Large scale energy storage in Uppsala, Sweden: an analysis of voltage fluctuations and a service stacked portfolio

J. Hjalmarsson, K. Thomas, C. Boström, A. Berlin and F. Carlsson

Abstract — **Extensive electrification has created an increased demand of electric energy and power. Congestion issues are expected to become more common as transmission and distribution grids reach their capacity limits. One of the regions in Sweden that has experienced this already is Uppsala. The distribution system operator, Vattenfall Distribution has initiated an R&D project that connects a 5 MW/20 MWh Li-ion battery energy storage system to temporarily ease the grid congestion. This study covers an analysis of grid voltage fluctuations using a large-scale battery in a distribution grid. The power quality is examined at the 10 kV connection point of the storage, where voltage and power flow are presented. Also, an example of how value stacking may be implemented is illustrated by adding a secondary service during the year. The test results indicate no significant distortion of the voltage level at the measurement point during smooth ramping. It can be concluded that smooth ramping of the BESS has very low or no impact on the local power quality, and additional services should be provided during the year to create several revenue streams. Future studies could focus on fast ramping of the BESS and stacking services in an intra-season perspective.**

Keywords—**Distribution grid, Energy storage, Power Quality, Service stacking, Voltage fluctuations**

I. INTRODUCTION

A. Background

Electrical power grids are facing major challenges worldwide because of several causes: urbanization, extensive integration of renewable energy resources (RES), electrification of industry and transport sectors, among others. The global electricity demand has increased continuously and more than doubled since 1990 [1] and is expected to further increase in the upcoming years. The energy transition is strongly correlated to political decisions, which makes it significantly more difficult to predict the future. Outlooks and forecasts regarding the electricity demand in 2030 varies depending on several assumptions, one official prediction though is made by the International Energy Agency (IEA) saying that 21 % of the global final energy consumption could be met by electricity – an increase from approx. 22 300 TWh in 2018 to 27 500 TWh in 2030 [2,3]. Depending on the prerequisites of the already existing grid infrastructure, actions will be required to maintain stable operation as the demand for electric energy and power increases. At present time, the annual increase in demand puts the grid expansion rate on its edge. Congestion issues have arisen in regions where the demand has increased faster than the grid expansion has been planned for. Taking Sweden as an example, major congestion issues have been identified in major cities such as Stockholm, Malmö, and Uppsala. The transmission system operator (TSO) has not been able to raise subscription levels to regional distribution system operators (DSO) in short time, which puts the DSOs in a tough situation with increasing queues for connection requests. In Sweden, the electricity distribution companies are under legal obligation to connect new customers, but this may be delayed if congestion issues arise. Since it is desirable to connect new customers as soon as possible, the DSOs are motivated to find alternative solutions before an eventual grid reinforcement can be made. Demand response (DR) and energy storage systems (ESS) are two commonly considered solutions due to the short time required going from seed to flower, but also when looking from a cost perspective.

In this study, the congestion issue in Uppsala has been developed as an R&D project in collaboration with the regional DSO, Vattenfall Distribution, Vattenfall Network

Manuscript received 3 September, 2021; revised 22 November, 2021; accepted 5 January, 2022; published 19 January, 2022.

 Digital Object Identifier https://doi.org/10.55066/proc-icec.2021.18

This project was funded through the Swedish Centre for Smart Grids and Energy Storage (SweGRIDs), by the Swedish Energy Agency, Vattenfall AB and E. ON SE. The authors are very grateful for the support.

J. Hjalmarsson, K. Thomas and C. Boström are with Uppsala University at the department of Electrical Engineering, Lägerhyddsvägen 1, 752 37 Uppsala, Sweden (e-mail: johannes.hjalmarsson@angstrom.uu.se).

A. Berlin is with Vattenfall Distribution, Österlånggatan 60, 461 34 Trollhättan, Sweden (e-mail: arne1.berlin@vattenfall.com).

F. Carlsson is with Vattenfall R&D, Evenemangsgatan 13C, 169 56 Solna, Sweden (e-mail: fredrik.carlsson2@vattenfall.com).

Solutions and Vattenfall Research & Development (R&D). The focus of this study is the recently connected battery energy storage system (BESS) in Uppsala. It is of great interest and importance to investigate how the power quality might be affected in the area, and voltage fluctuations have been chosen as the scope for this paper. Since the BESS is connected very recently, it is reasonable to first verify that the storage unit will manage the planned service provision without any power quality disturbance before executing more stressful testing. Finally, a suggested service portfolio offered by the BESS is proposed using the concept of value stacking.

B. Energy storage system overview

Since December 2020, a 5 MW/20 MWh Li-Ion BESS is connected to the 10 kV grid on the outskirts of Uppsala, see Fig. 1. The size of the area is about 50m x 30m, which is comparable to half the size of a soccer field. It is built, owned, and operated by Vattenfall Network Solutions and provides the BESS to the DSO Vattenfall Distribution through the service “power-as-a-service” [4]. It should be noted that this is a R&D project within Vattenfall and is one of the first large scale grid connected BESS in Sweden. A schematic overview of the BESS is shown in Fig. 2. The storage units are connected to the grid via a converter setup (a power conversion system, PCS) that transforms the grid AC current to DC when charging and vice versa when the BESS is discharging. The converter and a local transformer for each string are placed in a common container. Additionally, the system includes a thermal management system (TMS), monitors, switches, and breakers to ensure safety and stability during operation. Initially, the BESS operation is decided and controlled manually but will change gradually towards an automatic control mode as the energy management system (EMS) controller is optimized. More site-specific information is summarized and presented in table 1.

C. Regional flexibility market CoordiNet

The European Union (EU) finances the CoordiNet project, a research project that aims to create an improved synergy between TSOs, DSOs and consumers but also to shape the smart and resilient energy system of tomorrow [5]. One of the three main objectives of the project aims at developing cost-effective models for ancillary services, which has resulted in marketplaces for power flexibility in regions with major congestion issues. The Swedish section within CoordiNet is run in collaboration between Vattenfall Distribution, E. ON Energy Networks and the TSO Svenska Kraftnät together with additional local partners. As previously mentioned, Uppsala is one of the regions in Sweden with congestion issues that has gotten a lot of attention in media. Thus, the decision of choosing Uppsala as one of the testbeds within CoordiNet is clear as day.

At the marketplace, each participant may bid for one or more hours when flexibility is available. The participants may provide either single-hour bids or block-bids for two or more consecutive hours. The counterpart is the DSO, and matching bids are cleared by price in ascending order (i.e., cheapest bid is cleared first). Agreements can be settled for both demand and production management. Participating units have no requirement regarding full activation time during the demo stages of the project [6]. Finally, according to [6] the CoordiNet market in Uppsala is running from the first of November until the end of March, which will be the time frame boundaries for the BESS yearly operational planning.

Fig. 1. BESS in Uppsala [4].

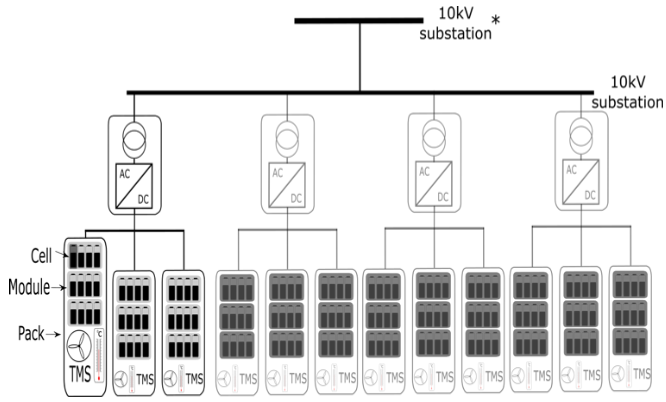


Fig. 2. Schematic overview of the BESS.

D. Frequency containment reserve - disturbance

There are several ancillary services available that target various functions and properties of the grid. Some of these services focus on frequency support, and one promising service to initially provide using the BESS in Uppsala is frequency containment reserve – disturbance (FCR-D). It includes an automatic counteracting function against frequency deviations below 49.9 Hz and is currently available as an up-regulating service only. The technical requirements for FCR-D include an activation time limit of 5 seconds for 50 % activation and 30 seconds for full activation of the unit [7]. The period between first of April and last of October will be the available time for FCR-D as main service provision.

E. *Value stacking*

The concept of *value stacking* (or *service stacking*) has become more interesting recently as the awareness of energy storage potential has increased. Investments in ESS for single applications have struggled financially due to narrow revenue streams and expensive technology [8]. Value stacking aims at finding additional revenue streams besides of the main purpose of the storage unit [8,9,10]. This will create a better economic situation for the storage owner, but it also increases the possibility to keep the storage unit in operation during longer time periods. What services to aim for depends entirely on what primary service the storage operates in. A reasonable assumption to make in this context is that the primary service sets the boundaries regarding available capacity for additional services. Possible service portfolios can look quite different depending on the main application, but they have in common that the secondary (and possibly third) service optimally is compensated for both capacity and energy. Short and small cycles of the ESS is also desirable to minimize degradation of the storage unit, but also to reduce the need of extra charging between services to ensure enough energy capacity and to facilitate operation planning. The ESS has a limited amount of capacity to offer regarding both energy and power, thus the capacity must be balanced between services according to the given priority [10]. Services can be offered in synergy over different time scales and varies from intra-day to overlapping between seasons. In cases where the main service is available during a few months only, it is certainly interesting to consider a secondary and possibly third service to offer during the rest of the year. The chosen portfolio for this case study is a combination of two services: flexibility provision and FCR-D, where flexibility provision is the main service of the portfolio.

II. METHODOLOGY

F. *Test cycle*

The aim of this study is to make a test run of the BESS in Uppsala, mainly to verify that smooth ramping of the storage unit will not cause any significant impact on the local power quality. As previously mentioned, the BESS will initially provide flexibility and FCR-D services and it is therefore reasonable to perform a test that fulfils the requirements for these. Since the required activation time is significantly shorter for FCR-D than for CoordiNet, the test run for this study will consider the activation requirements for FCR-D. If the results show no significant effects on the power quality, there should be no significant effects during CoordiNet service provision either. The test cycle consists of three events: (a) activation from approx. 0 MW idle to 5 MW discharge, (b) change from 5 MW discharge to 1 MW charge, and (c) change from 1 MW back to 0 MW idle. The complete event is illustrated in Fig. 3.

G. *Power quality measurement*

The power quality meter is connected to the 10 kV substation marked with a star symbol in Fig. 2. Since the distance between the two 10 kV substations is very short, it may be assumed that measurement differences can be neglected. The considered output signals for the three events of this study are active power flow from and to the BESS, as well as the voltage levels at the substation. The limit for long voltage variations is 10% according to the Swedish Energy Markets Inspectorate (EI), but each DSO can choose a lower limit as they desire.

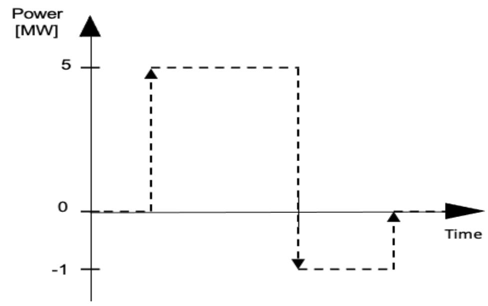


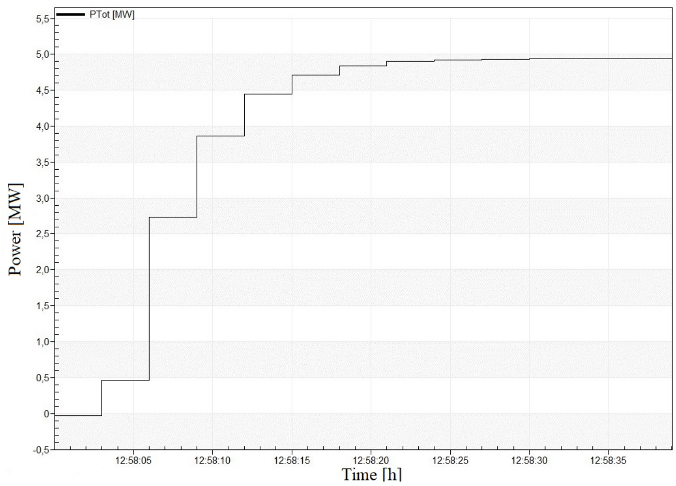
Fig. 3. Illustration of the performed test cycle.

III. RESULTS

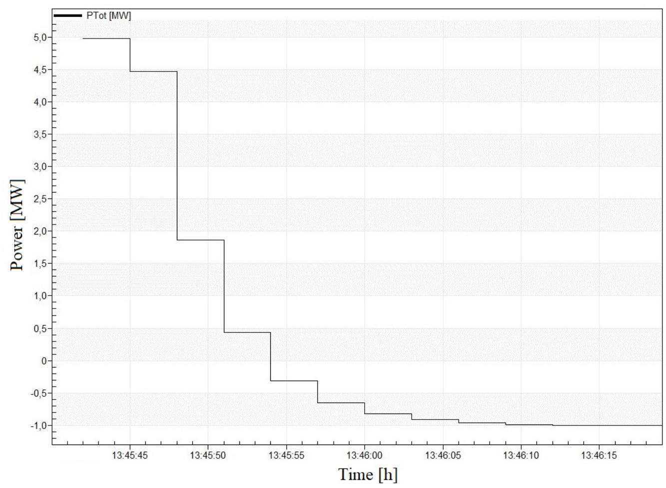
The results from the test cycle are presented in Fig. 4-6. Fig. 4 shows the changes of in- and output active power of the BESS for the three events (a)-(c). From Fig. 4 (a) it can be noted that it takes three seconds to reach a discharge level of 2.7 MW, and full activation is reached within 25 seconds. Furthermore, from Fig. 4 (b) it can be seen that the change from 5 MW discharge to 1 MW charge mode takes 30 seconds, where the initial decrease from 5 MW to 0.5 MW takes six seconds. Finally, Fig. 4 (c) shows how the BESS smoothly returns to idle mode, and it takes approx. 20 seconds.

Furthermore, the voltage levels for the three events are presented in Fig. 5 and includes the maximum (U max), minimum (U min) and average (U avg) line-to-line voltage levels for each time step. It is clear from the three subfigures (a)-(c) that the voltage level remains stable during all three events of the test cycle.

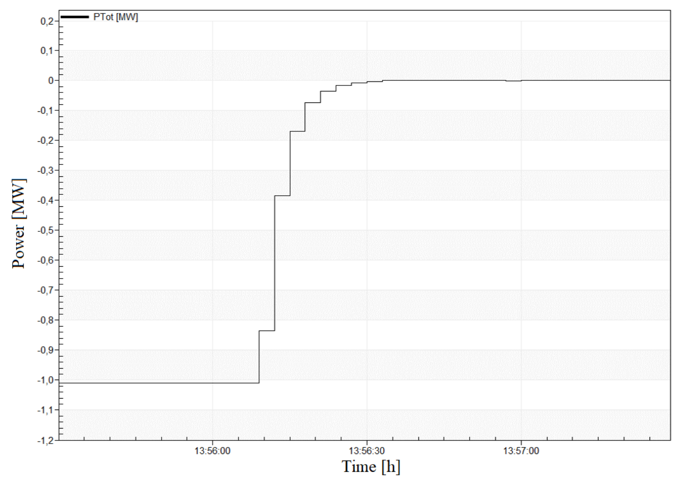
Finally, the voltage level during a longer period is presented in Fig. 6 to show the voltage during the test cycle in comparison to normal fluctuations in the grid. The maximum, minimum and average line-to-line voltage levels are included for all time steps of the interval. From Fig. 6 it can be verified that the voltage fluctuations that arise from the test cycle are very small in comparison to the natural variations in the grid. The observed variations are less than 1% of the nominal value. It should be stated that the voltage spike seen in Fig. 6 occurring at approx. 11.20am is outside of the period of the BESS test run, thus not relevant to discuss in this analysis.



(a)

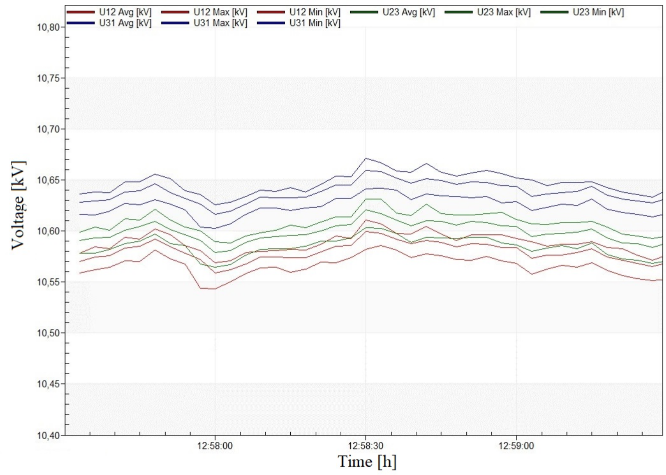


(b)

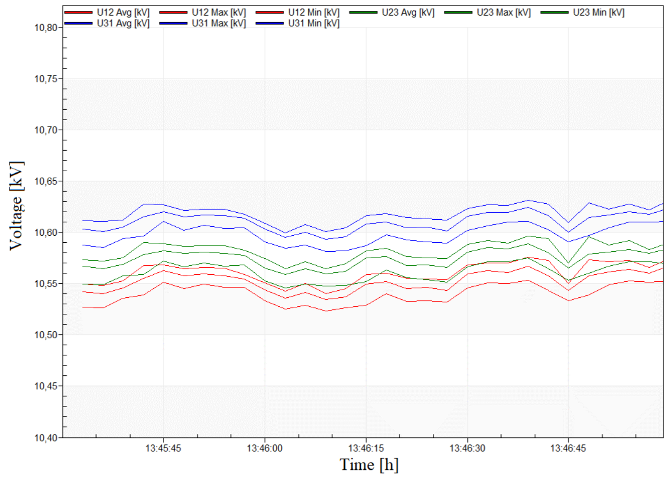


(c)

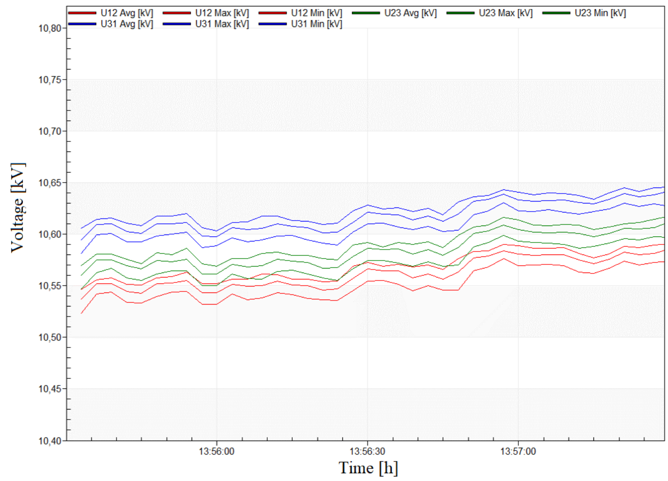
Fig. 4. Power flow during the three test cycle events.
(a) Ramp up from idle to 5 MW discharge mode.
(b) Change from 5 MW discharge to 1 MW charge mode.
(c) Ramp down from 1 MW charge to idle mode.



(a)



(b)



(c)

Fig. 5. Voltage levels during the three test cycle events.
(a) Ramp up from idle to 5 MW discharge mode.
(b) Change from 5 MW discharge to 1 MW charge mode.
(c) Ramp down from 1 MW charge to idle mode.

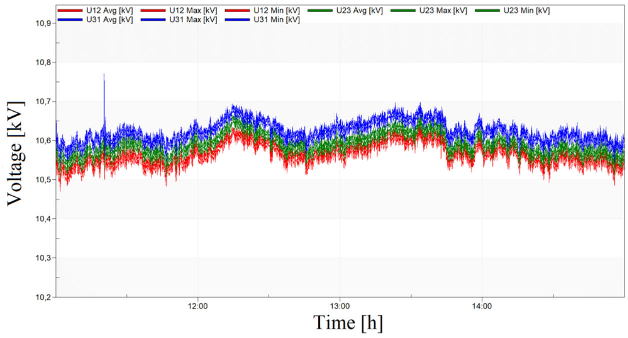


Fig. 6. Voltage levels at the connection point over a longer period.

IV. Discussion

It is clear according to the results that the power quality is not affected remarkably during the test cycle. This may be explained by the fact that the BESS is designed and prepared for participating in the market for fast frequency response (FFR) in near future. In the FFR market the requirements for full activation are significantly more demanding and varies depending on chosen activation level: from 1.3 seconds at 49.7 Hz to 0.7 seconds at 49.5 Hz. Activation times of 30 seconds or longer is therefore far from the full capacity of the BESS and should not cause any effects on the power quality. Further studies and tests of the BESS will be required to verify that the power quality is kept within acceptable levels during fast ramping for e.g., FFR provision.

Another interesting topic for further power quality studies in this matter is how the transfer function is designed for the ramping of the BESS. It may not play a vital role during slow and steady activation, but when the time required for full activation goes sub-second it would be interesting to see how important the ramp-design is. Also, additional power quality parameters e.g., total harmonic distortion (THD) could be analysed thoroughly.

Flexibility solutions like the CoordiNet market have obvious functions during periods of congestion, but digital solutions at system level are here to stay. In addition to traditional grid reinforcement, dynamic marketplaces and agreements for flexibility will operate in synergy to optimize the utilization of the electrical grid. Also, digital and live monitoring of several markets and price signals will be more important as storage units should provide several services in turns or in parallel to find the most profitable revenue streams. In future studies, it will be interesting and important to investigate how value stacking can be implemented in parallel within the same season. Most of the local flexibility is not provided on a regular basis, but rather correlates to cold temperature and other predictable parameters. This creates a good opportunity to provide additional services during low-demand periods.

V. Conclusion

This paper presents a test run of the recently connected BESS on the outskirts of Uppsala. The aim is to examine the local power quality, more specific the voltage level during flexibility and FCR-D service provision, and a test cycle that fulfils the requirements for both services is executed. The results from Fig. 5 and 6 show that the voltage variations are less than 1% during the observed period, thus it can be concluded that the voltage quality remains within accepted limits. Upcoming studies will aim at examining ramping of FFR service provision and include more power quality parameters. Finally, the service provision of the BESS is discussed in the paper, and an initial portfolio is presented. Future studies will compare more services and include intra-season value stacking to further optimize the portfolio.

VI. Acknowledgements

This project was funded through the Swedish Centre for Smart Grids and Energy Storage (SweGRIDs), by the Swedish Energy Agency, Vattenfall AB and E. ON SE. The authors are very grateful for the support.

VII. References

[1] International Energy Agency, "Data and Statistics: World energy consumption 1990-2018: electricity", Accessed: 27 January 2021, https://www.iea.org/data-and-statistics

[2] International Energy Agency. "Electricity Information: Overview", Accessed: 27 January 2021, https://www.iea.org/reports/electricity-information-overview

[3] International Energy Agency. "Data and Statistics: Global electricity demand by scenario 2010-2030", Accessed: 27 January 2021, https://www.iea.org/data-and-statistics/charts/global-electricity-demand-by-scenario-2010-2030

[4] Cision News - Vattenfall press release, "Sveriges största batterilager tas i drift i Uppsala", Accessed: 28 January 2021, https://news.cision.com/se/vattenfall-eldistribution-ab/r/sveriges-storsta-batterilager-tas-i-drift-i-uppsala,c3254858

[5] CoordiNet, "About CoordiNet", Accessed: 28 January 2021, https://coordinet-project.eu/projects/coordinet

[6] N. Etherden, Y. Ruwaida, S. Johansson, "Report on lessons learned, bug fixes and adjustments in products and routines within the Swedish demo", *(Horizon 2020 - Cooperation/Energy: CoordiNet)*

[7] Svenska Kraftnät, "Översiktlig kravbild för stödtjänster", Accessed: 29 January 2021, https://www.svk.se/siteassets/4.aktorsportalen/systemdrift-o-elmarknad/information-om-stodtjanster/marknader-for-stodtjanster.pdf

[8] A. Akhil, G. Huff, A. Currier, et al., "Electricity Storage Handbook in Collaboration with NRECA", Sandia National Laboratories, 2013, pp. 1-340

[9] G. Fitzgerald, J. Mandel, J. Morris, H. Touati, "The Economics of Battery Energy Storage: How multi-use, customer-sited batteries deliver the most services and value to customers and the grid", Rocky Mountain Institute, 2015, pp. 1-41

[10] T. Bowen, I. Chernyakhovskiy, P. Denholm, "Greening the grid – Grid integration toolbox. Grid-Scale Battery Storage - Frequently asked questions", National Renewable Energy Laboratory, 2019, pp. 1-8