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ScienceDirect
Journal of Power Sources 162 (2006) 884–892
JOURNAL OF POWER SOURCES
www.elsevier.com/locate/jpowsour

ABLE project: Development of an advanced lead-acid storage system for autonomous PV installations

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Received 9 March 2005; received in revised form 5 April 2005; accepted 5 April 2005
Available online 18 July 2005

Abstract

In the advanced battery for low-cost renewable energy (ABLE) project, the partners have developed an advanced storage system for small and medium-size PV systems. It is composed of an innovative valve-regulated lead-acid (VRLA) battery, optimised for reliability and manufacturing cost, and an integrated regulator, for optimal battery management and anti-fraudulent use.

The ABLE battery performances are comparable to flooded tubular batteries, which are the reference in medium-size PV systems. The ABLE regulator has several innovative features regarding energy management and modular series/parallel association. The storage system has been validated by indoor, outdoor and field tests, and it is expected that this concept could be a major improvement for large-scale implementation of PV within the framework of national rural electrification schemes.

Keywords: Lead-acid battery; Storage system; Photovoltaic

1. Introduction

There is a large market potential for small and medium-size PV systems in rural electrification infrastructures, but the main obstacle to the development of this market is the very low purchasing power of the potential customers. The implementation of PV systems is often related to specific regulatory frameworks where the systems are under concession. In such context, the energy operator is responsible for managing the financing, installation and operation of a large number of PV systems. He has to ensure a quality of service, and needs to be able to prove it. From his point of view, minimisation of the life cycle cost becomes more important than the investment cost, which is the key issue when the systems are owned by the users.

In this type of systems, the battery is often the weakest component and can be one of the most expensive parts over the life cycle cost, due to premature replacement. In scattered applications in rural areas, a low maintenance, a high robustness and a long battery life are key issues for the reduction of operation costs.

In this context, the EU-funded project advanced battery for low-cost renewable energy (ABLE) [1] aimed at developing an advanced storage system, specially designed for small and medium-size PV systems. This paper explains the ABLE storage system concept, and gives the results of the extensive tests performed on the battery, the regulator and the ABLE storage system.

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doi:10.1016/j.jpowsour.2005.04.037

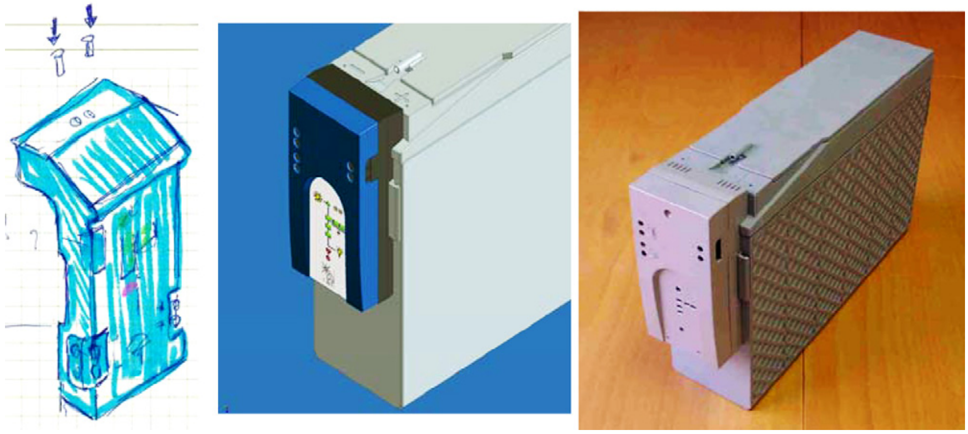


Fig. 1. Integrated ABLE system with battery and regulator.

2. The ABLE concept

The ABLE storage system is composed of a valve-regulated lead-acid (VRLA) battery with innovative design, optimised for a very good reliability and a lower manufacturing cost, and a regulator directly integrated into the system.

The five partners worked together on the different parts of the system. IEES-CLEPS and Exide-CEAC designed and manufactured the battery, and TTA, the regulator. Tests were performed additionally by two independent laboratories, ECN and GENEC.

One of the main innovative concepts of the ABLE system is to integrate the Battery Management System (BMS) directly in or on the battery, so that there is no mismatch between the controller and the battery. Fig. 1 shows the selected design for the integration of the controller on the battery. The integration assures that the battery is operated with the correct set point levels for that particular battery, and also improves the robustness of the system by avoiding fraudulent connection of user loads directly to the battery terminals. An additional advantage is the minimisation of ohmic losses in the cables, which means a more accurate measurement of the battery voltage for the controller.

Another important point in the ABLE concept is the possibility of modular series/parallel association of "battery + regulator" systems. This results in a modular "plug and play" battery with relatively small capacity (50–100 Ah), which can easily be connected in series and/or in parallel to reach the required capacity and voltage.

3. The ABLE battery development

3.1. Innovative battery design

Flooded lead-acid batteries are the most used energy storage media in PV systems, due to their wide availability and low-cost. VRLA batteries, although more expensive, have several advantages for this application. In particular, no water addition is required, which is very important for reducing maintenance costs, taking also into account the limited availability of distilled water in some remote areas.

In terms of internal design, the lead-acid batteries with positive tubular plates are the best suited for the PV application: the positive active mass is contained in tubes, which minimises shedding, and the current collector is thicker, which minimises the risk of grid breaking due to corrosion. Their main drawback is their cost, mainly due to a more expensive manufacturing process.

The ABLE project aimed at developing a VRLA battery, for reduced maintenance costs. The innovative design leads to an optimum compromise between the manufacturing cost and the reliability compared to existing products.

Fig. 2 shows a picture of this new grid design, which is called "strap grid tubular plate" (SGTP), developed by CLEPS [2]. This design shows several advantages:

- The current collectors are produced by die-cutting from a rolled sheet, instead of gravity casting [3]. This allows for a continuous production process, which is not the case for gravity cast grids.
- The shape of the tubes has been changed from cylindrical to flattened elliptic (Fig. 2), in order to increase the contact surface between active mass and current collector spine, and to decrease the battery internal resistance [3].

In addition to this new grid design, the active mass was also optimised, with several investigation axes:

- Process for preparing the positive active mass paste [4].
- Additives in the positive active mass and in the electrolyte [5].
- Combination of existing or new expanders in the negative active mass [6,7].

3.2. Battery test results

The ABLE battery prototypes are compared to three commercial lead-acid batteries of different designs: flooded bat-

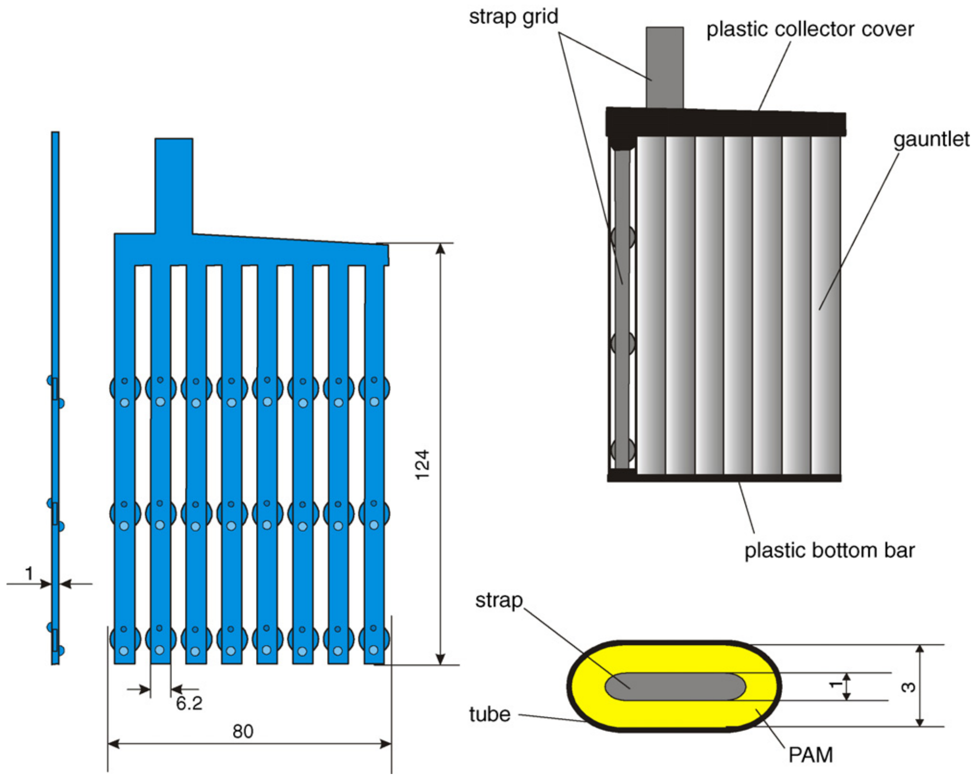


Fig. 2. Strap grid tubular plate (SGTP) design from CLEPS. Left: die-cut current collector; right: complete positive electrode.

tery with tubular plates, flooded "solar" battery with flat plates and VRLA battery with spiral plates.

The tests to be performed were designed in order to be representative of the constraints and battery degradations occurring in PV systems [8,9]. In the PV application, the main battery failure modes are, sorted by importance:

- active mass sulphation, enhanced by electrolyte stratification;
- active material loss (softening and shedding);
- corrosion of the current collector;
- for flooded batteries, electrolyte contamination.

Moreover, the energy efficiency of the battery is a very important parameter in this application, especially at low state of charge: avoiding energy losses is particularly important when little amount of energy is available. GENEC results have shown that the efficiency can be quite different from one battery to another [9].

This analysis led to the definition of the test procedures to be used for the ABLE battery prototypes. These procedures are designed to induce specifically one type of degradation, and they are thus called "informative tests". These tests allow to evaluate some characteristic parameters:

- efficiency at low state of charge;
- electrolyte stratification;
- active mass softening;
- recovery from deep discharge.

These tests were developed in previous works [8,9].

In addition, there are two standard procedures which allow reproducing an accelerated PV-type cycling. One of them is proposed in the international standard IEC 61427 [10], and the other one is proposed in the French standard NFC 58–510 [11]. As a validation, the ABLE prototypes in their final version and commercial batteries were tested according to these standards.

3.2.1. "Informative" tests

The description of each procedure and results of the tests will not be given in details here but is available in the publishable final report of the ABLE project [1]. The main results can be summarised as follows:

1. The ABLE battery efficiency is slightly higher than that of conventional tubular batteries, in comparison with the GENEC results database.
2. Its resistance to stratification can be very good (twice better than flooded batteries), but some prototypes shows as much stratification as flooded batteries.
3. Some prototypes have very good performances in the shedding test, as good as the tubular batteries, but some other prototypes have poor performances, and tear-down analysis then shows that the positive active mass filling in the tubes is unequal.
4. The deep discharge behaviour of the ABLE prototypes is intermediate between that of tubular batteries and of the other batteries.

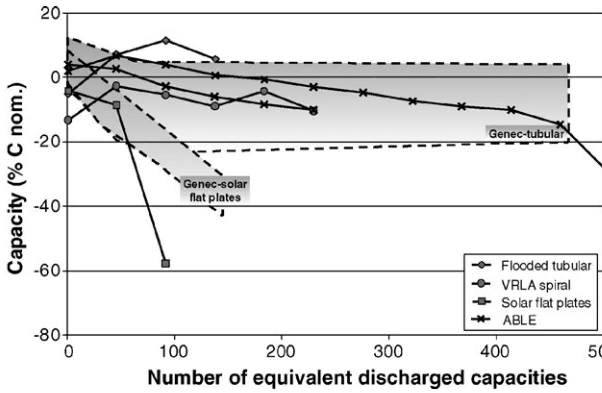


Fig. 3. Results of the cycling tests according to IEC 61427.

3.2.2. *PV cycling tests*

Fig. 3 shows the results obtained with the IEC 61427 test procedure for the ABLE prototypes in their final version, for the three commercial batteries, and the area of the results previously obtained in GENEC. The test consists of 50 cycles at low SOC, followed by 100 cycles at high SOC. The cycles are performed at I_{10} with 30% DOD. A capacity measurement is performed after each series of 150 cycles.

In this figure, the capacity loss is plotted against the "number of equivalent discharged capacities", instead of the number of cycles. There are two reasons for that: it allows for the comparison of different test procedures, with different cycling profiles and DOD per cycle. The significant parameter is then the total amount of charge (cumulated Ah) discharged by the battery. Anyway, this value has to be normalised to the rated capacity of the battery, to allow the comparison of different batteries. This ratio also represents the number of rated capacities given back by the battery during its life. It, thus, allows comparing the service rendered by a battery whatever the cycling profile.

The performances of the ABLE prototypes are comparable to those of flooded tubular batteries. Tear-down analysis showed that the reason for failure is not related to the active mass, but to the corrosion of the lug (connection of the plates to the top bar). This is mainly due to the non-industrial production of these batteries and manual welding of the connections, but could also be improved by a slight modification of the positive grid design.

Unfortunately, the results obtained with the other test procedure, from the NFC 58–510 standard, are not conclusive because the ABLE prototype used for this test was one of those which showed a strong tendency to stratification.

3.3. *Conclusion*

The ABLE prototypes show good performances, and a cycling ability in PV conditions close to that of flooded tubular batteries, which are the reference in medium-size PV systems. The ABLE battery is thus very promising for this application.

However, some prototypes have lower performances, with strong stratification and shedding. Tear-down analysis shows two main problems: a corrosion of the lug (plate to top bar connection), and unequal filling of the positive active mass in the tubes. These two problems are mainly due to the non-industrial production of the batteries.

4. The ABLE regulator

4.1. *Energy management in PV systems*

The regulator is a key component in a PV system, it is in charge of managing all energy flows in the system, taking into consideration user behaviour. In relation to the specific requirements of lead-acid batteries, the traditional functions of a PV controller are:

- To limit excessive charging of the battery by the PV-module, in order to minimise battery corrosion and water consumption.
- To limit excessive discharging of the battery by the user loads: the battery has to be protected from prolonged low state of charge to avoid the battery premature failure.
- To provide indication of operation: users need to have clear indicators to manage properly the battery.

Moreover, the charge strategy and energy deliverability to loads should be carefully adapted not only to the battery but also to its history, which is seldom done in existing systems.

The improvements of the ABLE regulator deal with all main functions of a BMS in a PV system: intelligent charging, load management, monitoring and user indication [12].

4.2. *Adaptative charge strategy*

The charge strategy developed here consists in introducing a compensation of the voltage settings according to the equalisation history of the battery:

- If the battery has not reached full charge for many days, the floating voltage is increased to compensate for a temporary higher impedance and assure a good equalisation charge.
- If the battery has reached full charge in recent days, the floating voltage is lowered to prevent excessive water losses and corrosion of the battery grid.

The equalisation history of the battery is quantified by a parameter called Historical Battery Index (HBI), which is calculated as a weighted function of the number of times the battery has reached the high voltage threshold during the previous 8 days. The charge strategy and variation of the threshold voltages are summarised in Fig. 4. The voltage values are given as an example.

4.3. *Load management*

In an PV system, the user behaviour can be very variable, and some users will daily use all the available energy until

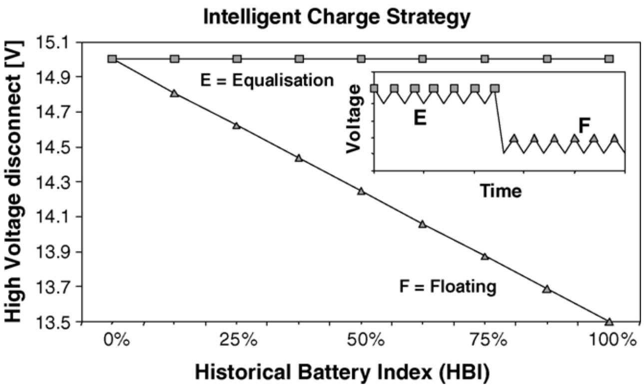


Fig. 4. Adaptative charge strategy of the ABLE regulator.

disconnection. When only a low voltage threshold is used to detect a discharged battery and disconnect the load, the charging on the next day will not be sufficient to recharge the battery. The result is a permanent operation of the battery at low–medium SOC.

The strategy of the ABLE regulator is to manage energy availability to the user. The load management is introduced with the EDA algorithm [12], which limits the daily energy available to the user. The user is assured to draw a daily assigned energy called energy deliverability assurance (EDA). This is verifiable and can be a contractual commitment.

In addition, daily extra energy deliverability (EDE) is given if the HBI is high (Fig. 5), which is an incentive for the user to save energy if not needed. Moreover, instantaneous excess energy can be always used during the day while battery is in floating charge.

If the system sizing has been correct, the EDA algorithm avoids long periods at low SOC and improves the average battery SOC, without reducing the performance of the system.

4.4. Monitoring and user indication

The EDA algorithm allows to provide a clear information to the user of how much energy is available for him. This method does not require SOC or SOH calculation, which is a difficult issue for lead-acid batteries [13,14].

A simplified built-in monitoring system provides data on operation of the system, with three objectives:

1. *Proof of service*: For regulating authorities or financing institution, the operator has to prove the service quality within a concession. This requires data recording of a few parameters that have to be easy to analyse.
2. *Proof of correct system use*: It often happens that users tend to use all energy available from the battery. The user is disconnected at low battery and complains stating that he "did not use a lot of energy". Without a clear indication of the energy consumed, the operator has no tools to check if the system is providing the energy service it should. This uncertainty is also a handicap to establish a clear contract with the user and can be an added difficulty to collect fees. On larger PV systems meters can be installed, but this would be costly for small systems.
3. *Battery warranty*: The monitoring data gives the charge, cycling and temperature history of the battery, which allows the battery manufacturer to check whether the battery has been operated within the specifications.

5. Test of the ABLE storage system

The ABLE regulator was first tested according to a number of criteria given in PV standards [15,16]. All functions described above operate properly after a few adjustments. Then, the ABLE storage system was validated in PV systems, through indoor, outdoor and field tests with PV-module and end-user. Commercial batteries and regulators were also tested for comparison.

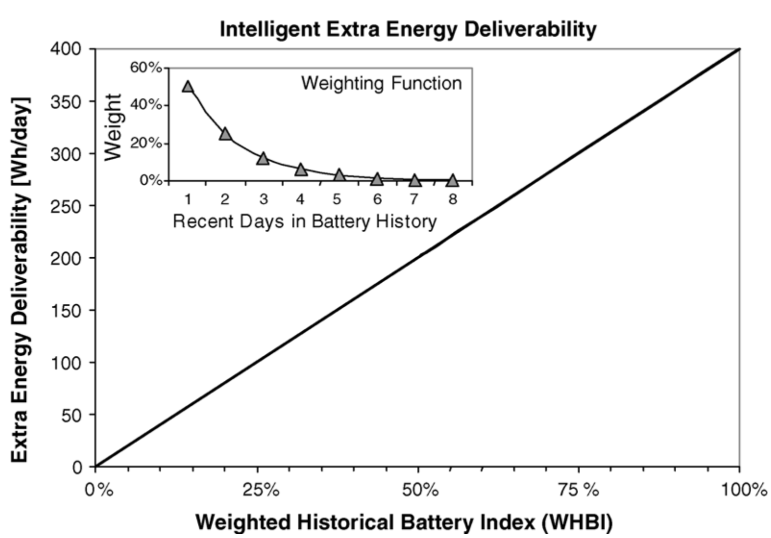
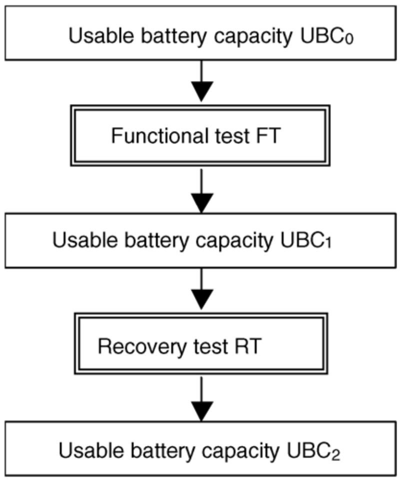


Fig. 5. Load management of the ABLE regulator.



Scheme 1. Test sequence for the IEC 62124 standard.

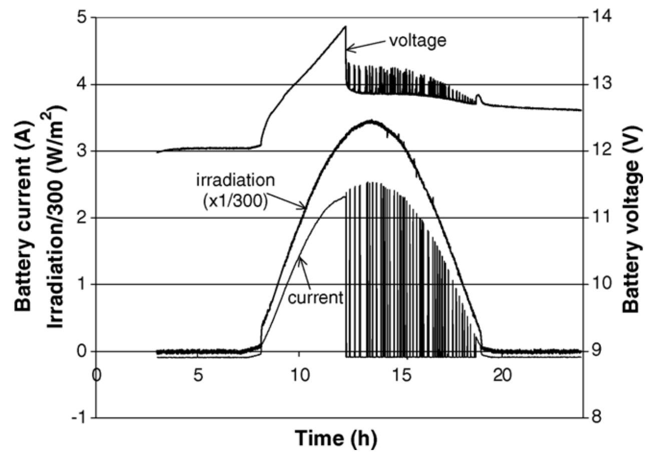


Fig. 6. Battery current, voltage and solar irradiation during one good weather day.

5.1. Indoor and outdoor PV test according to IEC 62124

5.1.1. Test procedure

The tests were performed by ECN (indoor) and GENEC (outdoor), with the draft standard IEC 62124 [17] as guidance.

The different steps can be described as follows (Scheme 1):

- *Usable battery capacity*: The battery is charged until it has been at HVD for a certain time (depending on the step UBC_0, UBC_1 or UBC_2). It is then discharged until it has been at LVD for 5 h. The discharged Ah is the usable capacity.
- *Functional test*: Starting from the charged state, the battery is charged and discharged daily during a period of 10 days (load on for a fixed duration every evening). The battery charge is performed according to the available irradiation for the outdoor test, and with a combination of low, medium and high-irradiation simulated days for the indoor test. The battery discharge is done by connecting the load during a fixed time every evening. However, the controller can disconnect the load when the battery reaches LVD.
- *Recovery test*: The battery is charged during the day, and is allowed for discharge in the evening only if the cumulated irradiation has reached 5 kWh m^{-2}, which can be achieved in one or several days for the outdoor test. This phase contains seven discharges, and is started with a discharged battery.

An overview of the tested battery/controller combinations is given in Table 1. Two sets of values for the energy management parameters (EDA and EDE) were chosen, in order to study two versions of the ABLE regulator:

- The first version was configured “with” the energy management system, which means “intelligent” EDA and EDE values. EDA was set slightly below the daily user request, in order to observe the presence of extra energy or not.
- The second version was aimed at disabling the energy management system and was called “without” EDA. EDA was set to a value above the nominal capacity of the battery, in order to observe load disconnection by LVD and not by EDA.

5.1.2. Results

Fig. 6 shows the charging of the battery during one good weather day of the outdoor test. At about 12:00, the battery reaches equalisation, and is then in floating during the rest of the day. An important observation is the high self-consumption of the ABLE regulator, which is around 100 mA. This is the reason why the current curve is clearly below zero during the night periods. This is to be compared to the self-consumption of the reference regulator, which is 0.7 mA. This means 0.17 Ah loss per 24 h, compared to 2.5 Ah for the ABLE regulator.

At the beginning of the test, the system with EDA has lower performances, the user gets less energy than for the system without EDA. After a few days in operation the HBI

Table 1
Tested battery/controller combinations

Combination	Battery	Controller	EDA (Ah)	EDE (Ah)
1	Reference	ABLE with energy management	1/3 C_{10}	1/2 C_{10}
2	Reference	ABLE without energy management	>C10	0
3	Reference	Reference controller	–	–
4	ABLE	ABLE with energy management	1/3 C_{10}	1/2 C_{10}
5	ABLE	ABLE without energy management	>C_{10}	0
6	ABLE	Reference controller	–	–

becomes lower for system without EDA, and the battery goes to LVD at every discharge. Then, a few days later, the energy supplied to the user becomes lower for the system without EDA.

This allows to conclude that the EDA algorithm, especially the variation of the extra energy (EDE) with the HBI is beneficial for the user who gets in final more energy; this effect is observed after a few days in operation.

This data also shows that the EDA algorithm is beneficial for the battery: the HBI is globally higher, which means that the battery is better recharged (equalisation voltage is reached more often).

On the other hand, the comparison between the ABLE regulator and a commercial regulator is not very good for the ABLE regulator. The user need is not always satisfied, especially during the recovery test. As explained above, the high self-consumption of the ABLE regulator, about 2.5 Ah per day, is the main reason for that. This high self-consumption is probably linked to the fact that the ABLE regulator is a prototype. Moreover, the influence of this parameter is increased by the fact that the batteries used had smaller capacities than those usually found on real systems, the self-consumption has thus a higher relative part.

However, this result clearly points out that this parameter is crucial for the overall energetic efficiency of the system, and that this self-consumption will need to be minimised for the final commercial version of the regulator.

In conclusion, all features of the ABLE regulators are operating properly in complete systems. It was difficult to observe the benefits of the innovative EDA battery management strategy, because the effects are hidden by the high self-consumption of the regulator prototypes. However, we can observe that the influence of the EDA algorithm on the user service is positive in the long term, even if the available energy is lower at the beginning.

5.2. Test of series/parallel association of ABLE systems

The ABLE regulator has a special feature allowing series and/or parallel association of several systems “battery + regulator”. Usually, the batteries are connected in series and/or in parallel in order to reach the required voltage and capacity, and one regulator manages the whole battery bank. The ABLE configuration has the advantage that each battery has its own controller and is protected against deep discharge and overcharge.

In order to check this functionality, a 24 V system with four prototypes in total (two parallel branches of two systems in series) was tested in outdoor conditions during 2 weeks. A weaker battery was used in order to introduce an initial imbalance in the system: in usual systems, most of the problems encountered are related to the presence of one weak battery. The daily load request corresponds to 20% DOD.

Fig. 7 shows the daily charge input in each of the four batteries, in comparison with the daily cumulated solar irradiation. During the 2 weeks, the weather was quite good except

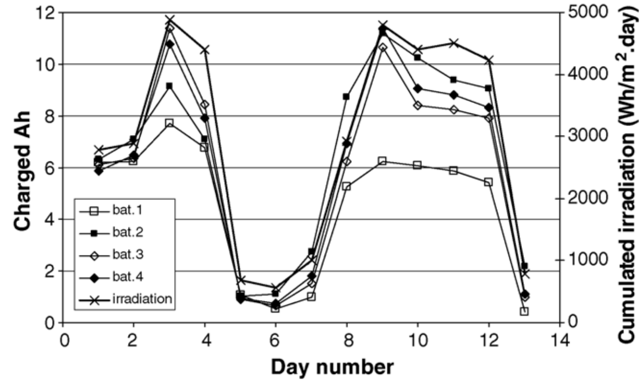


Fig. 7. Daily cumulated irradiation (right scale) and charge input to each battery (left scale).

3 very bad days in the middle of the period. This allows also, as an additional result, to see how the system is able to recover from a low SOC period.

There are significant differences in the charge input for the different batteries, which means that their charge acceptance is different. This is especially true for battery 1, which had lower capacity at the beginning of the test, and which appears to have a higher internal resistance. This observation becomes even more significant after the bad weather period: this period with insufficient recharge appears to have caused degradation to battery 1.

Fig. 8 shows the behaviour of each battery in discharge and the contribution of each one to the load supply. During the first days (when recharge is ensured), the contributions of all batteries are equivalent. This changes when a charge deficit appears: the contribution of battery 1 decreases, while that of battery 2 increases. This compensation of battery 1 weakness by battery 2, which is in parallel, is very clearly observed in Fig. 9: after a high irradiation day, the discharge current of each battery is equivalent. On the contrary, after a bad weather day, the current from battery 1 decreases, and the complement is ensured by battery 2.

This imbalance becomes more and more evident during the next days, and even when the bad weather period is fin-

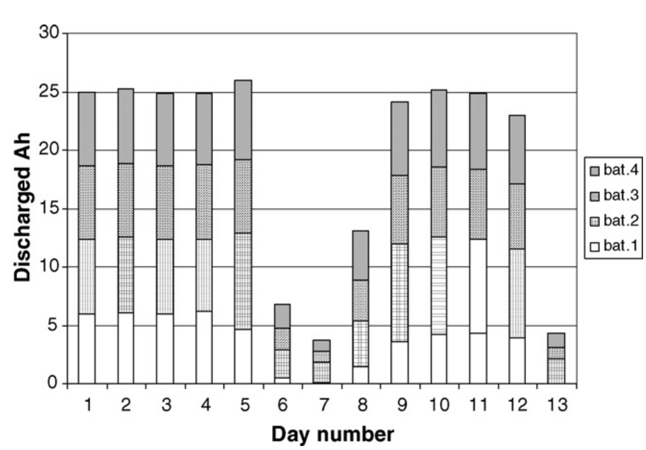


Fig. 8. Contribution of each battery to the load supply during the 2 weeks.

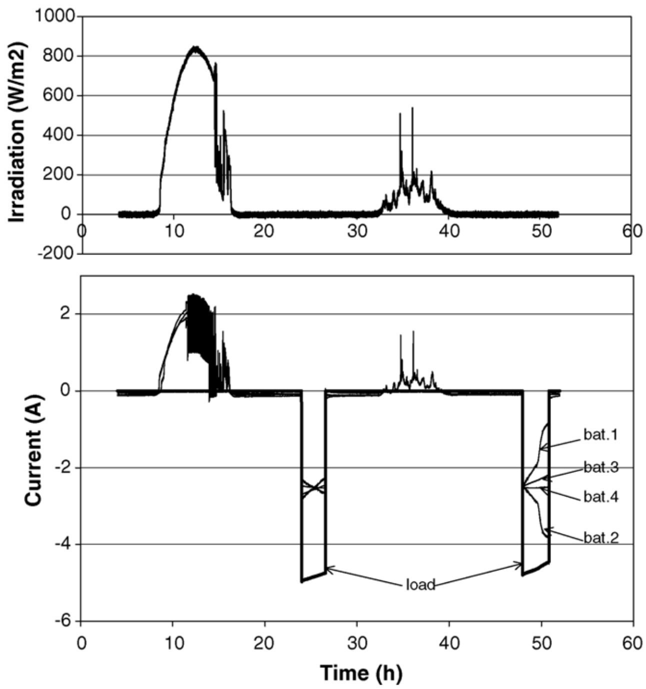


Fig. 9. Irradiation, load and battery current during 2 consecutive days.

ished, battery 2 continues to supply more than battery 1, and both go down to LVD every evening.

In conclusion, even if the drawback of series/parallel connection of batteries remains, that is, when a battery is weaker this has to be compensated by the other batteries, the advantage of the ABLE configuration is that a weaker battery will be disconnected at LVD and thus protected against deep discharge.

5.3. User acceptance test

This test was performed by TTA, who installed an ABLE system at a user's home. It is a rural house located in Spain, in the Pre-Pyrenees, and the user offered himself to perform the experiment. The electric installation of the house operates at 24 V, and two ABLE controllers were used. The system was operated during 5 weeks.

The objective of this test is complementary to the technical tests: it is more a "qualitative" validation, and special attention is paid to user acceptance and understanding of the EDA algorithm.

The discussions with users show that the system operation is simple and easy to understand, after an initial training to explain the EDA and EDE concepts and their operation. However, the multi-reading information LEDs depending of the flickering velocity appear slightly confusing, even in this problem is reduced with the user's daily routine and understanding.

The system operation, in general, has been appropriate. The courtesy LED lighting through the USB communication port of the EDA controller has been considered very useful and pleasant to the user. This functionality was introduced because users often wish to leave a light on all night for safety and company.

The technical problems encountered were rather minor. For instance, the ABLE regulator detects as a short-circuit the switching on of an halogen light of 20 W. Another point is that the temperature measurements are inaccurate.

In conclusion, this test allowed, together with the user, thinking about the evolution of the testfield process and understanding much better the controller behaviour.

6. Conclusion

It is expected that the ABLE storage system concept could be a major improvement for large-scale implementation of PV within the framework of national rural electrification schemes. The system appears very promising, but some small developments remain to be performed before industrialisation of the system. The self-consumption of the regulator has to decreased, which can be achieved by changing some of the electronic components, and the temperature measurements should also be improved. Concerning the ABLE battery, the industrialisation of the manufacturing process should allow to solve the problems observed on the prototypes, such as active mass filling of the positive electrode, and connection of the electrodes together.

Acknowledgements

The authors wish to thank the European Commission for funding this work under the contract no. ENK6-CT2000-00091, and Dr Laurent Torcheux for setting up this project.

References

[1] European Project ABLE (ENK6-CT2000-00091), Publishable Final Report.
[2] D. Pavlov, G. Papazov, B. Monahov, J. Power Sources 113 (2003) 255.
[3] D. Pavlov, J. Power Sources 53 (1995) 9.
[4] D. Pavlov, S. Ruevski, J. Power Sources 95 (2001) 191.
[5] T. Rogachev, D. Pavlov, J. Power Sources 64 (1–2) (1997) 51.
[6] G. Papazov, D. Pavlov, B. Monahov, J. Power Sources 113 (2003) 335.
[7] D.P. Boden, J. Arias, F.A. Fleming, J. Power Sources 95 (2001) 277.
[8] E. Potteau, D. Desmettre, F. Mattera, O. Bach, J.-L. Martin, P. Malbranche, J. Power Sources 113 (2003) 408.
[9] D. Desmettre, F. Mattera, P. Malbranche, S. Métais, Publishable Report of the QUALIBAT Project EUJOR3-CT97-0161, 1999.
[10] IEC 61427-1 standard: "Secondary Cells and Batteries for Solar Photovoltaic Energy Systems—General Requirements and Methods of Test".
[11] NF C 58-510 standard: "Lead-acid Secondary Batteries for Storing Photovoltaically Generated Electrical Energy".
[12] International Patent WO 03/036776, 01/05/2003.

[13] S. Piller, M. Perrin, A. Jossen, J. Power Sources 96 (2001) 113.
[14] F. Huet, J. Power Sources 70 (1998) 59.
[15] Universal Technical Standard for Solar Home Systems, European Commission, 1999, ISBN 92-828-5825-1.
[16] IEC 62093 draft standard (82/330/CDV): "Balance-of-System Components for Photovoltaic Systems—Design Qualification and Type Approval".
[17] IEC 62124 standard: "Photovoltaic (PV) Stand Alone Systems—Design Verification".