Consideration on Battery Energy Storage System for an LVDC Distribution System

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SUMMARY

In the paper, the design of the battery energy storage system (BESS) suitable for low voltage direct current (LVDC) electricity distribution system, is presented. The LVDC research site is a testbed for the novel electricity distribution concept in which the usage of the power electronics in electricity distribution is evaluated, in practise. The paper covers objectives regarding the BESS integration to the LVDC distribution system and dimensioning methodology including the essential design aspects of the battery chemistries and characteristics. For the research, the integration of the BESS proves technology readiness of the concept. In the paper the emphasis is on the technical perspective. Most of the existing energy storage systems are connected to the DC bus by using bidirectional DC/DC converters. The converter ensures proper charging and discharging of the battery as well as power flow and voltage regulation. However, inclusion of the converter increases the costs of the system and reduces the total efficiency. Therefore, the functionalities of the bidirectional DC/DC converter are transferred to front-end rectifying converters of LVDC network and the direct connection of the energy storage to DC network is considered. The results enable further feasibility studies considering also the market-oriented functionalities.

KEYWORDS

Low voltage, Direct Current, LVDC, Distribution, Back-up supply, Energy Storage, Battery, BESS

1. INTRODUCTION

The general consensus on future distribution systems development suggests aiming towards Smart Grid (SG) environment. The objective is to increase efficiency and quality of supply, enable integration of various distributed energy resources (DER) and more importantly, to achieve flexibility both in electricity generation and consumption.

Low voltage DC (LVDC) distribution system is a novel, smart electricity distribution concept. The concept was introduced in [1] and studied further in [2] and [3]. According to the performed studies the concept is economically feasible solution for replacement of medium voltage branch lines in certain target areas [3–4]. The solution is applicable also for suburban and urban distribution and the efficiency could be improved further by supplying at least some of the customer loads with DC [5]. As majority of the domestic appliances and distributed generation utilises DC there are possibilities to constitute hybrid AC/DC or fully DC operated entities. Various distributed energy resources are indisputable part of the SG and therefore, it is also desirable that the integration and operation of DERs in power systems is advantageous.

The main advantages of the LVDC systems are efficiency, versatility and easy implementation of the DERs, i.e. the essential before mentioned characteristics of future electricity distribution environment. Efficient integration of various distributed energy resources (DER) is possible due to the common DC network and embedded converters providing increased controllability. The interface between DERs and the DC network is simplified compared to AC systems in terms of synchronization and voltage control, i.e. there is no fundamental frequency to synchronize with. Furthermore, the voltage may vary widely in the utility DC network without disturbing the end-user electricity supply. By integrating BESS, the quality of supply and flexibility is increased. From research perspective it allows further studies concerning especially the management of the overall system also for market-oriented functionalities.

In the paper, the BESS integration on real network LVDC research site is considered. The design process, objectives regarding BESS integration and dimensioning methodology are covered. As the case under consideration is the integration of BESS to real network research site, the approach is not entirely theoretical but is instead highly interconnected with the practise.

2. CONSIDERATION ON BATTERY ENERGY STORAGE SYSTEM

The research site LVDC distribution system consists of 20/0.53/0.53 kV double-tier transformer supplied from the 20 kV medium voltage (MV) network, grid-tie rectifying converter, 1.7 km underground cabled, terrain-isolated functionally unearthed (IT) ±750 VDC DC network and three galvanically isolating customer-end inverters (CEI) supplying four actual end-customers. The system is located in Finnish DSO's (Järvi-Suomen Energia Oy) network and has been in operation since June, 2012 [6–8]. Figure 2.1 represents the setup and the planned location of the BESS installation.

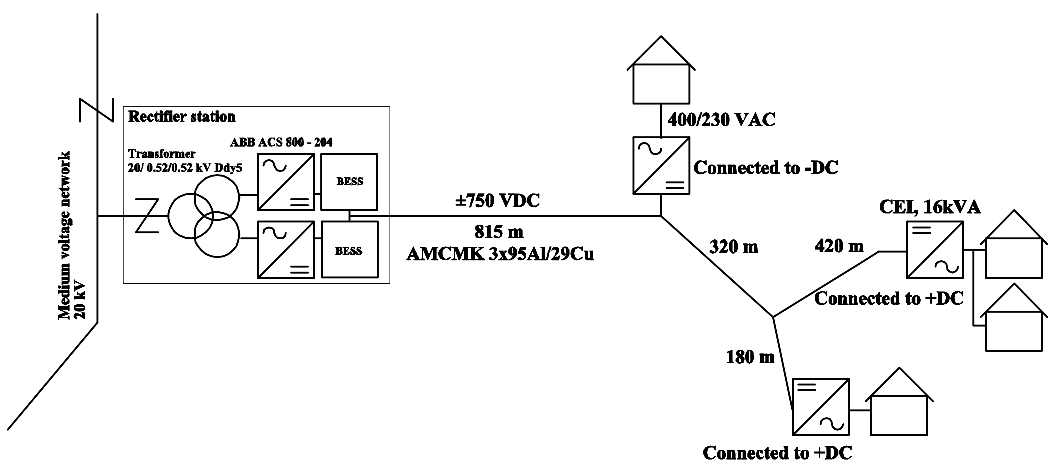

Figure 2.1. Field setup LVDC distribution system.

The installation is a research setup in which the operation of power electronics in distribution is evaluated. The setup is utilising commercial and self-made equipment. Therefore, it does not represent the spearhead efficiency but is instead a platform subject to constant development and serves as a testbed for implementation of various LVDC and SG related functionalities. The recent system update included replacement of the half-controlled thyristor bridge rectifiers with two ABB ACS800 grid-tie rectifying converters enabling accurate DC voltage control and bidirectional power flow. As a continuum the setup will be equipped with a battery pack which enables both island operation and demonstration of the BESS capacity for market-oriented and grid supportive actions. Natural development is to include distributed generation (DG) to constitute a small-scale, yet scalable microgrid for which especially the system management, control and operation functions are developed is assessed, in practise. The research setup speciality is that it is used constantly for supplying the customers, due to which the security of supply has to be ensured, also when integrating and assessing new components or functionalities.

2.1 Practical usage

In practice, the BESS in the LVDC system eliminates the supply interruptions experienced by the electricity end-users. Therefore, in case of severe fault in the feeding MV network the LVDC system can be used to provide backup supply enabling thus the principal backbone for microgrid operation.

In future, large poll of the BESSs integrated into the distribution networks, can be used to support the network, and therefore provide load management functionality. The integration of the marked oriented functionalities based on BESS usage, such as load-shedding, load-shifting and peak smoothing are non-invasive for the end-customers. The realisation of such possibilities sets the operational requirements for the BESS which have to be considered in the BESS integration process.

2.2 Initial operational requirements

To provide backup supply the energy storage must have sufficient capacity. Moreover, power rating of BESS must be sufficient to supply LVDC network loads. The rural LVDC network loads can be considered as residential loads. The residential loads have a degree of power variation as a function of time. This variation is highly dependent on household types and heating method of the house. As a result, the seasonly occuring variation is typical. In addition, repetitive patterns can be recognized in the daily and weekly load cycles. In the LVDC system the nominal power of the customer-end inverters (CEI) sets the limit for the maximum power. The nominal power of the research site CEI is 16 kVA.

Generally, the dimensioning of network components is done by using the existing information of the households, which are based on the measurements of typical household consumption. Therefore, the load profiles can be used the estimate of sufficient power and energy capacity of BESS to provide back-up supply operation in the LVDC distribution network. The automatic meter reader (AMR) installations will provide more accurate clustering of the customers and brings more accuracy to the dimensioning, as soon as sufficient historical data is obtained. Weekly power flow measurement data from research site is presented on Figure 2.2.

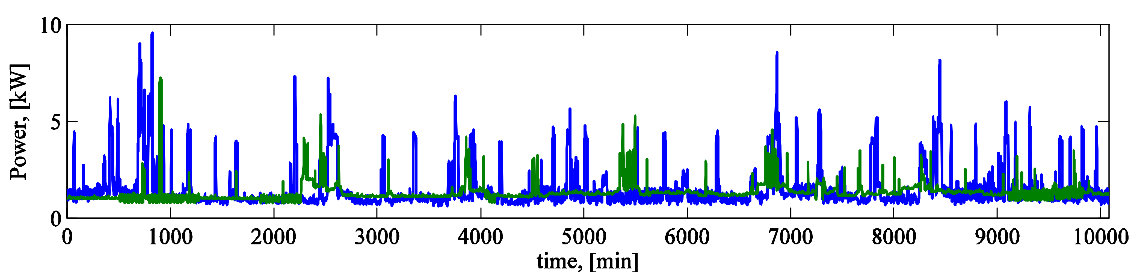

Figure 2.2. Measured power flow of the LVDC research site network during spring season (green - positive pole, blue - negative pole).

The maximum current rating of the front-end rectifier converter is restricting the maximum power flow in grid supporting application. For the power electronic converters used on research site, ABB ACS800 the maximum continuous DC current is 47.4 A. The utilised voltage level in the DC network is ±750 VDC.

To provide the required functionalities, for the studied application, the following initial technical requirements for the BESS have been considered:

- One hour back-up supply of the nominal power, 30 kWh/pole
- Continuous discharge current 40 A
- Voltage rating of 750 VDC

The nominal current requirement leads to overdimensioned and costly results. Therefore, the energy storage dimensioning methodology requires further specification especially when the market aspects are included. Finally, in research site environment, the maximum current is restricted by the rectifier maximum ratings. Also, following requirements leads to around 30 kWh energy capacity per pole. In practise such capacity allows the system back-up operation for several hours, as can be seen from Figure 2.2.

2.3 Network interface

Generally, energy storage systems are connected to the DC bus by using bidirectional DC/DC converters. The BESS converter ensures proper charging/discharging of the battery and manages the power flow and voltage regulation. In studied application, this can simplify design of power flow control. Moreover, in this case, the charging and discharging functionality is already implemented in the BESS converter. Furthermore, the DC network voltage variation and level are not dependent on BESS. However, inclusion of the converter increases the costs of the system and reduces the total efficiency. Therefore, the direct connection of the energy storage to DC network is considered for the case application.

To implement direct connection of the energy storage to DC network, the functionalities of the bidirectional DC/DC converter would be transferred to front-end converters of LVDC network. Such solution requires the battery terminal voltage to be equal with DC mains voltage level. This, in turn, leads to multiple cells connected in series to reach the DC voltage level. As more cells in series are required, the battery management system (BMS) acquisition costs become also higher. The principal enabler of this functionality is the grid-tie rectifier converter, capable of wide-range DC-voltage control. The requirements for the special case of the directly connected BESS in studied application are

- Nominal voltage rating of the BESS is matched with the nominal voltage rating of the DC mains (750 VDC)
- The minimum voltage in discharge and maximum voltage in charge is limited by the LVDC network configuration and the properties of the converters, especially the rectifier.
- 1C discharge at ~710 VDC pole voltage (front-end converter limits DC voltage minimum reference value to 707 VDC ($\sqrt{2} \times U_{\mathrm{ac}}$) [9]
- 1C charge at ~775 VDC pole voltage (front-end converter limits DC voltage maximum reference value to 778 VDC) [9]

Based on the operational requirements set and selected direct interface to DC network, the suitable battery chemistry for the application is considered in the following section.

2.4 Battery chemistry

The energy storage systems (eES) utilized nowadays are classified and the system features are reviewed, for instance, in [10]. The availability of the secondary battery chemistries and respective characteristics are varying remarkably due to which the design has to be carried out carefully for the case application. Among the available electrochemical storages (secondary batteries) the battery types applicable for the case are mainly determined according to the application specific requirements and electrotechnical properties of the eES. The economic feasibility is naturally another half of the techno-economic selection process. The possible alternatives considered for the application are traditional lead-acid batteries and lithium-iron phosphate (LFP) batteries.

One of the most widely used battery type globally is lead-acid, invented in 1859. Lead-acid batteries are not only safe and cheap but can be also effectively recycled after the end-of-life (EOL) is reached. The main disadvantages of the lead acid batteries are short cycle life (200-300 cycles) and relatively long charge time. The terminal voltage and capacity of lead-acid batteries are also highly dependent on the discharge current, state of charge (SOC) and cycle age of the battery. The lead-acid is mature technology approaching end of life and, therefore, for the application, the modern lithium-ion is considered as well.

Lithium-ion batteries have become the most important storage technology in the field of portable and mobile applications [11]. The present state of the lithium ion technology is overviewed for instance in [12]. Safety is an important issue when the lithium ion battery technology is utilized [13]. From the lithium based batteries, the lithium ion iron phosphate batteries (LiFePo4 or LFP) are the safest solution [13–14]. The main advantages of the LFP batteries are high power density and long cycle life. In addition, terminal voltage profile is relatively flat as a function of the state-of-charge (SOC).

In market-oriented and grid supportive actions the power flow is bidirectional between LVDC network and MVAC network. This sets requirements for the DC voltage level, because minimum operational DC voltage of the front-end converters is 707 VDC, as earlier described. Therefore, due to high variation of the terminal voltage of the lead acid batteries they may be not directly applicable for the direct connection. Possible solutions to meet the requirements are oversizing of the capacity and interconnection with the bidirectional DC/DC interface converter. Despite the terminal voltage fluctuation problem the practical use of directly connected lead-acid batteries as back-up power for the network is not completely excluded, as the voltage of the DC network can be let to vary within a certain range. The boundaries for the CEI terminal DC voltage variation are between 520 – 780 VDC, which are set due to protection and power quality requirements [7]. Nevertheless, based on the discussed requirements and characteristics of the BESS the comparison of the Lead-acid and LiFePo battery solutions for the LVDC research-site is summarized and presented in Table 2.1.

Table 2.1. Comparison of Pb-acid based and LFP-based BESS for the LVDC research site network.

Requirements	Lead-acid	LFP
Back-up supply, h	1	
Nominal power, kW	30	
Minimum voltage, V	710	
Maximum voltage, V	790	
Discharge current	0.2C - 0.05C	1C
Capacity due to requirements	150 kWh	30 kWh
Battery pack, cells in series	6 × 58	235
Nominal cell capacity	200 Ah @ 0.05C 110 Ah @ 0.5C	40 Ah @ 0.3C 38 Ah @ 1C
F.V. 1h, cell, V	2	3.2
F.V. 1h, pack, V	696	≈752
Stand-by voltage, V	783	≈752
Operational voltage, V	725	≈752
Battery	SZNAJDER 200AH	CALB CA40
Unit volume, m^2	1.479	0.226
Unit mass, kg	≈ 3500	≈ 329
Cycle life	400 @ 100% DOD 3600 @ 20% DOD	2000 @ 80% DOD, 0.2C rate

The use of the directly connected lead-acid battery pack enables the back-up operation of the energy storage in LVDC network, in particular in the case of LVDC network centralized energy storage. Due to the large variation in the DC voltage, the connection of the other types of DER on the complexity of the network configuration and should be carefully investigated. It can be concluded that, in practice, other than back-up applications of the lead-acid based energy storage will generally require bidirectional DC/DC converter.

2.5 Direct interface and BESS design

The directly connected BESS consisting of the battery cells and high current interconnection, BMS cell measurements cards, signalling interconnection and communication bus, BMS master control unit, BESS measurement and control card, embedded PC and protection devices is illustrated on Figure 2.3.

Due to the high energy and the high terminal voltage, the 750 VDC battery pack, consisting of the 235 LiFePo4 3.2 V cells connected in series, is divided into seven battery banks by the switch disconnectors (S1-S6, Figure 2.3). Therefore, six battery banks of 35 cells and one bank of 25 cells are formed. In case of the LPF based energy storages, the voltage of each of the cells must be monitored to prevent the operation outside of the cell safe operational area. Proper BMS circuits and algorithms monitor and control the battery and guarantee the safety and reliability of the energy storage devices [15]. The BMS monitors the condition of the battery pack, by sensing the voltages and temperature of the individual cells. A BESS measurement and control card based on TI F28335 DSP processor is monitoring battery pack voltage and current. Though the control board provides partially overlapping functionality with the BMS, it is alone controlling protection devices, such as BESS circuit breaker (F1) and main circuit contactors (C1, C2) (Figure 2.3). The main circuit is controlled with RSU (remote switching unit). The main circuit contactors provide functionality for the BESS connection to grid. The charging circuit (R1, C2) is used on connection of the BESS to unpowered DC mains in order to reduce inrush currents to DC network capacitors and on connection to powered DC mains to provide safe voltage matching.

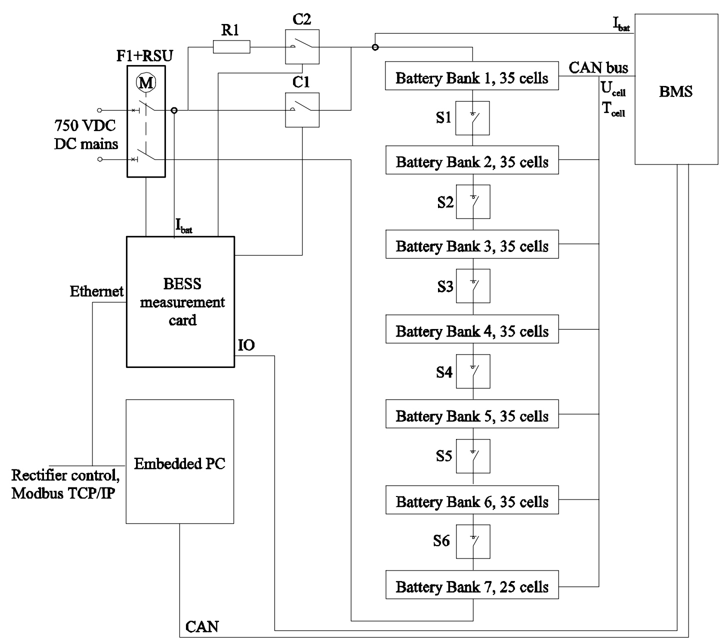

Figure 2.3. Directly connected BESS.

The BESS measurement and control card is required to imply the following functionality of the direct interface:

- Over-voltage protection (disconnection due to over-voltage in network)
- Under-voltage protection
- Over-current protection (current limit tripping)
- Contactor and relay control
- Current and voltage sensing

The embedded PC is acting as a master controller of BESS and interconnects the intelligent control devices (IED) of directly connected BESS:

- BMS over CAN bus with SocketCAN CANopen protocol
- BESS measurement card over Ethernet with custom TCP/IP based protocol.
- Network rectifying converter (ABB ACS 800) over Ethernet with Modbus TCP/IP protocol

The control solution running on the master controller of BESS is required to imply the following functionalities:

- Charging control (Constant Current, Constant voltage, Topping)
- Discharging control
- MV network reconnection
- Smart grid functionalities
    - MV and LV network voltage support
    - Power system frequency support
    - Trade oriented power flow control (peak shaving etc.)

The principles of controlling the directly connected BESS are covered [16] and will be applied to LVDC distribution network.

2.6 Ambient operational conditions

Energy storage system will be installed in cable distribution cabinet nearby the rectifying substation. The surrounding temperature range is between -40… +40°C and BESS operating temperature between 5...+40°C. Figure 2.4 illustrates temperature variation at rectifier station cabinet.

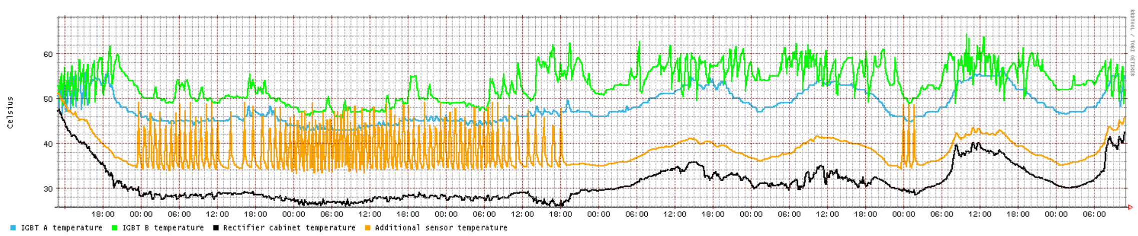

Figure 2.4. Rectifier cabinet temperatures, seven day frame during spring, 5–25 degrees ambient (coordinated universal time).

Above figure demonstrates that operation of the rectifying converters produce heat and also, naturally with ventilated cooling, the air flow is produced. Therefore, the heating energy can be obtained from excess heat of the rectifying cabinet by circulating the air throughout the cabinets. In subzero temperatures, the operation of the LPFs slows down. In the case of prolonged total system blackout, discharging of the BESS and resulted cooling of the BESS cabinet, the initial charging of the LFPs has to be delayed for the restoration of the operational conditions and charging ensured to be moderate enough. In addition, the relative ambient humidity varies heavily, ranging from around 20% to almost 100%, which has to be taken into account.

3. CONCLUSION

In the paper, the design of the battery energy storage system (BESS) suitable for low voltage direct current (LVDC) electricity distribution system was discussed. Objectives regarding the BESS integration to the LVDC distribution system and dimensioning methodology including the essential design aspects of the battery chemistries and characteristics were presented. In the paper, the novel approach in the BESS interconnection, i.e. the direct connection to the DC network was considered and the resulting requirements on the system control and protection were analysed. The next development step in the research setup is BESS implementation. The considerations and conclusions presented in the paper are utilised in the equipment selection and LVDC system integration. The implementation of the BESS is the principal backbone in achieving the flexibility, versatility and further LVDC development.

4. ACKNOWLEDGEMENT

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