PRACTICAL GRID BENEFITS OF BATTERY ENERGY STORAGE SYSTEM IN FALKÖPING DISTRIBUTION GRID

Carlos MARTINEZ
ABB – Estonia
carlos.nieto@ee.abb.com

Erik HANSEN
ABB – Denmark
erik.hansen@dk.abb.com

Tomas TENGNER
ABB – Sweden
tomas.tengner@se.abb.com

Willy HERMANSON
ABB - Sweden
willy.hermansson@se.abb.com

Jimmy EHNBERG
FEAB – Sweden
Jimmy.Ehnberg@poyry.com

ABSTRACT

This paper describes the research that has been conducted as a part of a pilot project commissioned by Falbygdens Energi in the Falköping distribution network consisting of a battery energy storage system. The main overall project set-up, main components and their relation to the performance of the system as well as the control system have been analysed. Practical measurements and the impact of the system in the grid have been studied and analysed.

I. INTRODUCTION

In the future, energy storage is likely to become a key component of smart grids, since the power landscape has shifted towards greater use of renewable energy in the form of wind and solar. These installations generate power only intermittently and with a highly variable output. Excess power generated, when the wind is blowing or the sun is shining, should be stored and made available during suboptimal generating conditions or during peak demand [1]-[5]. This requires the storage of energy at appropriate time and locations, both to balance generation with consumption and to maintain grid stability [3].

In December 2011 the first pilot installation of a Battery Energy Storage System (BESS) in a Swedish distribution system commissioned by Falbygdens Energi was energized in the city of Falköping. A BESS (see Fig. 1) is a packaged solution of power equipment such as coupling transformer and sensing transformer, medium and low voltage switchgear together with automation equipment such as inverters in a complete segregated enclosure. The energy is stored in batteries for use at a later time or to effectively optimize cost. This solution can store electrical energy and supply it to the loads as a primary or supplementary source [2]. It provides a stable and continuous power supply regardless of the supply source status and voltage. Moreover, generation smoothing and transient support for renewable energies are feasible with this solution [1], [5].

In Fig. 1 a typical BESS enclosure is shown. This design provides quick, simple installation and/or relocation, with a high level of safety for the equipment as well as for operators or people around it in case of an internal fault.

The main applications for this BESS installation are load shifting, peak shaving, power factor correction and harmonic mitigation [1]. Regarding the load shifting capability, the pattern of energy use can be shifted from high day-time load to low night time load [2]. With the elimination of short term peaks in the energy consumption pattern achieved by the peak shaving, the customer's power fee can be reduced. With the overcapacity in the converter, the reactive power compensation and the harmonic mitigation features of the BESS, the capacity of the distribution substation transformer can be increased and the losses in the transformer and in the medium voltage (MV) grid can be reduced. These practical grid benefits of the BESS in the Falköping distribution grid, with a significant portion of wind power, are presented in section III.

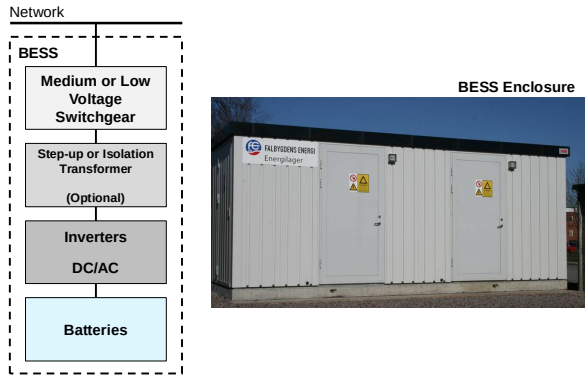

Fig. 1: Block diagram of a typical BESS system and enclosure.

II. PROJECT SET-UP

The BESS is designed to output 75 kW of power for 1 hour, during the discharging period, for its entire lifetime (10 years for the battery system). Charging of the batteries is scheduled during the night while the discharging is planned during high-consumption periods, when it is necessary. The BESS will perform one such cycle per day.

The BESS pilot installation also supports the grid on the low voltage side of the distribution substation (20 / 0,4 kV) (see Fig. 2), by regulating the reactive power and improving the power quality, through filtration of the desired higher harmonics of current. These functions are provided constantly during the normal operating conditions of the system regardless the state of charge (SOC) of the batteries. In this case, the BESS solution will operate as an active filter for the grid.

The specifications for the BESS in the Falköping distribution grid are summarized in Table I and the single-line diagram is shown in Fig. 2.

TABLE I. SPECIFICATIONS OF THE BESS SYSTEM

Parameter	Value
Maximum Stored Energy	75kWh
Maximum charging/discharging rate per hour (1C)	75kW
Maximum capacity of the converter	100kVA
Voltage (via 110 kVA 400/230 V coupling transformer)	400V
Battery life span	10 years

A) System components

Referring to the single-line diagram of the BESS shown in Fig. 2, some components can be distinguished in addition to the existing compact secondary substation (CSS) and the control system, which will be explained later.

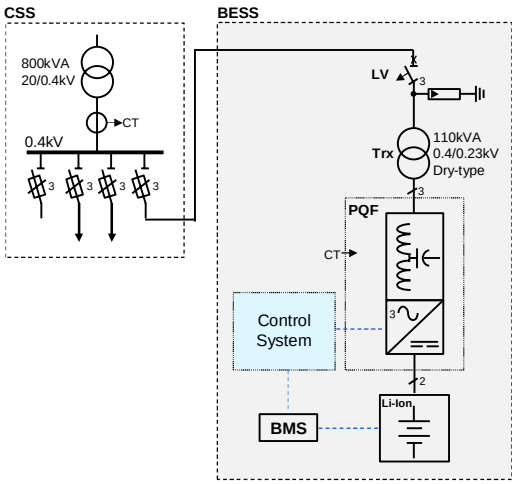

Fig. 2: Single-line diagram of the BESS.

Low voltage distribution and control switchboard:

The low voltage distribution and control switchboard (see LV in Fig. 2) includes the incoming AC circuit breaker, BESS station local control system's components and other protection and control equipment needed for the operation of the facility.

Coupling transformer:

In order to connect the battery system to the 400 VAC grid, a 110kVA dry-type coupling transformer (see Trx in Fig. 2) has been used, due to the low voltage present in the battery array.

Power electronic bi-directional converter:

The bi-directional power electronic converter (see PQF in Fig. 2) is one of the main components of the BESS. It acts as a rectifier during the charging of the batteries and as an inverter during the supplying of the energy from the batteries to the grid.

For this application, the converter selected is the PQFI - V1- M25 - IP21 manufactured by ABB [6].

The internal control, with a closed loop strategy, is able to generate a compensation current for each harmonic frequency. This is in perfect phase opposition to the polluting current taking into account the high frequency rejection filter included in this solution. The current transformers (CTs) are installed on the incoming busbars of the LV Switchboard inside the existing CSS (CT in Fig. 2) in order to monitor the power flow on the grid.

Battery Management System (BMS):

The BMS performs the measurement necessary to manage the batteries (voltage, temperature, current) in order to extend the battery life and increase the safety of the system.

Batteries:

The batteries have been selected according to the power and energy requirements. The LiFePO4 battery array has a nominal voltage of 547Vdc (428 Vdc – 616 Vdc), 80.5kW nominal power and 85kWh nominal energy. The deviation in the nominal power from 75kW is to compensate the losses inside the converter and the coupling transformer and the degradation in the batteries during their lifetime.

Enclosure:

A "Walk-In" type outdoor enclosure with thermally insulated walls, made from sheet steel, and climate control inside the station to keep the temperature under operation limits.

B) Control system

The BESS station presents a local control system that is able to initiate charging/discharging process according to the time-based algorithm programmed within the station controller. The control system architecture is presented in Fig. 3.

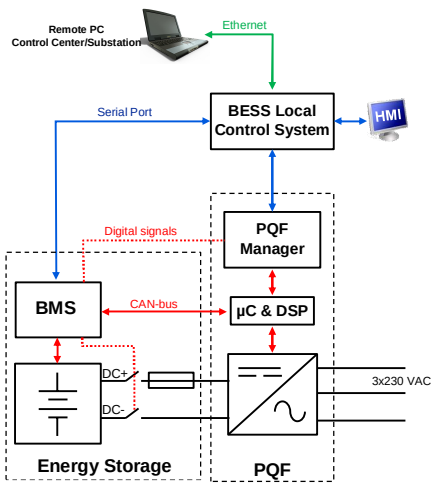

Fig. 3: BESS station control system.

In Fig. 3, the local control system is connected to the PQF manager control and to the BMS. These two connections are intended to operate the converter based on the time-based algorithm taking into account all the information received from the PQF converter performance and the battery status through the BMS.

As it can be observed, there is a communication between the local control system and a remote PC, so the BESS can be operated locally or remotely. Also a human-machine interface (HMI) is included in the control architecture, so the operating parameters can be set locally and the system status can be visualized.

The control system logs events, such as change in operational mode, commands sent to the PQF converter, received commands, faults, and shutdowns. Also, time based performance data are logged in a time-stamped format, including: power converter real power and reactive power flow, AC voltages and currents, battery state of charge, battery voltages and currents, temperatures and internal control variables.

All data logs are stored locally and can be retrieved locally

or remotely via a standard computer port. With the Ethernet communication, the BESS control system is able to transmit all the performance parameters to the control and monitoring centre with a defined frequency.

The local control system presents two possibilities regarding the control strategy: automatic control, in which a simple algorithm, based on the time of the day, has been implemented; and the manual control, which allows the manual control of the charging/discharging process of the system.

Automatic control:

- **Discharging mode:** The BESS control system will initiate the discharging process at the predefined time of the day if the batteries' SOC is more than some predefined value (for example 20 %), by sending the signal to the PQF Manager to start the discharging of the batteries with the predefined level of active power (75kW) for the predefined period of time (1 hour).

During the active power discharging mode the BESS supports the grid by reactive power compensation (up to 66kVAr) and by filtering some of the higher order current harmonics. After the total discharge of the batteries (this information is sent from the PQF Manager to the BESS control system), the system switches into another mode ("Battery stand-by mode").

- **Battery stand-by mode:** The system operates in this mode during the time of the day between the discharging and the charging modes with all the available capacity of the converter used for the reactive power compensation (up to 100kVAr) and higher order current harmonics filtration. During this mode there is no activity needed from the BESS local control system related to the active power dispatch.

- **Charging mode:** The BESS local control system initiates the charging process at the predefined time of the day if the batteries SOC is not higher than some predefined value (for example 95 %), by sending the signal to the PQF Manager to start the charging of the batteries with the predefined level of an active power (25kW) for the predefined period of time (3 hours).

During this mode the system is compensating reactive power with a capacity up to 96kVAr. When the battery system is fully charged the BESS control system initiates the ("Battery stand-by mode") again.

Manual control:

The BESS system allows the manual control of the system's charging/discharging process. The manual/automatic switch in the HMI panel is used for this purpose. It is possible to stop the initiated process (charging- or discharging) and start it again later.

III. PRACTICAL GRID BENEFITS

Due to the inclusion of a BESS in a distribution grid, some benefits may be achieved in terms of energy quality (power factor correction and harmonic mitigation) and transformer losses.

In Fig. 4 the loading of the distribution transformer in the Falköping grid during one typical day is shown considering two scenarios (taking into account the control strategy mentioned before): when the system is operating with and without energy storage system.

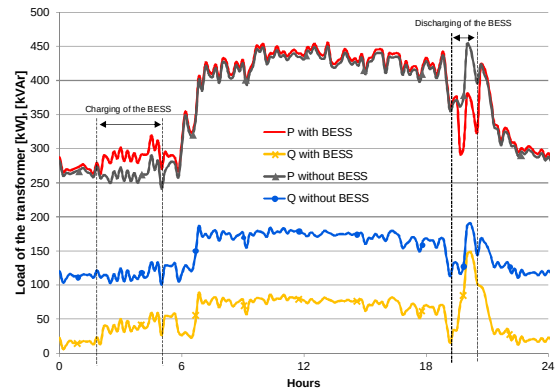

Fig. 4: Loading of the transformer for load shifting operation.

The first benefit that can be observed is the load shifting that the BESS is able to provide. The difference in the active power (around 5kW) is caused by the power consumption of the BESS, due to the losses in the inverter, filter, coupling transformer and the cooling system, in order to provide and benefit the grid with reactive power compensation and harmonic mitigation.

The transformer is affected in terms of losses and harmonic content by the operation of the BESS solution. The transformer losses are given by the load term and the no load term losses, as expressed in equation (1), where x is the utilization factor which has been defined in (2).

$$P_{losses} = x^2 P_{load\_losses} + P_{noload\_losses} \quad (1)$$

$$x = \frac{\sqrt{P^2 + Q^2}}{S_n} \quad (2)$$

Under nominal conditions, 800kVA, the load losses are 6.5kW and the no load losses are 1kW. With these values, the losses estimation can be obtained using expressions (1) and (2) for the data contained in Fig. 4. Fig. 5 shows the losses with and without BESS solution, as well as the achieved losses reduction.

It is important to remark that attending to (1) only copper losses (load losses) are affected by the BESS operation due to the charge/discharge of the batteries and the harmonic filtering and current balancing provided by the system. In this study the core losses (no load losses) term is constant, but in fact, the core losses are reduced as well, since the voltage harmonic distortion is related directly with the current distortion by means of the network impedance.

Regarding the achieved load shifting, it can be concluded that the distribution transformer operates in better conditions during this time due to the loss reduction and harmonic mitigation. During the charging of the batteries a slight increase in the transformer losses can be observed. This is caused by the increase of power due to the battery charging and the BESS losses mentioned before.

With the load shifting, the maximum power peak can be

eliminated. Therefore, the transformer does not need to be oversized. In the present study it is obvious that this is not the case, due to the fact that the peak power is in the order of magnitude of the power at normal load, but it is important to remark that this BESS is a pilot installation and so is a small unit in the grid.

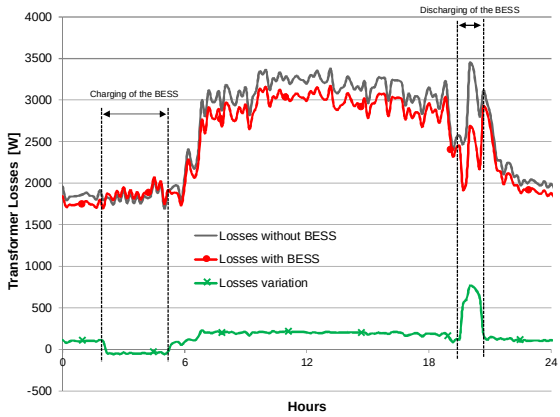

Fig. 5: Transformer losses with and without BESS solution and variation in the transformer losses for load shifting operation.

At the moment, the BESS solution is only working as load shifting and with the control algorithm described before, but the peak shaving operation can be also achieved by means of a different charging/discharging algorithm.

Fig. 6 shows the operation of the BESS under a peak shaving algorithm taking into account a round trip battery energy efficiency of 92% and average BESS losses of 5kW. The algorithm has been established in order to obtain as flat a power profile as possible in the transformer.

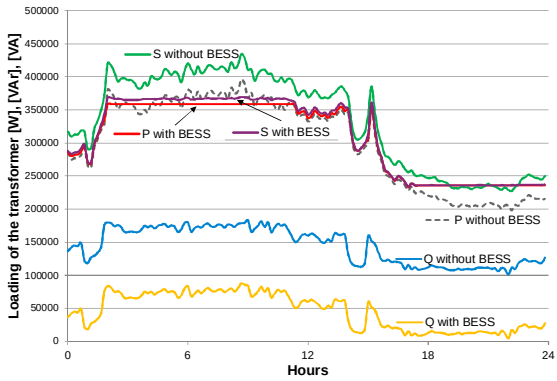

Fig. 6: Loading of the transformer under peak shaving operation.

As observed in Fig. 6, the difference in power during high load and low load has been reduced. With this achievement the power profile is flatter and so the consumer's power fee would not be penalized. The reduction of transformer losses is not the aim of the peak shaving operation, but as it can be observed in Fig. 7, they are slightly reduced.

It is important to notice that, for both control algorithms, the overall system efficiency has been reduced with the BESS solution due to the losses in the equipment (this is a small unit and so a bigger one would provide better efficiency). With this solution, the transformer benefits from a reduction in losses and harmonic content. These two achievements are related to the transformer heating and therefore the life span; overloaded transformer or with high harmonic content can reach unacceptable levels in the temperatures of the windings, insulation, oil, etc.

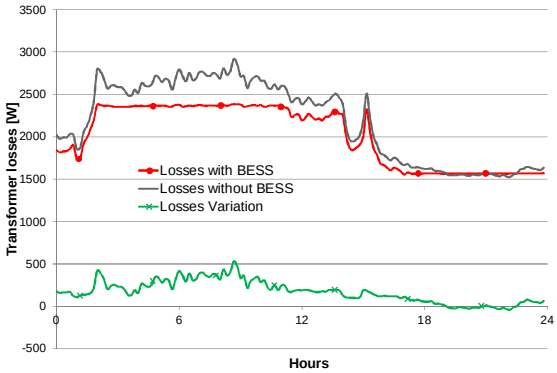

Fig. 7: Transformer losses for the peak shaving operation.

CONCLUSIONS

In this paper a BESS solution has been presented and tested in a real distribution grid. All the main components as well as the control system have been also presented. The main grid benefits achieved with the energy storage system can be summarized in the load shifting with high reduction in transformer losses when the batteries are discharging.

The peak shaving operation has been presented through an estimation taking into account a new algorithm focused on this purpose. With this operation the transformer losses and the consumer's power fee are not penalised.

Although the system overall efficiency has been penalised, the BESS solution provides a more stable voltage available for the end users of the grid, and benefits for the transformer in terms of life span.

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