load ratio is very important.

The altitude of resident areas in Tibet is 3000–5000 m, and the atmosphere pressure is 54–70 kPa, considerably lower than the standard atmospheric pressure of 101 kPa. The effect of the atmosphere on oxygen recombination in VRLA battery is not yet clear; further study needs to be done on this aspect.

4.3. The example of the Jiang An PV and wind energy hybrid power station in the Inner Mongolia Autonomous Region of China

The Jiang An PV and wind energy hybrid power station in Inner Mongolia was built in October 2002. There are three wind turbines, a solar array, and five parallel strings of 110 GFMU 2 V 1000 Ah VRLA batteries in series at the power station. A sketch of the station is shown in Fig. 5. The final voltage on charge of the battery strings is 252 V (2.29 V per cell) and the cut-off voltage is 204 V (1.85 V per cell). The working parameters of the Jiang An PV and wind energy hybrid power station on 19 October 2003 are given in Table 1 and Fig. 18. From the data in Table 1, we can see that in the peak hours (18:00–22:00 h) electricity from the wind turbine is not sufficient to provide the needs of the load, and in this situation the batteries supply electric energy to satisfy the demands. At other times, surplus electricity from the wind turbine and the PV array charge the batteries. The total output electric energy (126.6 kWh) generated from the wind turbine and the PV array is slightly larger than the electric energy (121.3 kWh) consumed during the same day by the load. Thus, the capacity of the batteries could theoretically reach the nearly fully charged state before the next day's discharge commences. But the highest voltage of the battery in Table 1 is 2.161 V, which shows that the batteries were not fully charged. So, in fact, the batteries work in PSOC. The DOD of batteries is about 5%. In order to attain long cycle life and achieve normal cycle capacity, the batteries should be fully charged in a suitable time.

To minimize sulfation of batteries in photovoltaic systems, the PV array is generally designed to recharge the battery during the average daily conditions during the worst insolation month of the year. By sizing for the worst month's weather, the PV array has a chance of increasing the seasonal battery state of charge. In hybrid systems using a generator or wind turbine, the batteries can be effectively kept fully charged in normal conditions. In general, proper battery and array sizing, as well as periodic equalization charging can minimize the onset of sulfation.

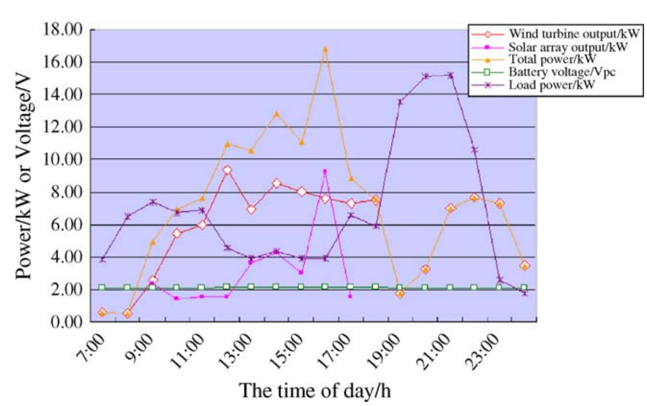

Fig. 18. The working parameters of the Jiang An PV and wind energy hybrid power station on 19 October 2003.

Prolonged electrolyte stratification can result in the bottom of the plates being consumed, while the upper portions remain in relatively good shape, and this reduces both battery life and capacity. Tall stationary cells, typically of those with large capacity, are particularly prone to stratification when charged at low rates. Periodic equalization charges could prevent stratification problems.

5. Conclusion

This report discusses the behaviour of GFMU VRLA batteries during three cycling test procedures, and that of batteries in practical stand-alone PV systems. The cycling test results show that GFMU VRLA batteries display good cycle life and could be successfully used for stand-alone photovoltaic application in northwest areas of China.

The GFMU VRLA battery can be recharged at low current with a minimum of energy; this is important for the overall efficiency of the PV system. The battery capacity will decrease gradually due to the daily cycles of operation, but the capacity decay of the GFMU battery is slow. The results of test sequences of the IEC 61427 cycling test reached seven for GFMU VRLA batteries. This number of test sequences is close to that of tubular plate batteries reported in the literature [4].

Concerning the ability of the test procedures to meet objectives by emphasising battery degradation effects, it appears that most of the cycling procedures lead to significant battery sulfation. Applying equalization charges could minimize the onset of this problem. Increasing the thickness of the positive plate, and raising the curing temperature of the positive plate, can extend the cycle life of the battery.

The results of battery tests in this report meet the criteria required for power storage for stand-alone PV power stations. This paper also provides data and recommendations about battery cycling test procedures that can be applied by project managers to evaluate the behaviour expected from batteries in a given application, and can help them to select an appropriate procedure. It is aimed at focusing the activities of battery testing laboratories on fewer selected procedures. A standard procedure such as that recommended by the IEC is still representative of real operating conditions and so constitutes a reasonable integrated cycling test. Other test methods can provide complementary information.

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