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Optimized battery-management system to improve storage lifetime in renewable energy systems

Rudi Kaiser*

Fraunhofer-Institute for Solar Energy Systems, Heidenhofstr. 2, 79100 Freiburg, Germany

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Abstract

Lead-acid batteries are the main technology used in renewable energy systems (RESs) and autonomous power-supply systems due to their maturity and low cost, factors that will remain valid for the next few years. It is often stated, however, that batteries in RES applications exhibit shorter lifetimes than those expected by manufacturers' data or those experienced in real traditional applications. Overall, in relation to all other components in RESs, the battery lifetime is quite short and has an intensive impact on the costs of the total system.

The Fraunhofer-Institute for Solar Energy Systems ISE has developed a new generation of battery-management system (BMS), which improves the storage lifetime and reliability of batteries in RESs and thus reduces maintenance and lifetime costs considerably. The BMS allows new operating strategies not possible with conventional battery systems. For this purpose, the battery bank is split into several strings that are connected in parallel. Each string is individually switchable according to its current state-of-charge (SoC) and state-of-health (SoH), which are determined continuously. For each battery string, the BMS enables shorter cycles at low SoC, an increase in the battery current rate, and intensive full charges during normal operating conditions. Furthermore, the BMS considers the ageing mechanisms of each string and can operate with different battery types or battery technology. For this reason, the BMS combines the different advantages of each string and generates an optimized battery. Furthermore, the BMS is established as an active two-terminal network. System planners and designers can handle the BMS like a conventional battery, which implies no essential changes in electrical installations.

Keywords: Battery-management system; Stand-alone system; Lead-acid battery; State-of-charge; State-of-health; Renewable energy system

1. Introduction

In stand-alone power supplies that utilize solar energy, the energy input fluctuates substantially depending on climatic and meteorological conditions. As a result, the batteries are frequently operated at low state-of-charges (SoCs), are frequently partial cycled, and are recharged with low currents. This adversely affects the lifetime of lead-acid batteries.

A simple solution to this problem could be an oversized battery with an early load shedding, to prevent deep SoCs. Nevertheless, a lack of full charges is still unavoidable with this method. Stand-alone power-supply systems, called hybrid systems, have an additional controllable power supply, such as a genset (Fig. 1). With such a generator, a full charge can be reached anytime, but this causes additional fuel consumption, even when the battery still has sufficient energy stored to supply the stand-alone system. An increase in battery lifetime is therefore a reduction of the solar fraction. Furthermore, the oversized battery increases investments costs.

Lead-acid batteries have a high impact on the lifetime costs of stand-alone power-supply systems. To operate such systems economically, oversized batteries and extensive fuel consumption should be avoided.

The main aim of a battery-management system (BMS) is to reduce the continuous expense of energy storage with improvements in storage lifetime and reliability.

To fulfil this task, a special operation management for stand-alone systems with optimized charge strategies and knowledge of SoC and state-of-health (SoH) is necessary. In any case, even if all this information is available, batteries in conventional stand-alone systems are connected permanently with the power supply and the load. Battery management can obviously be improved

* Tel.: +49 761 45885220; fax: +49 761 45889220.
E-mail addresses: kaiser@ise.fraunhofer.de, kaiser@ise.fhg.de.

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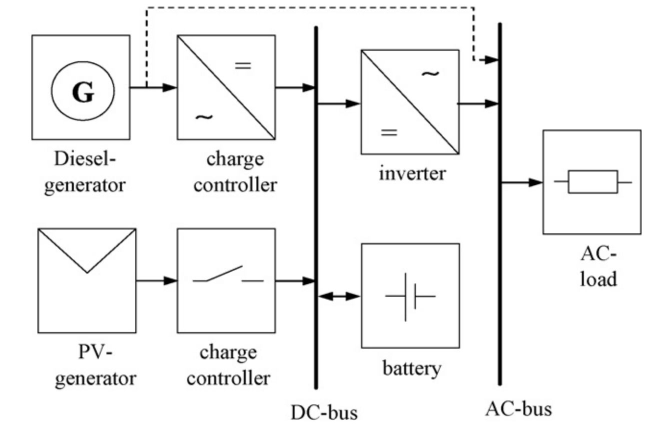

Fig. 1. Basic concept of stand-alone renewable power supply system with photovoltaic-generator and diesel-genset.

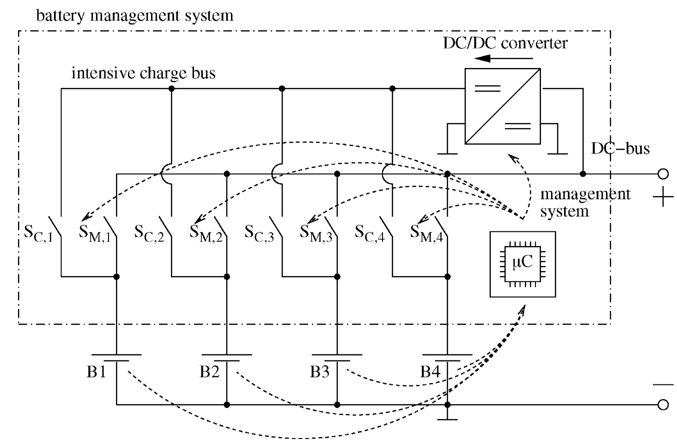

Fig. 2. Circuit concept of BMS with four parallel-switched battery strings (B1–B4). The storage concept is a two-terminal network and externally operates like a conventional battery.

by running the battery temporarily independent of the load profile and cutting the battery off from the remaining stand-alone system. This method generates a new degree of freedom and enables new battery-management strategies, which are not, or only to a limited extent, possible with conventional stand-alone systems.

The load to a stand-alone system has to be supplied with energy permanently. For this reason, it is necessary to split the entire battery into multiple battery strings.

2. Concept of battery-management system

The BMS is established as an active two-terminal network. It operates in stand-alone systems like a conventional battery. It will be charged by the power supply, if sufficient energy is available, and discharged by the shortfall between power supply and consumption. The system load is delivered directly by the power supply without using the battery. This prevents additional losses in the stand-alone system.

The BMS is connected to the remaining stand-alone system, like a conventional battery to the dc-bus, via its two contacts (plus, minus). In contrast to a conventional battery, the BMS is able to output data on the SoC and the SoH of the battery system, for example to a primary energy-management system.

The circuit concept of the BMS is shown in Fig. 2. The entire storage volume of the battery is sub-divided into several parts (battery strings). The battery strings are interconnected in parallel via the main switch $S_{M,1}$–$S_{M,4}$. This provides the option of connecting and disconnecting the individual battery strings (B1–B4) independent of each other to/from the dc-bus. Several battery strings can thus be charged or discharged simultaneously, while the remaining battery strings do not have to be involved. The individual battery strings can be connected or disconnected independently of each other during the charging or discharging process.

In addition, the BMS comprises a dc–dc converter, which also is connected to the dc-bus. At its output, the converter is connected via the intensive charge bus with the switches $S_{C,1}$–$S_{C,4}$ to the individual battery strings. Thus, BMS is in a position to perform a full charge for each individual battery string. The dc–dc converter exclusively performs the charging steps during which only minor currents are used at higher voltages.

By means of the circuit concept and with the assistance of the dc–dc converter, the BMS is able to operate each battery string quite individually. The internal operating management, which provides information of the SoC, the SoH, and the actual capacity, as well as the voltage, current and temperature of each individual parallel battery string, is responsible for controlling the BMS. With this information, the BMS decides the manner in which the individual battery strings have to be operated.

3. System management of the battery-management system

The task of the BMS is to use the renewable energy efficiently and to increase the lifetime and reliability of the battery system. The ageing mechanism of the lead-acid battery results from various stress factors,[1] which result from the performance characteristics of the stand-alone system. The most important stress factors are listed are: (i) long period in low SoC; (ii) partial cycling in low SoC; (iii) rare full charges; (iv) elevated temperatures. With the exception of temperature, an intelligent system management can favourably influence all factors, so that their negative influences can be minimized.

Total and partial discharge conditions of the batteries cannot be prevented completely, since the BMS is unable to provide the battery system with more energy for charging than a conventional stand-alone system. A lower depth-of-discharge (DoD) of an individual battery string can be achieved only by means of a higher DoD of another string. As the result of the independent charging and discharging of the individual battery strings, these strings are not dependent on the load profile of the stand-alone system.

The number of connected battery strings can be varied by means of the BMS. The charge or discharge current is dis-

[1] Stress factors are parameters that have a negative influence on the ageing characteristics of the battery through known mechanisms [1].

tributed, depending on the switch position, to the number of connected battery strings. The battery current of the individual battery strings can thus be set up to a certain degree. This option enables the achievement of higher charge or discharge currents and/or the operation of the battery strings in the preferred current range.

By means of the dc–dc converter in Fig. 2, individual battery strings can be charged selectively, even if the energy available to the battery system is inadequate for a full charge of the entire battery system. Intensive full charges according to a constant current/constant voltage/constant current charging strategy, have a positive influence on capacity development and reduce long-term tenacious sulfation in the lead-acid battery [2].

A targetted discharge of a battery string can be achieved by means of independent connection of the battery strings, while the other battery strings continue to store the generated current. This allows a capacity test with variable discharge current. The discharge current is determined by the loads in the stand-alone system and is not predictable. The available battery capacity can be determined with an error margin of less than 8% by means of the process developed at Fraunhofer-Institute for Solar Energy Systems [3]. The energy discharged during the capacity test is used in full by the loads of the stand-alone system, and will not be lost via a dump load. The result of the capacity test serves as an indicator of the SoH of the battery string and as a reference parameter for determining the SoC. While determining the SoC, a fuzzy expert correction is applied, which was also developed by the Fraunhofer-Institute for Solar Energy Systems. The method was designed especially to meet the requirements of stand-alone systems and has an error margin of less than $8\%_{\mathrm{abs}}$ [3].

To ensure that the BMS uses the renewable energy efficiently, individual battery strings are operated so as to prevent an early cut-off of the PV generator. This process particularly uses renewable energy for charging and avoids a reduction of the solar fraction.

The system management of the BMS is responsible for determining which battery string is charged or discharged and when this is to commence and/or when an intensive full charge or a capacity test is to be performed. The system management is therefore sub-divided into two main task areas, as follows:

(i) The general system management decides which and how many battery strings are charged or discharged.
(ii) The special system management of the BMS determines the battery string on which an intensive full charge or a capacity test is to be performed.

3.1. General system management

The general system management decides which and how many battery strings are to be connected to the dc-bus. The less it is discharged and the more frequently it is fully charged, the more favourable is the effect on the lifetime of a lead-acid battery. When selecting the individual battery strings, one must differentiate between the strings that are to be connected or disconnected. The deciding factors are the current status of the battery string and various criteria that are examined in the following discussion.

The number of battery strings to be connected is determined via their nominal current and the total current. In conventional stand-alone systems, battery currents mainly occur in the range of I_{20}–I_{200}, which have an unfavourable effect on battery lifetime. Small currents discharge the active mass of the battery both horizontally and vertically in an even manner. In the vertical direction, this produces a high mechanical stress in the vicinity of the grid. Due to the increasing volume of the active mass, its contact with the grid may be lost. The more even the discharge in the vertical direction, the better it produces a discharge of the lower part of the electrode. Especially in stand-alone systems, acid stratification frequently occurs with flooded batteries. The resulting insufficient charge in the lower regions of the electrode, combined with small discharge currents, produces a very high DoD in this area [4]. The high discharge currents cause an inhomogeneous current distribution, but very low mechanical stress. Charging batteries with small currents is also disadvantageous. At the start of charging, only small overvoltages are achieved, which are unable to dissolve the existing sulfate crystals, and therefore result in an inhomogeneous charging of the active mass. On the other hand, larger currents cause higher overvoltages and are thus able to dissolve the crystals more readily. In principle, higher currents with lead-acid batteries produce better charging or discharging characteristics. The BMS thus has the task of operating the individual battery strings in the area of their given nominal current.

Depending on the available total current, I_{G}, in the sequence of the list of priorities, the number of battery strings is connected in that the total of the individual nominal currents I_{N} is in keeping with the total current. The condition of the following equation states how many batteries (n) are to be connected:

$$\sum_{i=1}^{n} I_{\mathrm{N},i} + kI_{\mathrm{N},n+1} > |I_{\mathrm{G}}| \geq \sum_{i=1}^{n-1} I_{\mathrm{N},i} + kI_{\mathrm{N},n},$$

$$k = \begin{cases} 0.6 \Leftarrow \dfrac{\mathrm{d}I_{\mathrm{G}}}{\mathrm{d}t} \geq 0 \\ 0.4 \Leftarrow \dfrac{\mathrm{d}I_{\mathrm{G}}}{\mathrm{d}t} < 0 \end{cases} \qquad (1)$$

By means of the hystersis factor k, a continued connection and disconnection of the battery strings due to the fluctuating load profile is prevented.

On account of the condition in Eq. (1), the individual battery strings are operated with higher currents, even if the total current is small with respect to the battery system.

The condition of the battery system is optimum when the fewest possible battery strings are in an unfavourable condition (e.g., low SoC) and the largest possible number of strings is in a favourable condition (fully charged). In order to find this optimum condition, the individual battery strings are recorded in a charge priority and discharge priority list. The more charge a battery string requires, the higher is its position on the charge priority list. On the other hand, battery strings, which preferably can be discharged, are in a higher position on the discharge priority list.

The ranking order at which the individual battery strings are listed are linked to the following criteria.

3.1.1. Criterion for charging or discharging

This criterion decides on the necessity of whether a battery string must be charged or whether it can be discharged. For example, if an intensive full charge of the battery string is required, one should refrain from partial discharging and the string will be given the highest charge priority.

3.1.2. Criterion for cycle priority

The criterion for cycle priority takes into consideration the cycle stability of the individual battery strings and describes to what extent a battery string may be cycled by the BMS. This criterion makes possible the operation of various battery types of the same technology and varying battery technologies (such as lead-acid and nickel–cadmium) in a single BMS.

3.1.3. Criterion for battery status ranges

If several similar battery strings are used in a BMS, they all may be given the same cycle priority. For a further sorting in the lists of priority, the batteries are differentiated in terms of status, thus providing a statement on their actual status range. Each battery string may be in one of four different status ranges (FULL, GREEN, YELLOW and RED). The FULL status describes the most favourable battery status and RED the most unfavourable status. The transition from one status to another is linked to a combination of conditions that consist of SoC, voltage and time, as shown in Fig. 3.

Each status range has its own conditions, which differentiate the charging and discharging process. If during a charging process the conditions for the next most favourable conditions are satisfied, the battery string changes to this higher status. Similarly, during a discharging process, the battery string drops to the next lower status, if the occurrence conditions are satisfied.

In principle, higher status ranges are achieved more slowly than lower ones. Since the BMS generally tries to run the battery strings to a higher status, battery strings in lower status ranges are expeditiously charged and preferably discharged in higher status ranges. Consequently, longer periods in the lower charging status ranges and more frequent partial cycling are reduced.

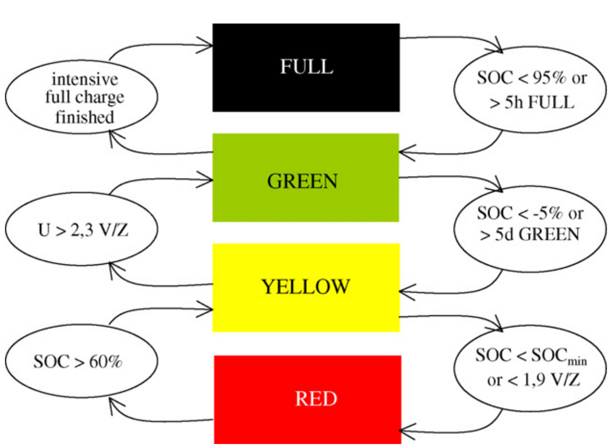

Fig. 3. As a result of Ah-throughput of battery strings and specified status conditions, battery strings achieve varying degrees of status. As a result of charging process, higher status ranges can be reached, whereas a discharge of battery condition can reduce the status.

3.1.4. State-of-charge criterion

If several battery strings are in the same battery status range, the strings are sorted upward or downward in the list of charge or discharge priorities in accordance with their current SoC. To avoid alternating processes, as a result of continuous switching between battery strings with similar SoCs, the battery strings are charged or discharged until they reach a new status range. Only then will battery strings with the same status range be charged and/or discharged with the next higher or lower SoC.

4. Special system management

In addition to the general system management, the BMS contains a special system management, which performs a capacity test or an intensive full charge on the battery strings. These special treatments considerably differentiate from the normal operation, so that in this mode, the battery strings receive special system management.

4.1. Intensive full charge

The intensive full charge ensures a full charge of the battery strings with the constant current/constant voltage/constant current charging regime. In [2], it was illustrated that a full charge according to this charging strategy increases the available battery capacity of lead-acid batteries and is able to dissolve tenacious sulfation in the battery. By this method, the reliability and lifetime of the battery is influenced positively. During the intensive full charge, the battery string does not participate in the normal operation and is charged exclusively.

Under the requirement that the BMS is to operate energy efficiently, the intensive full charge of the battery string starts always after charging in the general system management until the charge controller of the energy supply has to disconnect excessive energy during the charging step at constant voltage. For this reason, the battery string to be maintained is excluded from the regular operation of the BMS and continues the charging with the dc–dc converter, as shown in Fig. 2, via the intensive charge bus. By means of the dc–dc converter, a higher voltage can be admitted in the second constant current charging step, which reduces the sulfation in lead-acid batteries and cannot be achieved in normal operation. The required energy for maintaining full charge of the battery string can be supplied both by the energy supplies of the stand-alone system and from the battery strings to be discharged in normal operation. The required amount of charge is low, so that the loss of the dc–dc converter and/or the conversion charging from normally operated battery strings can be disregarded.

Under the premise that for each battery string, an intensive full charge is performed every 14 days, the battery system performs 10 Ah-throughputs per month and according to further assumptions, the following additional losses arise as a result of the intensive full charge.

When assuming a charge factor $1/\eta_{\mathrm{Ah,general}} = 1$ during regular operation of the stand-alone system and with an intensive full charge $1/\eta_{\mathrm{Ah,intensive}} = 1.12$, the following additional amount of charge is required as a result of the intensive full charge:

$$C_{\mathrm{intensive}} = \left(\frac{1}{\eta_{\mathrm{Ah,intensive}}} - \frac{1}{\eta_{\mathrm{Ah,general}}}\right) C_{\mathrm{N}} = 0.12C_{\mathrm{N}} \qquad (2)$$

Under the premise that after the intensive full charge, about 2–10%$_{\mathrm{abs}}$ of $C_{\mathrm{intensive}}$ can be discharged, this will produce charge losses of about

$$C_{\mathrm{int,tot}} = (0.02\ldots0.1)C_{\mathrm{N}} \qquad (3)$$

When considering the efficiency of the dc–dc converter to be $\eta_{\mathrm{dc}} = 0.9$ with the additional amount of charge $C_{\mathrm{intensive}}$ being taken from the battery string, this produces additional losses of:

$$C_{\mathrm{dc,tot}} = \frac{C_{\mathrm{intensive}}}{\eta_{\mathrm{dc}}} - C_{\mathrm{intensive}} = 0.0133C_{\mathrm{N}} \qquad (4)$$

The total losses resulting from the intensive full charge thus lie in the range of:

$$C_{\mathrm{tot}} = C_{\mathrm{int,tot}} - C_{\mathrm{dc,tot}} = (0.0333\ldots0.1133)C_{\mathrm{N}} \qquad (5)$$

Based on the 10 Ah-throughputs per month, a greater amount of charge is required as the result of the 14-day intensive full charge, i.e.,

$$\frac{2C_{\mathrm{tot}}}{10C_{\mathrm{N}}} = 0.66\ldots2.266\% \qquad (6)$$

This additional amount of charge is to be disregarded, especially given the considerable extension in battery lifetime.

In order to increase the security of supply of the stand-alone system, there is the option of interrupting the intensive full charge and terminating the special system management prematurely. For example, this could be for reasons of high battery temperature, long charge period, and low SoCs of the remaining batteries.

4.2. Capacity test

About every 6 months, the BMS performs a capacity test of the individual battery strings. The test serves to determine the actual available battery capacity and provides information on the ageing condition of the battery. The BMS thus takes into consideration the ageing characteristics of the individual battery strings and automatically adapts the system management to the newly determined capacity.

The battery string first is charged to the FULL battery status range. After this intensive full charge, the capacity determination reported in [3] follows. The special system management has the task of not admitting any interim charges during the test. After determination of the capacity, the battery string returns to general system management. If the energy for charging the total battery system is available, the discharge is interrupted and the remaining battery strings are charged in accordance with the general system management. If a new discharge occurs, the test will be continued. For this reason, the entire SoC of the battery system can increase, even though a capacity test is performed. To be able to perform the recharging primarily with renewable energy supplies, the test is primarily performed during seasons that are high in irradiation.

5. Influence of battery-management system on battery lifetime

A numeric model was developed in order to investigate the influence of the BMS on battery lifetime. This BMS model was integrated with simulation software for stand-alone systems. The software used by the Fraunhofer-Institute for Solar Energy Systems generates a current profile by means of weather data (irradiation and temperature) and the components of the stand-alone system[2] in which the battery system is used [5]. This simulation environment can be employed for examining targetted long-term periods of operation, and thus enable an estimation of battery lifetime.

5.1. Simulation environment

For simulation of the BMS, the components (switch, dc–dc converter and batteries) were modelled. The switches according to Fig. 2 are assumed to be digital and are able to assume exclusively the status ‘ON’ (1) or ‘OFF’ (0), because transient effects can be disregarded.

5.1.1. Battery model

The semi-empirical Shepherd Model [7] was selected to describe the current–voltage characteristics of the lead-acid battery. It offers an average accuracy for currents typically applied in stand-alone systems, i.e, better than 2% [8]. The required model parameters were determined on the basis of experimental data [9]. In spite of the physical significance of each parameter, which results from the derivation, a theoretical calculation of the parameters is not possible. The original Shepherd Model only describes discharge procedures for stationary currents and constant temperatures. By introducing a second set of parameters [10], it was extended for the charging processes. The terminal voltage of a battery has an additive composition consisting of the open-circuit value, which approximately is in proportion to the acid density and thus to the SoC, as well as the reaction, diffusion, crystallization and resistance overvoltages. The individual terms of the Shepherd Model take these overvoltages as a basis. The open-circuit voltage comprises a constant (U_0) and a term (g) dependent on the SoC. An expression follows, which represents the influence of internal resistances (ρ), which are assumed to be constant. The last term describes the reaction overvoltage (M). Diffusion processes based on concentration gradients are not taken into consideration. Another term of the Shepherd Model, which describes the crystallization overvoltage, can also be disregarded. The so-called Hyman formulation

[2] The dimensioning of the stand-alone system was performed on the basis of a real system at “Rappenecker Hof” [6].

Table 1
Parameter data set for battery model

	Charge, c	Discharge, d	Description index
U_{0i} (V)	2.26	2.1	Equilibrium voltage
g_i (V Ah^{-1})	0.13071	0.09654	Electrolyte coefficient
ρ_i (Ah)	0.43609	0.37885	Internal resistance
M_i	0.36488	0.28957	Transfer overvoltage coefficient
C_i	1.001	1.642	Capacity coefficient

$i = c$ or d.

[9] produces the following equations:

$$U_{\text{cell}}(t) = \begin{cases} U_{0c} - g_c\,\text{DOD}(t) + \rho_c(t)\dfrac{I_{\text{batt}}(t)}{C_{\text{N}}} + \rho_c(t)\,M_c\dfrac{I_{\text{batt}}(t)}{C_{\text{N}}}\dfrac{\text{SOC}(t)}{C_c - \text{SOC}(t)} & \text{for all}\ \ I(t) > 0 \\ U_{0d} - g_d\,\text{DOD}(t) + \rho_d(t)\dfrac{I_{\text{batt}}(t)}{C_{\text{N}}} + \rho_d(t)\,M_d\dfrac{I_{\text{batt}}(t)}{C_{\text{N}}}\dfrac{\text{DOD}(t)}{C_d(t) - \text{DOD}(t)} & \text{for all}\ \ I(t) \le 0 \end{cases} \tag{7}$$

The battery model was used with the parameter set from Table 1, which was determined experimentally.

5.1.2. dc–dc converter model

The dc–dc converter is simulated by two coupled current sources (Fig. 4). This model was selected in order to guarantee a mathematical solution of the simulation. The efficiency of the dc–dc converter is $\eta_{\text{dc}} = 0.9$. The factor m is introduced so that the efficiency with this model is taken into consideration, i e.,

$$I_{\text{dc,out}} = m I_{\text{dc,in}} \tag{8}$$

On the premise that the dc–dc converter will supply a voltage range of $U_{\text{dc,in}} = [1.9 \ldots 2.4]$ V per cell and at the output side supplies voltages of $U_{\text{dc,out}} = [2.4 \ldots 2.6]$ V per cell at currents of $I_{\text{dc,out}} = [2 \ldots 10]$ A, according to:

$$\eta_{\text{dc,tot}} = \frac{U_{\text{dc,out}} I_{\text{dc,out}}}{U_{\text{dc,in}} I_{\text{dc,in}}} \tag{9}$$

Input currents are produced for the dc–dc converter in the range of $I_{\text{dc,in}} = [2.4 \ldots 14]$ A. When considering Eq. (8), while taking into account Eq. (9), this produces a range of $[1.1 \ldots 1.5]$ for the factor m.

Since the dc–dc converter is mainly operated with $U_{\text{dc,in}} \approx 2$ V per cell, this produces $m = [1.33 \ldots 1.44]$. For the simulation, the factor $m = 1.4$ is determined in Eq. (8) and thus represents the efficiency of the dc–dc converter with intensive full charge.

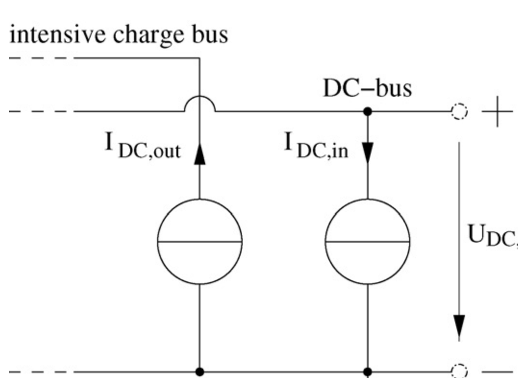

Fig. 4. Simplified model of the dc–dc converter, which according to Eq. (8) is developed from two coupled current sources.

5.2. Long-term investigation of battery-management system

During the long-term investigation of the BMS, a period of 1 year was simulated. A quantitative assessment of the quality of the BMS was undertaken in a comparative investigation. The first simulation is performed for operation with the BMS, i.e., the battery system consists of four parallel switchable battery strings, which can either be connected or disconnected via the BMS. By contrast, the second simulation operates without influence of the BMS, and uses the battery system in the 'classical' variant, so that only a single battery string can be connected permanently to the stand-alone system. The simulation result consists of a load profile represented in the form of a time sequence comprising the voltages, currents and temperatures of the individual battery strings. The load profile was examined for stress factors, in order elucidate the ageing characteristics and the resulting ageing mechanisms of the battery strings. The result is suitable for evaluating the influence of the BMS on battery lifetime.

The results of the examined stress factors are listed in Table 2.

By means of the converter, the BMS can perform periodic full charges on any battery string. The maximum time between two full charges is between 14.82 and 24.39 days, while the stand-alone system without the BMS has a 66.26-day period. The periodic full charges can clearly be identified in the SoC characteristic in Fig. 5. By comparison, Fig. 6 shows the SoC characteristic of the battery system without the BMS, which operates with only one battery string. A very distinct difference can be observed during months with low irradiation. The battery string without the BMS thus remains for an extended period in a partial SoC, which leads to strong and partially

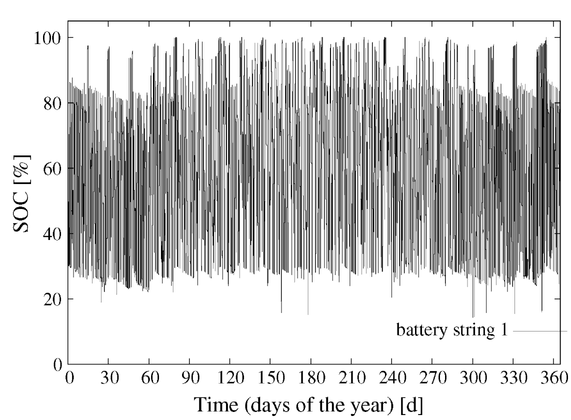

Fig. 5. State-of-charge characteristic of battery string 1, which is operated with BMS in battery system of stand-alone system.

Table 2
Stress factors of individual battery strings each with BMS compared with battery system without BMS under equal system conditions

	Battery system				
	With BMS				Without BMS
	String 1, 100 Ah	String 2, 100 Ah	String 3, 100 Ah	String 4, 200 Ah	Single string, 500 Ah
Maximum time between two full charges (days)	14.82	16.67	20.58	24.39	66.26
Charge factor ($\%_{Ah}$)	101.72	101.75	101.76	101.65	100.41
Charge factor ($\%_{Wh}$)	118.54	118.57	118.57	117.32	113.77
Ah-throughput (Ah C_{10})	202.86	200.54	201.42	202.89	201.12
Partial cycles, 0–40% (%)	20.38	20.60	20.53	20.49	24.01
Rate of charging, I_{10}	0.92	0.93	0.94	0.87	0.79
Rate of discharging, I_{10}	−0.89	−0.90	−0.89	−0.68	−0.33

irreversible sulfation of the battery string and thus reduces the battery lifetime.

The frequent full charges of the battery system with the BMS also increase the Ah-charge factor and Wh-charge factor. As a result of the intensive full charge, the battery receives a higher amount of charge, which will result in increasing charging losses. The discharged amount of charge, on the other hand, remains almost unchanged, so that the Ah-charge factor is increased. The Wh-charge factor increases due to the high voltages that occur during the intensive full charge. The increased charging losses and charge voltages result in most of the gassing and corrosion of the battery. On the other hand, the time intervals during this condition compared with 'normal' operation are very short and therefore can be disregarded. When considering the results in [2], the positive influence of the intensive full charge outweigh the disadvantages due to gassing and corrosion. Furthermore, the intensified gassing reduces acid stratification and thus improves the charge-acceptance of the battery, which significantly increases the battery lifetime.

The Ah-throughput makes no difference in situations with or without the BMS. The total Ah-throughput cannot be influenced by the BMS. The available amount of energy is exclusively dependent on the energy supplies and the loads in the stand-alone system and is determined by them. On the other hand, within the battery system, the Ah-throughput between the various battery strings may vary. This is influenced by the cycle priority discussed in Section 3.1. Battery strings with a high cycle priority are cycled more severely, and therefore have a higher Ah-throughput. The remaining battery strings have a lower Ah-throughput and are used to a lesser degree. The influence of varying cycle priorities has not been investigated in detail during this simulation.

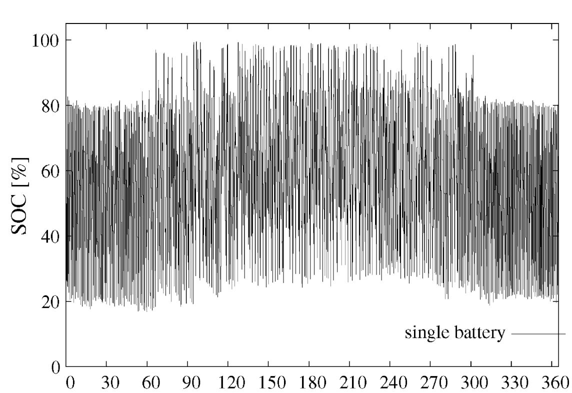

Fig. 6. State-of-charge characteristic of individual battery string, which is operated in stand-alone system individually without BMS.

A comparison of the results in Figs. 5 and 6 shows that the battery string in the stand-alone system without the BMS frequently achieves lower SoCs than in the stand-alone system with the BMS. Consequently, the battery string in the stand-alone system without the BMS is cycled for longer periods in deep SoCs that range from 0 to 40%. During these periods, the battery system without the BMS does not fully charge, so that more severe acid stratification and sulfating occurs, which causes irreversible damage and shortens the battery lifetime. This ageing effect has been described in detail in [11]. By contrast, the deep SoCs of the battery system with the BMS are regularly interrupted by full charges and thus are less harmful to the battery strings, which significantly extends the battery lifetime.

Apart from the stress factors, the load profile was also examined for the average charge and discharge rates. According to the data in Table 2, the charge rate increases only slightly due to the large diesel generator, which generates high charge currents. The discharge rate, however, indicates a clear increase due to the influence of the BMS. As explained in detail in Section 3.1, higher currents have a positive effect on the battery characteristics and thus reduce different ageing processes.

The analysis of the stress factors demonstrates an improved system management for the individual battery strings with the BMS. In particular, the periodic full charges and the increased charging and discharging currents prevent a premature ageing of the battery strings, also refer to [11]. Since this new system management also is converted into a real BMS, improved reliability and lifetime of the battery system is expected.

6. Conclusions

Through the development of the BMS, the lifetime and reliability of the battery system in a stand-alone system is increased.

A circuit concept is developed, which enables parallel operation with several battery strings. Furthermore, it is possible to use battery strings that are comprised of the same or different battery technologies. The battery strings can be charged or discharged independently of each other, so that new operating system strategies are possible. This procedure cannot be realized with a single battery string. Furthermore, the circuit concept of the BMS comprises a dc–dc converter, which performs intensive full charges, whereas other battery strings can be discharged via the loads of the stand-alone system.

The developed operating system takes into consideration the various characteristics of the individual battery strings and decides, depending on the load profile, how the strings are to be treated. For this purpose, the voltage, current and temperature are measured for each battery string, and the SoC is determined. The BMS decides by means of various criteria which and how many battery strings are to be connected or disconnected. Without limiting the stand-alone operation, intensive full charges are performed according to the constant current/constant voltage/constant current charging regime. Consequently, irreversible ageing processes on the battery strings are markedly reduced. Likewise, without limiting the stand-alone operation, capacity tests are performed to determine the available capacity of the battery strings. The discharged energy during the capacity test is used completely by the loads of the stand-alone system. Comparable investigations are performed by means of a simulation. The battery characteristic is tested in a stand-alone system with and without the BMS over a period of 1 year. The analysis of the results according to varying stress factors indicated that the BMS decidedly improves the system management of the individual battery strings. Full charges are performed periodically, and the battery strings are operated at higher current rates. With this operating management strategy, a significantly extended lifetime and improved reliability of the entire battery system is expected.

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