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Journal of Power Sources 67 (1997) 163–172

JOURNAL OF POWER SOURCES

Large lead/acid batteries for frequency regulation, load levelling and solar power applications

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Received 27 August 1996; accepted 27 December 1996

Abstract

Lead/acid batteries are suitable for a multitude of utility applications. This paper presents some examples where large lead/acid batteries have been used for frequency regulation, load levelling and solar power applications. The operational experiences are given together with a discussion about the design and technical specialities of these batteries. In 1986, a 17 MW/14 MWh battery was installed at BEWAG in Berlin which, at that time, was the largest lead/acid battery in the world. Designed to strengthen Berlin's 'island' system, it was used since the beginning of 1987 for frequency regulation and spinning reserve. In December 1993, when Berlin was connected to the electricity grid, frequency regulation was no longer required but the battery was still used for spinning reserve. For many years, the industrial battery plant of Hagen in Soest has used a large lead/acid battery for load levelling. The experience gained during more than ten years shows that load levelling and peak shaving can be a marked benefit for customers and utilities with regard to reducing their peak demand. In the summer of 1992, a 216 V and 2200 Ah lead/acid battery with positive tubular plates and gelled electrolyte was installed at a solar power plant in Flanitzhütte, a small village in the south of Germany which is not connected to the electricity grid. A report is given of the first years of use and includes a discussion about the best charge strategy for such gel batteries when used for solar power applications. © 1997 Published by Elsevier Science S.A.

Keywords: Frequency regulation; Load levelling; Solar power applications; Operational experiences; Valve-regulated lead/acid batteries; Negative copper grids; Lead/acid batteries

1. Introduction

Lead/acid batteries have been used for more than 130 years in many different applications that include automotive, uninterruptible power supply (UPS), telecommunication systems and various traction duties. There is a wide range in size and capacity of commercially available lead/acid batteries. Some are rather small with an energy of only a few Wh (or even less in some special cases), whereas the largest have more than 10 MWh. In general, the small types are valve-regulated lead/acid (VRLA) batteries mainly used for consumer applications.

The range of automotive batteries employed in starter applications is between some hundreds of Wh to more than 2 kWh. In comparison with the huge market for these starter batteries, which are mainly 12 V blocks, there is up to now only a very small market for electric vehicle (EV) batteries. Nevertheless, the latter could become much larger in the future [1]. Anyway, it should be realized that batteries for EVs are much larger than starter batteries. Currently, lead/acid batteries for electric passenger cars have an energy of around 10 to 15 kWh and often more than 20 kWh for electric delivery vans.

Although much more energy is desired for EV applications, it is remarkable that, as in many other applications, lead/acid batteries are mostly used and have a relatively low specific energy in comparison with several alternative electrochemical storage systems. This is due to the fact that it is not sufficient to consider only the specific energy. In the end, the ratios between specific energy/life/cost are more relevant for industrial use. Moreover, further parameters such as specific power, reliability, availability of raw materials and the possibility of recycling are also important. Taking all these factors into consideration, the lead/acid battery provides a good comprise and remains the world's most important secondary power source.

Important traction applications (e.g., fork-lift truck duty) require, in general, batteries with an energy between a few kWh and 100 kWh, in some special cases the energy can be even greater. Batteries for UPS duty have a similar energy range. Other stationary batteries are used for a multitude of utility applications. These batteries can have

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PII S0378-7753(97)02509-3

an energy of up to many MWh and are the largest in the world.

This paper presents some examples of the use of such large lead/acid batteries for frequency regulation, load levelling and solar power applications. The operational experiences are given, together with a discussion about the design and technical specialities of these batteries.

2. Copper-stretch-metal technology

Lead/acid batteries with high capacities often have rather tall plates. The general rule is that the taller the plates, the greater is the ratio of the grid electrical resistance to the total internal resistance of the cell. This causes, especially for plates taller than 50 cm, a lower depth-of-discharge (DOD) at the bottom area of the cell. The large voltage drop along the grid reduces the available energy of the battery and also increases the heat generation in the cell. In order to improve this situation, a new cell type called Hagen CSM was developed and placed on the market more than a decade ago [2].

Copper-stretch-metal (CSM) cells have the same weight and volume as the standard PzS cells, but copper is used instead of lead as the negative-grid material. Actually, it is an expanded copper grid covered with a thin layer of lead. On the positive side, tubular plates are used and have been shown to have a long life. The influence of copper as the grid material for the negative plate on the discharge and charge behaviour of the cell has been estimated by using a theoretical model developed in earlier papers [3,4]. In this model, the cell is considered as a network of vertical and horizontal resistances. A comparison of cells with plates of the same height (555 mm) has given the CSM cell an internal resistance that is about 17% lower than that of the standard PzS cell. Due to the lower resistance of the negative plate, CSM displays a markedly more equalized current distribution between the top and the bottom of the cell [5]. Experimental investigations of the current distribution in CSM and standard PzS cells have confirmed the predictions obtained from the theoretical model.

Fig. 1 shows the local current-density distribution of PzS and CSM cells with the same plate height (555 mm) at the beginning of a discharge with $2 \times I_5$. At the top of the plate, there is a much higher current density with PzS than with CSM. Conversely, in the bottom area, the CSM cell has a higher current density than the PzS cell. This means that there is a much more equalized current distribution in CSM plates. The difference in local current density also means a difference in the local DOD of the plate.

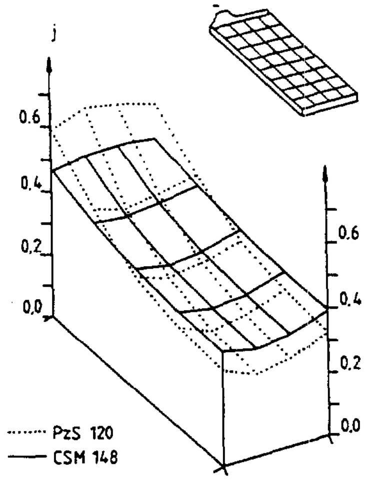

Fig. 1. Local current density distribution of PzS and CSM with the same plate height at a discharge rate of $2 \times I_5$.

Fig. 2 presents the relative deviation of the local DOD at the top of the plate to the DOD in average $(Q_{\mathrm{top}} - Q)/Q$ for different discharge rates between $0.5 \times I_5$ and $7 \times I_5$. In addition to PzS 120 and CSM 148, both with a height of 555 mm there is also a PzS 70 plate with a height of 315 mm. It can be seen that the CSM plate displays similar behaviour to the much shorter PzS cell. The relative deviation of the local DOD is a measure for the unbalanced mass utilization. PzS 120, with a plate height of 555 mm, has a significantly different mass utilization between the top and the bottom areas, especially at high discharge rates. This means that the mass utilization at the top is relatively high, while at the bottom there are mass reserves that cannot be used.

As the electrical conductivity of copper is much higher than that of lead, less grid material is necessary. This gives the possibility of having more active mass and electrolyte in the cell which, in turn, results in a further increase in volume energy density and power density. It is important

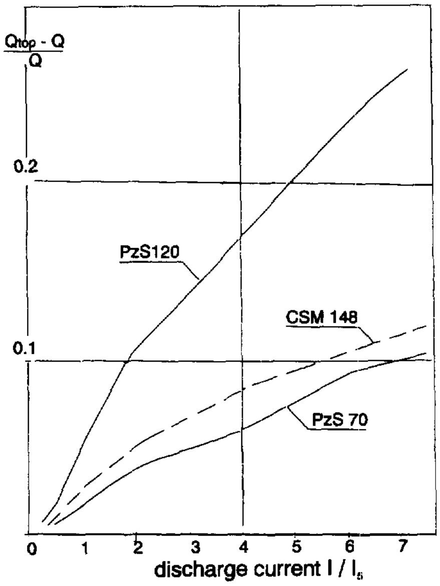

Fig. 2. Relative deviation of the local DOD at the top of the plate to the DOD in average $(Q_{\mathrm{top}} - Q)/Q$ for different discharge rates of PzS and CSM with a plate height of 555 mm and PzS with a plate height of 315 mm.

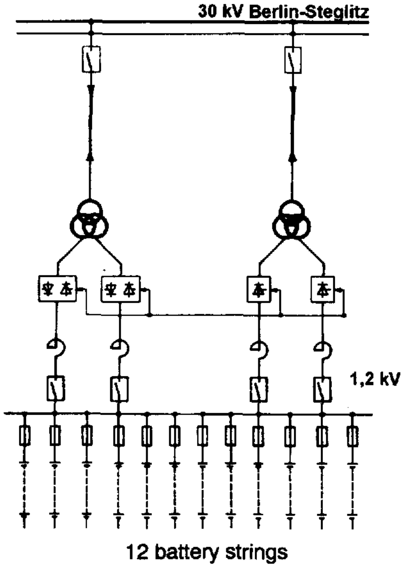

Fig. 3. Schematic of the BEWAG battery storage system.

to realize that the use of copper instead of lead for the negative grid is not only a benefit during discharge, but also provides a greatly improved charge acceptance with better energy efficiency. Hagen CSM cells for traction applications and Hagen OCSM cells for stationary applications should be used where cells with tall plates, medium or high discharge power, and high energy efficiency are required [2,6,7].

3. Frequency regulation and spinning reserve

In 1986, a 17 MW/14 MWh battery was installed at BEWAG in Berlin. At that time, the battery was the largest in the world [8,9]. Designed to strengthen Berlin's 'island' system, it was used from the beginning of 1987 for frequency regulation and spinning reserve. In December 1993, when Berlin was connected to the electricity grid, frequency regulation was no longer required but the battery was still employed for spinning reserve.

A schematic of the BEWAG battery storage system is presented in Fig. 3. There are 12 battery strings in parallel and each string has 590 cells in series with a capacity of 1000 Ah. This provides, in total, a 1180 V, 12000 Ah battery which, via converters and transformers, has been connected directly to the 30 kV grid of BEWAG in Berlin. A view of the complete battery storage system at the BEWAG plant in Berlin–Steglitz is shown in Fig. 4, while one of the battery rooms can be seen in Fig. 5. There are 118 Hagen OCSM modules of 10 V and 1000 Ah per string and the whole BEWAG battery has 1416 modules.

A typical current flow in one battery string over 42 h during frequency regulation at BEWAG is given in Fig. 6. The current was limited to ±700 A per string. This corresponded to a maximum power of ±8.5 MW which was sufficient to keep the frequency always at 50 Hz with a maximum deviation of ±0.2 Hz. When spinning reserve was needed, the limit of the discharge current was changed to 1400 A per string so that 17 MW were then available.

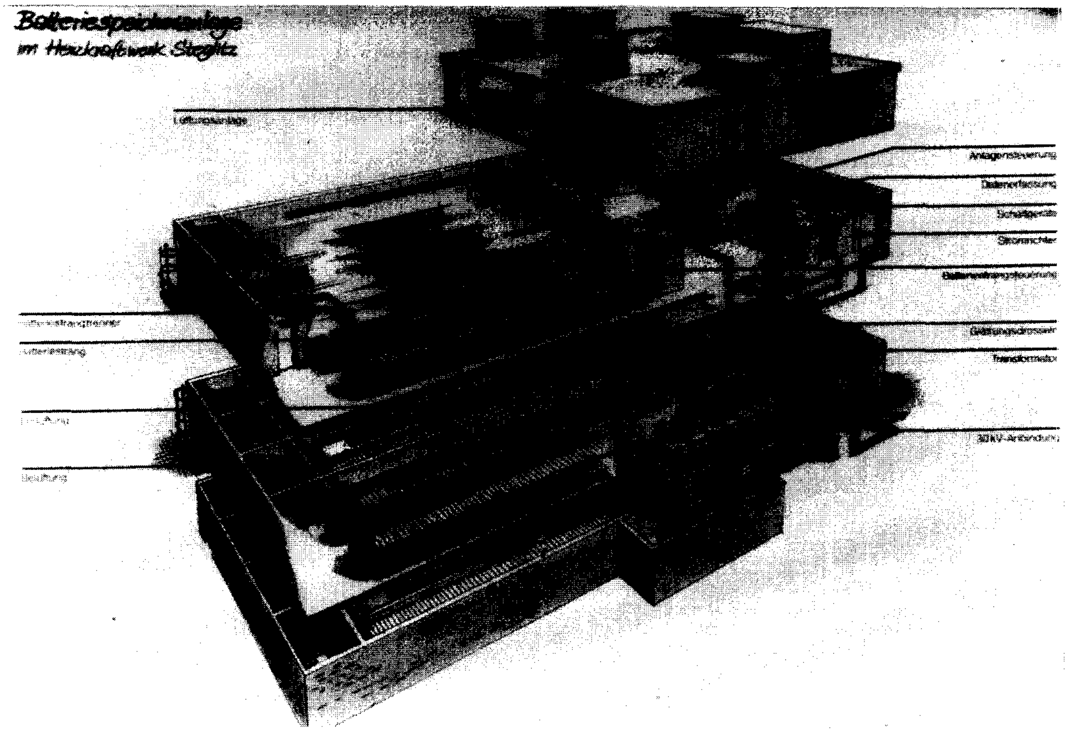

Fig. 4. The battery storage system at BEWAG plant in Berlin–Steglitz.

Fig. 5. One of the battery rooms at BEWAG plant in Berlin–Steglitz.

The state-of-charge (SOC) of the battery during the same time period over 42 h is presented in Fig. 7. The SOC was kept to around 70% with a deviation of ±20% so that there was always good charge acceptance and a certain reserve of capacity. Even the minimal SOC of 50% made it possible to have a spinning reserve of 17 MW maximum for at least 30 min. After two days of frequency regulation duty, the cells were charged over 4 h by an *I–U* charging procedure. Every week, there was also a complete recharge over 14 h. For such application, batteries with high power and good charge acceptance, as well as good cycle life, are needed. An important target was to have a total energy efficiency of more than 80%. Therefore, it was decided to use Hagen CSM design with negative copper grids and positive tubular plates. From 1981 to 1986, there were some preliminary tests in order to evaluate all the information required for the use of such lead/acid batteries in frequency regulation, and to obtain some basic data about the service life and the energy efficiency. The results were very promising and strongly influenced the decision to install the 14 MWh battery at the BEWAG plant in Steglitz [10].

In order to get high power and an energy efficiency of more than 80%, 10 V block batteries were used, rather than a single-cell design. In order to minimize the resistance of the intercell connectors, there was a direct connection through the partition, a well-proven technique for starter batteries. The 5-cell block container was made of polypropylene and the Hagen patentpole was used with copper inserts. There was an automatic water refilling system for each cell so that the maintenance work could be kept to a relatively low level. As the plate height was 800 mm and the charge voltage had to be limited to 2.4 V/cell problems with acid stratification were expected. In order to overcome these problems, an electrolyte agitation system was installed. In the beginning, it was estimated that the maximum turnover would be 2.2 times the nominal capacity per day. In fact, it turned out that the daily turnover was much higher (up to 3.3). Plastic pipe heat-exchangers were used to avoid extreme temperature differences within the whole battery.

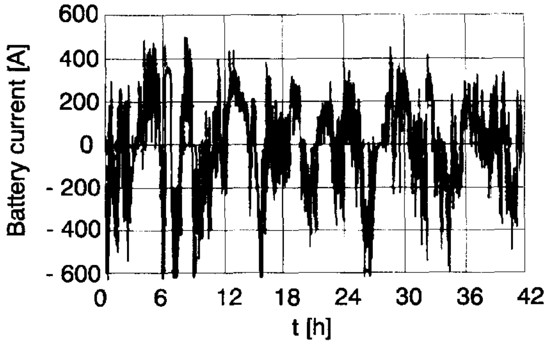

Fig. 6. Typical current flow of one battery string during frequency regulation at BEWAG.

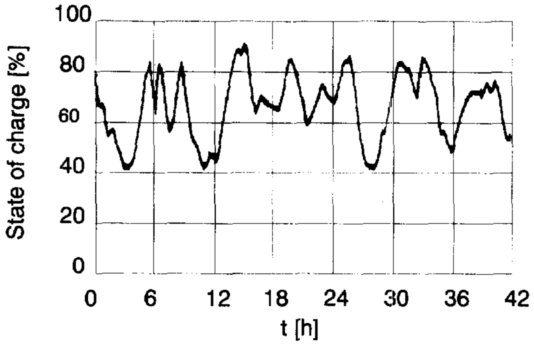

Fig. 7. SOC of the battery during frequency regulation at BEWAG.

In 1987, when the 14 MWh battery commenced operation at the Steglitz plant, BEWAG placed some 48 V, 1000 Ah batteries in their test facilities in order to investigate in more detail the behaviour of batteries under the operating conditions of the Steglitz plant [11]. These investigations included some comparative tests of different battery types. The main targets were to develop an optimal operating regime for battery storage systems used for frequency regulation and spinning reserve and to collect more data on the energy efficiency and the service life [12].

In December 1993, Berlin was connected to the West European grid. Therefore, frequency regulation was no longer a serious problem. From that time on, there were only small frequency deviations and the capacity turnover became rather small. Nevertheless, the battery continued in service as a spinning reserve for nearly a further two years. The battery then reached the end of its service life. Over the whole time in service, the 14 MWh battery storage system operated successfully with virtually no problems [13,14]. This is a very remarkable result as the operating conditions were rather severe. During the period of seven years that it provided frequency regulation, the battery had a capacity turnover of some 7000 times the nominal capacity. The total energy turnover of the battery was about 100 GWh.

Originally, BEWAG planned to install four more battery storage systems of the same size in the Berlin electricity grid. Due to the political changes in Eastern Europe, however, Berlin lost its 'island' position and all plans for more battery storage systems were abandoned. It should be noted, however, that a battery design as has been used at BEWAG could be of much interest for other 'island systems' around the world.

Although in large inter-connected grid systems such as the European grid, frequency regulation is not a serious problem, there are still other areas in which large batteries can be very useful. For example, it has been pointed out that there can be a marked economical benefit when batteries are used for primary and secondary control [14]. Such an application could become a very interesting market for lead/acid batteries.

4. Load levelling

In order to have a more levelled consumption of electric energy, utilities often try to influence the behaviour of their customers by offering them attractive tariffs for periods where there is a rather low demand for power and charge them much higher tariffs at periods of high power demand. In addition, customers can save costs by avoiding the supply of high peak power. A load-levelling and peak-shaving system can be very useful in cases of high peak power demand and can give a marked reduction in costs for electric energy.

In 1982, the industrial battery plant of Hagen in Soest set up a pilot system for load levelling. During the next few years, a fully automatic control system was developed [15]. In 1986, a complete system was installed and since that time considerable cost savings have been made every year by taking as much electric energy as possible during the low-tariff periods and by avoiding the supply of high peak power from the utility.

A schematic of the load levelling system in Soest is shown in Fig. 8. This uses a 7 MWh lead/acid battery with positive tubular plates and copper as the negative-grid material. There are two strings in parallel; each string has 200 cells with a capacity of 9000 Ah. An electrolyte-agitation system has served to avoid significant acid stratification. There are two d.c./a.c. converters, each of 250 kW, together with a computer that controls the system and stores all relevant data for statistical reasons. The computer program includes a measurement regime for voltage, current and all the required battery parameters, a calculation routine for power, energy and battery capacity, and an operation procedure that takes into account, among other things, the tariff situation and the SOC of the battery as well as data monitoring and evaluation.

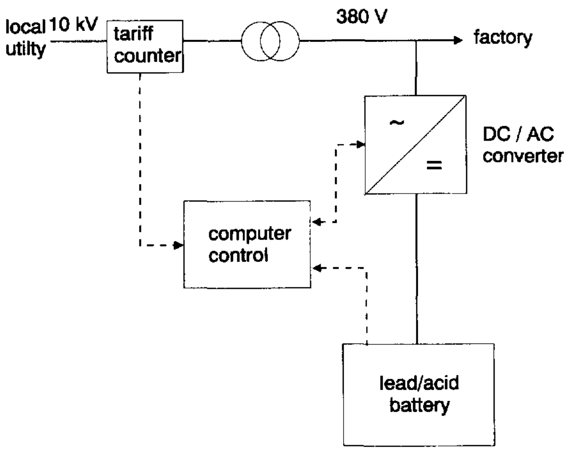

Fig. 8. Schematic of the load-levelling system in Soest.

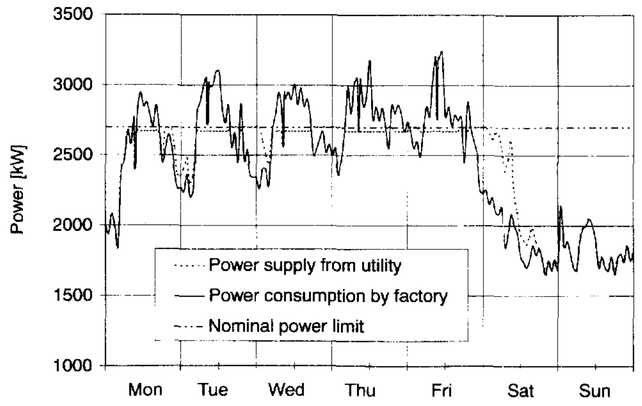

Fig. 9. Typical power profile of the load-levelling system in Soest over one week.

A typical power profile over one week is shown in Fig. 9. The power limit was set to 2750 kW, and although the peak power demand of the factory during the day increased to about 3200 kW, the battery delivered so much energy that the power, supplied by the utility, never exceeded the limit of 2750 kW. As the battery had been charged completely during the weekend, the SOC was 100% at the start of the week. The SOC decreased during the week so that steadily more energy was needed during the night to charge the battery. From Wednesday to Saturday morning, a virtually constant power of 2750 kW was supplied by the utility as the difference between the power demand of the factory during night and the power limit was completely used to increase the SOC of the battery. On Saturday, the power demand of the factory decreased markedly and, therefore, the battery could now be recharged completely. On Saturday evening, the SOC of the battery was again 100% and then the supplied power by the utility became equal to the power demand of the factory.

A power profile is shown in Fig. 10 in more detail over one day at the end of the week. Before 6 a.m., the power required by the factory was lower than the set power limit of 2750 kW and, therefore, some energy could be used for charging of the battery. As usual for the end of the week, the SOC of the battery was relatively low. Therefore, there was a rather good charge acceptance and the power sup-

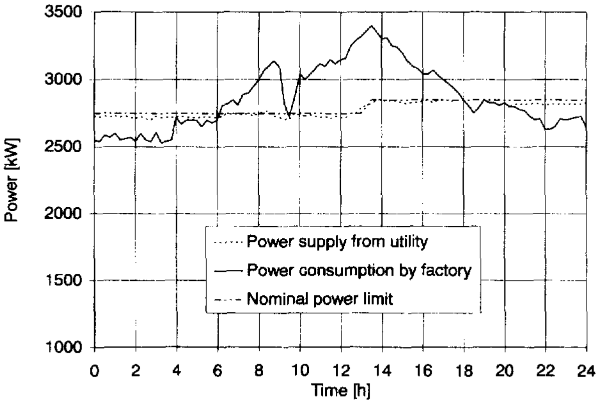

Fig. 10. Power profile of the load-levelling system in Soest in more detail over one day.

plied by the utility was always at the set power limit. After 6 a.m., the power demand of the factory exceeded the power limit of 2750 kW so that the battery could not be charged any longer but had to be discharged. At 1 p.m., the power consumption of the factory increased to more than 3250 kW, this means it exceeded the maximal power of the load-levelling system (500 kW), and therefore the power limit was set to a new value, 60 kW above the previous limit. At 6 p.m., the power needed by the factory became lower than the new power limit and battery charging started again. These data are an example of what happens if there is an unusual high demand of power. The computer program also considers the actual SOC of the battery. If the latter becomes rather low so that it probably would be difficult to get sufficient energy from the battery until the evening, the power limit is set to a higher level. Another possibility is to reduce, during such a critical period, the energy consumption of the factory by shedding a load that is acceptable to the production operations.

There has been a marked cost reduction for the Soest factory during all the years that the load-levelling system has been in action. In general, the saved amount has been more than 200000 DM per year. The results over more than ten years have shown clearly the benefits that such load-levelling systems can offer customers. Of course, there will be a different peak power demand and tariff situation for other companies and, for each application, the economics have to be calculated with respect to the required investment and the tariffs of the respective utility. Anyway, it should be realized that the use of such a system will become more beneficial if: (i) there are rather high power peaks; (ii) a significant part of the energy is needed during high tariff periods; (iii) any marked investment for the power installation can be avoided; (iv) the same battery can be used also for emergency power delivery, and (v) a load release management can easily be incorporated.

It can be expected that there will be an increasing demand for lead/acid batteries in such applications [16]. In the main, rather high capacities are needed. Positive tubular-plate design and copper as the negative-grid material have proved to be very useful. It is possible to use either single-cell arrangements or bloc batteries, for example, 10 V blocs as have been employed at BEWAG. The design can be a flooded system with low-antimony grid alloys, electrolyte agitation and an automatic water-supply system in order to have relatively low maintenance. There is also the possibility to use VRLA batteries with all the advantages discussed in the following section.

5. Valve-regulated lead/acid gel batteries

Two characteristics of the flooded-electrolyte design can often be quite unfavourable. There is water loss due to some water decomposition and, moreover, there can be a release of sulfuric acid, although it is in general only a very small amount; both these phenomena occur mainly during the charging period. The loss of water in a flooded cell cannot be disregarded and makes topping up with water necessary after certain periods of use. As a consequence of water decomposition, there is some release of hydrogen that requires special ventilation of the charging rooms in order to avoid an explosive concentration of hydrogen.

There is no need to add sulfuric acid during the whole life of the battery because of the extremely low amount that might leave the battery. As sulfuric acid is rather aggressive to most materials (it causes, for example, heavy corrosion of many metals), even such very low amounts of released sulfuric acid are quite unpleasant and make it often necessary, especially in case of larger batteries and severe charge regimes, to use special battery rooms. In the past, this behaviour restricted the use of lead/acid batteries in some applications.

All these disadvantages can be overcome by using lead/acid batteries of the recombination type, called, nowadays, VRLA batteries. The development of VRLA technology has made it possible to abandon the topping up with water over the whole life of the battery and to use lead/acid batteries for new applications where a standard battery with flooded cells cannot be used because a 'clean' battery without any risk of acid release is needed. Moreover, VRLA batteries can be designed to survive a 30 day short-circuit test so that, after recharge, the battery has the same capacity as before the test.

In VRLA designs, the electrolyte is immobilized by an absorptive glass-mat (AGM) or as a gel. The immobilization of the electrolyte makes a recombination process possible where oxygen can migrate from the positive plate, where it is produced especially during the end of charging, to the negative plate where it reacts (recombines) to water. As this reaction reduces the amount of evolved hydrogen gas, there is a marked reduction in the amounts of hydrogen and oxygen that leave the cell. Nevertheless, the

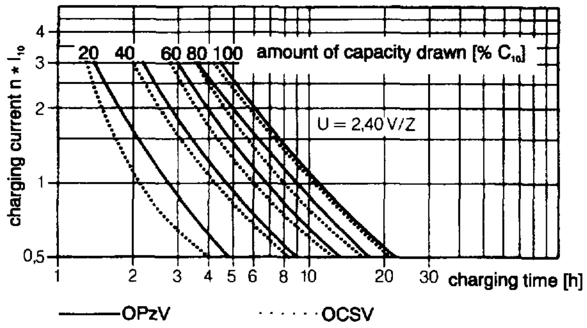

Fig. 11. Charging time and initial charging current to return an OPzV and an OCSV battery to 100% of discharged capacity after different DODs.

amount of released gas is not exactly zero and the often used term 'sealed battery' should not lead to the assumption that there is no gas release at all.

Growing markets for VRLA batteries include UPS, telecommunication systems, consumer batteries, solar power applications, EVs, and various other traction applications. There is also a probability that VRLA batteries will eventually replace flooded-electrolyte designs of starter batteries. Many studies about VRLA batteries have been published in recent years, e.g., in Refs. [17–29].

When Hagen developed VRLA batteries — both of the gel and the AGM design — for nearly all applications, the intention was to use negative copper grids also for these batteries. Of course, negative copper grids would mainly be used in gel cells as copper is most useful with tall plates and in such designs gel should be used exclusively otherwise acid stratification cannot be avoided. There has been an investigation of the combination of negative copper grids and gel and it has been found that this combination gives high-power, maintenance-free batteries without any risk of copper dissolution [30]. The results of this investigation agree well with experiences with high-performance lead/acid batteries with gelled electrolyte and negative copper grids that have been used for several years in different applications and where no noticeable amounts of copper have been found either in the electrolyte or on the negative active-mass surface.

Besides higher power, such cells have also a better charge acceptance. Fig. 11 shows the charging time for different initial charging currents to return a standard gel cell, OPzV, and a gel cell with copper grids, OCSV, to 100% of the discharged capacity. It can be seen that the use of copper grids reduces markedly the charging time due to the better charge acceptance of OCSV cells.

6. Solar power applications

Flanitzhütte is a small village in the south of Germany. There are five houses and two hotels and ten people reside there all the year round. Additionally, tourists come to Flanitzhütte for holidays and this increases the number of people staying there to up to 70. The electric energy demand is about 40 MWh per year. Flanitzhütte is located in a forest and the next village is quite some distance away. It is not connected to the electric grid. In former times, there was an old 20 kV line that required much maintenance and, finally, it was in such a bad condition that it was abandoned.

As the installation of a new line would have been quite expensive, the utility in this area, Bayernwerke, decided to take the opportunity to gain some experience on the use of a solar power plant for electric energy 'island' systems. Accordingly, a solar power plant was installed in Flanitzhütte in collaboration with Siemens Solar, the supplier of the solar generator, and Hagen, the supplier of the battery. Since the summer of 1992, there has been no supply of electric energy from the utility, the whole demand has been provided by the solar power plant [31–34].

A schematic of the solar power plant is shown in Fig. 12. This includes the most essential parts, i.e., the solar generator, the battery, the gas engine with generator and the converters. The solar generator consists of 360 m^2 silicon solar cells with a peak power of 40 kW. Via a d.c./d.c. converter and two three-phase d.c./a.c. converters, one 25 kW system for the basic demand, a second one of 40 kW for peak power, there is three-phase a.c. available with the usual voltage and frequency for all houses in Flanitzhütte. On the d.c. side, there is a lead/acid battery that can supply some additional electric energy when the solar cells deliver less electric energy than needed by the consumer. The battery will be charged when the solar cells supply more electric energy than the actual demand. This means that during night, and whenever the light intensity is rather low, the battery takes over in the main the energy supply. On the other hand, during sunshine periods, the solar cells provide all the needed energy to the customer and the excess of energy is given to the battery for charging.

The 216 V and 2200 Ah lead/acid battery has positive tubular plates and gelled electrolyte. Actually, the battery consists of 2 V OCSV cells with a capacity of 1100 Ah and there are two strings in parallel, each with 108 cells of

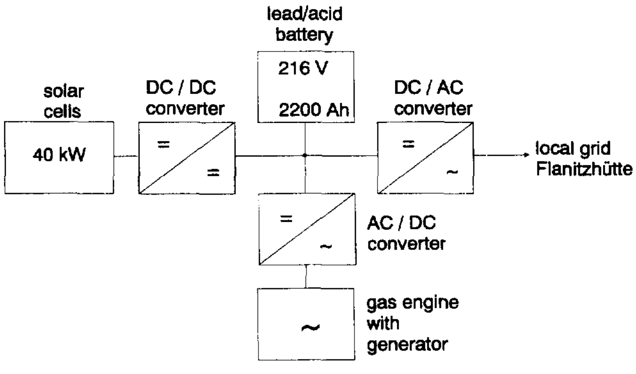

Fig. 12. Schematic of the solar power plant in Flanitzhütte.

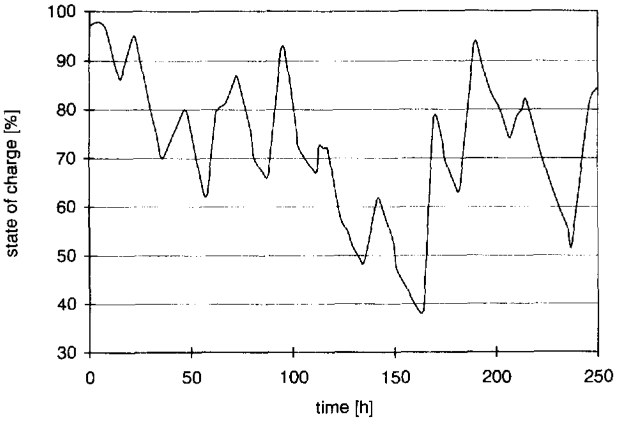

Fig. 13. SOC of the battery over 250 h during summer time in Flanitzhütte.

1100 Ah. In total, it is a 475 kWh battery and this size has been chosen in order to have provide Flanitzhütte with an electrical automomy for at least three days. Copper has been used as the negative-grid material because, for such a high capacity, tall plates are needed and, although the discharge currents are rather small in case of solar power applications, copper grids give a much better charge efficiency.

In recent years, the portion of solar energy in the total amount of consumed electric energy of Flanitzhütte has been about 65% over the whole year. It has been about 98% during summer time and less than 50% during winter time. These contributions could be increased by installing a larger solar generator, but it has to be considered that this would incur higher costs and there would be a marked excess of electric energy during summer time that could not be stored in the battery.

The difference between the consumed energy and the energy produced by the solar cells is supplied by a gas engine with a generator that is used for some hours whenever the SOC of the battery becomes too low. This happens seldom during summer, but is needed much more during winter, especially after longer rainy periods. In general, the gas engine starts to work when the SOC of the battery is lower than 40% and stops when the SOC has increased to 80%. In fact, the algorithm for the use of the gas engine is more complex and is controlled by a computer program that addresses further conditions, for example, whether it is summer or winter, the time of day or night, and the SOC of the battery. The strategy is to avoid, as much as possible, an excess of solar energy that cannot be stored due to a too high SOC of the battery. This means, for example, that a SOC of down to 30% is acceptable if it is achieved by the end of the night when it can be expected that the solar cells will quickly supply sufficient energy to restore the SOC of the battery.

In recent years, there were some detailed investigations into how the SOC of the battery changed during summer and winter time. From the balance sheets of energy consumption of Flanitzhütte and the energy supplied by the solar cells, this computer program has been improved to increase even further the portion of solar energy and to reduce as much as possible the use of the gas engine [35]. As a consequence, it can be expected that the portion of solar energy will increase from about 65% to more than 70%.

The SOC of the battery over 250 h during summer time in Flanitzhütte is shown in Fig. 13. The SOC is measured by Ah balance corrected by parameters such as battery temperature and voltage as well as charge/discharge currents. A complete recharge with an additional constant-current charging is given to the battery occasionally in order to recharge it completely and to set afterwards the SOC indicator to 100%. This extra charging is discussed later in more detail. From the curve of Fig. 13, it can be seen that the SOC is mostly between 90 and 40%. Of course, the SOC profile depends very much on the time of the year, the energy demand of Flanitzhütte and the number of sunshine hours.

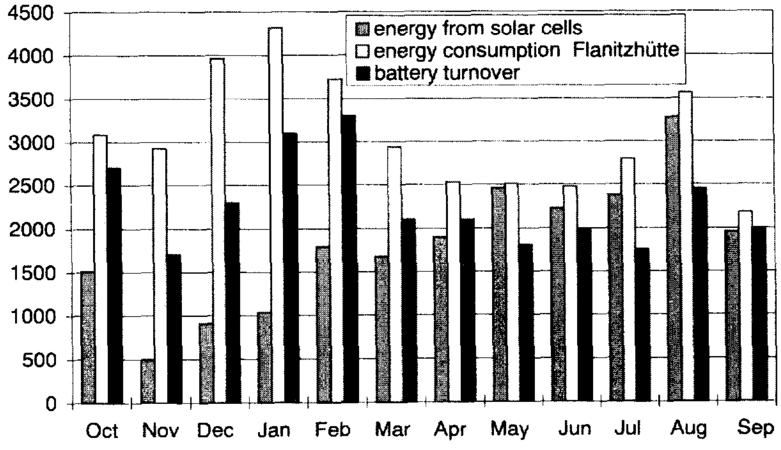

Fig. 14. Typical year profile (from October 1992 to September 1993) of the supplied energy from the solar cells, the energy consumption of Flanitzhütte, and the battery turnover.

A typical year profile (from October 1992 to September 1993) of the supplied energy from the solar cells, the energy consumption of Flanitzhütte and the battery turnover can be seen in Fig. 14. The most unfavourable period was between November and February because, during that time, there was the lowest amount of energy from the solar cells but a rather high energy demand. The battery turnover per month was between 1.7 and 3.3 MWh to give, in total, nearly 30 MWh per year. The energy efficiency of the battery has been found to be about 91%, which is a remarkably good value.

It is well known that the charge regime has a significant influence on the life of a lead/acid battery. Studies of the influence of charge that consider especially degradation phenomena of the positive mass have recently been published [36,37]. A discussion about the special situation in valve-regulated batteries can be found in Refs. [27,38–42]. In general, for solar power applications, the maximum charge voltage must be higher than the floating voltage but the choice of the most beneficial charge voltage depends, of course, on the charge/discharge profiles during use. For such an application, there is often only a small range between overcharging that results in accelerated grid corrosion as well as water loss and drying out, and undercharging that produces sulfation or an accelerated degradation of the positive active-material.

There has been some investigation about the behaviour of AGM cells under different charge regimes and it has turned out that, for heavy cycling, a voltage of 2.4 V/cell is necessary to avoid sulfation [27,41]. Moreover, the use of an even higher charging voltage than 2.4 V/cell, of course only for a limited period of a few hours, is helpful in keeping the active mass in good condition for a long time. Changes of the crystalline structure of the positive active-material and the softening process are slowed down and the cycle life can be improved markedly. This has recently been confirmed by studies about the influence of the charge regime on cycle life of AGM batteries under EV cycling conditions [43].

This high charging voltage has to be used carefully. There are two possibilities. Either to use a constant-voltage charging of more than 2.4 V/cell for a limited time period or to use a constant-current charging at the end for a few hours on a level that automatically gives a voltage above 2.4 V/cell. Both have been shown to extend the cycle life of valve-regulated batteries. Nevertheless, the use of a constant current rather than a constant high voltage during the last charging period has the advantage of reducing the danger of thermal runaway. This benefit applies to both AGM and gel batteries, but is has to be considered that the actual value of the most useful charge voltage is influenced by the specific gravity of the electrolyte (i.e., a lower specific gravity requires a lower charging voltage and vice versa), and by the particular application of the battery.

There has been some laboratory investigations about the best charging voltage by using similar charge/discharge profiles and gel cells to those in Flanitzhütte. It has been found that a maximum charge voltage of 2.33 V/cell is too low to keep the active mass in good condition although it is markedly above the floating voltage (2.25 to 2.27 V/cell). With the use of a maximum charge voltage of 2.38 V/cell and, occasionally, an extra constant-current charge, sulfation could be virtually avoided. These laboratory results fit well to the experience gained in Flanitzhütte where the maximum charge voltage was varied between 2.33 and 2.38 V/cell and the higher voltage of 2.38 V/cell has given markedly better results.

There has also been some investigations about the effect of a complete recharge including an extra charging with a constant current of 11 A per battery string (1 A/100 Ah) over 8 h. In the beginning, this extra charge was applied alternately to one string of the battery at least once a month resulting in up to 20 extra charges per year and per battery string. According to analysis of the charge/discharge profiles over three years, the period between the extra charge was extended in 1995 to two months during summer time and one month during winter time. This means that the number of extra charges could be reduced markedly to a total of ten extra charges per year and per battery string.

7. Conclusions

Battery energy storage has made significant progress in the past ten years. Batteries are beginning to be implemented in high-value markets for both storage and system-regulation applications. The examples given in this paper, namely, frequency regulation and load levelling, have shown the benefit of using lead/acid batteries. It can be expected that there will be an increasing demand in lead/acid batteries for a multitude of such utility applications.

The solar power plant of Flanitzhütte has been in use for more than four years and up to now the gel battery has operated successfully and without any problem worth mentioning. It seems that solar power application too will become an interesting market for the lead/acid battery in future and probably a significant portion will be valve-regulated batteries. The market is preferably in the developing countries, but there seems to be also a significant demand in Europe at places where there are electric 'island' situations. In such cases, it is often too expensive to make the connection to the electric grid so that a solar power plant including a battery can be the more economical solution.

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