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Modeling and Implementation of a Highly Efficient Solar-Powered Storage Installation through Self-Reconfigurable Batteries

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Abstract

Self-reconfigurable batteries represent a new and promising technique of electrochemical storage. The application of self-reconfigurable batteries can resolve the challenge of efficient renewable storage in solar-powered installations. In this paper, the problem of solar panel's Maximum Power Point (MPP) tracking utilizing self-reconfigurable batteries is explored through modeling. The efficiency of energy storage is improved by removing the intervening DC/DC converter, which is usually necessary for solar PV applications. To make such a system functional, a Switching Battery Management System (SBMS) is proposed instead of a traditional couple of DC/DC converter and usual BMS. This system allows the series connection of multiple battery modules of different sizes, States-of-Charge (SoC), and States-of-Health (SoH). Two main challenges arise by the proposed implementation: tracking MPP of solar panels through battery cell switching and maintaining an equal (balanced) SoC of the separate cells/modules. The theoretical investigation includes developing the distinct software parts: digital twins of the battery module and solar PV modules that interact with the SBMS and the algorithm according to which the proposed SBMS will operate. The SBMS algorithm, based on sorting the battery cells according to their SoC, resolves both challenges. Having this promising theoretical starting point, a working prototype was developed. The prototype worked as expected and was tested under field conditions, being integrated into the power grid as part of a virtual power plant.

Keywords

Self-Reconfigurable, Switching, BMS, Solar Photovoltaic, Efficiency

1. Introduction

Several challenges regarding energy production from sustainable energy sources and its storage with electrochemical means (batteries) are combined in the framework of an RVO RE-USE project. The stochastic nature of renewable energy sources requires a mechanism to smooth the fluctuating energy supply for reducing its impact on the power grid. In addition, many of these energy sources, such as photovoltaic (PV) panels, require maximum power point tracking (MPPT) techniques to maximize power output. Energy storage can help smooth the supply of renewable energy; however, it introduces additional costs. Batteries are expensive and require a lot of raw materials. Thus their operational life should be prolonged to the maximum to achieve the goal of sustainability. Additional components, such as converters and Battery Management Systems (BMS), are necessary components of an energy storage facility, which further increase costs and need optimization.

A solution is required to answer multiple problems together, including MPPT, battery storage optimization, and energy storage component reduction, considering all control constraints of renewable energy supply, demand, and storage. An existing but relatively new concept known as self-reconfigurable batteries seems to be promising. For this reason, it is further explored and developed.

The self-reconfigurable battery concept appeared in literature back in 2011, when Taesic Kim *et al.* [1] proposed a system to optimize the energy discharge from a battery pack under different demand scenarios, such as constant current (CC) and constant resistance (CR). Later, in 2012, Ye Zhao *et al.* proposed a reconfigurable solar cell battery charger where the reconfiguration takes place in the connection topology of the solar cells for optimal charging [2]. In the same year, Taesic Kim *et al.* proposed a series-connected self-reconfigurable multiple-cell battery pack equipped with a bi-directional DC/DC converter to enable the health monitoring and individual cell balancing of the battery pack, enhancing the safety, reliability, energy conversion efficiency, and life cycle of batteries [3]. A network optimization strategy was proposed in 2016 by Nejmeddine Bouchhima *et al.* to optimize the cell balancing and increase the energy efficiency of self-reconfigurable batteries for electric vehicles [4]. Similarly, Ni Lin *et al.* proposed a theoretical framework to optimize the performance of dynamically configurable batteries for electric vehicles [5]. In their 2016 and 2018 papers, Sebastian Steinhorst *et al.* discussed different Battery System Management Architectures (BSMAs) that follow the trend of decentralized management and reconfigurable battery cell connection topology [6] [7]. They found that the advantages of reconfigurable batteries are cell balancing and the isolation of defective cells.

Closer to the requirements of the current topic is the work of Yu Zhang *et al.* In their paper they proposed a system where the self-reconfigurable batteries are used to increase the quality of an external power supply, (dis)charging based on the load demand, and maintaining a constant voltage for the battery pack without losing individual cell balance [8]. Focusing on the energy supply from storage was Feng Ji *et al.* in 2019, presenting the concept of self-reconfiguration batteries without the DC-DC converter. The main idea was to sort cells according to SoC and then add cells into the string subsequently until the desired voltage for (dis)charging was reached [9]. A final display of the balancing capabilities of self-reconfigurable batteries was done by Rémy Thomas *et al.* in 2021. They showed the performance of a high-frequency self-reconfigurable battery for vehicles receiving the maximal power from a battery pack with cells of higher than 50% initial SoC dispersion [10].

The concept of self-reconfigurable batteries seems to have been explored over the past decade for different applications. However, an all-in-one solution from the energy storage side is missing. The literature shows applications of reconfigurable connections on the side of the energy source, *i.e.*, optimizing the connection of the solar cells and keeping the battery pack connections intact, or reconfiguring the battery for maximizing power delivery instead of efficient energy storing from renewable sources. In this paper, the self-reconfigurable batteries are used to optimize energy storage, *i.e.*, at the energy storage side.

Based on the idea of reconfiguration, a battery pack (string) is proposed that automatically changes its voltage to enable MPPT of the renewable energy source it is connected to. This scheme can also reduce the total storage installation cost by reducing the power conversion stages and voltage sensors. In more detail, the proposal is a new advanced Battery Management System (BMS) that makes possible the electronic switching of separate battery cells in a string. Each cell can be either connected to the series or bypassed (shunted). For clarity, the new BMS will be called Switching Battery Management System (SBMS) further on. The topology of the proposed SBMS is shown in **Figure 1**.

The proposed approach introduces several new challenges that require investigation. The first new challenge is to find an optimal switching strategy that can maximize the output power of a solar PV system and simultaneously keep the

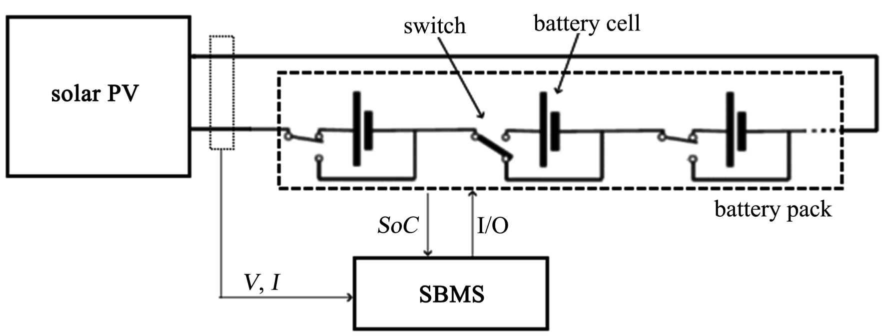

Figure 1. Layout of the system with solar PV, battery pack, and SBMS.

proper voltage within an acceptable range. The second challenge of the SBMS will be tracking the unequal State-of-Charge (SoC) and operating voltage of individual cells, which will also be of a different State-of-Health (SoH).

The digital twin of SBMS is presented in this paper to resolve these challenges. Such an approach is novel and was not traced in the literature known by authors. Numerical experiments with the digital twin have shown a considerable increase in the energy efficiency of the solar PV-charging equipped by SBMS. Therefore such systems will be helpful in highly sophisticated energy management systems such as described in [11]. The simulation approach has once again proven to be highly successful in solving various scientific and engineering problems, see, e.g., [12].

2. Model

Following the theoretical investigation, this section describes how the problem was modeled to provide a solution, *i.e.*, develop a low-cost energy storage device with integrated MPPT capabilities for the renewable energy source. An overview of the tasks is shown in **Figure 2**.

2.1. Data Acquisition

A data acquisition process took place in three parts. The first part was obtaining information on the equilibrium voltage of the battery cell/module as a function of its SoC. This objective was found via experimental cell characterization. Consecutive discharges of the cell with C-rates varying from 0.03 to 0.96 were performed while the module voltage was monitored. The equilibrium voltage is found by extrapolating the recorded voltage towards zero C-rate (**Figure 3**) [13]. The resistance of the module is considered constant according to the recorded data and the simple internal resistance model.

The next two parts of the data acquisition were straightforward. It was assumed that the solar panel operates precisely according to the manufacturer's datasheet (**Figure 4**). The I - V curve displays the output current of the panel for

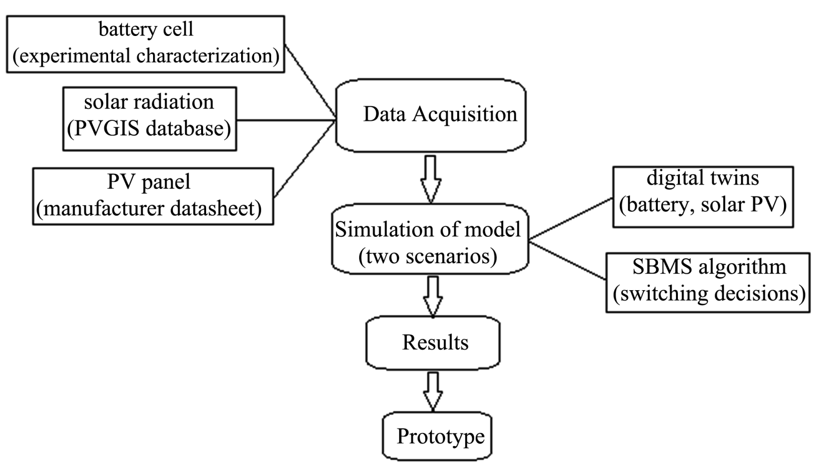

Figure 2. Flowchart of the performed research.

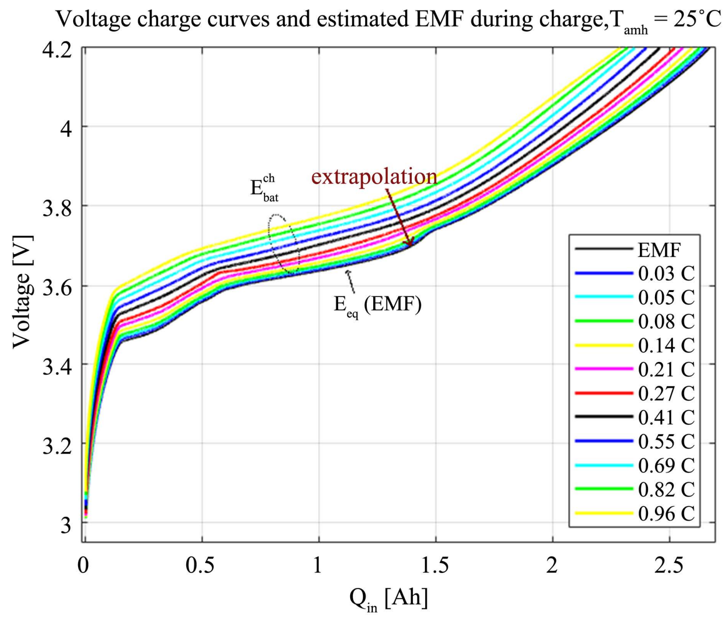

Figure 3. Battery cell Li NMC himax electronics voltage vs. extracted charge curve.

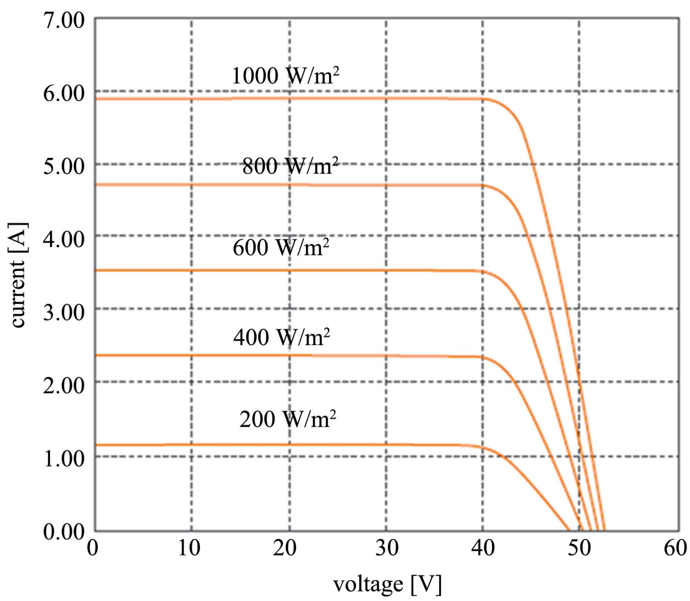

Figure 4. I-V curve for the solar panel panasonic VBHN240SE10.

different voltage values and solar irradiation levels. The solar irradiation data was obtained from the European Commission's Science Hub platform PVGIS that constitutes the PVGIS-SARAH database. Solar irradiation is a function of the time of the year and the day.

2.2. Digital Twins

Two software modules were developed to create a foundation based on which the proposal is tested. These were: 1) the solar PV panel and 2) the battery module. Their purpose was to simulate the battery charging through the solar PV panel by applying Kirchhoff's circuit laws. The size selection of the battery modules and the solar panels was in accordance with the intended prototype to be developed.

For the solar PV module, the electric power production is a function of the solar irradiation (**Figure 4**), the selected solar panel topology, and the system's voltage. The irradiation values were calculated for the location of Eindhoven, the average for May, on a surface with slope (tilt) 51˚ and azimuth of 0˚ (South orientation). This data was digitized, smoothed, and stored in the code via MATLAB. The current as a function of voltage can always be found via interpolation between the given irradiation levels.

Each battery module is modeled as an ideal voltage source (EMF), depending on the SoC of the particular modules and constant internal resistance in series with this voltage source. The SoC of each module is calculated according to the integration of current passing through this module. The EMF as a function of SoC for each module literally coincides with a single-cell EMF given in **Figure 3**, but the capacity of the module is equal to 14·2.6 = 36.4 Ah.

2.3. Control Algorithm

Having created the building blocks for the simulation of the proposed SBMS, the development of the control algorithm follows. The SBMS's algorithm performs the switching decisions that enable the tracking of the MPP of the solar panel so that the battery pack is charged most efficiently while its modules remain balanced. The battery pack is simulated as a string of modules, some of those are connected while others are shunted, the choice of which is made according to the algorithm.

Inputs to the algorithm are the initial SoCs and characterization curves of the battery modules and the MPP voltage of the solar panel. The development of the SoC has then tracked with the coulomb counting (book-keeping) method.

The algorithm was named Sorting and Cumulative Voltage Summation (SCVS). With this approach, the battery modules are sorted by ascending SoC. Their operating voltages are added progressively until the desired MPP voltage is reached. The selected modules are connected, all others are shunted. Such configuration is kept for a specific time interval. Afterward, the process repeats itself until the battery pack is fully charged or there is no available solar power.

The programming logic can be mathematically expressed in the following equation.

$$M = \max\left\{m \in \mathbb{N}, m \geq 1 \mid \sum_{i=1}^{m}\left(E_{eq}\left(x_{(i)}\right) + R_{(i)}^{int} \cdot I\right) \leq V_{mp}\right\}$$

where,

m: the number of battery cells/modules in series (integer);

M: the number of modules that matches MPP;

$\Sigma(\ldots)$: the voltage of the system (V), common for the battery pack and solar PV panel;

E_{eq}: the equilibrium voltage (EMF);

(i): the index of the battery module sorted by SoC ascendingly;

$x_{(i)}$: the SoC of battery module (i);

$R_{(i)}^{int}$: the internal resistance of battery cell (i);

I: the current running through the system, common for the battery pack and solar PV panel;

V_{mp}: the maximum power point voltage of the solar array.

This mathematical expression is a maximization problem of finding the amount of batteries M to be connected so that their operating voltages summation does not exceed the MPP voltage of the solar panel.

The voltage and current of the system are found through iterations, following Kirchhoff's current law. The voltage and current are common for the solar panel and the battery pack. The following formula gives their values, solved with the *fzero* function of MATLAB.

$$I_{pv}\left(V, G_i\right) - \frac{V - E_{eq}}{R_{int}} = 0$$

where,

I_{pv}: the current from the solar PV, function of V and I_{sun};

G_i: the solar irradiation at a given moment.

2.4. Prototype

Based on the results of this investigation, a prototype model has been developed as part of the RE-USE RVO-funded project. It consists of 1) a modular battery system that enables flexible utilization of second-life battery cells, 2) an energy management system that allows the sharing of this energy storage in a Virtual Power Plant (VPP), and 3) an array of solar panels. The battery pack contains 150 battery modules connected in series via the proposed switching topology. Each module contains 14 Himax Electronics Li NMC cells connected in parallel. The capacity of each cell is 2.6 Ah. The SBMS runs on a hardware embedded program closely based on the developed algorithm in MATLAB. The solar panel is a 240 W_p Panasonic model VBHN240SE10.

3. Results

Two simulation scenarios were examined for the same system using the digital twin of the prototype: 1) one-day charging of a completely discharged battery pack, *i.e.*, all battery modules have SoC equal to zero, and 2) one-day charging of a battery pack with modules of random initial SoC, ranging from 0% to 100%. The other simulation parameters were set as follows: 15 solar panels in 3S5P connection (3 in series of 5 in parallel), one battery pack of 150 battery modules in series comprising of 14 cells in parallel, one full day of charging (up to 100% SoC), switching decision interval of $\Delta t = 240$ sec, average irradiance of June in Eindhoven on 51˚ tilted panels with south orientation. The success criteria of the simulation results are the answers to the new challenges: 1) maximize the energy output of the solar panels, and 2) track and maintain equal SoC among the battery cells.

The operating coupling factor of the PV panel operation can be used as an index for the first success criterion. The coupling factor measures relative efficiency for the solar panels, defined as the instantaneous power extraction over the maximum power point of the panels for the present conditions (solar irradiance). A coupling factor of 100% suggests that the solar panels' output power is at their rated MPP. The coupling factor can be calculated for each moment, and its average over the whole charging process is a success metric for the capability of the proposed method.

The range of the various battery cells' SoC can be used as an index for the second criterion of success. A low difference (range) of SoC between the highest and lowest charged cells indicates that the SBMS and its control method optimally balance the cells.

Figure 5 and Figure 6 give insight into the battery modules connected at each moment for the first and second scenarios, respectively. For the first 3 min, the solar panels are disconnected from the battery. Figures display the modules that are being connected for each moment in time. At each moment, the set of the connected modules is represented by a sequence of colored dots placed in the vertical row. The first moment in time is marked by the blue arrow. The dot's color indicates the SoC of the module ranging from red (0%) to green (100%). For the first scenario (battery modules at 0% SoC), at the very first charging moment in time, the first 37 battery modules are connected in series because they produce the closest voltage to the MPP voltage of the solar panels. At the next moment (after Δt = 240 s), the next 37 modules are connected, and so on (Figure 5). For the second scenario (random initial SoC), the battery modules

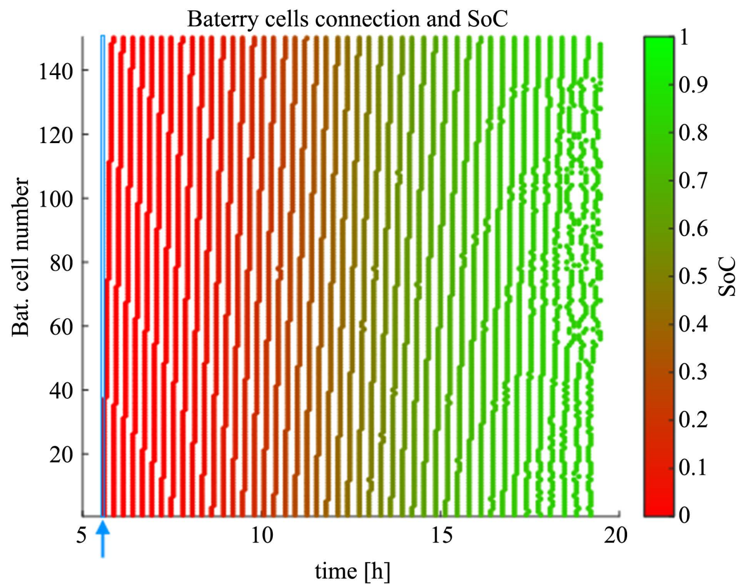

Figure 5. Battery module connections and state of charge (blue rectangle = first charging instance).

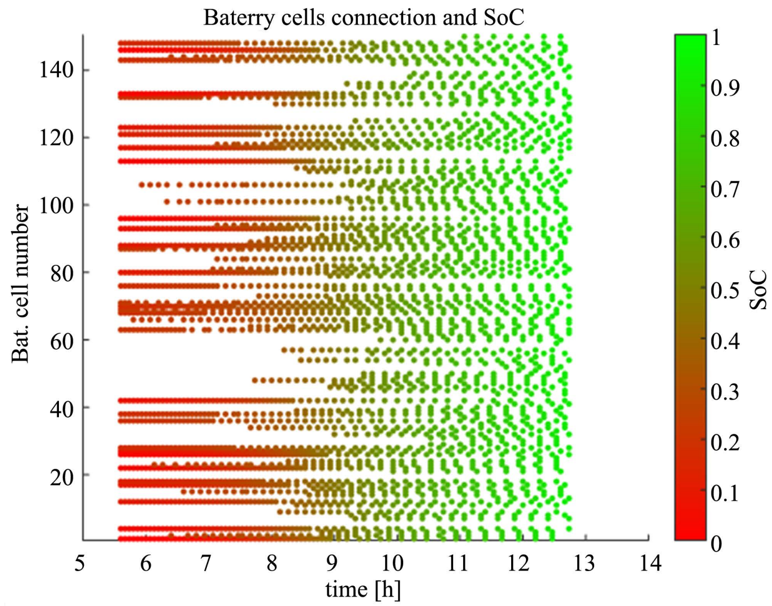

Figure 6. Battery module connections and state of charge.

connected at the first charging moment are scattered throughout the pack. The algorithm selects the least charged modules. As the charging progresses, other modules are connected for charging too because the SoC of the depleted modules reaches their value of SoC (Figure 6).

Figure 7 and Figure 8 displays information on the instantaneous coupling factor of the solar panels. For the first scenario, at the beginning of charging, more battery modules are connected, as more empty modules are required to reach the MPP voltage. As the charging progress and the SoC grows, the operating voltage of the modules rises, and fewer modules are connected. The coupling factor of the solar panels is kept near 100%, averaging at 99.83% for the whole charging process (Figure 7(b)). Few modules are connected at the beginning of the charging in the second scenario because the battery modules are randomly charged. However, their number increases slightly to keep track of the MPP voltage, increasing with solar irradiation throughout the day. The coupling factor is also very close to 100% in this scenario, averaging at 99.82% (Figure 8(b)).

Figure 9 and Figure 10 display the voltage variation throughout the charging in comparison to the MPP voltage of the solar cells, which varies as a function of the irradiation. Subplot a) displays the voltage values, while b) their difference, $\Delta V = V_{mp} - V_{sys}$. In the first scenario, the average voltage mismatch is 0.581 V, while in the second, this is 0.300 V.

Figure 11 and Figure 12 display 1) the SoC of the highest and lowest charged module and 2) the difference between those values, $\Delta SoC = SoC_{(max)} - SoC_{(min)}$. In the first scenario, the initial ΔSoC is zero as all modules are depleted. It reaches its highest value which is around 3%, at the highest power period of the charging process. It then drops down to zero as the charging reaches an end. In the second scenario, the ΔSoC starts at 100% as the battery modules are randomly

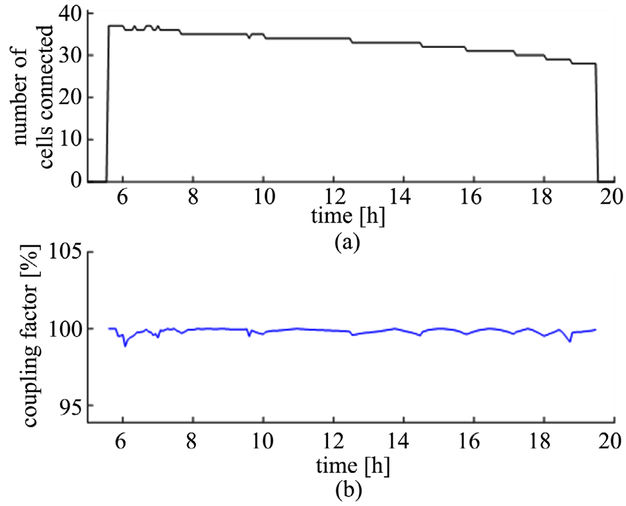

Figure 7. Total battery modules connected and coupling factor.

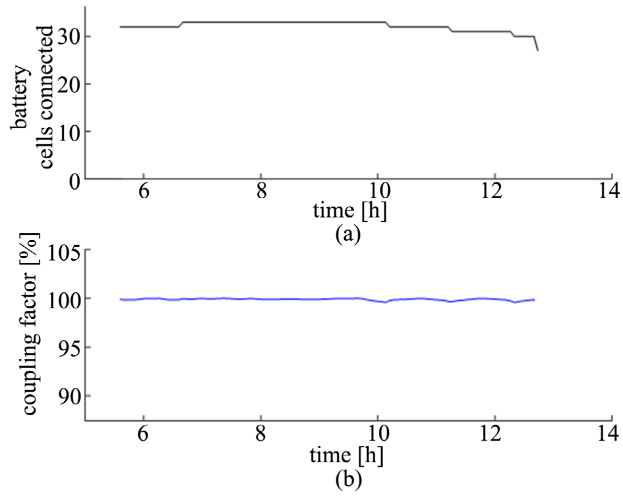

Figure 8. Total battery modules connected and coupling factor.

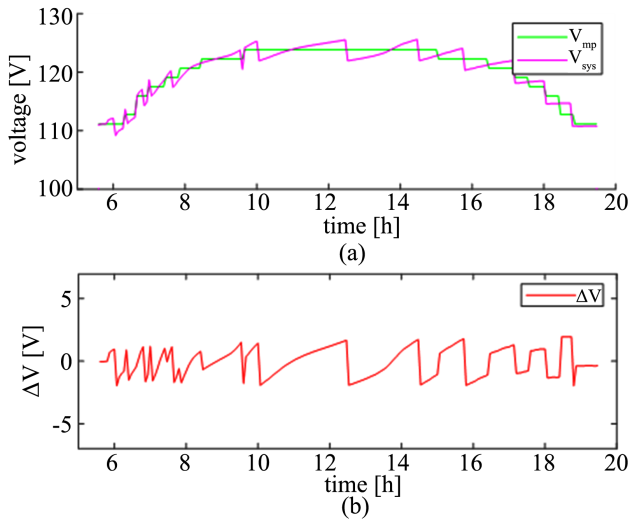

Figure 9. MPP voltage, charging voltage, and ΔV.

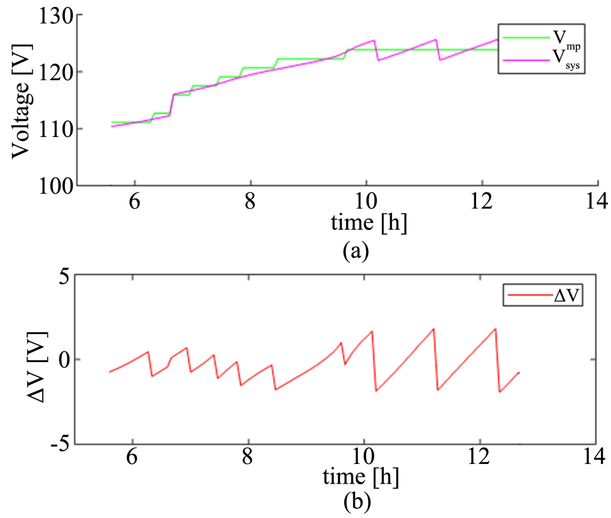

Figure 10. MPP voltage, charging voltage, and ΔV.

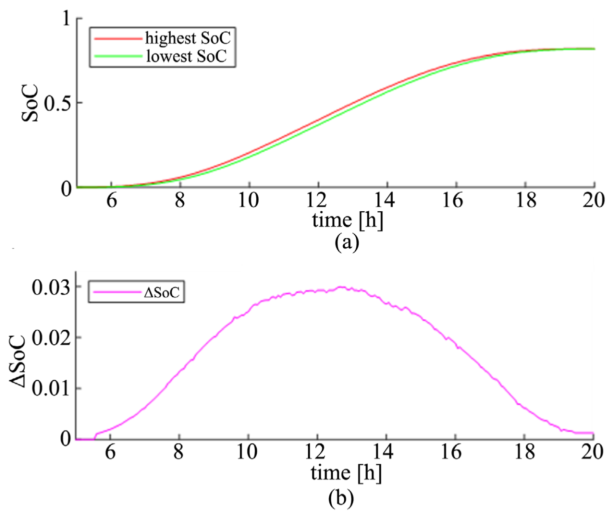

Figure 11. Highest, lowest, and difference of SoC.

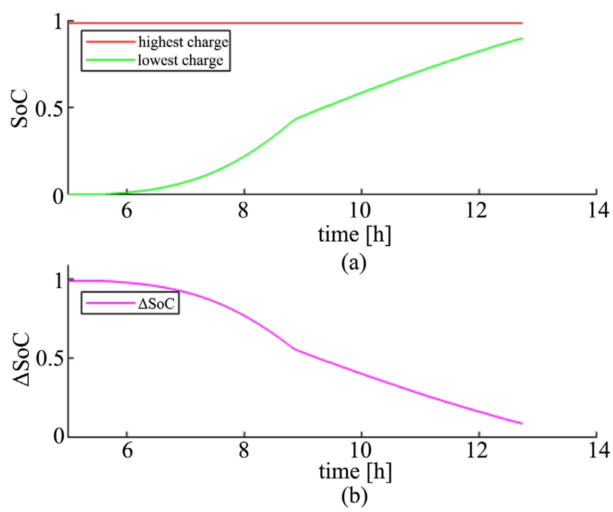

Figure 12. Highest, lowest, and difference of SoCs.

charged. It then continuously drops while the charging progresses as part of the objective of the algorithm.

Figure 13 and Figure 14 display information on the power extraction from the solar panels, the charging power of the battery pack, and the system's voltage. The power of the solar panels and the battery pack is the opposite. No losses are considered in cabling, and there is no connection to the grid. The system's voltage is equal for all components, as the panels and the modules are connected in parallel.

Figure 15 and Figure 16 display the operational point of the solar panel through the charging process. The P-V curves are drawn for each time moment as they vary with solar irradiation. A dot on each curve represents the instantaneous operating point (voltage). The dot color represents the total SoC of the battery pack, with red equal to empty and green equal to fully charged. In both scenarios, the operating point is very close on the top of each drawn curve. The

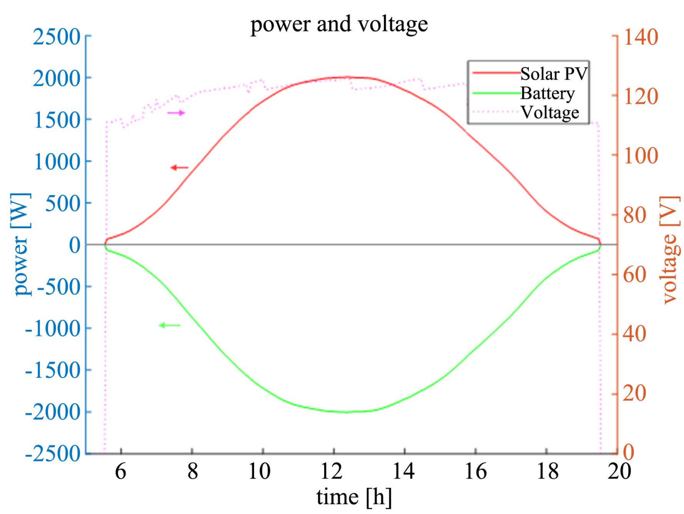

Figure 13. Battery and solar PV power, system voltage.

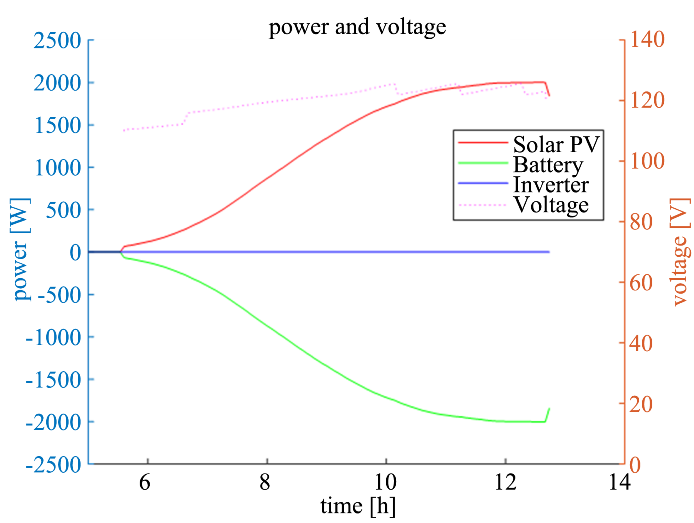

Figure 14. Battery and solar PV power, system voltage.

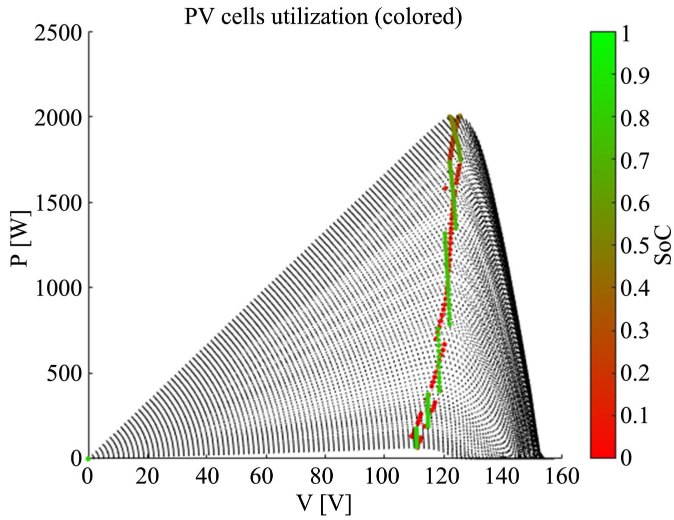

Figure 15. Operating point of PV panels and battery pack SoC.

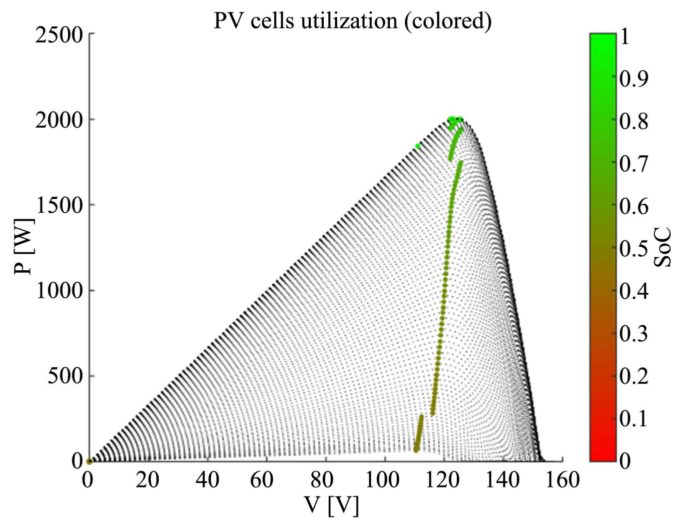

Figure 16. Operating point of PV panels and battery pack SoC.

charging starts at 0% (red) in the first scenario, and the process lasts longer (more colored points). The charging begins at a higher level (brown point) in the second scenario, as the initial SoC is the average of randomly charged battery modules. Full charge is reached sooner (a smaller number of colored points means shorter duration). From the algorithm's output, it can be seen that the charging time was 836 minutes in the first scenario. The final SoC reached 81.81%. The charging time was 432 minutes in the second scenario, and the final SoC was 91.78%.

4. Discussion

4.1. Performance

The proposed SBMS brought excellent results in extracting the maximum possible power from renewable energy sources. For both scenarios, the initially equally depleted and the initially randomly charged battery cells, the developed algorithm maintained the power extraction from the solar PV cells at an average coupling factor of 99.8%.

The SBMS algorithm also performed well in balancing the battery cell's SoC. In the first scenario, based on initially depleted cells, the maximum difference in SoC between cells observed during charging was 3% and occurred at the moment of the highest power charging around 12:00 o'clock. In the second scenario, with the randomly charged cells, the SoC gap, which was 100%, started narrowing with an increasing rate as the solar PV cells produced more power until it reached a point after which the narrowing rate remained almost constant to the end of charging. This point in time represents the charging interval at which the maximum number of individual battery cells is connected in series simultaneously.

4.2. Evaluation of the Method

The proposed SBMS and software algorithm seems to work excellently to maximize the energy-storage potential of solar-generated power to battery cells. A prototype with very similar characteristics to the simulated system has already been developed, displaying similarly promising results, proving the real-life applicability of the system.

The developed algorithm based on which the simulation was executed lacked the capability of tracking of actual maximum power point of the solar PV panels. MPPT occurred with the V_{mp} considered a known parameter for arbitrary irradiation intensity. Irradiation, in turn, is a function of time. The clear sky irradiation was considered as the input value, without any variations (*e.g.*, due to clouds). MPPT could be added by accommodating any of the known techniques in the algorithm. However, such an MPPT procedure itself can reduce energy extraction efficiency. For this reason, the frequency of MPPT should be carefully optimized.

The SoC determination is performed by coulomb counting. The initial SoC is considered a known parameter. Ideally, the SoC of the battery cells should be periodically verified with an additional method. This verification could be done by the equilibrium voltage measurement or any other known technique, but that would require some computational time for the storage system [14]. In addition, battery degradation is another factor that the currently developed algorithm does not consider. Battery cells degrade over time, especially second-life batteries that already experienced many (dis)charge cycles, and their maximal capacity is reduced. The correct SoC determination cannot be performed only with the book-keeping (coulomb counting) method as the cells' capacity gradually degrades over time [15]. An additional software module that estimates the cell's SoH must be implemented.

4.3. Additional Advantages

The proposed system offers multiple advantages in energy storage besides the efficient power extraction from the renewable source and the balancing of the battery's cells. This system can operate with a virtually unlimited number of battery cells in series, given that the correct number of solar PV panels is connected in series to provide the desired voltage range. A unique feature of the system is the possibility to replace battery cells or modules when the pack is in operation by bypassing the desired module. In addition, fewer electronic components are required, as the DC/DC converter and multiple voltage sensors can be removed from the system, reducing its cost. Finally, the system can handle battery cells or modules of different capacities and chemistries, which makes easier the utilization of second-life batteries.

5. Conclusions

The challenge of efficient and low-cost storage of solar PV-generated energy has been addressed using the idea of self-reconfigurable battery cells in the form of a Switching Battery Management System (SBMS). This system was shown to work constantly at peak efficiency, extracting the maximum possible power from the solar PV panels. At the same time, the challenge of keeping the SoC balance among battery cells was addressed successfully through the programming logic of the operating algorithm.

The developed digital twin of SBMS is novel and has never been discussed in the literature known by authors. It demonstrated that properly implemented SBMS can reach almost 100% charging efficiency without using a costly DC-DC converter.

A self-reconfigurable battery, along with the proposed SBMS, is a promising idea for the future of energy storage. As the number of renewable energy sources in the total energy mix increases, introducing more uncertainty to the energy supply, efficient energy storage systems will be increasingly demanded.

Acknowledgements

Forschungszentrum Jülich is a research center in Germany aiming to provide the key technologies to solve the challenges facing society in the fields of energy, environment, information, and brain research. The Institute of Energy and Climate Research (IEK) investigates modern energy conversion technologies within the framework of climate and environmental protection. The topics it covers in the energy sector range from photovoltaics and fuel cells, through nuclear fusion and nuclear safety research.

RVO is the Netherlands Enterprise Agency, which operates under the auspices of the Ministry of Economic Affairs and Climate Policy. The RE-USE project is an action of the RVO to help the development of methods that allow the reuse of old batteries with faded capacity for extending their lifetime. The following parties were affiliated with the development of the prototype of this RE-USE project:

KAGO develops the electronics and embedded software for a smart measurement and control system where real-time switching can be made between indi-

vidual battery modules.

Van Opdorp sets the system requirements, designs the modular system, the system architecture, and develops and tests the robustness and safety of the system.

Energie Planeet develops the Virtual Power Plant Platform for which smart logic and algorithms are developed for the autonomous control of a distributed RE-USE system.

The Department of Energy and Resources (University of Utrecht) develops a simulation model with which the financial and technical performance of a VPPs can be predicted.

The Department of Control Systems (Eindhoven University of Technology) investigates the State-of-Health, and the degradation of battery cells and develops algorithms with which the battery modules can be smartly charged and discharged.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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