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Journal of Power Sources 95 (2001) 135–140

JOURNAL OF POWER SOURCES

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Development of a VRLA battery with improved separators, and a charge controller, for low cost photovoltaic and wind powered installations

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Abstract

There are many applications and uses for which it is more advantageous to use solar installations than to extend the electrical network and connect to it. This kind of applications are numerous covering from isolated houses to telephone repeaters and the like. These kind of applications share some common characteristics like being located in remote not easy accessible areas, require relatively low power for operation, and being difficult to maintain.

Up to now the use of photovoltaic systems, no matter the impressive growth they are experimenting, suffer from some drawbacks, mainly related with the life expectations and reliability of such systems, and as a consequence of the cost of these systems, when calculated on a lifetime basis. To try to contribute to solve these problems, a project partially founded by the European Commission, has been carried out, with the main objective of increasing the life of these systems, and consequently to make them more attractive from the point of view of cost on a lifetime basis for consumers.

Presently, the life of PV systems is limited by its weakest component, the battery. Battery failure modes in PV applications, are related with well known phenomena like corrosion, but also due to the special nature of this installations, with other factors like corrosion and growth in the upper part of the group, induced by the development of acid stratification inside the battery, with the more prone standard flooded types now in major use, and to a lesser extent the new valve regulated lead acid (VRLA) types beginning to be used. The main objectives of this project, were: to develop a new glass microfibre separator material, capable of minimizing acid stratification inside the battery. To develop a new VRLA battery, with a life duration of 800 cycles on cycling at 60% DOD and partial state of charge (PSOC) conditions. To develop a new charge regulator, that takes into account the condition of the battery in the near term, to modify its setting charging point. The fourth objective was the design and implementation of a PV/wind demonstration system, to test all the PV components under real conditions. The project has been successful, having achieved a life increase of 50%, moving achievable life from previous 500–750 cycles for the new battery and system.

Keywords: Stand-alone PV systems; Batteries; Battery storage and control

1. Introduction

The background to this research project is the provision of power in isolated areas for systems such as telecommunications repeaters, navigational beacons, environmental monitoring systems, as well as home light and power. These systems often have modest power requirements, and in many cases it may not be possible or economic to connect to the utility electrical network. The utilization of renewable energy sources such as solar photovoltaic (PV) and wind turbine generators can provide an economic alternative source of power.

This paper describes the development of an improved low cost PV/wind power system, consisting of three main subsystems: solar photovoltaic (PV) or wind turbine generators, a battery bank for storing the generated energy, and a charge controller and power conditioner. The system has been designed with the philosophy of allowing a discharge of the battery, up to 70%, with an autonomy of 5 days, and for a daily consumption of 30 A h. Once making the necessary calculations, a battery capacity of the order of 220 A h at the 100 h rate result. These design criteria take into account, not

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0378-7753/01/$ – see front matter
PII: S0378-7753(00)00613-3

only the technical considerations, but also economic aspects, by defining the smaller possible battery compatible with the utilization. This is so, because one of the main objectives of the project is to decrease as much as possible the cost of PV installations, to make them more attractive to consumers.

The specific problem limiting the battery performance and lifetime in PV applications is the progressive development of acid stratification (different acid densities from the bottom to the top) in the battery. This is mainly due to the fact that in solar PV/wind applications, due to the random nature of the resource, a complete recharge of the batteries cannot always be guaranteed, and the battery may be required to operate for long periods at low SOC. The development of electrolyte stratification leads to the following problems: lower energy capacity available from the battery, high sulphation of the plates, and high corrosion and growth of the positive plates. The result is a severe reduction of the expected life.

Valve regulated lead-acid (VRLA) batteries, which hold the acid in either a gel or an absorptive glass mat (AGM) are inherently resistant to acid stratification, and have the additional important advantage of being maintenance free. On the other hand, flooded cells will suffer from acid stratification unless they are periodically over-charged, or alternatively provided with a means of electrolyte stirring. Therefore, VRLA batteries are a suitable choice for low-cost standalone applications. In order to further improve their performance, a new AGM separator material has been developed for the VRLA battery. The new separator includes special filling materials which modify the structure of the glass microfibre, in order to achieve the desired properties. This significantly reduces acid stratification, thus prolonging battery lifetime and reducing the overall system lifetime cost.

VRLA batteries require careful recharging, because overcharging can provoke water consumption, and eventually thermal destruction due to high recombination efficiency and associated heat generated. Most small charge regulators have two regulation modes (bulk charge, and taper charge), and sometimes include temperature compensation. A further innovation of this project is the development of an adaptive charge controller which takes the previous operating conditions of the battery into account. The SOC history for the previous week is used to modify the voltage set-points, ensuring that the battery is fully recharged whenever possible, while avoiding overcharge.

Prototype batteries and charge controllers have been designed, constructed, tested, and incorporated in a demonstration PV/wind system. The results of laboratory and application testing are presented, to demonstrate the increased cycling capacity of the batteries, and the improved battery recharge achieved by the charge controller. Bench tests of the new battery indicate a 50% increase in the expected lifetime. The expected system operational benefits are presented.

In summary, the project has the following objectives:

- To develop a new glass microfibre separator material, capable of minimizing the acid stratification that develop inside the battery along life.
- To develop a new VRLA battery, capable of giving a life of 800 cycles at 60% DOD, under PSOC conditions.
- A new charge regulator, capable of taking into account the previous condition of the battery in the near term (1 week), to modify its setting charging point accordingly.
- To define and implement a PV/wind demonstration system, to test all the system components under real conditions.

2. Development of a new separator material

The basic idea to produce a material with the already indicated characteristics, in terms of minimizing acid stratification, was to modify its internal structure by either changing the characteristics and proportions of the base glass microfibre, or to include in their structure some inert fillers, that make the same function.

Of these two possibilities, the first one is rather expensive due to the cost of the fine microfibre. Also due to the characteristics of the microfibre (specific surface), the degree of improvement, is limited. Due to this, the second approach (inert fillers), was selected.

In extensive testing program, including organic, and inorganic fillers, anionic and cationic, ceramic fillers, and retention helpers, were tested, both at the laboratory and production level. This extensive testing program, showed, that one of the most important parameters of the filler, was its specific surface area together with the absence of chemical attack by the components of the battery.

Several different filling materials including anionic and cationic silica, and ceramic fillers, were selected and tested for inclusion in the new separator material. Laboratory samples, were prepared and extensively tested to determine and measure the most important parameters relevant to battery performance improvement, as shown in Table 1.

Table 1
Characteristics of two new separator materials compared with the standard material

Characteristics	Standard	Low filler content	High filler content
Specific surface area (m^2/g)	1.17	7.28	14.83
Pore size distribution (μm)			
Minimum	2.54	2.40	2.25
Maximum	15.05	8.77	3.05
MFP	4.78	3.29	2.84
Capillary rise (mm)			
2 min	65	56	45
24 h	620	780	830
Tensile strength (daN/25.4 mm)	2.44	1.70	1.20

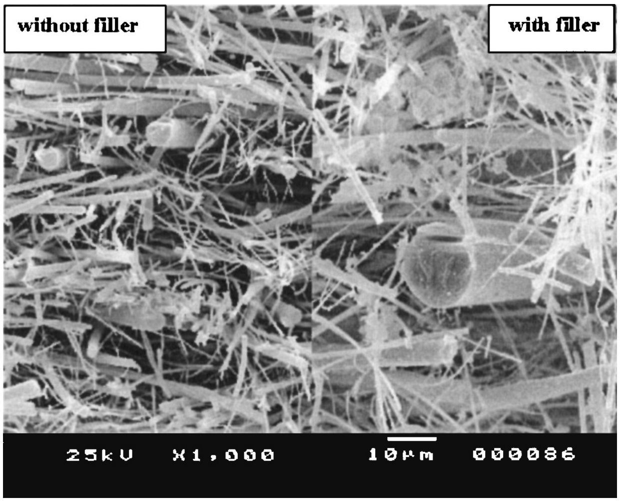

Fig. 1. SEM photographs of the standard (without filler) and modified (with filler) separator material.

The variation of characteristics due to the inclusion of low and high levels of filler are clearly shown in Table 1. There is a great increase of surface area, pore size distribution shifted to lower values, and an increase of capillary rise at long times (these last two properties are essential to eliminate acid stratification). The decrease in pore size has another important benefit, that is the ease of developing short circuits by the growth of lead dendrites is reduced. Magnified view of the modified and standard materials, is shown in Fig. 1, illustrate the increased specific surface area, and decreased pore size.

The inclusion of filler in the structure of the separator modifies the interlocking of the fibers, decreasing the tensile strength of the material. This places additional requirements on the manufacturing process on industrial conditions.

These new separator materials were expected to give improved battery performance, and were suitable for assembly in battery prototypes, and battery cycling performance tests. It becomes evident, when looking at the results of the battery prototypes in the next paragraph.

3. Development of new VRLA battery

Once the new separator material was successfully obtained, the new stage concerned with the development of the new VRLA batteries incorporating it, began (Fig. 2). The purpose in developing this new battery, was to increase as much as possible its life and reliability, hence all the parameters related with life were tried to be optimized.

The main characteristics of the new battery are

Technology	Valve regulated lead-acid
Dimensions (L × W × H)	244 mm × 190 mm × 280 mm
Weight	33 kg
Voltage	6 V
Capacities	
100 h	220 A h
5 h	180 A h
Stored energy 100 h rate	1350 W h
Specific energy 100 h rate	40.9 W h/kg
Expected life	~800 cycles at 60% DOD
Special features	New separator material to avoid acid stratification

3.1. Cycling tests

In order to simulate as close as possible real use in solar applications, and due to the lack of approved official specifications, an internal cycling test was developed. This cycling schedule, includes two levels of depth of discharge, because it is a key parameter to specify the life. Details of the testing profiles are

- Profile I: 20% DOD (state of charge on cycling varies between 60 and 80%).
- Profile II: 60% DOD (state of charge varies between 20 and 80%).

Before beginning cycling, the batteries were discharged 20% of their rated capacity, leaving its SOC at 80%. In this way PSOC operation, was assured all along cycling to simulate a condition that normally occur on PV installations.

Charge on each cycle, amounted to exactly the same value as previously discharged, as a consequence, the batteries lost capacity steadily. After each series of 25 cycles, batteries received a complete recharge. This procedure, try to simulate rather hard real working conditions.

Control discharges were made after each 50 cycles, and included a previous complete recharge, followed by a full discharge at the 5 h rate. Failure criteria were established when the capacity dropped below 80% of its initial value.

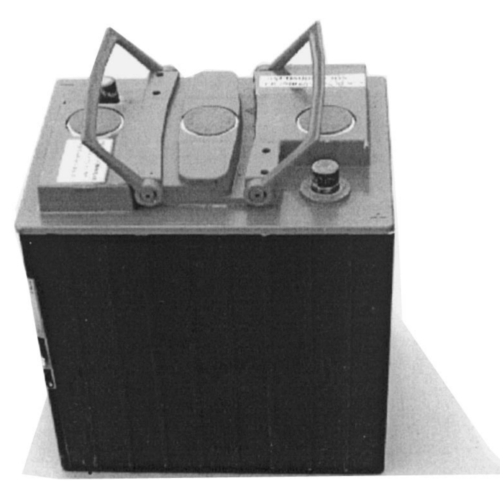

Fig. 2. The new VRLA battery.

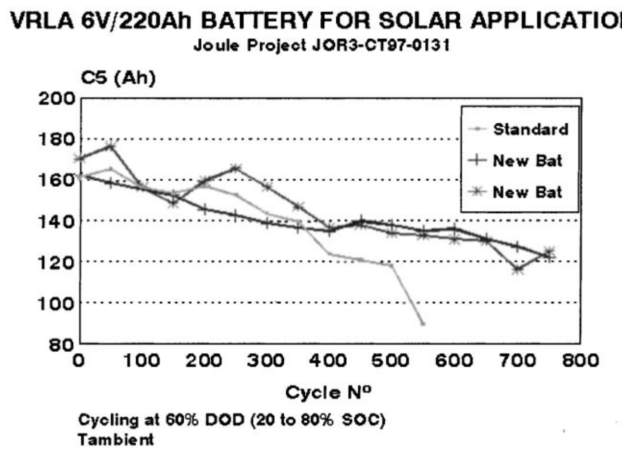

Fig. 3. Cycling at 60% DOD.

Values of weight loss, internal resistance, and final current on charge were also taken in order to try to establish the cause of failure on cycling.

Three groups of batteries were assembled using the standard separator material (Group I), the material with low filler content (Group II), and the material with high filler content (Group III). The three Groups were submitted to the cycling tests already specified, giving the following results:

3.1.1. Cycling with 20% depth of discharge (DOD)

Results show no differences among the three groups, all of them reaching the same number of cycles. There is a steady capacity loss independent of the type of separator used.

3.1.2. Cycling with 60% DOD

Results are included in the Fig. 3, and show clear differences between groups with standard and newly developed separators. In fact, while standard batteries reach a mean value of 500 cycles, both groups incorporating separators charged with inert fillers reach 750 cycles, a life increase of 50%.

3.1.3. Weight loss

Batteries were weighed after 50 cycles on each control.

Results shows very low weight loss for both groups. For the group cycled at 20% DOD it amounts to 75 g, which represents a value of 0.05 g/cycle. For the group cycled at 60% DOD it is slightly higher, amounting to 125 g, equivalent to 0.17 g/cycle. In both cases, weight loss figures represent less than 2% of the initial electrolyte volume, indicating that it will not be a cause of failure at least on ambient temperature conditions.

4. Development of adaptive charge controller

4.1. Adaptive features of the new charge regulator

The new charge regulator utilizes a microcontroller and MOSFET technology to optimize the charge control efficiency, and in addition provides an information display and keyboard for the user.

The charging cycle, illustrated in Fig. 4, includes two phases, deep charging and float charging. Following a discharge, the regulator allows the available charging current to flow to the battery without interruption, until the battery reaches the end point charging voltage, when the battery is almost fully charged. The end point is calculated as a function of temperature, charging current, and battery capacity. Float charging is made within the limits of a ‘dynamic floating band’, where the maximum and minimum voltages are calculated as a function of the SOC during the

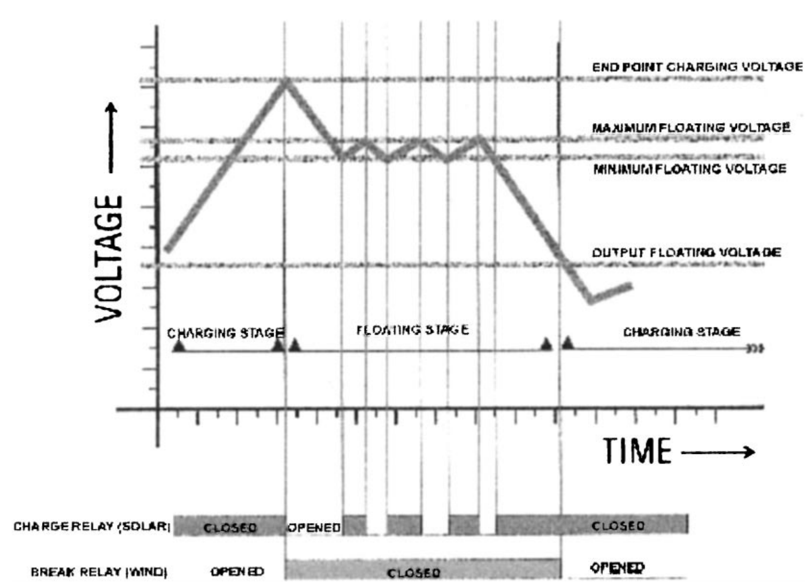

Fig. 4. Illustration of charge control.

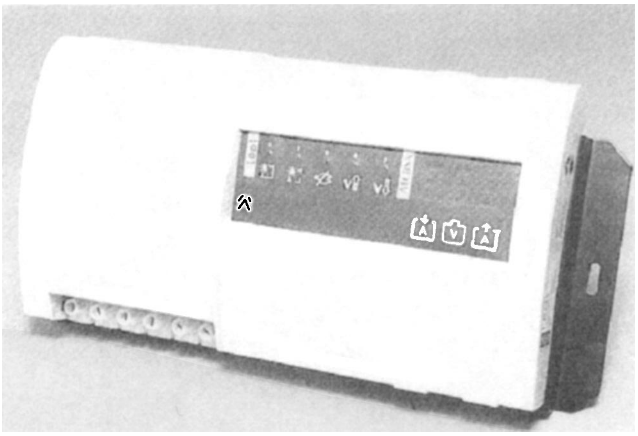

Fig. 5. The completed charge regulator.

previous 7 days (higher voltages after lower SOC). The charging current is pulse width modulated (PWM) in a limit cycle mode, and when the battery reaches full charge the battery voltage response to charging current becomes fast, automatically reducing the duty cycle and reducing the mean charge current. The adaptive setting of the 'dynamic floating band' ensures that the battery charge is completed in the minimum time, and the battery is automatically equalized after a period of low SOC, while minimizing overcharge after a period of higher SOC (Fig. 5).

Other features of the regulator include:

4.1.1. Load disconnect

Disconnection of the supply to the load when the battery SOC is low, to avoid deep discharge of the battery.

4.1.2. Status indicators

Battery low and over voltage; load under-voltage; float and deep charge.

4.1.3. Alarm systems

Battery low and over-voltage.

4.1.4. Protections

Short circuit, over-voltage and reverse polarity.

4.1.5. Technical data

Consumption (mA)	40
Maximum PV charging current (A)	50
Maximum wind charging current (A)	10
Maximum load current (A)	25

5. Application testing

5.1. PV/wind power system

A PV/wind system was implemented to demonstrate and test the new battery and regulator. The system is installed in the UK and was sized to supply a load of up to 30 A h per day, see Fig. 6.

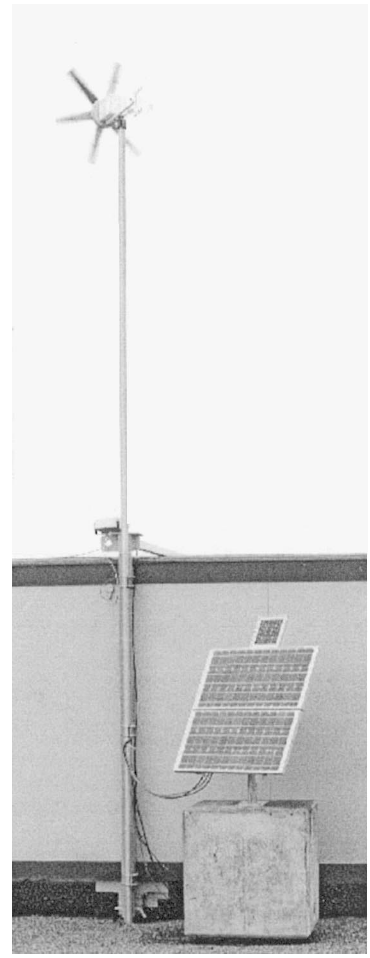

Fig. 6. The PV/wind standalone power system used for demonstration and test.

Conventional energy balance techniques were used to size the system, and computer simulation was used to investigate operation for a period of 1 year. The combination of PV and wind generators is particularly advantageous in climates similar to the UK, where the solar resource in winter is rather low, and where the seasonal PV and wind resource tend to be complementary [1,2].

The main characteristics of the system are

PV array	120 Wp, two ATERSA A-60
Wind turbine	50 W at 10 m/s, Marlec FM 910
Charge regulator	New ATERSA 12 V/50 A
Battery	Two new TUDOR 6 V/220 A h
Load	8 $\times$ 15 W nominal, computer controlled

The PV/wind system is implemented with instrumentation and data-logging for generator, battery, and load voltages and currents, solar panel and battery temperatures, solar irradiance on the PV panel plane, and wind speed. The data acquisition system is PC-based, incorporating a

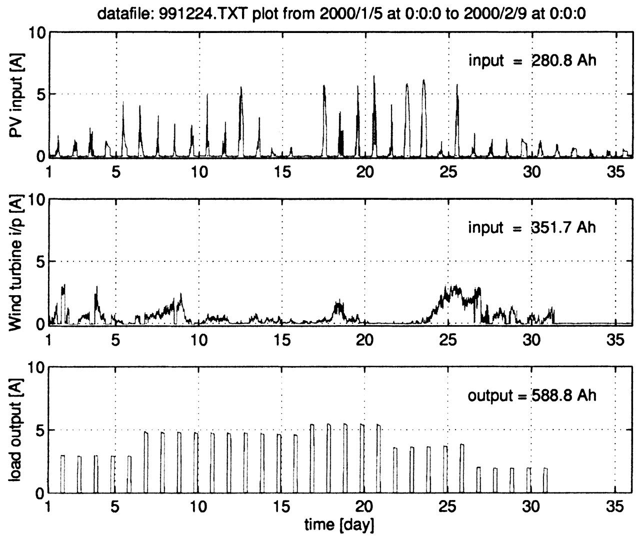

Fig. 7. PV, wind, load currents for a period of 35 days.

National Instruments AT-M10-16E-10 DAQ board with a custom LabVIEW program. Data analysis following acquisition is by Matlab programs.

5.2. Results

Battery capacity and coulombic efficiency tests were made before the operating period (capacity 213 A h, energy 2580 W h at the rate of 40 h, coulombic efficiency 95%, watt-hour efficiency 89%). A test procedure using a variable daily load cycle was developed to test the system over a range of operating conditions in a short operating period of 35 days. The PV, wind, and load currents are shown in Fig. 7, where the 5 h evening load period promotes battery cycling, with most of the load supplied through the battery.

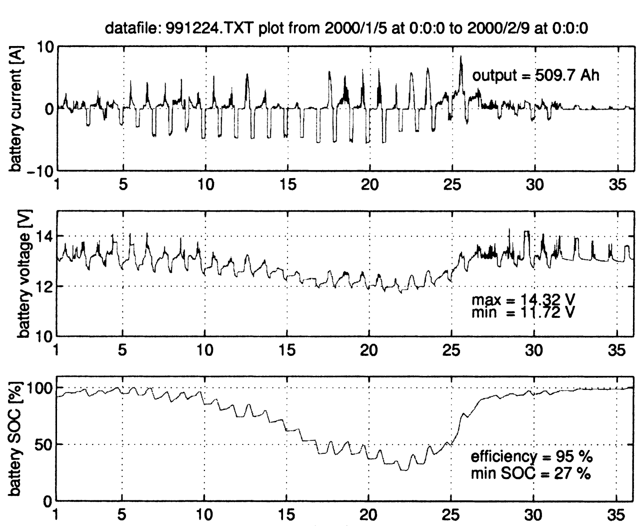

Fig. 8. Battery performance for a period of 35 days.

The performance of the battery during this period is shown in Fig. 8. The battery SOC has been calculated using A h counting, utilizing the measured coulombic efficiency. It can be seen that the load cycle subjected the battery to a deep cycle, with superimposed daily cycles. The results confirmed the efficiency of the battery, and the adaptive charge control, ensuring that the battery is fully recharged, and is not overcharged.

6. Conclusions

The new VRLA battery, incorporating an improved separator material to reduce acid stratification has already demonstrated a significantly increased cycle life. Tests conducted so far show an increased lifetime from the present value of around 500 cycles, to figures of the order of 750 cycles, for cycling at 60% DOD (20–80% SOC),which represent a 50% increase. The battery is expected to have increased lifetime in all applications where acid stratification tends to develop in standard VRLA batteries, including standby, light cycling, and deep cycling applications. The main areas of use are expected to be

- Small and medium-sized solar PV installations.
- Applications requiring deep and repetitive cycles, such as light motive power applications.
- Standby applications in which the battery remains on float charge most of the time.

The new charge regulator has demonstrated the precise recharge procedure necessary to fully recharge a VRLA battery in the minimum possible time, while avoiding overcharge. This ensures that the PV/wind system is operated at high efficiency, and the battery is operated to ensure maximum lifetime.

Acknowledgements

This work was partly funded by the European Commission Joule program, Contract No. JOR3-CT97-0131.

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