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A Novel, Scalable, Low-Cost, and High-Efficiency Battery Storage System Topology

Arthur Singer
m-Bee GmbH &
Universität der Bundeswehr München
Munich, Germany
arthur.singer@unibw.de

Cong Nam Truong
m-Bee GmbH &
Universität der Bundeswehr München
Munich, Germany
nam.truong@unibw.de

Martin Sprehe
m-Bee GmbH &
Universität der Bundeswehr München
Munich, Germany
martin.sprehe@unibw.de

Christoph Dietrich
m-Bee GmbH &
Universität der Bundeswehr München
Munich, Germany
christoph.dietrich@unibw.de

Holger Hesse
Institute for Electrical Energy Storage Technology
Technical University of Munich
Munich, Germany
holger.hesse@tum.de

Andreas Jossen
Institute for Electrical Energy Storage Technology
Technical University of Munich
Munich, Germany
andreas.jossen@tum.de

Hans-Jürgen Pfisterer
Elektrische Antriebe und Grundlagen
University of Applied Sciences Osnabrück
Osnabrück, Germany
j.pfisterer@fh-osnabrueck.de

Thomas Weyh
Institut für Elektrische Energieversorgung
Universität der Bundeswehr München
Munich, Germany
thomas.weyh@unibw.de

***Abstract*—Battery Storage Systems are increasingly deployed in the grid for commercial applications and ancillary grid services. Current state-of-the-art systems suffer from several drawbacks regarding safety, efficiency, and costs. This paper presents a novel approach that avoids major challenges for the production, installation, and operation of battery storage systems. Based on modular power electronics the central inverter is omitted and each battery module acts according to grid voltage and power requirements. This leads to the flexibly adjustable m-Bee system with the highest efficiency and fail-safety. This new topology also increases the usable battery capacity compared to state-of-the-art systems.**

Keywords—inverter, power electronics

I. Introduction

The installation of battery energy storage systems (BESS) for commercial and utility-scale applications is increasing. The primary applications in Germany today are frequency control [1] and photovoltaic home systems [2].

Today's state-of-the-art battery systems consist of a high-voltage battery pack, a bidirectional inverter, and auxiliary components, such as the battery management system (BMS), for monitoring and balancing the battery cells [3].

The batteries are connected by welding to form battery modules and these are usually fixated with joint bolt connections to HV battery packs. These allow the use of one-stage inverters that are more efficient and cost-effective compared with conventional two-stage inverters.

The HV battery packs, however, are challenging for the installation, maintenance, and operation of BESS. The high voltages are a hazard for personnel safety during installation and maintenance. It, therefore, requires additional safety gear, equipment, and time-consuming safety procedures to minimize the risks. A large amount of serially connected battery cells increases the need, complexity, and costs of battery balancing to maximize the usable battery capacity in the presence of varying states-of-charge. [3]

This paper presents a novel BESS topology: The Modular Multilevel Parallel Converter based Split Battery System (M2B) presented before [4, 5]. The general advantages are described, and the increase in usable battery capacity is highlighted.

II. Design of Battery Energy Storage Systems

A. State-of-the-Art Battery Energy Storage Systems

BESS today include HV battery packs with joint bolt connected battery modules. The total number of battery cells in series is about 200 cells. This way the achievable efficiency and costs of the required inverter are improved, compared to low-voltage battery packs with 2-stage inverters. The steps of the system assembly are depicted in Figure 1 above.

The battery packs are equipped with BMS for monitoring the batteries and to ensure their operation in the allowed range for longevity and safety. A variety of grid-connection topologies are possible with varying benefits and trade-offs regarding costs, efficiency, modularity, and safety [6]. The further paper assumes that each battery pack is connected to a dedicated, central inverter for each battery pack. These inverters are then connected in parallel to the grid.

Besides the aforementioned battery specific limitations, there are also several disadvantages of the commonly used transformer based single- and multi-pulse bidirectional converters, such as poor efficiency especially in partial load condition, high total harmonic distortion (THD), the need of high voltage switches, poor fault tolerance and the drawbacks of the needed filters like high costs, weight, volume and losses, even if the system is shut down [7, 8].

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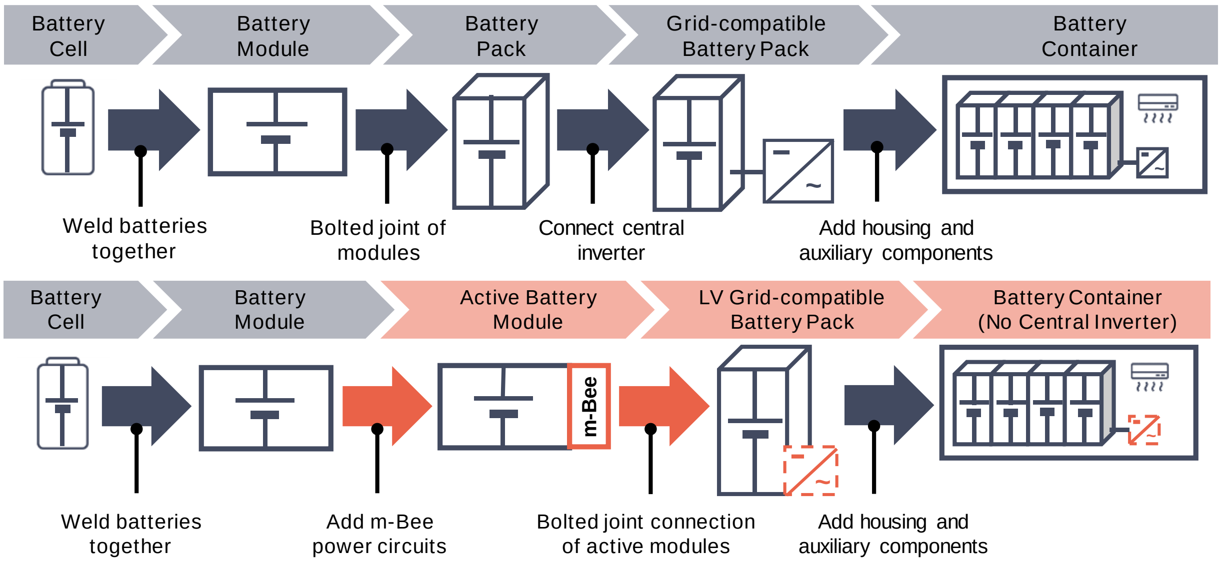

B. A Novel Battery Energy Storage System Topology

Figure 1: Steps of the system integration with conventional inverters and a HV battery pack (above) and with the m-Bee approach. The power electronics is attached to each module instead of each battery pack.

Instead of utilizing a single HV battery pack, the M2B uses the separate battery modules as multiple voltage sources. The resulting BESS topology consists of multiple battery modules that are not statically fixed with joint bolt connections but are equipped with the M2B power electronics modules. These dynamically interconnect the battery modules to build the required sine-wave of the grid voltage with multiple voltage levels. The assembly procedure is depicted in Figure 1.

When lower voltage levels are required, any number of batteries can be connected in parallel, as depicted in Figure 2. There the first voltage step can be achieved by a parallel connection of four cells which decreases the current through the individual cells. In contrast, the fourth voltage step is built by four battery cells connected in series, the same way as in common multilevel systems. The central inverter for each battery pack is replaced by several M2B modules that are each wired to separate battery modules.

In consequence, a single-phase system based on the proposed technology can be composed of a single string of battery cells as seen in Figure 3. The resulting voltage characteristic of such a single-phase system with one hundred battery cells, each with 3.5 V working voltage is outstanding. These small voltage steps result in a THD of 0.44%, whereby no overlaid pulse-width modulation is needed. For economic reasons it is necessary not to use single battery cells but battery packs for each module. The lesser need for electronics with higher pack voltages leads to higher filter effort on the output side, as THD rises proportionally to the chosen voltage step size.

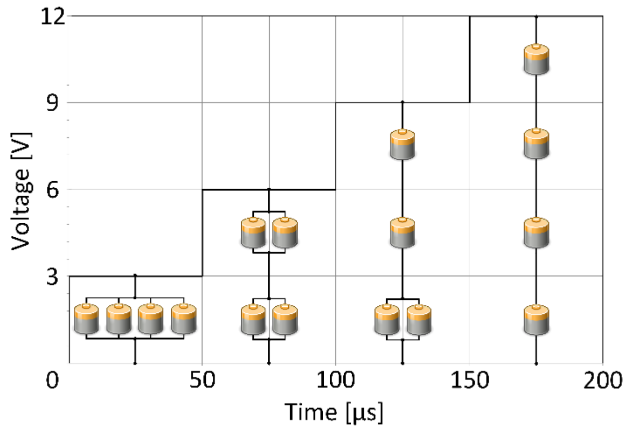

Figure 2: Illustration of the BESS output voltage with the m-Bee concept.

A converter arm is built with n modules. Due to the basic requirement that batteries need to be connectable not only in series but also in parallel, at least two interconnections between neighboring modules are needed. These interconnections between batteries are established by a combination of switches, whereby low voltage metal-oxide-semiconductor-field-effect transistors (MOSFET) should preferably be used. In order to exclude unregulated discharging / charging or short circuits of batteries, even if the system is shut down, the combination of switches has to

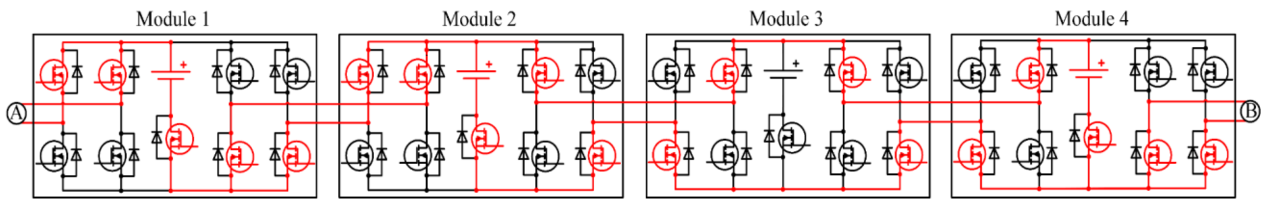

Figure 3: M2B converter arm with four modules and nine switches per module – the current paths for the switching states to be described are highlighted in red: The first storage unit is connected in series to storage units 2 and 4, which are connected in parallel, while storage unit 3 is bypassed.

ensure that no unintentional current flows from one battery to another.

A three-phase battery converter with these converter arms can be structured in several manners. As common split battery multilevel converter systems, the system can be built with three converter arms in star configuration, where each converter arm generates positive and negative voltage levels [8, 9–12]. The states of charge of the three converter arms under unsymmetrical loads can be balanced with the zero-sequence voltage method [13]. Alternatively, the three converter arms can be in delta configuration or – to save on the number of modules – it suffices to connect just two arms. This connection point will be one reference voltage, whereas the open ends of the converter arms will form the other two-line voltages respective to this fixed point. Directly integrating the batteries into the modules leads to a simple system architecture without a high DC-Link voltage and an overall reduction in capacitance per module.

An overview of the conventional and proposed system topology is shown in Figure 4.

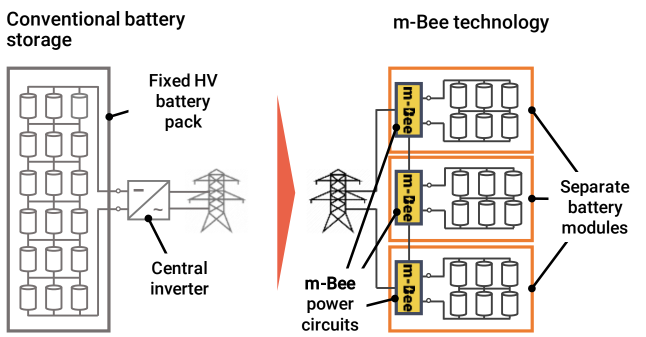

Figure 4: Illustration of the conventional system design and the novel BESS topology.

III. Working Principle of the System

A. State-of-the-Art Systems

For state-of-the-art systems to generate the sinus-wave of the grid voltage, the battery pack voltage is chopped by the inverter. Figure 5 above depicts the pulse-width modulation (PWM) of the inverter output voltage to match the grid voltage. The output voltages are either $+u_{battery}$, 0, or $-u_{battery}$. The chopped voltage is switched with the respective duty cycle and filtered with an LCL-filter to match the grid voltage.

B. The Proposed Battery Energy Storage System Topology

The modules are activated in series or parallel connection according to the required voltage. The grid voltage's sinus wave is approximated by a staircase-like voltage with the step heights equaling the modules' voltages (Figure 5 below). The number of possible output levels is *2n+1*, whereas *n* is the number of modules in a converter arm.

Due to the lower voltage steps compared to state-of-the-art systems the grid filters are reduced as well as EMI. The staircase-like output voltage can be pulse-width modulated to further reduce grid filters.

IV. Qualitative Comparison of the System Designs

A. State-of-the-Art Systems

State-of-the-art systems rely on HV battery packs that require personnel to work with dangerous voltages. Additional safety gear, tools, and safety procedures are required to minimize the risk of life-threatening electric shocks in case of errors.

In addition to the issues of handling voltages of more than 600 V, balancing of the battery cells is required to increase the usable battery capacity. The dissipative balancing method is the dominant method in the industry because of its low costs for the electronics, compared to other methods. It is, however, the method with the lowest energy efficiency. All battery cells are discharged by resistors, to match the state-of-charge (SOC) of the battery cell with the lowest SOC. The energy is dissipated and cannot be used.

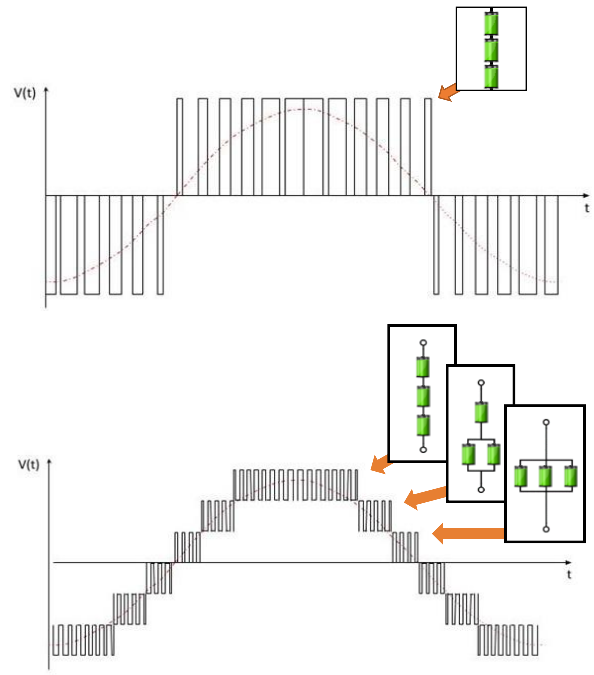

Figure 5: Illustration of the output voltage. Above is the conventional BESS with a 3-point H-bridge inverter. Below is the m-Bee inverter with 3 voltage levels.

The malfunction of a single parallel battery cell compound leads to the shutdown of the entire battery pack for safety reasons. High requirements for the fail-safety of BESS, therefore, require the redundancy of at least an entire battery pack plus inverter.

B. The Proposed Battery Energy Storage System Topology

The m-Bee technology turns static battery modules into active and dynamic components. The effects of deploying the m-Bee technology for battery storage systems are the following: Enhanced fail-safety, improved personal safety, higher efficiency, increased usable battery capacity and simplified system design and operation.

The new topology features a higher failure safety. While the breakdown of a single battery cell results in a failure of an entire battery pack with the conventional topology, the m-Bee technology can compensate for the malfunction of single cells or modules. Detected failures are bypassed by the battery module chain (see Figure 3), allowing further operation of the battery storage system (with reduced performance), until the faulty battery module is replaced. The risk of liability for the battery storage manufacturer and the downtime of the system is reduced. Instead of immediate deployment of field engineers/technicians to repair the system, the assignment can be scheduled with the regular service interval.

The split topology of the battery modules significantly increases the safety of handling the storage system, by reducing the maximum system voltage in an off- or safe state to a single module's voltage.

The higher efficiency is achieved by smaller switching voltages and frequencies compared to conventional battery storage topologies. Instead of trimming the voltage of the entire battery pack that is higher than 600 V, the AC-voltage is generated by dynamically connecting battery modules with switching voltages of only about 50 V (the battery module voltage). An added benefit of the low switching voltage is a favorable total harmonic distortion (THD) value. The values achieved by the m-Bee technology are significantly lower than those of conventional inverters (before filtering). The required grid filter for the m-Bee technology is, therefore, smaller, cheaper, and more efficient. The resulting levelized cost of energy stored (LCOES) is reduced with superior system efficiency.

Passive balancing happens only on module level. Unequal SOCs between the modules are compensated in a lossless manner using the grid or the load, what we call "proactive balancing". Its principle of work can be described as follows: the modules are switched into the load current in such a way, that the SOCs of the modules are being equalized, e.g. a module with a higher SOC is activated earlier in regarding the current sine wave (or output voltage steps) and deactivated later compared to a module with lower SOC, thus this module is actively supplying energy for a longer period of time when the BESS is discharged. When the battery system is being charged, the algorithm is working in the opposite way. In doing this, no surplus charge is being wasted. The effect is quantified in the following chapter.

Using the m-Bee technology simplifies the design and installation of battery storage systems. The structure is modular, and the amount of battery modules is scalable, allowing custom storage sizes for each use-case. Additionally, it is possible to selectively charge and discharge individual battery modules. Battery storage systems today require a pre-determined reference cycle to recalibrate the battery management system's state estimation and achieve a well-defined balancing of the batteries. These cycles require the system to halt the actual operation. The m-Bee technology enables the execution of these reference cycles simultaneously to the ordinary operation. This increases the system availability for the application.

The benefits mentioned above lead to a cost reduction of the upfront costs and the operational costs of battery storage systems and improve their safety and handling.

V. Increase of the Usable Battery Capacity

A. Background

Dissipative BMS are mostly used in battery storage systems for cost reasons. These convert the additional energy of fuller cells into heat with simple resistances, until they are at the same charge level as the battery cell with the lowest SOC. When the BESS is discharged, the empty cells are the earliest to reach the cut-off voltage, the storage system will not be discharged further to prevent deep discharge.

With a higher voltage battery pack, many cells are connected in series, as shown below. In this series connection of cells, the BMS balances to the weakest cell in the chain, e.g. the performance of the entire battery pack is determined by the weakest cell.

However, when employing m-Bee battery modules, a BMS no longer optimizes for the globally weakest cell of the battery pack, but for the locally weakest cell of each battery module. This results in an increase of usable capacity for the BESS, even though the same cells are being used. This effect is illustrated in Figure 6.

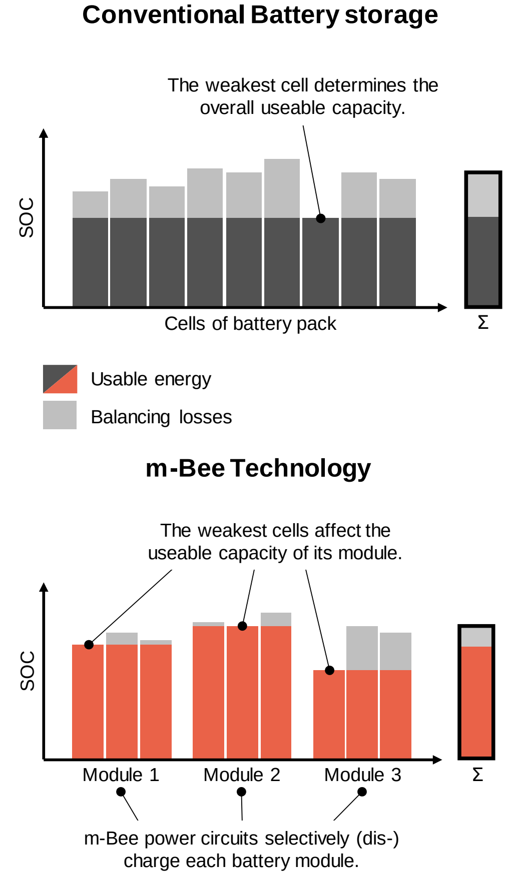

Figure 6: Illustration of Battery Capacity Increase with m-Bee technology.

B. Statistic Analysis

The effect is quantified by Monte-Carlo simulations with a varying number of cells in series and battery cell capacities with a normal distribution. Table 1 shows the results of the simulations.

The numbers in Table 1 are based on the following assumptions: cell voltage $u_{cell} = 3.6$ V, nominal battery module voltage 48 V and thus 14 cells per module and a resulting module voltage of $u_{module} = 50$ V. With a battery voltage u_{batt} of 400 V, 112 cells are connected in series or 8 modules are formed, at 600 V there are 168 cells or 12 modules, at 800 V 224 cells or 16 modules and 1000 V correspond to 280 cells or 20 modules. The cell capacities are modeled via a normal distribution with the expected value $\mu = 1$ (or 100% of the nominal capacity C_N). The standard deviation σ varies according to the top line of the table.

Table 1: Gain of usable capacity with m-Bee technology for different battery pack voltage and standard deviation of battery cell capacities.

Modules	Cells	σ	1%	2%	3%	4%	5%	10%
(14s)	(3.6V)	u_{Batt}	Capacity increase in %					
8	112	400 V	0.8	1.8	2.8	3.8	4.9	11.7
12	168	600 V	1.0	2.1	3.3	4.4	5.7	13.8
16	224	800 V	1.1	2.3	3.5	4.9	6.3	15.3
20	280	1000 V	1.2	2.5	3.8	5.3	6.8	16.6

First, the appropriate amount of random numbers was generated according to the normal distribution specified above as the capacities of the individual cells and the global minimum was determined. This represents the available capacity in a conventional BESS with a series connection of cells and dissipative balancing. This number serves as the reference value. Subsequently, every 14 cells are grouped as a module and the local minimum is determined. The local minimum is then taken as the available capacity of the respective battery module, representing the available capacity of an m-Bee system. The difference of the available capacity of conventional systems and the m-Bee system is then taken as capacity increase achieved by the m-Bee approach. The steps were repeated a million times from the random number generation to improve the statistic reliability of the results. The mean value of the calculations' results is the expected, mean gain in usable capacity shown in Table 1. This average value remained constant over several runs of the algorithm, indicating that the values can be considered the expected value of this distribution.

The gain of useful capacity correlates with the value of the standard deviation σ of the variation of the battery capacity C_n and increases with the total battery voltage u_{Batt}. Only with higher spreads does the gain in usable capacity increase disproportionately. If new battery cells of a production batch have very small capacity variations [14], this effect is rather small for new BESS.

Several factors, however, increase the expected variation of the battery cell parameters. The battery cell temperature has an immediate impact on the available battery charge. Any temperature difference within a battery pack, due to the ambient temperature or non-optimal thermal management, has an impact. This is further reinforced in later cycle life stages by the aging of the batteries, as both the inner resistance and battery capacity are worsened.

The effect of increasing the usable capacity is also more relevant in case of battery replacement. The malfunction of a battery module or the replacement because of the end-of-life criterion leads to parameter variations. The new battery module's performance is impaired by the reduced performance of the remaining batteries in the conventional case. Second life concepts for automotive batteries are also simplified by the increase of usable capacity enabled by the m-Bee approach. Current 2nd life approaches require the matching of batteries [15] causing additional costs that could be alleviated with m-Bee systems.

In Figure 7 the frequency distribution for the case 600 V and $\sigma = 5\%$ shown. On average, as shown in the table, this configuration yields an increase of the usable capacity of 5.73%, with a minimum of 0.64% and a maximum of 31.02%. This model calculation thus shows that the use of the M2B system always provides more capacity. For 1,000,000 iterations, the median of the displayed histogram is 5.37% and the 25% and 75% percentiles are 4.19% and 6.88%, respectively.

The gain calculated above can be viewed as a direct effect and quantification of the lossless proactive balancing described above. The increase of usable capacity is the energy that would be converted into heat by the dissipative balancing with a correspondingly long battery string and thus would not be available to the user.

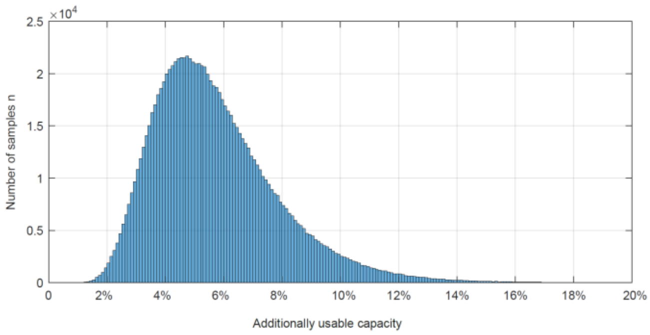

Figure 7: Distribution of simulation results for a nominal battery pack voltage of 600 V and a standard deviation of 5%.

VI. Conclusion and Outlook

A. Conclusion

This paper presents a novel BESS topology that is enabled by a multilevel converter approach. The new design is described together with its benefits and drawbacks in comparison with current state-of-the-art BESS.

The proposed topology exhibits a variety of benefits, such as safe voltages during installation and maintenance, high efficiencies, and an increase of the usable battery capacity. These benefits are achieved solely by the new system design, made possible by the new inverter type. The losses due to dissipative balancing in a string of cells in an HV battery pack have been quantified compared to the novel m-Bee approach and its lossless balancing method.

B. Outlook

The next steps are to build a full-scale prototype of the m-Bee storage system and demonstrate the performance of the system. The benefits are expected based on reasoning and simulations. Actual measurements are mostly limited to small-scale systems demonstrated in a laboratory environment. Further validation of the claimed benefits is necessary and need to be assessed in detail. This includes the efficiency of the system, as well as, the increased usable battery capacity. The presented technology will be commercialized by the university spin-off m-Bee GmbH with the aim to increase the availability and usability of renewable energy dispatch.

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