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DESIGN AND CONSTRUCTION OF A TEST BENCH TO CHARACTERIZE THE CHARGING AND DISCHARGING BEHAVIOUR OF BATTERIES IN HIGH VOLTAGE STORAGE SYSTEMS

Christoph Roggendorf[1], Tobias Blank[2], Stephan Thomas[3], Ionut Trintis[4]

[1]Institute for High Voltage Technology (IFHT), RWTH Aachen University
Schinkelstraße 2, 52056 Aachen, Germany
[2]Electrochemical Energy Conversion and Storage Systems Group (EEC), Institute for Power Electronics and Electrical Drives, RWTH Aachen University
Jägerstraße 17-19, 52066 Aachen, Germany
[3]Institute for Power Generation and Storage Systems (PGS), E.ON Energy Research Center,
Mathieustraße 6, 52074 Aachen, Germany
[4]Department of Energy Technology (IET), Aalborg University
Pontoppidanstraede 101, 9220 Aalborg East, Denmark

ABSTRACT: Battery energy storage systems are able to compensate volatile energy sources, such as wind and solar energy. One system topology for medium voltage grids uses high voltage batteries. This yields in an improvement of the overall system efficiency. High voltage batteries may be advantageous for future DC-grids as well. However, as there is little expert knowledge about series connected batteries up to several kV, this makes investigations of the charging and discharging behaviour of such systems necessary. For this purpose, a test bench for high voltage storage systems is built to analyse these processes for different battery technologies. A special safety infrastructure for the test bench must be developed due to the high voltage and the storable energy of approximately 120 kWh. This paper presents the layout of the test bench with all components, the safety requirements with the resultant safety circuit and the aim of the investigations to be performed with the test bench.

1 INTRODUCTION

Strongly increasing power generation based on volatile energy sources, such as wind and solar energy, sets new requirements on design, planning and operation of power systems. In addition, the demand for regulating reserve power and ancillary services is drastically increasing, forcing power system operators to intensify the use of system flexibility measures and non conventional operating concepts. Here, battery energy storage systems or electrochemical energy storage systems in general may offer unique and scalable solutions for high power and long term energy demands in the range of up to approximately 100 MW and several 100 MWh.

To reach these power levels, an obvious possibility is to use high voltage storage systems. Large battery energy storage systems show high reliability and robustness. Thus, the usage in high voltage applications is feasible in general [1]. However, the series connection of batteries up to several kV leads to nontrivial charging and discharging characteristics of such a storage system. To investigate the cell balancing behaviour for different battery technologies, a high voltage battery test bench is under construction. The concept of the test bench is shown in Figure 1.

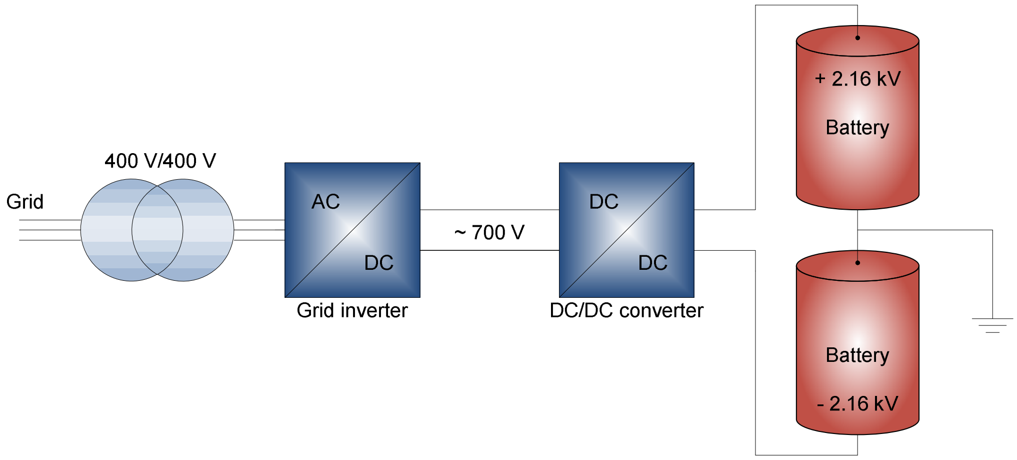

Figure 1: High voltage battery test bench (principle drawing)

The test bench consists of an insulation transformer with connection to the low voltage grid, an inverter, a DC/DC converter as charge/discharge unit and the high voltage storage system. The power capacity of the power electronics and the grid connection is in the range of 100 kVA. In the basic configuration the storage system consists of 360 lead-acid batteries (12 V / block) in series connection. Thereby a nominal voltage of ± 2.16 kV and a storable energy of approximately 120 kWh will be reached.

The construction details and the mode of operation of the different components of the test bench, the developed safety infrastructure as well as the aim of the charging/discharging investigations are presented in the following.

2 COMPONENTS OF THE TEST BENCH

An optimised DC/DC converter topology with high transformation ratio will be constructed to realize the charging and discharging of the storage system. Thus, it will be possible to investigate the cycles of charging and discharging which are necessary should such a storage system be used to compensate volatile energy sources efficiently. A battery monitoring system which includes the measurement of voltage and temperature will be installed to analyze the behaviour of single battery blocks. The asymmetric charging/discharging process of the battery blocks, as well as the temperature development under high stress, can be accessed in detail, too.

2.1 GRID INVERTER

The classical two-level hard-switched converter is state-of-the-art for low voltage applications, being the most used topology in industry. For grid connection of such converter it is necessary to have a higher dc-link voltage than it is usually used for drives, in order to be able to inject power into the grid.

The converter is connected to the 50 Hz low voltage grid. The converter’s switching frequency is 3 kHz. In order to comply with the grid codes, an LCL output filter is used together with a current control which is able to compensate low order harmonics [2]. The leakage inductance of the 1:1 isolation transformer (neglecting the core loss and magnetizing inductance) acts as the filter inductance on the grid side (Figure 2). The resonance frequency of the filter must be lower than half of the converter’s switching frequency, in this case 1.3 kHz. The delta connection of the filter capacitors leads to a smaller installed capacitance for the same resonance frequency.

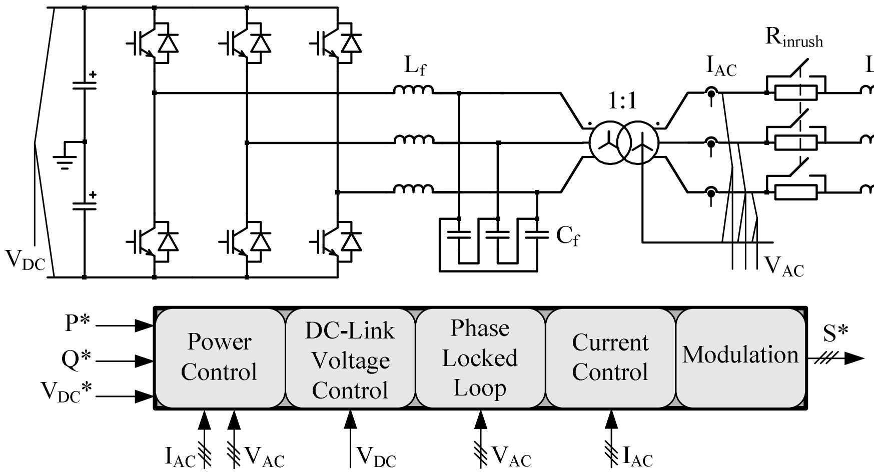

Figure 2: Structure of the grid converter

Limiting inrush resistors are used to reduce the DC-Link capacitor's charging current as well as the transformer magnetizing current.

Nominal operation is at 100 kW with unity power factor. On demand the inverter can generate or consume 10% reactive power, therefore the nominal installed power is 110 kVA.

The applied control structure is a triple closed-loop with a decoupled operation: current control loop, dc-link voltage control loop and power control loop. The power references are given by the test bench control and the power flow is bidirectional. The current injected into the grid is synchronized using a structure which is able to operate during unbalanced and distorted grid also. The Space Vector Modulation technique is chosen to have a good dc-link utilization and to optimize the switching states transitions.

2.2 DC/DC CONVERTER WITH HIGH TRANSFORMATION RATIO

The DC/DC converter acts as a charging/discharging unit for the high voltage battery. In the test bench, there is a wide range of operation conditions. Depending on the charging status of the batteries, the voltage varies between 3.3 kV and 6 kV. The power transfer varies from 4 kW to 100 kW. Low power transfer is needed to investigate the voltage distribution of the series connected battery cells. The converter is optimized for the whole operation range. The output voltage is controlled by the grid coupling inverter to be constantly 750 V. Hence, a high voltage transformation ratio from output to input is necessary. Therefore, a galvanic isolated topology was chosen to benefit from the winding ratio of the included transformer. The topology, a dual-active bridge [3], [4], can be seen in Figure 3.

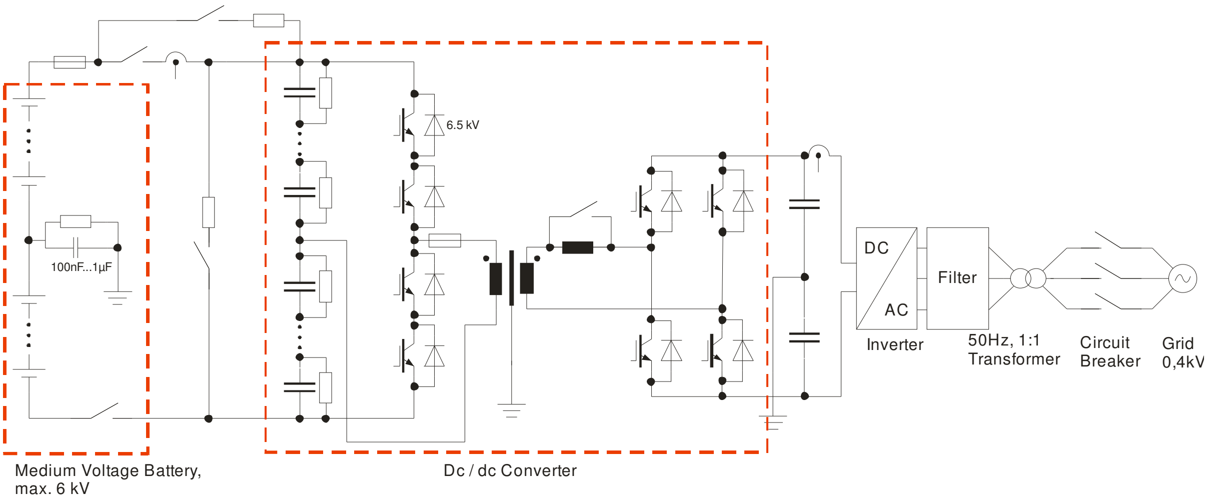

Figure 3: Topology of the dual active bridge in the high voltage test bench

A half-bridge configuration on the battery's side is chosen (Figure 3). With this configuration, the input voltage is divided by two compared to the H-bridge on the output side and the current is doubled. Therefore, the number of expensive HV-IGBTs is reduced. This is a major advantage for the power electronic switches. A series connection of 6.5 kV IGBTs with a current rating of 200 A has to be used for blocking voltage capabilities. Due to the maximum power of 100 kW and the high input voltage, the current flowing is small. The IGBTs switch small currents very fast and may become snappy, leading to ringing problems. Therefore, doubling the RMS current is advantageous. The input and output bridges generate square-wave voltages on the transformer terminals. Depending on the phase-shift angle between these two square-wave voltages, power is transferred via the leakage inductance of the transformer, which can be increased by an additional inductor for low load operation. Typical voltage and current waveforms on the terminals of the transformer can be seen in Figure 4.

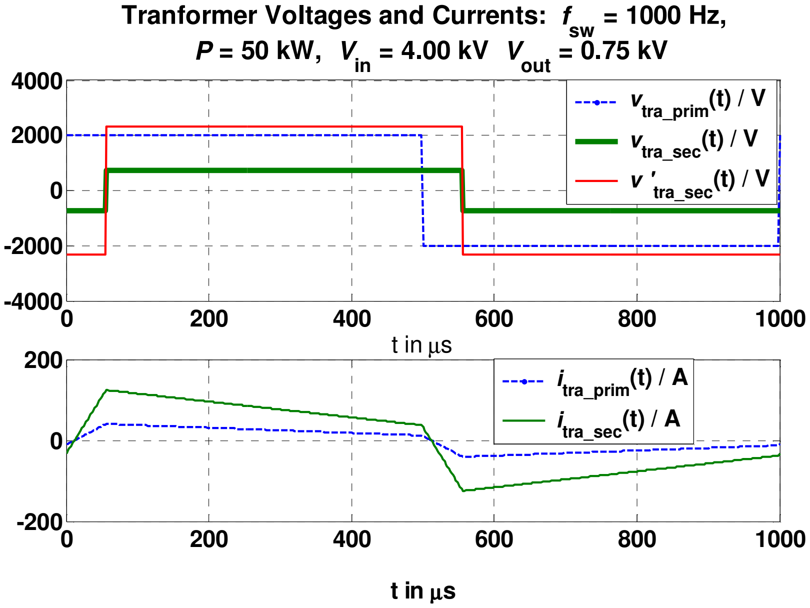

Figure 4: Transformer voltages and currents (v' is the secondary voltage referred to the primary side)

With this phase-shift angle the amount of power and the direction of the power flow can be controlled. Figure 5 depicts the transferred power as a function of the phase-shift angle with the battery voltage as a parameter.

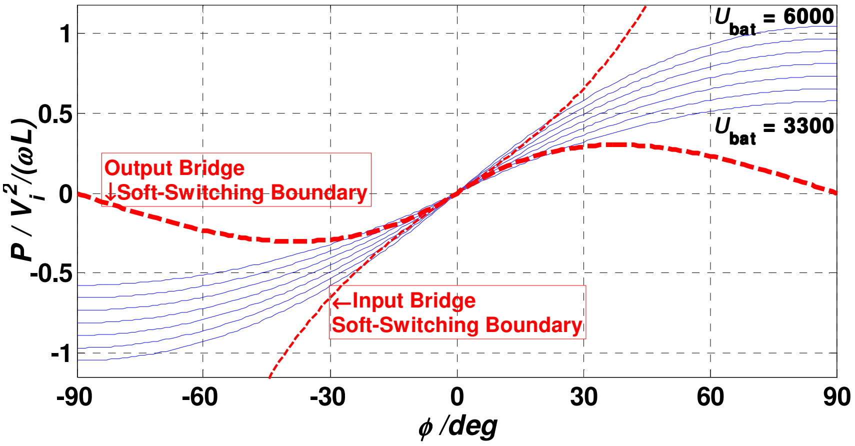

Figure 5: Normalized output power vs. phase shift of the input and output square-wave voltages with various input voltages as parameter (winding ratio of transformer: 3)

2.3 HIGH VOLTAGE STORAGE SYSTEM

The battery storage system consists of a large number of cells in series, thus the optimum topology and reliability are major issues. Lead-acid batteries are robust and competitively priced in comparison to other battery technologies. The test bench's battery is constructed of 360 12 V lead-acid blocks, with a capacity of 27 Ah each. The test bench's battery system can store approximately 120 kWh of electrical energy.

The topology of the test bench mainly consists of six battery building blocks with 720 V each. Thus, the nominal string voltage is ±2160 V. The maximum voltage for the charging process including the voltage drops over the cables, fuses and disconnectors is about 6 kV. Figure 6 shows a battery building block with its cable connections. Each battery building block consists of ten substrings of 72 V. The batteries in the test bench are stored in two separate battery racks, each containing 3 of the 720 V building blocks. This design was chosen to reduce connection length in order to decrease the internal resistance of the storage system.

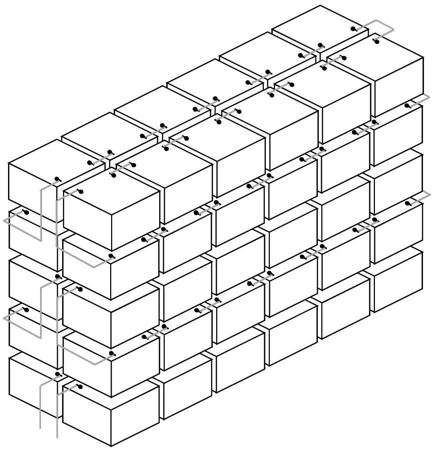

Figure 6: Battery building block with a nominal voltage of 720 V

The battery monitoring system for the test bench consists of 360 *LEM Sentinel* sensors. They measure the voltage, temperature and impedance of each battery block independently. The sensors will be connected in six substrings of 60 sensors. This is necessary because the data bus of the monitoring system cannot withstand the high voltage otherwise. The data bus will be connected to a *National Instruments CompactRio* real time controller via RS 232 bus for the evaluation of the measured data.

3 SAFETY INFRASTRUCTURE

Due to the high voltage and the high energy storage, elaborate safety requirements for a high voltage battery test bench are necessary. Therefore a special safety infrastructure is developed and will be integrated into the system.

In the laboratory operation regular maintenance and adaptation of the system is indispensable. In the special case of the high voltage storage system it is not possible to switch off or to ground the high voltage. The maximum DC touch voltage is 120 V [5]. Therefore, within the safety infrastructure the high voltage storage system can be separated into battery stacks of 72 V. To avoid long wiring distances a special disconnector system, which is directly constructed into the battery shelves, was developed. Figure 7 shows the principle of these disconnectors for the first two levels of the battery rack. All in all, 60 disconnectors are realised in this way.

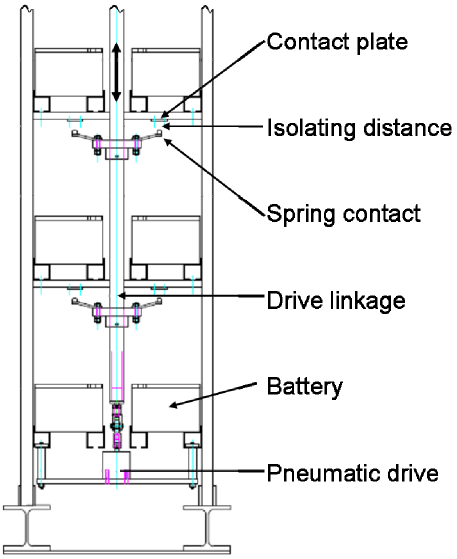

Figure 7: Disconnector system in the battery shelve

The control of power electronics, the battery monitoring, as well as the door of the safety cage, emergency switches and smoke detectors are integrated into the safety circuit. Hence, monitoring all critical conditions is possible. In case of emergency the test bench can be switched into a secured status. Figure 8 shows the principle structure of the safety circuit.

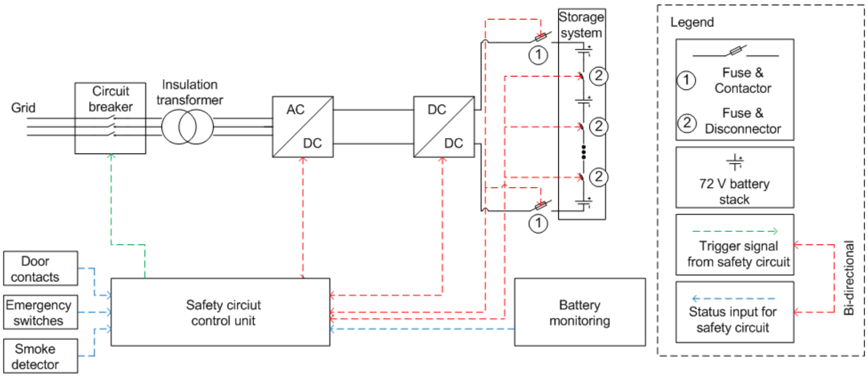

Figure 8: Structure of the safety circuit

Depending on the nature of the failure the safety circuit and the superordinate test bench control react in different ways. The measures can be distinguished into three categories:

- Monitored values (voltage and temperature) of the batteries reach critical values → the test bench control reduces the power transfer
- Monitored values exceed the critical values → the test bench control triggers the power electronics to interrupt the power transfer. After that the circuit breaker disconnects the test bench from the grid. Then the contactor separates the storage system from the power electronics. Finally all disconnectors switch the system into a secured state.
- In all other cases of emergency such as:
  - ➢ Open door contact
  - ➢ Actuation of an emergency switch
  - ➢ Signal from the smoke detector
  - ➢ Failure signal from the power electronics
  - ➢ Power loss at the control unit

  → the circuit breaker and the contactor interrupt the test bench immediately and subsequently the disconnectors switch the system into a secured state.

4 INTENDED INVESTIGATIONS

In the presented test bench it is possible to investigate the behaviour of different battery technologies in a high voltage series connection. Efficiency and reliability of such a system are of special interest and can be investigated with the described set-up.

The main focus is on the necessary measures for cell balancing in series connected batteries. The modular construction of the high voltage battery and the wide operation range of the power electronics in the test bench allow a variation of different parameters to find the optimal topology. For example it will be possible to adapt the voltage level and to investigate the charging and discharging behaviour for other battery technologies by replacing some of the lead-acid battery strings.

The usage of battery storage systems in medium voltage grids requires a high reliability of the system. Therefore, with the monitoring systems for each 12 V block a detailed examination of possible failures within high voltage storage systems can be performed. In addition, a connection of some battery strings in parallel allows a reliability analysis of redundant topologies.

5 ACKNOWLEDGMENTS

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