BENEFITS OF BATTERY ENERGY STORAGE SYSTEM FOR SYSTEM, MARKET, AND DISTRIBUTION NETWORK – CASE HELSINKI

Hannu-Pekka HELLMAN
Helen Electricity Network – Finland
hannu-pekka.hellman@helen.fi

Atte PIHKALA
Helen Electricity Network – Finland
atte.pihkala@helen.fi

Markku HYVÄRINEN
Helen Electricity Network – Finland
markku.hyvarinen@helen.fi

Pirjo HEINE
Helen Electricity Network – Finland
pirjo.heine@helen.fi

Juha KARPPINEN
Helen – Finland
juha.karppinen@helen.fi

Kristiina SIILIN
Helen – Finland
kristiina.siilin@helen.fi

Perttu LAHTINEN
Helen – Finland
perttu.lahtinen@helen.fi

Minna LAASONEN
Fingrid – Finland
minna.laasonen@fingrid.fi

Jussi MATILAINEN
Fingrid – Finland
jussi.matilainen@fingrid.fi

ABSTRACT

This paper presents the first performance results of a large battery energy storage system (BESS) that is connected to a medium voltage distribution network and used simultaneously by multiple stakeholders. The paper presents the background of the purpose of a BESS as part of the Nordic power system and markets, and the functionalities it is able to perform. The first test cases ran in the fall 2016 included simultaneous controls of frequency, reactive power and voltage according the requests from Transmission and Distribution System Operators. The results showed that the first functions of the BESS performed were successful. Valuable experience has also been reached when observing e.g. the energy capacity limits of the batteries.

INTRODUCTION

In August 2016, Helen Ltd commissioned the largest Battery Energy Storage System (BESS), "Suvilahden sähkövarasto", in Nordic countries. The BESS, rated 1.2 MW / 600 kWh, was built by Toshiba Transmission and Distribution Europe S.p.A. using Toshiba's state-of-the-art SCIB battery modules and supplied to Helen by Landis + Gyr Ltd. It is located in Suvilahti, an urban district in downtown Helsinki, the capital of Finland. The BESS is installed next to a primary substation of the local Distribution System Operator (DSO), Helen Electricity Network, where Helen commissioned Finland's first large-scale (380 kWp) solar power plant in April 2015. Both the BESS and the solar power plant share the same connection point to the DSO's 10 kV medium voltage network.

BACKGROUND

During the first three years of operation, the storage is used as a research platform by Helen, an energy retailer and producer, Fingrid, the national Transmission System Operator (TSO), and Helen Electricity Network, the DSO of Helsinki. The main objectives of the research are to:

1) investigate the practical feasibility of the benefit stacking on a single BESS for multiple services and beneficiaries,
2) determine the value of the fast and accurate response of the BESS in ancillary service markets and finally,
3) further develop the open market places to extract the most benefit from the storage technology.

Helen as an energy retailer pursues the electricity storage for the smart grid integration, ancillary market operations and the development of end customer services. Fingrid's main aim is to test the electric storage as a versatile resource for power system frequency control, and Helen Electricity Network will investigate the usage of the BESS for the control of reactive power and voltage, the demand response, and the peak shaving functionality. Similar research projects of multiuse of a BESS have previously been presented e.g. in [1] and [2].

The three-year research period started in the beginning of August 2016 and the first set of practical tests has been concluded. The first tests focused on the technical capability of the BESS to execute simultaneous functionality requests from multiple stakeholders.

Frequency control

Fingrid is responsible for reserve power markets that include Frequency Containment Reserve for Normal operation (FCR-N) to maintain the system frequency in the normal area between 49.9 Hz and 50.1 Hz. FCR-N must be able to both increase and decrease power. It shall be activated in full in three minutes. In addition, there is the Frequency Containment Reserve for Disturbances, FCR-D. FCR-D is activated in low frequency 49.5-49.9 Hz and only needs to control the frequency upwards by increasing generation or decreasing load. The time frame for FCR-D is 5 to 30 seconds. In the interconnected Nordic system, the amount of FCR-N is 600 MW, and the amount of FCR-D is normally 1200 MW. The share of Finland is approx. 140 MW of FCR-N and 220-265 MW of FCR-D. [3]

One of the most promising applications of the BESS is the participation in FCR. The BESS can perform either FCR-

N or FCR-D, or both. It is possible to combine both FCR-N and FCR-D functionalities in a single control curve by changing the slope at 49.9 Hz. Advantages of a BESS for FCR include e.g. extremely fast reaction time and flexible modification of the control curves. The reaction time of a BESS to achieve full power is few hundreds of milliseconds compared to traditional reserve power suppliers' tens of seconds. This is beneficial as the inertia of the power system is expected to decrease in the future as renewables replace traditional power generation.

Voltage and reactive power control

The reactive power has become a challenging issue during the last few years. From a system point of view, the reactive power should be at the TSO/DSO connection point within the determined PQ-window. The reactive power should be compensated locally, as it is not economically reasonable to transfer large amounts of reactive power in the system. The DSOs have to pay the TSO reactive power tariff when they exceed the limits of the window by feeding or consuming too much reactive power. The TSO has launched tariff development steps for the coming years including considerably tightening costs for the reactive power. At the same time, the reactive power balances within the DSOs operating areas have experienced notable changes – generally:

- In Finland, many DSOs execute major cabling projects during the coming years. Compared to overhead lines, underground cables have much higher capacitance values, which means a possibility of considerably higher amounts of feeding of reactive power.
- The reactive power consumption of customers has dramatically changed within the past decades. Nowadays, more and more capacitive power is fed to the network from the customers.

Among other DSOs, also Helsinki has experienced the above mentioned development notices of reactive power. The distribution network of Helsinki has a high cabling rate. Nearly 100 % of the 10 kV and 20 kV medium voltage network and 34 % of the 110 kV subtransmission network is comprised of underground cables. During the coming decade, the 110 kV cabling will proceed meaning a prominent extra influence on the balance of reactive power. Previously, customers used to consume large amounts of reactive power. However, a decreasing trend has been observed for over a decade, especially during the last few years. This has led to a situation where capacitive reactive power is being fed in to the system especially during the night time when the power consumption is low.

To react to this development, Helen Electricity Network has already commissioned 110 kV capacitors and a reactor to its network to be able to control the reactive power levels. It has turned out that the existing reactor capacity is still insufficient, and new investments seem necessary. In the research environment presented in this paper, BESSs are seen to act as one possible mechanism of controlling the balance of reactive power. During the tests the BESS was given instructions to function as a reactor during the night by consuming the maximum possible amount of reactive power.

The voltage level of the 10 kV MV network is normally managed by automatically controlling the tap changer of the 110/10 kV transformer. The target value for the 10 kV voltage depends on the current flowing through the transformer. When the current is high, the target value for the voltage is higher, to ensure that the customers at the end of the MV feeder have a sufficiently high voltage.

The voltage control is applied by giving a V-Q –curve to the BESS. Historical voltage fluctuations of the substation's 10 kV side were analyzed to determine a linear voltage control curve. The main voltage was usually observed to be between 10.1 and 10.4 kV with a target value of around 10.25 kV.

TEST PROGRAMS AND RESULTS

Since commissioning the BESS has executed test periods ranging from two weeks to one month that have included different types of control functions. The main objective was to test how these perform simultaneously. The BESS operates within a PQ-curve where the apparent power maximum is 1.8 MVA. The maximum power can be consumed or produced for 30 s after which the BESS returns to normal operation of 1.2 MVA. Within the operation the maximum of reactive power is restricted to +/-900 kvar and active power can vary within the apparent power operation limits as previously addressed. The results of two test periods are presented in this paper. The time resolution of the reported measurements is one second.

Test period 1

In September 2016, a simultaneous use of FCR and voltage regulation was tested. Figure 1 presents the applied control curve for the frequency regulation.

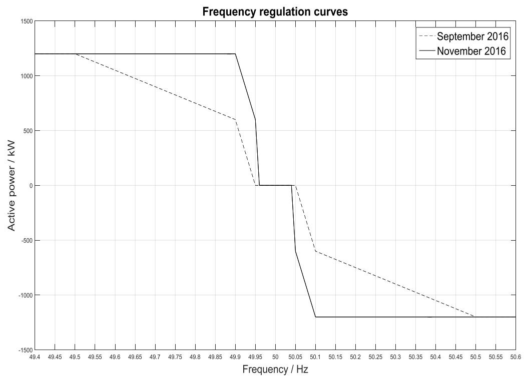

Figure 1: Frequency regulation curves in September and November 2016.

The frequency control curve combines FCR-N and FCR-D. When the frequency was within the deadband, i.e., between 49.95 Hz and 50.05 Hz, the active power was zero. When the frequency varied from 49.95 Hz to 49.9 Hz the power generation was controlled linearly from zero to 600 kW. As the frequency altered from 50.05 Hz to 50.1 Hz the power consumption was changed linearly from zero to 600 kW. This represented FCR-N. If the frequency dropped below 49.9 Hz, the slope of the control curve changed. The full power generation of 1200 kW was reached when the frequency dropped to 49.5 Hz. This represented the FCR-D. In contrast to the FCR-D, the power consumption was also increased when the frequency exceeded 50.1 Hz to study over frequency control. The voltage regulation was set as a linear function. When the arithmetic mean of the three main voltages was below 10.1 kV, the BESS fed reactive power 900 kvar, and when over 10.4 kV, the BESS consumed 900 kvar. The stability point when the BESS did not feed or consume reactive power was at 10.25 kV. The FCR control was prioritized over the voltage control if the PQ-curve would have limited the required real power and the apparent power would have exceeded 1200 kVA. While the frequency stayed within the deadband, the BESS was programmed to run with a power of 200 kW to reach the targeted 50 % state of charge (SOC) level.

Figure 2 shows the time series of the difference between measured and ideal active power, and the measured grid frequency between September 11th and 12th. It can be seen that at one point the time period of the demanded consumption of the active power lasted longer than the battery was able to consume so the capacity of the battery went full. Shortly after this, the demand of the active power feeding lasted long enough to drive the battery empty. At these points the BESS was not able to fulfill its tasks. The difference between the measured and ideal active power was 92.2 % of the time within 5 % of the nominal 1200 kW active power. Figure 3 shows the SOC of the BESS during the same time. The BESS returned well to the targeted SOC as it spent 70.7 % of its time at an optimum level, i.e. between 45 % and 55 %.

The BESS managed excellently to feed and consume the reactive power as programmed. On September 11th and 12th the BESS followed the ideal control curve 99.8 % of the time within 5 % of the nominal 900 kvar reactive power. This was an understandable behavior as the frequency did not vary to levels where active power would limit the reactive power.

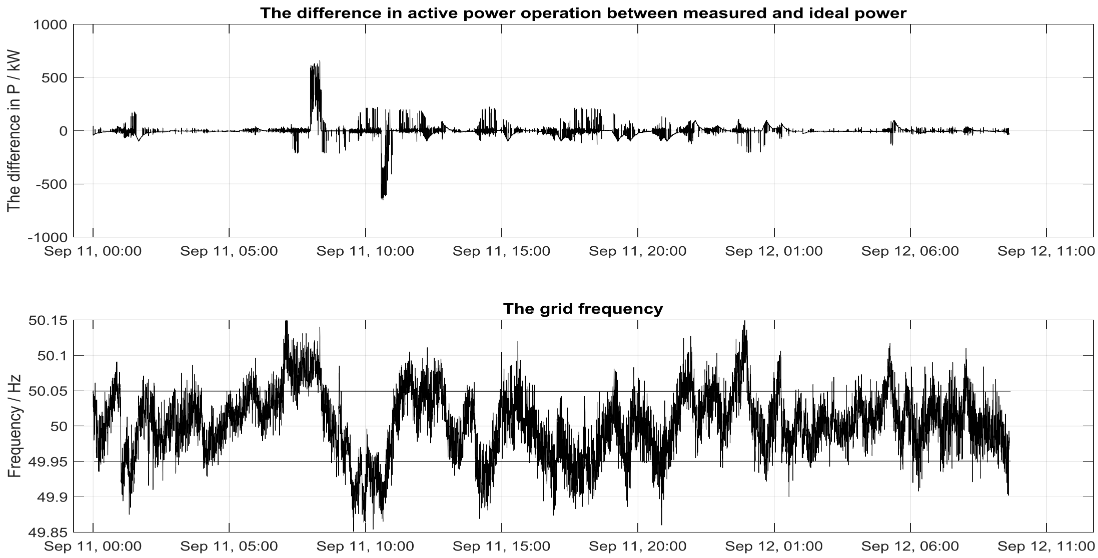

Figure 2: The difference between measured and ideal active power, and the grid frequency on September 11th and 12th, 2016.

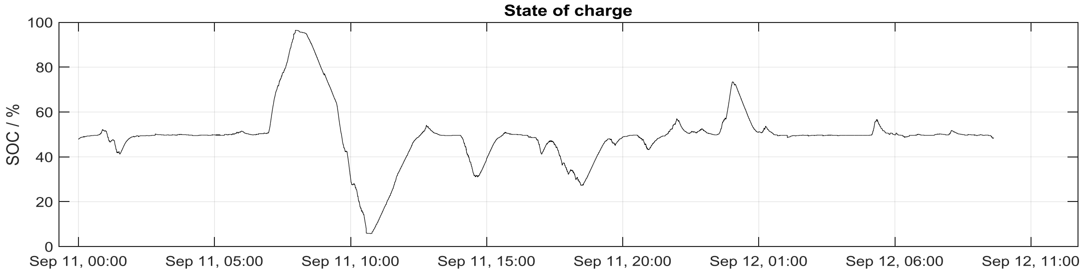

Figure 3: The state of charge of the BESS on September 11th and 12th, 2016.

It was also noted that when applying the V-Q-curve of voltage regulation to both the day and night time, the use of the BESS results in an undesired behavior during the night time from a system point of view. The BESS has no information of the current flowing through the 110/10 kV transformer. During the night, the target value of the transformer tap changer control is around 10.10 kV as the consumption level is lower than during the day. This resulted in the BESS to feed reactive power to the network, while exactly the opposite is aimed to manage the reactive power balance of the whole network. Because of this, the program would then be modified in upcoming test periods so that the BESS functions as a reactor at full power during the night and the V-Q-curve is followed only during the day time.

Test period 2

In November 2016, the BESS performed either the voltage regulation or the reactive power compensation depending on the time of the day in addition to the frequency control that was always active. The reactive power compensation was applied during the night time starting at 11 PM and ending at 7, 9 or 10 AM on weekdays, Saturdays or Sundays respectively. These time periods were chosen as there is excessive reactive power in the DSO’s network on these hours. During the day time the BESS performed voltage regulation similar to the previous test period in September but with a minor adjustment: The BESS was set to feed 900 kvar when the arithmetic mean of the main voltages was below 10.11 kV and to consume 900 kvar when it was over 10.41 kV. The stability point when the BESS did not consume or feed reactive power was at 10.26 kV.

Figure 1 presents also the frequency regulation curve in November 2016. The full power capacity of the BESS was set for FCR-N and there was no FCR-D functionality. The generation or consumption was increased stepwise from zero to 600 kW as the frequency fell below 49.95 Hz or exceeded 50.05 Hz. The generation or consumption changed linearly from 600 kW to 1200 kW, as the frequency varied from 49.95 to 49.9 Hz or from 50.05 to 50.1 Hz respectively. The maximum apparent power limit of 1.2 MVA was changed to 1.8 MVA in this test period.

Figure 4 shows the difference in measured and calculated active power, and the grid frequency on November 12th. It shows that the demanded power could not be fed or consumed multiple times during this period. The measured active power followed the ideal value 66.2 % of the time within 5 % of the nominal active power. It should be noted that inaccuracies between the measured and ideal active power are present when the active power demand would change stepwise at 49.95 Hz and 50.05 Hz because the BESS measures the grid frequency more accurately than is shown in the collected data. Figure 5 presents the measured reactive power and the grid voltage. The reactive power compensation followed the ideal curve 98.8 % of the time within 5 % of the nominal reactive power. This was expected as the BESS was not programmed to operate in parts of the PQ-curve where feeding or consuming reactive power would be limited due to a conflict of overload demand of active power.

As in the previous test period the BESS was programmed to apply a power of 200 kW to reach the targeted 50 % SOC when the frequency was within the deadband.

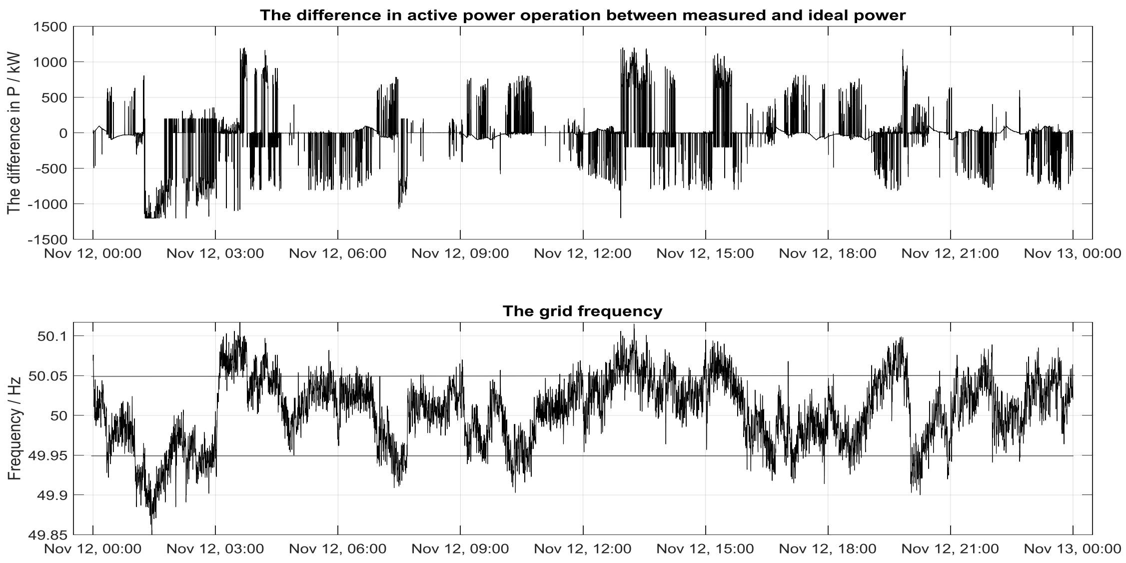

Figure 4: The difference between measured and ideal active power, and the grid frequency on November 12th, 2016.

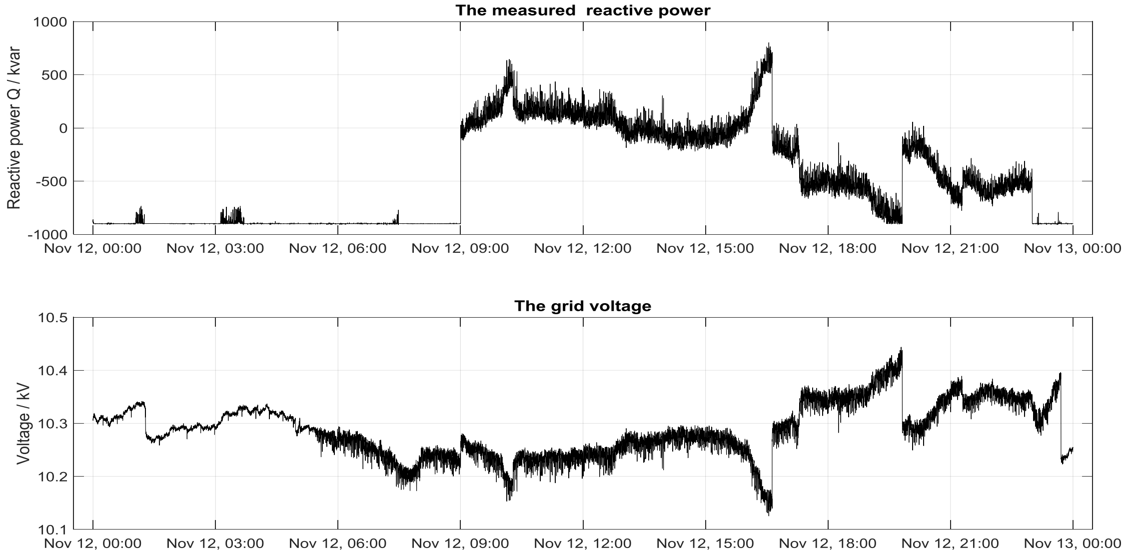

Figure 5: The measured reactive power and the grid voltage on November 12th,, 2016.

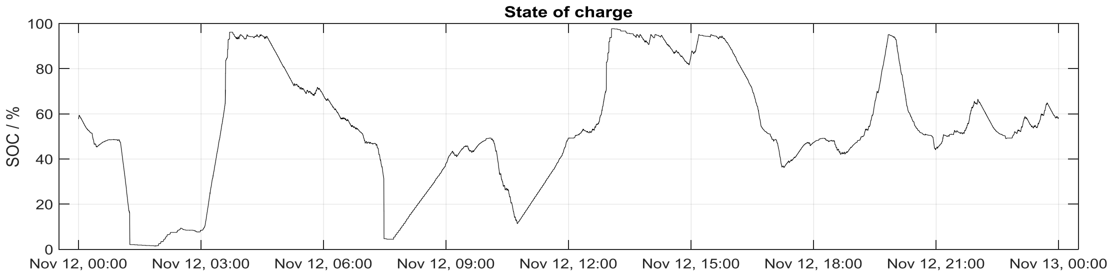

Figure 6: The state of charge of the BESS on November 12th, 2016.

During this test the capacity limits of the battery were reached multiple times (Figure 6). This indicated that the applied frequency regulation curve that started feeding or consuming active power at the level of 600 kW or higher immediately outside of the deadband was not an optimal choice. Another reason that may have contributed to this is that the programmed power of 200 kW was not sufficient enough to achieve the targeted SOC of 50 % during the deadband periods. The reached capacity limits of the batteries had an effect that the BESS could not always perform the desired frequency regulation and thus there could be lost revenue from the ancillary service markets. The BESS spent only 28.9 % of its time between SOC levels 45 % and 55 %.

FUTURE RESEARCH

The BESS in Suvilahti is currently continuing to work as a research platform, and different control parameters and functionalities will be tested. Local optimization in utilizing on-site photovoltaic power production and high-power electric vehicle charging will be introduced in addition to ongoing benefit stacking of DSO and TSO functionalities. The main focus of the upcoming research will be to investigate the limits of multifunctionality and to determine the most efficient utilization of the BESS for the asset owner. The goal is to discover sufficiently profitable operation models to encourage market-driven 3rd party investments in BESS units. The increased availability of BESS service providers will in turn help TSOs and DSOs in procuring cost-effective BESS-enabled ancillary services, such as synthetic inertia.

REFERENCES

[1] D. Colin et al., 2016, “Enhancing the Business Model of Distributed Storage through Optimized Multi-Service Operation for TSO, DSO and Generation Owners: the VENTEEA Real Example”, *CIRED Workshop 2016*

[2] D. Greenwood et al., 2015, “Scheduling Power and Energy Resources in the Smarter Network Storage Project”, *CIRED 23rd International Conference on Electricity Distribution 2015*

[3] Fingrid. 2017 [cited 2017, January 11th], “Reserves”, Available from: http://www.fingrid.fi/en/electricity-market/reserves/Pages/default.aspx