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A multifunctional energy-storage system with high-power lead–acid batteries

R. Wagner [a,*], M. Schroeder [b], T. Stephanblome [b], E. Handschin [c]

[a] *EXIDE German Group R&D Centre, Sonnenschein GmBH D-63654 Büdingen, Germany*
[b] *EUS, Gelsenkirchen, Germany*
[c] *Universität Dortmund, Dortmund, Germany*

Abstract

A multifunctional energy storage system is presented which is used to improve the utilization of renewable energy supplies. This system includes three different functions: (i) uninterruptible power supply (UPS); (ii) improvement of power quality; (iii) peak-load shaving. The UPS application has a long tradition and is used whenever a reliable power supply is needed. Additionally, nowadays, there is a growing demand for high quality power arising from an increase of system perturbation of electric grids. Peak-load shaving means in this case the use of renewable energy stored in a battery for high peak-load periods. For such a multifunctional application large lead–acid batteries with high power and good charge acceptance, as well as good cycle life are needed. OCSM batteries as with positive tubular plates and negative copper grids have been used successfully for a multitude of utility applications. This paper gives two examples where multifunctional energy storage systems have started operation recently in Germany. One system was installed in combination with a 1 MW solar plant in Herne and another one was installed in combination with a 2 MW wind farm in Bocholt. At each place, a 1.2 MW h (1 h-rate) lead–acid battery has been installed. The batteries consist of OCSM cells with the standard design but modified according to the special demand of a multifunctional application. © 1999 Elsevier Science S.A. All rights reserved.

Keywords: Lead–acid batteries; Negative copper grid; Power conditioner; Peak-load shaving; Power quality

1. Introduction

Lead–acid batteries have been used for more than 130 years in many different applications that include automotive, uninterruptible power supply, telecommunication systems and various traction duties. In spite of extensive work on alternative electrochemical power sources the lead–acid battery remains the world's most important electrochemical energy storage device. This is remarkable as the lead–acid system has a relatively low specific energy, but in the end, it is the combination of specific energy, lifetime and cost that is relevant for industrial use. Moreover, additional parameters such as specific power, reliability, availability of raw materials and the possibility of recycling are also important.

In order to fulfill functions like uninterruptible power supply, improvement of power quality and peak-load shaving, the batteries need to be connected to the grid. In the presented multifunctional energy storage system, this connection is realised by a special kind of converter. The abilities of this converter cover all the function mentioned above. The most important function of the storage system presented is peak-load shaving, where the battery stores the energy and the converter manages the power transfer. In the case of a mains supply failure the system is capable of supplying a selected group of consumers as a UPS system. If the load voltage experiences shows disturbances the system can be used to work as an active filter. This special function is described in detail later on.

Transferring electric power from and into the battery is a process that needs to be controlled due to the needs on both sides: battery and electrical grid as well. Therefore, a process control function is implemented within the system in order to guarantee the exact operation necessary and to keep an eye on the operating conditions. The control is done by a programmable logic device (PLD), that works automatically. For purposes of checking the system or doing experiments with it, a visualisation system is installed which provides manual access to the process.

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[*] Corresponding author. Fax: +49-6042-81224

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2. Battery design

Lead–acid batteries are suitable for a multitude of utility applications. Often, such batteries are quite large and 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 a lower depth-of-discharge at the bottom area of the cell especially for plates taller than 50 cm. In order to improve this situation, a new cell type called HAGEN OCSM was developed and placed on the market more than a decade ago [1].

For OCSM cells 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. OCSM cells have a markedly reduced internal resistance and a much more uniform current distribution between the top and the bottom of the cell and therefore a significantly better mass utilization [2]. It is important 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. OCSM cells for stationary applications should be used where cells with tall plates, medium or high discharge power, and high energy efficiency are required [1,3,4].

For a multifunctional application large lead–acid batteries with high power and good charge acceptance, as well as good cycle life are needed. HAGEN OCSM batteries with positive tubular plates and negative copper grids have successfully been used for various utility applications, for example, at BEWAG in Berlin where a 17 MW/14 MW h-rated battery was in operation from 1987 to 1993 for frequency regulation and spinning reserve [5–9]. It was, at that time, the largest lead–acid battery in the world. Over the whole time in service, the battery storage system operated successfully with virtually no problems. This is a remarkable result as the operation 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 and a total energy turnover of about 100 GW h.

The good operational experiences gained from the practical use of OCSM batteries for many utility applications have strongly influenced the decision to use the OCSM technology also for the multifunctional energy storage system. Two batteries were needed each of 1.2 MW h. The development included some modification of the standard OCSM design according to the special demand of a multifunctional application.

A schematic of one of the 1.2 MW h battery is given in Fig. 1. In total, it is a 544 V, 4140 A h battery and there are three battery strings in parallel whereas each string has 272 cells in series with a capacity of 1380 A h. Fig. 2 shows the battery room at the 1 MW solar plant in Herne. The battery consists of 2 V OCSM cells and has positive tubular plates and copper as the negative grid material. A low antimony grid alloy was used on the positive side. The cell container has been made of transparent SAN and

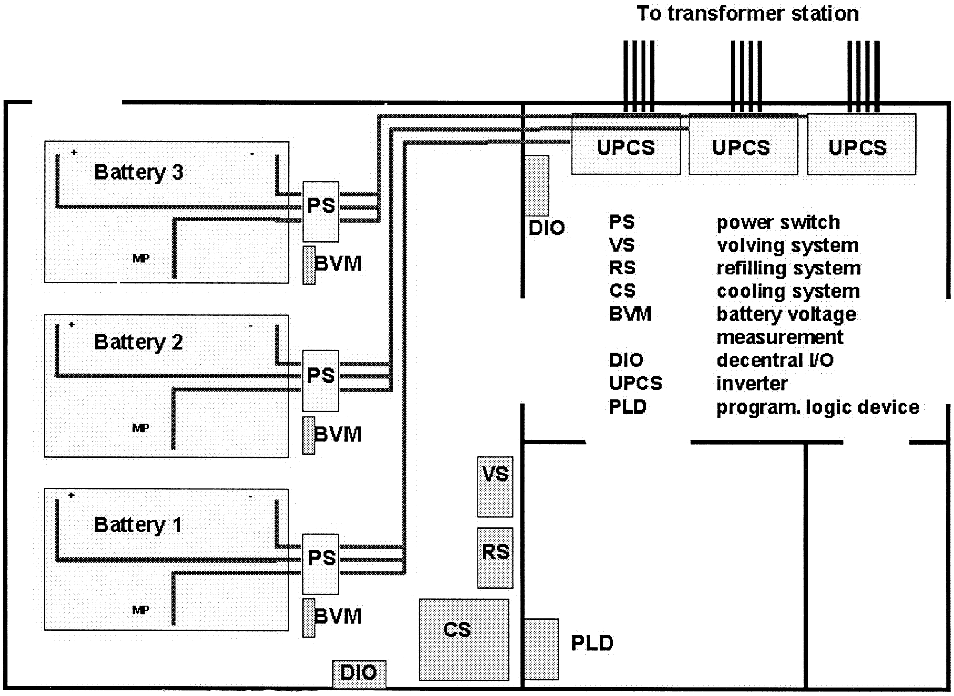

Fig. 1. Schematic of the 1.2 MW h multifunctional lead–acid battery.

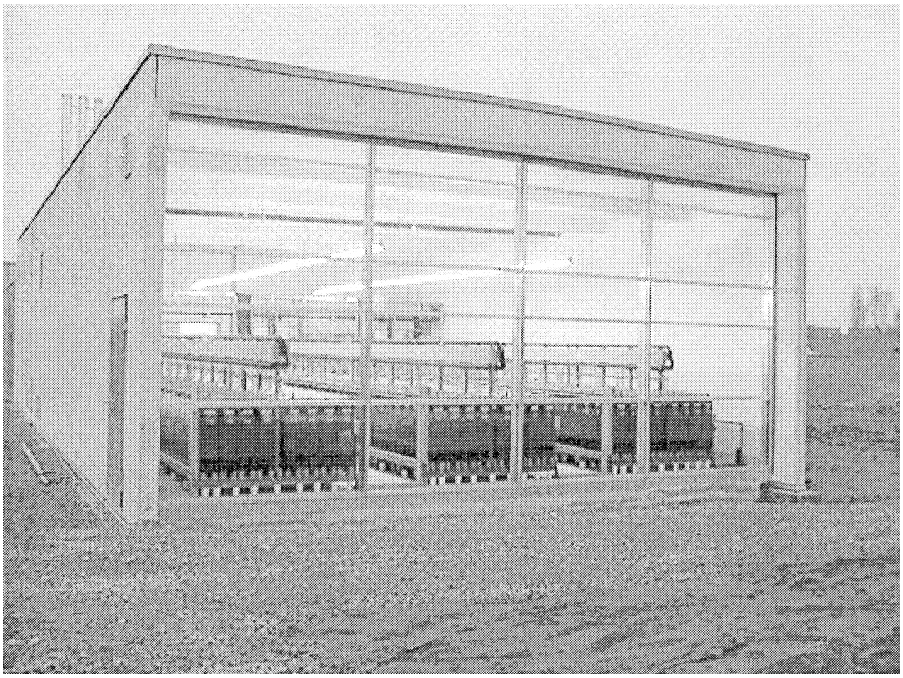

Fig. 2. Battery room at the 1 MW solar plant in Herne.

HAGEN patentpole is used with copper inserts. A special lid has been designed which has five holes, two for the cooling pipes, one for the electrolyte agitation system, one for the automatic water refilling system and one as an option to install an electrolyte level indicator. Currently this hole is used in 24 cells for temperature sensors.

There is an automatic water refilling system for each cell so that maintenance work can be kept to a relatively low level. Actually, a bfs 3 (battery filling system) system has been put on the cells and connected to a large 280 l water tank which serves as a water reservoir for the complete battery. This tank is automatically filled with water via an ion exchanger.

Acid stratification is a well known problem especially in the case of large cells. A way to overcome this problem is to overcharge the battery significantly, resulting in a marked gassing that can re-mix up the electrolyte. Unfortunately such a strategy gives a markedly worse charge efficiency. Moreover, it increases significantly the water loss and the heat generation in the cell. The use of an electrolyte agitation system can avoid all these disadvantages. The development of the multifunctional battery has included some work on the electrolyte agitation system which has the same principle as had been used for the BEWAG battery but slightly modified according to the demand of the 1.2 MW h battery. The air blown into all the cells is supplied by a central compressor. For the complete battery the amount of air is about 24 m^3/h. Every day the electrolyte agitation system is in use for about 15 min which has been proved to equalize the specific gravity throughout.

The application as a multifunctional battery includes, at least occasionally, a rather extensive use of the battery with relatively high currents. In order to avoid higher temperatures or marked temperature differences within the whole battery a special cell design was developed which includes plastic pipe heat-exchanger. Each cell has four windings of a plastic pipe with an inner diameter of 3 mm. In order to have enough space and to keep the windings completely within the electrolyte a larger cell container with a height of 797 mm was used. This provides an increase of the electrolyte minimum level of about 40 mm. Although the distance between the minimum and maximum levels was reduced markedly, which is possible in case of an automatic water refilling system, the terminals had to be extended too by about 20 mm. The cooling system has a power of 40 kW. For the battery in Herne four cells are cooled in series in one circuit whereas for the battery in Bocholt there are only two cells cooled in series. The cell separation is 10 mm and the battery temperature is measured by 24 PT100-sensors.

As the batteries shall supply rather high power and since slightly longer terminals are used the terminals have copper inserts which have been extended from the top of the terminal down very close to the top bar in order to minimize the internal cell resistance. The cells have four terminals, two in parallel for each polarity. The voltage of every eighth cell is measured during use of the battery in order to control any deviation from balance within the battery. The cells are connected by flat copper bars each of 300 mm^2 which means, in total, a connection with 600 mm^2 as two terminals are used in parallel.

3. Test of the battery

A group of six 1380 A h OCSM cells were tested in the laboratory in order to confirm the expected performance of the battery. After the standard capacity investigations with different discharge currents there were also some high rate discharge tests. Fig. 3 gives the discharge curves for the 1380 A h OCSM cells at constant power discharge of 1.47 kW and 2.94 kW per cell. It can be seen that the voltage of OCSM is at a relatively high level for a rather long part of the discharge even at the very high discharge rate of nearly 3 kW per cell. This is the typical behaviour of a cell when copper is used as the negative grid material. The diagram shows also the discharge curves of the standard OPzS cells with the same weight and seize. The much better performance of the OCSM design can be seen clearly. There was also a test of the charge acceptance and again the OCSM cells behave markedly better in comparison to the standard OPzS design due to their much lower internal resistance.

There was also a test of all the other components including electrolyte circulation, automatic water refilling and the cooling system and it turned out that they all work properly. Fig. 4 shows the result of a test of the cooling system during a 1 h discharge with 818 A where three of the six cells were cooled. The flow rate of the cooling water, with a temperature of 18°C, was 300 ml/min. During a 1 h rate discharge the electrolyte temperature increase was about 4°C with, and about 6°C without, the cooling system. This result confirms the efficiency of the cooling system.

4. Power converter design

To achieve a large variety of functionality, a converter is needed that can transfer active and reactive power from and to the electric grid. Moreover, to perform active filtering, the converter must have a fast and intelligent control system. Details of the functionality, the hardware and the control concept for active filtering are described below.

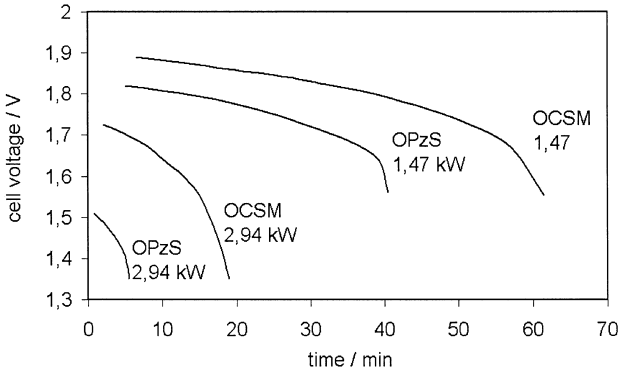

Fig. 3. Discharge curves of the 1380 A h OCSM cells in comparison to standard OPzS cells at high discharge rates with constant power of 1.47 kW and 2.94 kW, respectively.

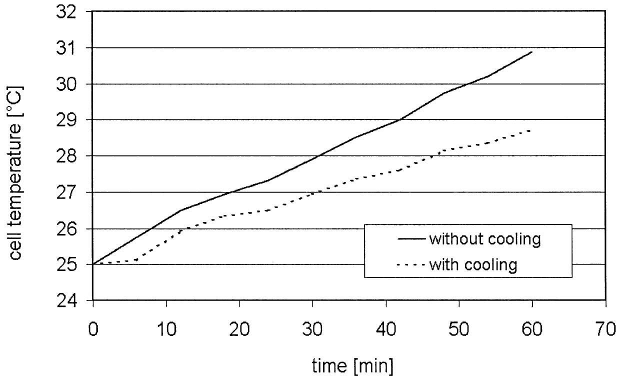

Fig. 4. Change of electrolyte temperature of the 1380 A h OCSM cells for the multifunctional battery during a 1-h discharge with 818 A with and without cooling.

- Substitution of peak-load power by power produced from renewable energy sources.

The use of a battery makes it possible to substitute the required peak-load power by stored power from renewable energy sources with high efficiency. This smoothing of system load by the use of storage leads to an improved use of the existing system capacity and, thus, to a delay in system extension measures. At the same time, the transmission losses in the system and the costs for the reserve are reduced. The cost advantages, which are achieved by the reduction of the primary energy use and the optimal use of the power station and grid capacities, result in attractive tariffs for the customers of utilities.

- Improvement of reliability of power supply.

Structural changes and steady modernization of production plants cause a growing use of high technology equipment (electronic control, microprocessors, etc.). These plants react to inevitable disturbances in electric grids by functional interruptions, malfunctions or failure leading to production interruptions and to production stops. In this connection the energy storage represents an uninterruptible power supply for the time of failure.

- Improvement of quality of power supply.

On the consumers' side, the requirements regarding power quality are growing steadily. In the case of discontinuous production by renewable energy sources using power converters, the sinusoidal shape of the power is corrupted by harmonics that have disturbing effects on parallel operating, vulnerable consumers. The subject of system perturbations is discussed more and more intensively. In the future, a reduction of the permitted disturbance level may be expected for a secure operation of existing grids. Present disturbances may be compensated more economically in most cases by the use of energy storage systems with suitable power converters than by system extensions. The power converter presented here consists of a real-time control algorithm to compensate disturbances of load voltage by triggering the insulated gate bipolar transistors (IGBT) of the converter bridge.

The starting point of the development of such an active filter is a UPS [10]. Fig. 5 shows the basic schematic of a so-called ‘on-line’ or ‘double conversion’ static UPS. Power is taken from the mains supply by a 6-pulse or 12-pulse controlled thyristor rectifier to the DC link of the device, at the same time charging the battery. A fast switching IGBT inverter is connected to the DC link and feeds the AC load. In case of any failure of the mains voltage (over- or undervoltage, frequency deviation, voltage distortions, dips, spikes or interruptions), the load is continuously supplied by the inverter with an excellent undistorted sinusoidal voltage. For the inverter there is no difference whether it is supplied from the rectifier or from the battery. As long as the mains voltage is within certain limits, the inverter synchronises its output voltage with the mains. In case of an overload exceeding the capability of the inverter, the load is transferred to the mains via the static switch, which is connected in parallel.

The static UPS shown in Fig. 5 can be changed to a shunt type voltage controlled active filter by simply switching on the static switch. The rectifier is not needed anymore. Fig. 6 shows this configuration. For acting only as an active filter, the static switch and the battery are not needed. They are optional and needed for additional functionality explained later. The converter is connected in parallel to all the loads to the so-called point of common coupling (PCC). It is controlled to act as a voltage source. The mains supply voltage source and the filter voltage source are connected in parallel, decoupled only by the mains impedance Z_S.

Any difference in the instantaneous voltages of the two sources leads to an instantaneous current [11]. Since the voltage reference value of the converter is an ideal sinewave, the converter feeds instantaneous current into the PCC to correct any deviation from the ideal curve. So the converter acts as an active filter against harmonics in the busbar voltage regardless of whether they are caused by load1 or load2 or they are injected into the PCC by the mains supply. Furthermore, it filters commutation effects, voltage dips, sags and flicker. It is a great advantage that all loads connected to the PCC can gain from the filtering activity. Since the output current of the converter is limited, it is obvious that the average value of the busbar voltage cannot be corrected over a period of time. So the amplitude and phase angle of the reference voltage is adjusted to minimise the fundamental of the active and reactive compensating currents. If the optional static switch and a battery are used, additional functionality is provided: If the mains supply exceeds certain limits or breaks down, the static switch opens and disconnects load2 from the faulty busbar. The converter is then supplied by the battery and provides power to load2. This means that this device can also be used as a UPS for part of the load [12]. By switching the control mode of the converter to current or power control of the total load, the battery performs peak-load shaving. Because of this wide application range the device is called a Unified Power Conditioning System (UPCS).

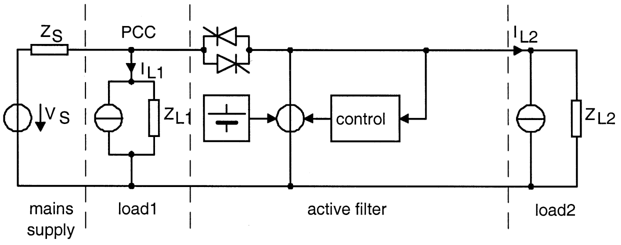

Fig. 6. A shunt (parallel) type active filter with instantaneous voltage control mode (the battery and the static switch are optional).

Fig. 7 gives the design concept of the UPCS in more detail. The UPCS consists of an optional static switch, an IGBT converter, a filter circuit and, optionally, a DC/DC-converter with a battery. Instead of the battery any other energy storage system such as a flywheel may be connected. The converter consists of three individually controlled IGBT half bridges. It is fed by a split DC link. The neutral is directly connected to the midpoint of the DC link. Each half bridge has an output filter to suppress the high frequency harmonics produced by the converter [11]. There is no output transformer needed to connect the UPCS to the low voltage busbar.

A test configuration was set up with a supply transformer, loads, a 100 kW-rated UPCS and a welding device

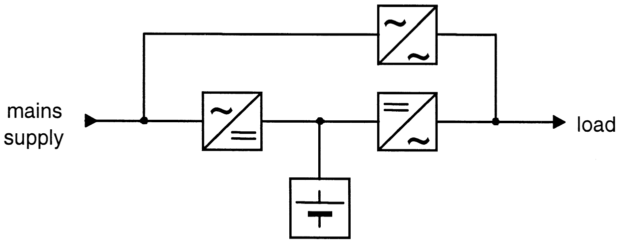

Fig. 5. Basic schematic of ‘on-line’ or ‘double conversion’ static UPS.

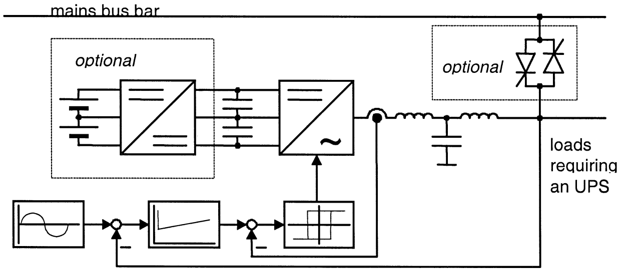

Fig. 7. Instantaneous voltage control of the UPCS.

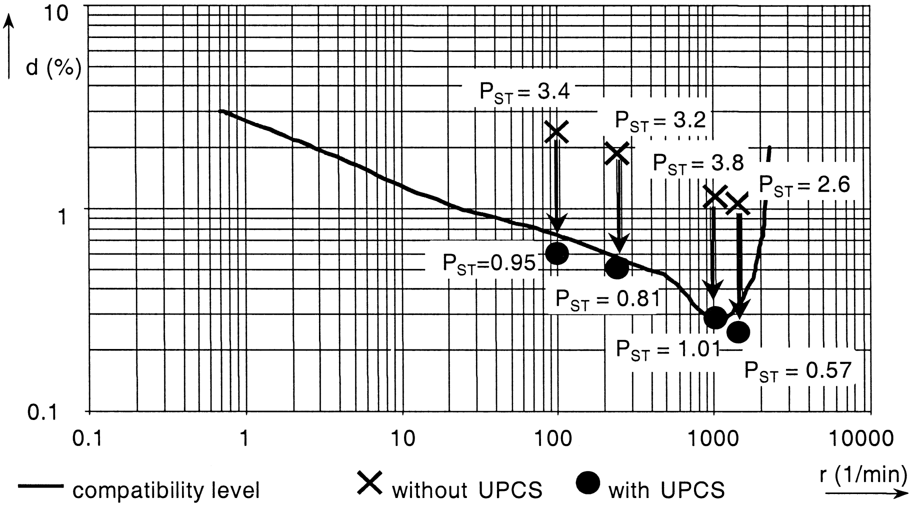

Fig. 8. PCC voltage dips over refresh rate and short-term flicker caused by welding equipment with and without 100 kW-rated UPCS.

with adjustable duration of operation and pause mode. This welding device produces voltage dips that can be measured as a voltage flicker. Fig. 8 shows PCC voltage dips over refresh rate, which are reduced to a compatibility level by the use of the UPCS. Also, the short-term flicker value P_{ST} is reduced significantly. A detailed picture of the UPCS power converter is given by Fig. 9. It shows one of the three 400 kW-rated power converters, each of them being part of an individual module. The battery energy storage system is divided into three modules. Each module consists of a 400 kW-rated power converter and a battery string with a nominal voltage of 544 V and a 10 h-rate capacity of 1380 A h. These three storage modules are controlled by one process automation system as presented below.

5. Process automation system

The process automation system of the battery storage is divided into a data acquisition and a data evaluation module. For an optimal battery operation sufficient data describing the actual battery state are necessary. Thus, a

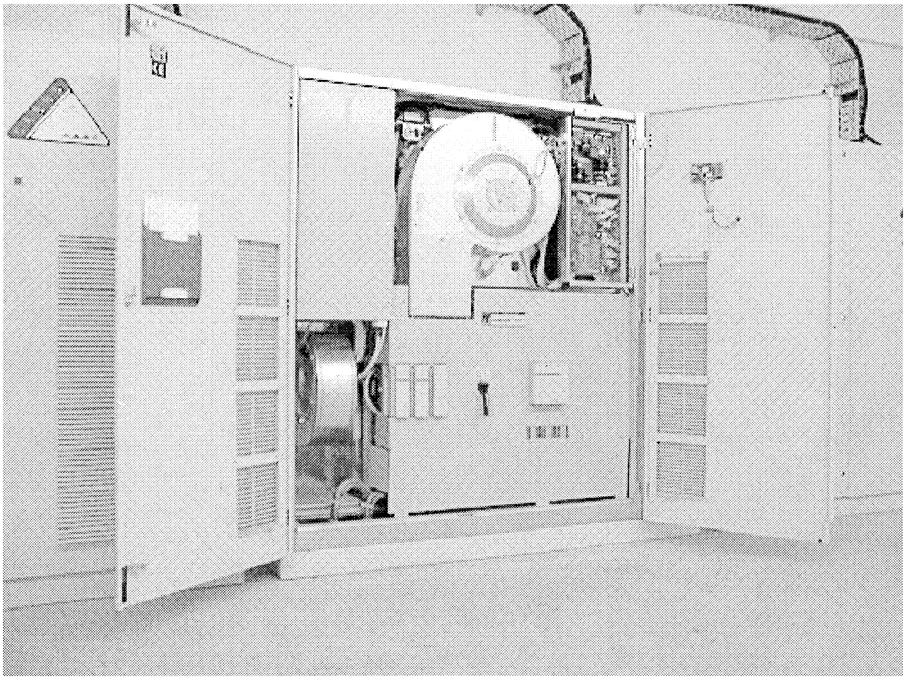

Fig. 9. Detail picture of a 400 kW-rated UPCS power converter.

data acquisition system especially for the battery has been installed. This system gathers information on charge and discharge currents, cell temperature and cell voltages in groups of eight cells. In addition, the converters and auxiliaries are measured and controlled. The data communication with the operator of the electrical grid is important for a correct operation of the energy storage.

A major part of the automation system is the data evaluation unit which is generating commands for battery control. Highest priority is given to the security relevant information, followed by measurement validation and generating typical battery data from acquired data. Data validation is primarily the detection of possible measurement errors which is done by range checking. Also, range checking gives information on points in the system where the measured values cling to the upper or lower limit of the possible range of the equipment. Equipment malfunction can easily be detected as well. Methods for data evaluation are mainly data smoothing or offset correction. This is done to achieve a high data quality and reliability. Further validation concepts as described in DIN VDI 2048 are used to get additional information on the data quality, especially in the case of measuring in wide ranges, e.g., measuring the battery current covering a range from a few amperes up to 1 kA. Battery specific data like discharged ampere hours describing the state of charge cannot be measured directly, so they have to be calculated. Calculated data forms a base for estimating the reserve power of the battery and the necessary operating time on the grid. Comparing the two values leads to an optimised operation. Measured and calculated data are stored in a relational database which provides data safety and care. The database is equipped with the possibility of a connection to other software tools that can perform a long-term optimisation of the system.

The heart of the control system is the hardware of the data acquisition unit and the general system components as shown in Fig. 10. Using a distributed data acquisition structure, the cable lengths for measurement are reduced to a minimum and a local galvanic separation is possible. The communication between the distributed measurement units is done on a bus system, enabling the system to set and get data rapidly.

The high DC voltage of the battery strings leads to problems with the data acquisition as far as galvanic separation is concerned. In order to avoid this problem special modules are used which provide the necessary voltage separation ability. These modules need their own bus system, which can be connected to the general bus system by so-called bridges.

The general bus system is the main communication line. Transferred data are not only measured data but commands as well. Data evaluation is responsible for creating decisions for the PLD to give out signals to the converters and the other peripheral units. These commands influence the state and the mode of the energy storage modules, i.e., activating or stopping the converters, setting desired values for power transmission, activating or stopping the auxiliaries, etc. While the process control itself is done by a PLD, an operator can interact through a visualisation system. Moreover, the visualisation system gives information on the process state and controls the database. The visualisation system works on the same bus system as the PLD and can be interpreted as a supervising unit. The process state can be viewed on various screens, each giving the possibility for interaction.

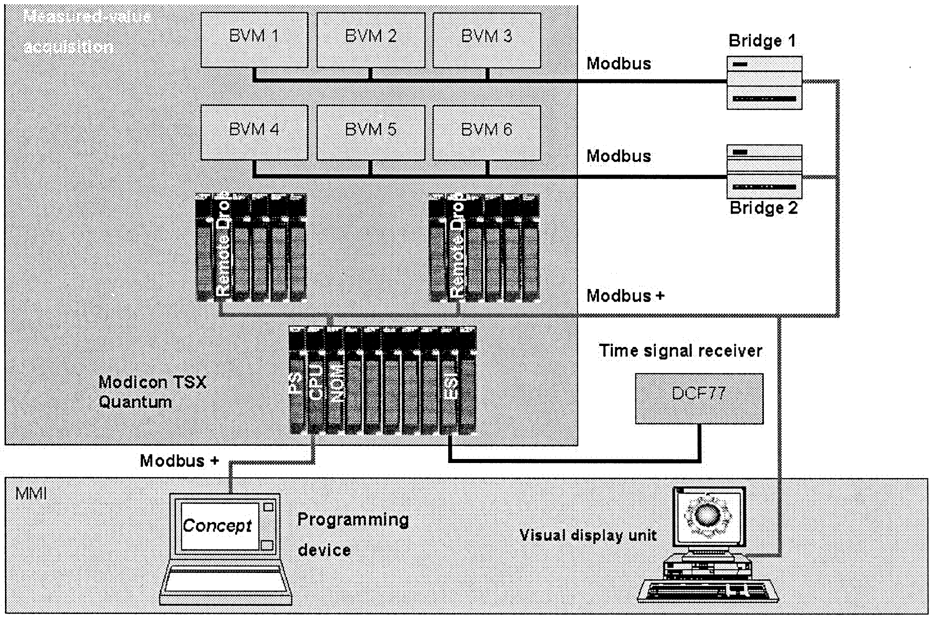

Fig. 10. Hardware of the process automation system.

6. Conclusion

Multifunctional battery energy storage systems are useful in order to improve the utilization of renewable energy. Such batteries include three different functions: (i) uninterruptible power supply (UPS); (ii) improvement of power quality; (iii) peak-load shaving. There will be an interesting market in the future especially as there is a growing demand for high quality power arising from an increase of system perturbation of electric grids. For such multifunctional applications, large lead–acid batteries with high power and good charge acceptance, as well as good cycle life are needed. OCSM batteries with positive tubular plates and negative copper grids have been used successfully for various utility applications. This technology is also a good choice in the case of a multifunctional application. There has already been development of gel batteries with negative copper grids and it has been found that this gives high power, maintenance-free batteries without any risk of acid release [13,14]. It seems that for utility applications there will be an increasing demand for rather large gel batteries. A careful design of such batteries is necessary in order to overcome potential difficulties such as temperature problems.

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