Ilari Alaperä

GRID SUPPORT BY BATTERY ENERGY STORAGE SYSTEM SECONDARY APPLICATIONS

ACTA UNIVERSITATIS LAPPEENRANTAENSIS 882

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Abstract

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Global developments in renewable energy and energy efficiency of the power consumption present challenges to maintain the frequency stability of the electricity grids. The objective of the research is to investigate how the current and potential future install base of battery systems could be used to provide secondary grid support applications. The research focuses on stationary battery applications, and more specifically, uninterruptible power supply (UPS), telecommunications, and grid storage systems.

This doctoral dissertation is based on articles published in scientific journals and international conferences. The results presented in the articles and the dissertation show that the existing battery systems can be used to provide grid services. The conducted research focuses on specific types of services that these systems can provide and their economic and technical feasibility. In addition, several critical boundary conditions and potential limitations on participation are identified and analyzed.

The investigations leading to the conclusions include preliminary studies and simulations and were further confirmed by several successful market pilots performed with Nordic transmission system operators. In these pilots, data center UPS systems were used to provide primary frequency reserve and fast frequency reserve services.

Another main objective of the research was to develop business models where battery system investments could be made with significantly reduced costs by using the existing data center infrastructure or battery systems could be sold as a service for distribution system operators. The business models are presented in the dissertation and have resulted in several pilot projects.

Keywords: battery system, UPS, data center, telecommunications, distribution system operator, primary frequency reserves, grid balancing

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When I started working with batteries nearly a decade ago, I was privileged to be mentored by Pekka Waltari, whose knowledge in the field I still highly admire. He cautioned me that once I got into batteries, I would be spending my professional life with them. So far, he has been absolutely right. This work is the culmination of that experience, and I am extremely grateful for his guidance and enthusiasm.

I would like to thank my supervisor, Associate Professor Samuli Honkapuro, who agreed to supervise my project and has been very supportive and engaged from the time I introduced my idea and preliminary study plan all the way to the completion of the research and this dissertation.

I am also extremely grateful to Fortum for the opportunity to pursue the academic degree while still continuing my work with the company. Undoubtedly, the topic of my academic research and my daily work are synchronized, which has had a tremendous impact on the schedule in which the research, the related articles, and this dissertation have been completed. I would like to extend my specific thanks to Janne Happonen, my current manager and CEO of Fortum Spring, who has been very supportive and accommodating throughout the entire process. Additionally, to name a few, my colleagues Johan Salmelin, Pekka Manner, Tatu Kulla, and Juhani Rantaniemi have contributed greatly to my work as coauthors or/and through supportive conversations.

As a major part of the research has been done in cooperation with Eaton, I would like to extend my thanks to them as well, especially to Janne Paananen, who has coauthored most of the papers in this dissertation and with whom we have had several discussions and given several joint presentations around the topic of using UPS systems to provide grid support. I also want to mention and highlight the role that Teemu Paakkunainen had in the completion of this work. His in-depth knowledge of the UPS technology has been of paramount importance in the feasibility studies related to this work.

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Ilari Alaperä
October 2019
Espoo, Finland

Contents

List of publications

This doctoral dissertation is based on the following publications. The rights have been granted by the publishers to include the publications in the doctoral dissertation.

I. Alaperä, I., Honkapuro, S., and Paananen, J. (2018). Data centers as a source of dynamic flexibility in smart grid. *Applied Energy*, 229, pp. 69–79.

II. Alaperä, I., Honkapuro, S., and Paananen, J. (2019). Dual-purposing UPS batteries for energy storage functions: A business case analysis. *Energy Procedia*, 158, pp. 5061–5066.

III. Alaperä, I., Honkapuro, S., Paananen, J., Dalen, K., and Hornnes K. (2019). Fast frequency response from an UPS system of a data center, background and pilot results. Accepted for publication in *16th International Conference on European Energy Markets (EEM).* Ljubljana, Slovenia.

IV. Alaperä, I., Manner, P., Salmelin, J., and Antila, H. (2017). Usage of telecommunication base station batteries in demand response for frequency containment disturbance reserve: Motivation, background and pilot results. In *Proceedings of IEEE International Telecommunications Energy Conference (INTELEC),* pp. 223–228. Gold Coast, Australia.

V. Alaperä, I., Hakala, T., Honkapuro, S., Manner, P., Pylvänäinen, J., Kaipia, T., and Kulla, T. (2019). Battery system as a service for a distribution system operator. Accepted for publication in *25th International Conference on Electricity Distribution (CIRED).* Madrid, Spain.

Author's contribution

Ilari Alaperä is the principal author and investigator in Publications I–V.

Publication I.

The author designed the research plan, searched the articles, developed the simulation tools and performed the analyses by using these tools, analyzed the excess capacities and limiting factors, designed the laboratory experiments based on transmission system operators' (TSOs) requirements, managed the market pilots, and wrote the vast majority of the article.

Publication II.

The author designed the research plan, conducted the background research, constructed the business model, performed the analyses and calculations, and wrote the vast majority of the article.

Publication III.

The author designed the research plan, managed the pilot with the customer and Statnett, and wrote the majority of the article.

Publication IV.

The author designed the research plan, developed the simulation tools and performed the analyses by using these tools, analyzed the excess capacities in base stations, managed the pilot with the telecommunications operator, and wrote the article.

Publication V.

The author designed the research plan, was involved in the construction of both the business model and the technical concept, managed the pilot with the distribution system operator (DSO) (Elenia), and wrote the majority of the article.

Nomenclature

Latin alphabet

C	cost	–
r	discount rate	–
E	energy	Wh
P	power	W
R	revenue	€

Greek alphabet

α	(alpha)
β	(beta)
Δ	(delta), symbol for relative change

Subscripts

b	battery
bc	battery converter
g	grid
est	estimated
l	load
m	market
r	rectifier
t	time

Abbreviations

2G	Second generation
5G	Fifth generation
AC	Alternating current
aFRR	Automatic frequency restoration reserve
BESS	Battery energy storage system
BSP	Balancing Service Provider
BRP	Balance Responsible Party
CAN	Controller area network
CAPEX	Capital expenditure
CO2	Carbon dioxide
DC	Direct current
DoD	Depth of discharge
DR	Demand response
DSO	Distribution system operator
DUT	Device under testing
EPC	Engineering procurement construction

EV	Electric vehicle
FCR	Frequency containment reserve
FCR-D	Frequency containment reserve for disturbances
FCR-N	Frequency containment reserve for normal operators
FFR	Fast frequency reserve
HVAC	Heating, ventilation, and air conditioning
ICT	Internet communications technology
IGBT	Insulated Gate Bipolar Transistor
IT	Internet technology
ISO	Independent system operator
LV	Low voltage
mFRR	Manual frequency restoration reserve
MV	Medium voltage
NPV	Net present value
OL1	Olkiluoto 1 (nuclear reactor)
OL2	Olkiluoto 2 (nuclear reactor)
OPEX	Operating expenses
O&M	Operation and maintenance
PCS	Power conversion system
PV	Photovoltaic
RE	Renewable energy
RES	Renewable energy source
ROC	Regulatory outage costs
R&D	Reseach and development
SEDC	Smart Energy Demand Coalition
SLA	Service-level agreement
SNMP	Simple Network Management Protocol
SoC	State of charge
SoH	State of health
SoSS	Security of supply service
SvK	Svenska kraftnät
TSO	Transmission system operator
UPS	Uninterruptible power supply
VRLA	Valve-regulated lead-acid (battery)

1 Introduction

The energy systems are globally going through a significant change. The increasing penetration of renewable energy (RE) poses major challenges. The inherent volatility of RE makes it difficult to maintain a stable and functional power system, and further, renewable energy sources (RES) are displacing traditional, dispatchable generation assets that have traditionally provided flexibility for the system. As traditional synchronous generation is replaced by energy sources, such as photovoltaic arrays (PV) and wind turbines coupled with power electronics, the system-level inertia (kinetic energy in the power system) will decrease. This is further affected by the increasing use of electrical drives in, for example, heavy industrial processes. While these drives will significantly increase the energy efficiency, they will also effectively decouple large rotational masses of industrial-size motors from the grid frequency and hinder their ability to provide natural inertia for the electricity system. Another major challenge arises from the electrification of transportation, which will increase peak power demand in the grids and require mitigating actions such as smart management of electrical vehicle (EV) charging or grid reinforcement.

Traditionally, power systems have been organized so that electricity has been produced centrally in large power plants and distributed to the consumers through transmission and distribution systems. Electricity retailers have forecasted the consumption of their customers by applying statistical methods relying on historical data. Electricity producers have also adjusted the production profiles of their generation assets based on market demand (i.e., consumption forecasts of the electricity retailers). Fine-tuning of the consumption/production balance has been carried out by adjusting the power output of the power plants. In a power system where the majority of the power is generated from adjustable sources, such as fossil fuel-fired power plants (and hydro power where available), this has been a viable option, the balancing costs of the system have remained under control, and the system stability has been maintained.

However, renewable energy sources are significantly different by nature: they produce energy when there is wind or sunshine available. The output profiles of renewable energy sources can be forecasted, but they cannot be adjusted to meet the real-time demand. Although the energy output of RES can be curtailed, this should be avoided for socio-economic reasons, as RE is produced basically without any (or very low) marginal production costs. Another aspect of the RES is that they are highly distributed. A significant increase in distributed generation will pose challenges to the power delivery infrastructure, as instead of the traditional unidirectional power flow, power can now be generated in numerous locations and at different levels of the transmission and distribution grid (high, medium, and low voltage).

This development has increased the need for system-level flexibility and energy storages. Stationary energy storage deployments are expected to grow from the current 12 GWh to 158 GWh by 2024, equaling $71 billion of investments in energy storages (Wood Mackenzie, 2019). Concurrently, ubiquitous digitalization and exponentially increasing data consumption, along with the developments in telecommunications (telco) processes (e.g. 5G), will significantly increase the demand for data center capacity and telecommunications infrastructure.

The research of this doctoral dissertation focuses on 1) the use of existing energy storages to perform grid services, including battery systems that are widely deployed to provide local backup in telecommunications and data center applications and 2) dual-purposing of the existing power infrastructure to significantly reduce the required investment costs related to the building of battery energy storage systems.

Additionally, the study addresses the potential of using battery energy storage systems in distribution grids to provide security of supply services, which can be considered an alternative or at least a complementary approach to massive infrastructure reinforcement projects going on globally. As natural monopolies, distribution system operators (DSOs) are under strict regulation, which, for example, limits their ability to own and operate battery energy systems, even though these systems could be highly beneficial for the DSOs as shown in various publications discussed in the literature review of this doctoral dissertation. One part of the dissertation describes a business model within the framework of the current regulation in which the battery system is offered as a service to the DSO.

1.1 Electricity system balancing and different marketplaces

Electricity systems are interconnected grids with electricity producers and consumers. In order to keep the systems within the allowed operating range, the systems have to be balanced (electricity consumption and production matched).

Typically, electricity systems have marketplaces for future deliveries or need for electricity, where the electricity production is matched to the forecasted consumption. In addition to this forecasting and planning of production and consumption, real-time balancing is required to sort out imperfections in the forecasts and ensure that sudden changes in the electricity flow will not jeopardize the system.

Real-time balancing is organized in different ways in different grid areas. For instance in some areas the responsible authorities apply market-based solutions in which different stakeholders (in electricity systems) make voluntary offers to either increase and/or decrease their electricity production and/or consumption in different time frames, while in other areas the authorities use more regulated solutions, for example, such that every electricity producer must maintain a capacity reserve in each of their power plants.

In addition to system-level balancing, local management of the electricity flow is implemented. This is to ensure that the physical transmission limitations are not exceeded. Again, different solutions have been adopted, some of them (which are more relevant in the context of this doctoral dissertation) including connection sizing (by fuse size or contract capacity), dynamic grid tariffs (time of usage or power tariff), and different market-based solutions for distribution-system-level flexibility, which are currently in the development/pilot phase.

1.1.1 Frequency containment (in the Nordic power system)

Figure 1 illustrates a collection of current and upcoming reserve products that are hosted by the Finnish TSO, Fingrid (as well as other Nordic TSOs). Current capacity-based products include frequency containment reserves for disturbances (FCR-D) and frequency containment reserves for normal operations (FCR-N). The fast frequency reserve (FFR) is a forthcoming reserve product intended to be introduced during 2020. The current energy-based products are automatic frequency restoration reserve (aFRR) and manual frequency restoration reserve (mFRR).

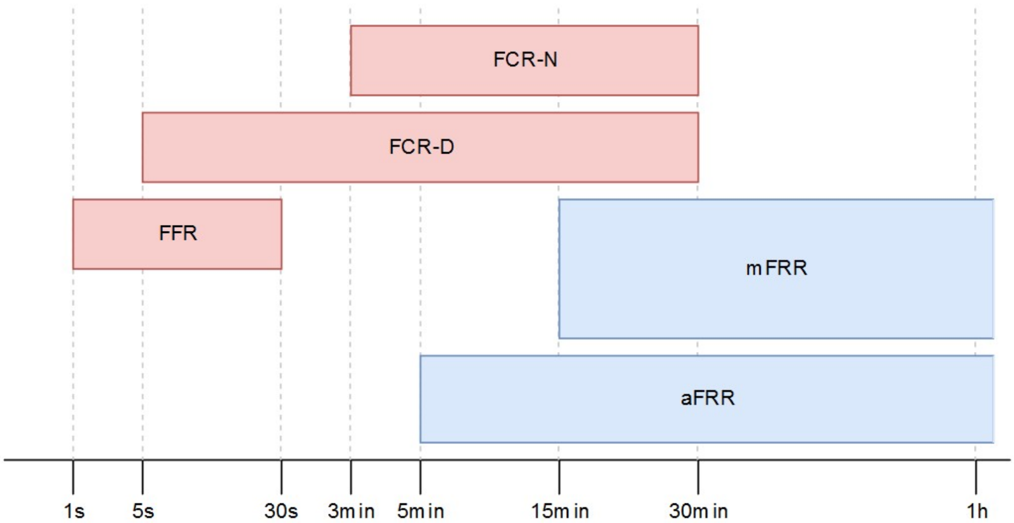

Figure 1. Different reserve products currently hosted/announced (FFR not yet implemented) by Fingrid; FFR, FCR-D, and FCR-N (indicated by red color) are capacity-based products, while aFRR and mFRR (indicated by blue color) are energy-based products.

1.1.2 Implicit and explicit demand response

Smart Energy Demand Coalition (SEDC) identifies two main categories of demand response in its position paper (SEDC, 2016):

- "*Explicit Demand-Side Flexibility*" is committed, dispatchable flexibility that can be traded (similar to generation flexibility) on the different energy markets (wholesale, balancing, system support and reserves markets). This is usually facilitated and managed by an aggregator that can be an independent service provider or a supplier. This form of Demand-Side Flexibility is often referred to as “incentive driven” Demand-Side Flexibility.”

- “*Implicit Demand-Side Flexibility”* is the consumer’s reaction to price signals. Where consumers have the possibility to choose hourly or shorter-term market pricing, reflecting variability on the market and the network, they can adapt their behavior (through automation or personal choices) to save on energy expenses. This type of Demand-Side Flexibility is often referred to as “price-based” Demand-Side Flexibility.”

The latter (implicit demand response) has been extensively studied, as the opportunities to benefit from it have been there for decades. However, explicit demand response is a novel area of research, mostly because it requires advanced market mechanisms, and these markets have started to emerge only lately.

1.2 Research questions

The specific research questions that the research reported in this doctoral dissertation aims to answer are:

1) Can existing battery systems and the related power protection systems (i.e. UPSs and rectifiers) be used to provide grid services in a technically and economically feasible manner?
2) Can the existing power protection infrastructure (for example in data centers) be used as a “platform” for battery energy storage systems, and what are the limitations and benefits of the approach?
3) Can UPS systems be used to provide fast frequency response (FFR) services?
4) What are the boundary conditions and limiting factors in the above-mentioned cases, and what is their impact on the primary purpose of the systems?
5) Can a third-party company (e.g. an aggregator) find an economically feasible business model that would enable it to offer batteries as a service to the distribution company?

1.3 Structure of the doctoral dissertation

The doctoral dissertation is structured around three main topics: 1) data center demand response, 2) telecommunications demand response, and 3) batteries in distribution systems. The work on these topics includes several desk studies, simulations, laboratory experiments, pilots, and development of business concepts.

The first chapter of the dissertation provides an introduction to the general theme and motivates the research around demand response and energy storages. The first chapter also formulates the main research questions and the scope of the research. Additionally, the chapter presents a brief introduction to different types of demand response, as understanding the basic concepts of explicit and implicit demand response is crucial for comprehending the added value of the conducted research (i.e., novelty in the explicit demand response). The second chapter describes the state of the art and the identified research gaps for all the main topics. The main body of the doctoral dissertation consists of Chapters 3, 4, and 5. These chapters present the research methods, achieved results, and specific discussion for all the main topics (Chapter 3 addresses the UPS and data center demand response, Chapter 4 the telecommunications demand response, and Chapter 5 distribution battery systems). More general discussion tying together the different topics addressed in the dissertation is provided in Chapter 6. Finally, conclusions are drawn in Chapter 7, followed by the publications included in the dissertation.

1.4 Scope of the research

The objective of the research is to investigate how the current and potential future install base of battery systems could be used to provide secondary grid support applications. The research focuses on stationary battery applications, and more specifically, UPS, telecommunications, and grid storage applications. The first two are currently dominating the global stationary storage demand, while the grid storage applications are expected to increase significantly in the near future. For the UPSs, the research focus is on large-scale systems (MW range). Data centers are among the major users of such systems, and as such, in the focal point of this dissertation; however, it should be noted that the findings of the research and related approaches could well be extended to other UPS application areas, such as more traditional industrial cases.

Electric vehicles and their battery systems have been omitted from the scope of the research. While they possess a significant potential and a massive (future) scale, the topic is quite extensively covered in the current scientific literature.

The research focuses on investigating the technical and economic potential of data center and telco batteries, determining the boundary conditions and impacts of their participation on grid support, and testing the assets against the current and future market requirements. However, development of the technology enabling the participation is not in the focus of the research.

Implicit demand response of data centers (e.g. peak shaving or time of usage) has also been extensively studied (as illustrated in the literature review of Chapter 2). However, explicit demand response, such as participation in reserve markets hosted by local transmission system operators has significant research gaps (as identified in the literature review). These research gaps can mostly be explained by the fact that explicit demand response markets have only recently started to form, and in many places in the world, participation from the demand side is still regulatorily forbidden. The research of this dissertation deals specifically with the FCR and upcoming FFR markets found in the Nordic countries and contributes to the common knowledge by providing experimental and simulated data and several pilots in which the technology is tested against real reserve markets in an environment where demand response is expected to provide a significant proportion of future grid balancing reserves.

Chapter 5 about the DSO batteries presents a novel business model that answers a highly topical question of how distribution system operators could benefit from battery systems without disturbing the open markets (electricity and balancing) as a natural monopoly.

1.5 Scientific contribution

The scientific contribution of the dissertation can be divided into three main categories:

1) Covering the participation of data centers and telecommunication base stations in explicit demand response and specifically in primary frequency regulation. This is done by analyzing their technical and economical participation potential (in demand response) as well as providing concrete evidence of the fact by participating in live market pilots and demonstrating the performance against the actual market rules.
2) Identifying the boundary conditions and analyzing the potential impact of the participation. The boundary conditions are identified for different scenarios and the impact (basically the effect on the battery service life) is analyzed based on simulations conducted with historical frequency data as well as market data and requirements.
3) Presenting a battery as a service business model so that the benefits of the battery systems could be maximized in compliance with the current regulatory framework. The model directly answers a very topical question about whether the DSOs are allowed to own and operate battery systems.

2 State of the art

2.1 Data center demand response

The role and potential of demand response in future energy systems is a generally accepted and extensively researched topic. The flexibility that demand response could provide has been addressed for example in such publications as (Mussin et al., 2018) and (Zheng et al., 2018). Data center demand response has also been covered elsewhere in the scientific literature. The research can be divided into two major categories: (1) demand response carried out by server workload management and optimization and (2) demand response enabled by the data center hardware (generators, UPS, and auxiliary systems).

Nearly all of the publications approach the subject from the viewpoint of implicit demand response. In implicit demand response, the incentive to perform demand response operations is "internal," a common (and much studied) example of this being the time-of-use optimization, where consumption of electricity is shifted from high-priced hours to low-priced hours of the day. This can be even further developed by shifting consumption from a higher-priced region to lower-priced ones as was presented in (Li et al., 2015). This method has also been suggested to be used to minimize CO_2 emissions (Ruddy & O'Malley, 2014) and to optimize the usage of renewable energy for data center operations with an algorithmic approach (Liu et al., 2015). Bahrami et al. (2018) presented related research, where they showed that data center operators can achieve significant electricity cost savings (18.7%) by shifting their consumption to off-peak hours.

The topic of how to incentivize data center participation in the demand response programs and to share the profits has also been an extensively covered research area, specifically relating to multitenant or colocation (colo) data centers, where the data center operators do not run their processes on servers of their own but rent server space and/or capacity. Zhan et al. (2018) presented a related concept for a workload flexibility pricing model, where the model included usage-based pricing, which is standard in the industry, but added a flexibility component related to deadlines and set by the tenants for completion of their workloads. In their research on colo center demand response, Tran et al. (2016) focused on emergency demand response. Emergency demand response is a type of explicit remand response, in which an external incentive is used to motivate demand response (e.g. capacity payments or, in the case of a primary regulation market, a market-based revenue).

The demand response in the above-mentioned cases was carried out by server load management. For the hardware-enabled demand response, the recent research interest has been in the time-of-use application, but also in peak shaving, where the objective is to minimize the momentary power consumption peak, thereby minimizing the grid tariffs (or at least the power-related cost component). The majority of the research papers have aimed at presenting different kinds of estimation models for battery aging caused by participation in these demand response activities. The most prominent research on this topic has been conducted by S. Gonvindan, A. Sivasubramaniam, B. Ungaokar, A. Mamun, I. Narayanan, and H. Fathy. Some of the research of these scholars is published for instance in (Mamun, Sivasubramaniam, & Fathy, 2018), where a battery life cycle analysis was carried out and the potential of collective learning in predicting battery aging was assessed. Further, in (Mamun et al., 2016), the Li-ion battery degradation resulting from constant cycling (related to peak shaving operations) was studied. In (Mamun et al., 2018), a physics-based model for battery performance and battery degradation in combination with stochastic models of data center demand was introduced. In (Narayanan et al., 2014), the authors also posed a very relevant research question, which is also the title of their article: “Should we dual-purpose energy storage in data centers for power backup and demand response?” However, the study concentrated on peak shaving and time-of-use applications rather than frequency-based balancing.

Cupelli et al. (2018) studied how a combination of a battery energy storage system (BESS, here a UPS battery system), HVAC, and IT workload management could be used in price- and incentive-based (implicit/explicit) DR. However, the incentive-based demand response uses a three-stage control signal, which is, by nature, significantly different from primary frequency regulation. Li et al. (2014) studied integrated power management of data centers and electric vehicles (EVs). Their work features explicit DR operations, particularly frequency regulation. However, the addressed frequency regulation differs from the primary frequency regulation that has been studied in this dissertation, as the one covered by Li et al. is an ISO-based control signal rather than a requirement to react to the grid frequency. Moreover, their paper focuses on presenting a control framework to incorporate different assets, rather than the specifics of data center UPSs in frequency regulation.

Apart from the last few mentioned publications, the focus of academic research has so far been on implicit demand response, specifically peak shaving. The lack of research on explicit demand response, and in particular, primary frequency regulation, can mainly be explained by the fact that explicit demand response markets are still in the development phase, and active, commercially available markets can only be found in a couple of European countries. Figure 2 illustrates the market situation of explicit demand response in Europe in 2017. It shows that only Belgium, Finland, France, Great Britain, Ireland, and Switzerland are classified by the SEDC to be commercially active (SEDC, 2017).

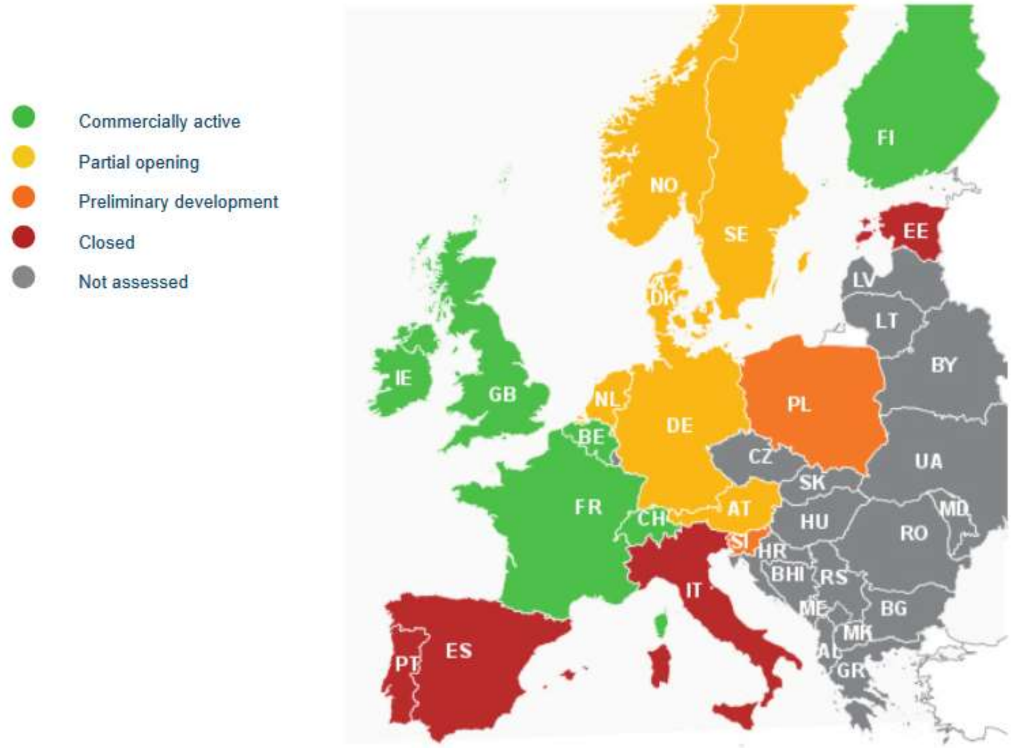

Figure 2. Map of explicit demand response development in Europe in 2017 (SEDC, 2017).

2.2 Telecommunications demand response

The topic of energy efficiency and incorporation of RES and smart grids (referred to as "green mobile networks") to telecommunications and the related infrastructure is widely studied in the scientific literature. An review article (Ahmed et al., 2018) shows for example that the published research can be divided into five categories: 1) energy efficiency metrics and consumption models, 2) energy efficient hardware and technologies, 3) energy efficient architectures, 4) energy efficient resource management, and 5) incorporation of renewable energy sources (RESs).

Furthermore, there are several publications such as (Ghazzai et al., 2012) and (Hassan et al., 2014), where the authors have presented on/off switching of base stations in order to reduce the electricity costs of the network operations. However, there are only a few publications addressing explicit demand response, and most (if not all) of them seem to focus on energy-based ancillary services (secondary, such as the aFRR, or tertiary, such as the mFRR). The most probable reason for the lack of research published on explicit demand response is the same as previously identified: explicit remand response markets are still very much in the development phase, and large-scale implementation has not yet started.

In (Bellifemine et al., 2018), the authors present results from studies into the economic feasibility of providing upward tertiary reserve with BSs (or Base Transceiver Stations, BTS as termed in the article). The article also mentions other balancing products, such as FCR, but the analysis is conducted only for tertiary reserve operations. In another publication (Renga et al., 2018) related to tertiary services, it is presented how a mobile network could adapt its energy consumption to respond to SG (smart grid) requests. In the research, the SG requests either increasing or decreasing the consumption in order to perform imbalance management (i.e., to correct the difference between the actual energy consumption and the day-ahead forecasted consumption), which can be considered a tertiary service.

2.3 Battery systems and distribution system operators

The benefits of battery energy storage systems for distribution system operators are well identified in the current academic literature. There are also several publications about the interplay of battery systems between DSOs, TSOs, and consumers.

In (Celli et al., 2018), the authors list the following benefits for the DSO:

1) Investment deferral
2) Increment of hosting capacity
3) Reduction of Joule losses
4) Improvement of continuity of supply
5) Reduction in reactive power exchange between the DSO and the TSO
6) Voltage dip regulation

In (Celli et al., 2018), a multiobjective optimization was carried out combined with a cost/benefit analysis to determine the profitability of the battery investment cases. According to the analysis, most of the cases investigated in the paper failed to be profitable. These applications have also been studied elsewhere. For example, Wang et al. studied using BESS to provide active and reactive power support in the MW distribution systems in (Wang et al., 2017), Narayanan et al. (2017) investigated using BESS in secondary substations to reduce interruption experienced by the distribution customers, and Petrichenko et al. (2018) evaluated the financial feasibility of using BESS to support grids during cases of temporary overloads. Moreover, Celli et al. (2018) published research that presented a multiobjective optimization approach to optimize the implementation of energy storages to distribution networks.

In a highly relevant article, Hellman et al. (2017) presented results from a pilot project where a DSO had installed a BESS to study the potential to stack benefits from different sources. They studied performing FCR and voltage and reactive power control simultaneously for a 1.2 MW/600 kWh battery system.

Probably the most relevant study considering the topic of DSO batteries addressed in this doctoral dissertation is (Grzanic et al., 2018), in which the authors presented a sharing concept where the DSO could "rent" the flexibility of end-customer-owned battery storage systems. In the concept, the end-user purchases these systems for arbitrage purposes and makes them available to the DSO through an aggregator. The DSO rents the capacity to handle short-duration voltage dips in the distribution system instead of investing in a grid reinforcement.

2.4 Summary of the state of the art

Based on the literature review, the following research gaps were identified:

1) Data center participation in primary frequency reserves has not been covered in the current scientific literature. The current state of the art focuses on implicit demand response and using the IT hardware (load management) to provide peak shaving and electricity cost reduction. The research into batteries and demand response is also mostly related to implicit demand response.
2) In the current literature, the research on telecommunications systems and their participation in demand response is limited to only a few publications about participation in tertiary reserves, whereas the academic focus is more on the energy efficiency.
3) The benefits of battery systems and their applications in distribution systems are well documented; however, business models in which the benefits of the battery systems could be maximized (in compliance with the current regulatory framework) are not covered in the current literature.

3 UPS and data center demand response

The objective of the study was to find out whether current and future installations of the MW-scale UPSs could be used for demand response. The division into current and future installations is explained by the fact that there is a technological paradigm shift going on in the UPS system design, and more and more UPS installations are being equipped with Li-ion batteries instead of traditional lead-acid batteries. Most Li-ion batteries have a significantly higher cyclic and service life and can be maintained in a partial state of charge. For the primary UPS application, this will generate certain benefits, such as reduced service and maintenance costs, but from the viewpoint of demand response, Li-ion technology will enable significant benefits by making the systems much more flexible (at least in theory). The topic will be discussed in detail later in this chapter.

The primary objective of the research regarding the current install base of the UPS systems was to study 1) the amount of energy required for primary regulation services (specifically for FCR-D, owing to the technical limitations of currently installed systems to perform FCR-N services) and the availability of this energy in typical data centers, 2) the number and occurrence of activation events and their impact on the service life of the battery systems, 3) reaction speed and reliability considerations of the operations, and 4) economic feasibility of the approach. The topics are covered extensively in Publication I. The initial assumption was that as data centers are using redundant UPS systems to maximize the server up-time, they should have (under normal circumstances) plenty of underutilized capacity.

For future installations/system upgrades (a.k.a. green/brown field sites), the research focuses on the technical and economic feasibility of dual-purposing data center power protection systems to provide similar functions as large grid-connected battery energy storage systems (BESSs). Publication II covers the topic in brief, but the information given in this chapter extends the scope of the conference publication.

The research around the topic of UPS demand response is divided into three subcategories: background work and simulations, laboratory experiments, and pilots (technical and market). The technology used to enable UPS systems to perform these functions has been developed by Eaton over the last decade, and as such, is not a topic of this doctoral dissertation. However, application of the technology to meet the technical market requirements and economic feasibility of the approach is addressed in this study. Further, it should be noted that while the research focuses on data centers, the approach could be extended to other UPS application areas such as more traditional industrial cases.

3.1 Controlling the power flow in the UPS systems

In order to provide demand response operations with UPS systems, the system has to be able to respond to external commands and adjust internal power flows of the system (i.e., to divert power drawn from the grid to batteries or even push more power to batteries when required). One part of the research was to conduct an analysis of the currently available technology and what kinds of limitations it would set to demand response operations. The results of the analysis are later used for different purposes in approaches for the current install base of lead-based battery-backed-up UPS systems and future Li-ion-based systems.

Initially, Eaton (one of the largest UPS manufacturers in the world and a coauthoring party in several of the publications included in this doctoral dissertation) developed their bidirectional converter technology to enable load testing of UPS system batteries without the need to use external resistive load banks. However, the technology also has potential to enable UPS systems to contribute to grid support. This chapter briefly explains the technology and the boundary conditions it sets related to demand response activities.

Traditionally, UPS systems have used thyristors as rectifier components (Figure 3, left); however, most (if not all) modern dual-conversion UPS systems are designed using insulated gate bipolar transistors (IGBTs) as the core power electronics components in the converters (Figure 3, right). IGTBs enable bidirectional power flows in the components by modified control algorithms. Some UPS manufacturers use these features to enable discharging of battery systems to the grid to perform battery load tests without external load banks. Major UPS manufacturers are developing or have launched DR features based on the above-mentioned technology (Eaton, 2017), (E. On, 2018).

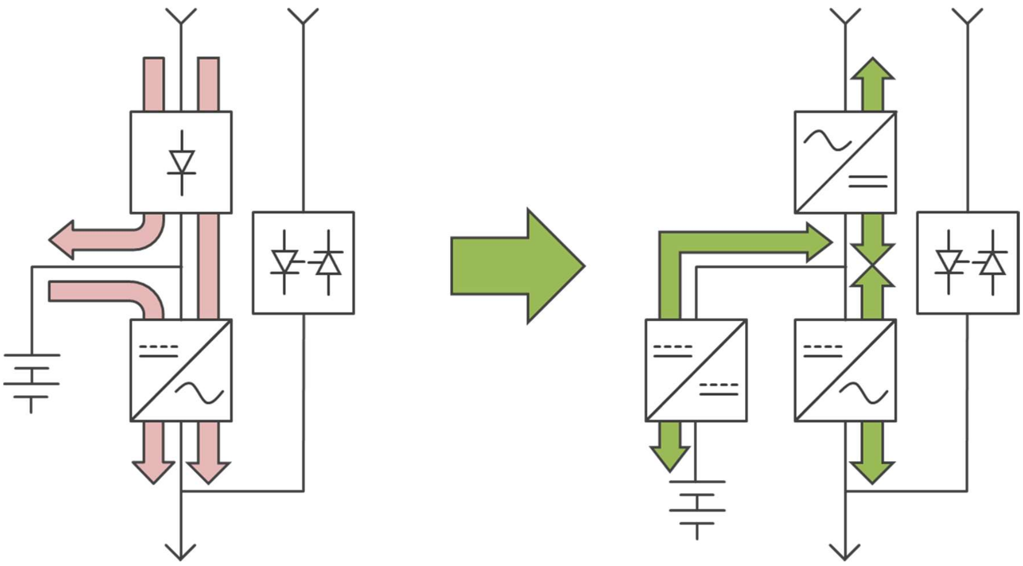

Figure 3. Comparison between a thyristor- (left) and IGTB-based (right) UPS.

The capabilities of bidirectional IGTB-based UPS systems have been presented in Publications I and II. Moreover, the topic has been addressed in some third-party reports and announcements (e.g. (Svenska kraftnät, 2018) and (Statnett, 2018)) about pilot projects in which UPS systems have been used to perform grid support and which are associated with the research covered in this doctoral dissertation.

The basic concept is that by controlling the power flows within the UPS and the associated battery system, it is possible to affect the input power of the UPS device without influencing the power that is being fed to the protected loads. Figure 4 illustrates the different potential power flows within the UPS system in different situations. The related power consumptions of these modes are gathered in Table 1, where P_l is used to denote the critical load power (consumption) and P_b the power discharged and charged from and to the battery system of the UPS.

It should be noted that for simplification, all losses have been omitted and the UPS is considered "ideal." In real systems, each of the converters has a nonunity efficiency cofactor in addition to general parasitic and resistive losses present in the system.

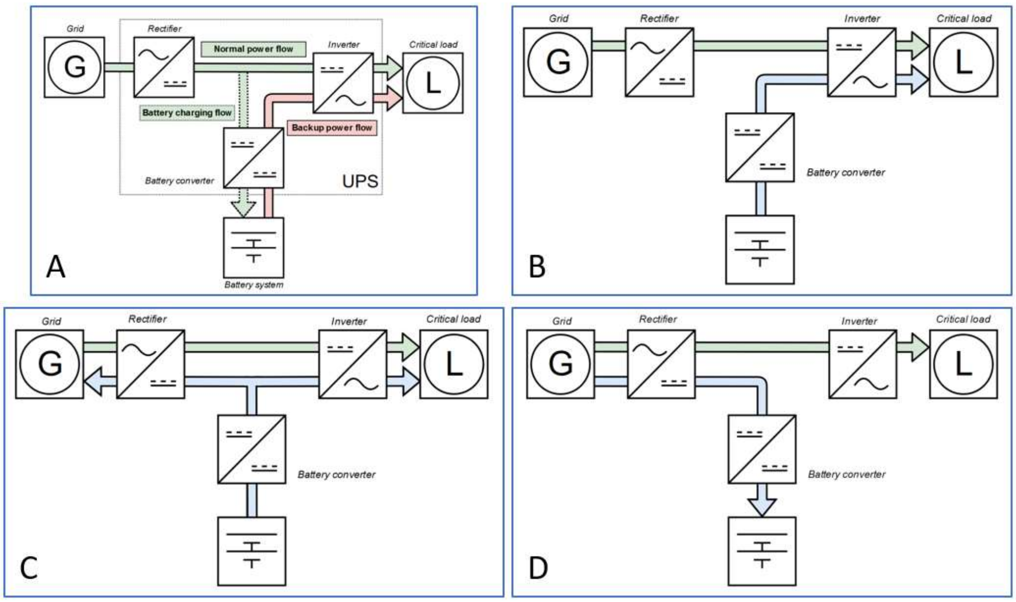

Figure 4. Power flows of the UPS system; during normal and backup operations (A), input power reduction (B), input power reduction and back-feed (C), and input power increase (D).

Table 1. Power draws from grid with different demand response operation modes.

Case	Power from Grid	Power to Load
Input power reduction (B)	$P_l - P_b, where\ P_l > P_b$	P_l
Input power reduction and back-feed (C)	$P_l - P_b, where\ P_b > P_l$	P_l
Input power increase (D)	$P_l + P_b$	P_l

As stated in the introductory chapter, different reserve types require different responses. In the Nordic power system, the following technical, reserve-power-related limitations apply to the UPS demand response.

3.1.1 FCR-D

The FCR-D reserve requires that a reserve unit either reduces the power consumption seen by the grid and/or increases the power injection to the grid (input power reduction, shown in Figure 4b, or input power reduction and back-feed, Figure 4c). This kind of a reserve can be considered an up-regulating reserve, as the objective is to increase the frequency of the grid.

The amount of up-regulating power ($\Delta P_{up,max}$) that the UPS system can deliver is limited by either the load power (P_l) if back-feed is not possible, or the maximum rated power of the rectifier ($P_{r,max}$), the maximum rated discharge power of the battery converter ($P_{bc_{discharge},max}$), and the maximum rated discharge power of the battery system ($P_{b_{discharge},max}$). If back-feeding is possible, the maximum up-regulating power of the UPS is defined by

$$\Delta P_{up,max} = \mathrm{MIN}(\Delta P_{r,max}\ ;\ P_{bc_{discharge},max}\ ;P_{b_{discharge},max}) \tag{1}$$

and if back-feeding is not possible, $\Delta P_{up,max}$ is obtained by

$$\Delta P_{up,max} = \mathrm{MIN}(P_L\ ;\ P_{b_{discharge},max}\ ;P_{bc_{discharge},max}). \tag{2}$$

However, it should be noted that as the discharge power of the battery converter and the battery system are always sized according to the UPS primary functionality (protection of the critical loads, “backup power flow” in Figure 4a) and the UPS capacity, hence they will not limit $\Delta P_{up,max}$.

If the power electronics in the first conversion stage is fully bidirectional and capable of feeding the same amount of power both up- and downstream from the converter, $\Delta P_{up,max}$ will be technically limited (from the UPS’s point of view) only by the rated power of the converter. It is pointed out that the up-regulation could be limited by the total power consumption in the point of grid connection. This will be the case if the local distribution system operator (DSO) does not allow power injection to its grid from a “consumption point.”

As a result of the increasing solar PV penetration, many DSOs have begun to allow power injections to the network from consumers. Further, some data centers are already performing their periodical generator tests by feeding energy back to the local DSO network.

3.1.2 FCR-N

FCR-N reserve requires that the participating unit is able to increase and decrease its power consumption or production. This reserve type is therefore a bidirectionally regulating reserve, consisting of both up- and down-regulating parts. Participation in bidirectional primary regulation requires the UPS system to be able to reduce the loading that the grid sees (up-regulation, ΔP_{up}, Figure 4b and Figure 4c) and to increase the loading (down-regulation, ΔP_{down}, Figure 4d) Typically, a symmetrical reaction is required, and thus, the ability of the UPS to provide grid support (ΔP_g) is the smaller of these two values

$$\Delta P_g = \mathrm{MIN}(\Delta P_{down,max}\ ;\ \Delta P_{up,max})\ . \tag{3}$$

Up-regulation is limited as was previously discussed. During a down-regulation event, the UPS is expected to increase the power consumption that the grid sees. Basically, this means that the UPS will draw a higher amount of current from the grid and charge it to the battery systems. During normal operation of a double conversion UPS system, the power of the critical loads is fed through the UPS. This means that both the conversion stages are under constant load (normal power flow in Figure 4a). This load is directly proportional to the critical loads that the UPS is supplying.

The fact that the first conversion stage (the rectifier) is constantly loaded reduces the ability of the UPS to increase energy absorbed from the grid. The maximum power change that the rectifier can perform ($\Delta P_{r,max}$) can be calculated by deducting the power drawn by the critical loads connected to the UPS output (P_l) from the maximum rated power of the rectifier ($P_{r,max}$)

$$\Delta P_{r,max} = P_{r,max} - P_l. \tag{4}$$

In addition to the rectifier, the ability of the battery system to absorb energy ($P_{b_{charge},max}$) and the maximum charging power of the battery converter (DC/DC converter) ($P_{bc_{charge},max}$) will limit the down-regulation potential of the UPS, which can be calculated by the equation

$$\Delta P_{down} = \mathrm{MIN}(\Delta P_{r,max}\ ;\ P_{b_{charge},max}\ ; P_{bc_{charge},max}). \tag{5}$$

It should be noted that sizing of the upstream equipment (e.g. switchgear, transformer), could (at least in theory) limit ΔP_{down}, but as it is typically sized for the maximum UPS capacity, this is highly unlikely in a real-life situation.

3.2 Present lead-based installations (FCR-D/FFR markets)

3.2.1 Methods for the background work and simulations

In order to study the energy requirements of primary frequency regulation and the availability of that energy in current data center installations, a preliminary study was conducted.

The assumption was that data centers have a lot of excess battery capacity because of the redundancy requirements. The approach was to study common data center topologies (illustrated in Figure 5) and find out how much excess capacity they have by design.

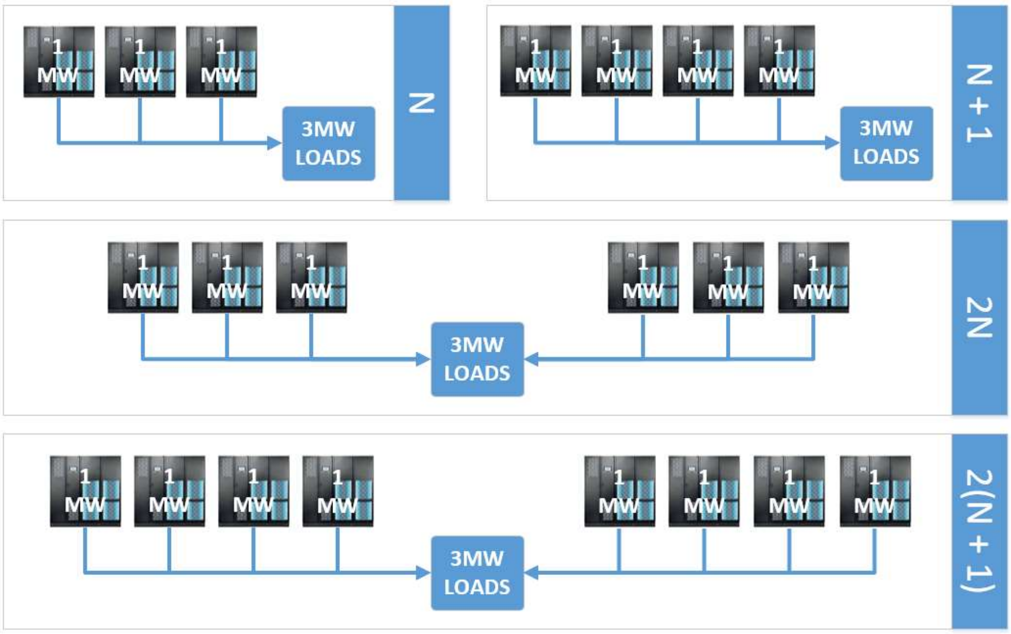

Figure 5. Typical UPS topologies in data centers (Trash, 2015), (McCarthy & Avelar, 2015).

In the study, the following assumptions were made:

- IT load (design load) was assumed to be 3 MW
- Battery autonomy requirement was assumed to be 10 min
- UPS unit size was assumed to be 1 MW

The second part of the study focused on defining the amount of energy required to perform the primary frequency regulation service (specifically FCR-D) according to the requirements of the Nordic power system. This was done by developing a C#-based simulation program that included historical frequency data, market rules, and battery system characteristics, and based on them, simulating the state of charge (SoC) behavior of the battery system. The simulation program was based on a previously developed program to analyze the wear and tear of mobile base station batteries (addressed in Chapter 4) and was specifically aimed to provide further confidence in the utilization rates of the battery systems (a simplified flowchart of the simulation program can be found in Appendix A).

One key research target was to determine the amount of additional stress exerted on the battery systems during FCR-D operations and its impact on their service life. The simulation results were compared against the performance characteristics of commonly used data center batteries. An example of such characteristics is the cycle life expectancy chart of the Sprinter XP battery by Exide/GNB in Figure 6.

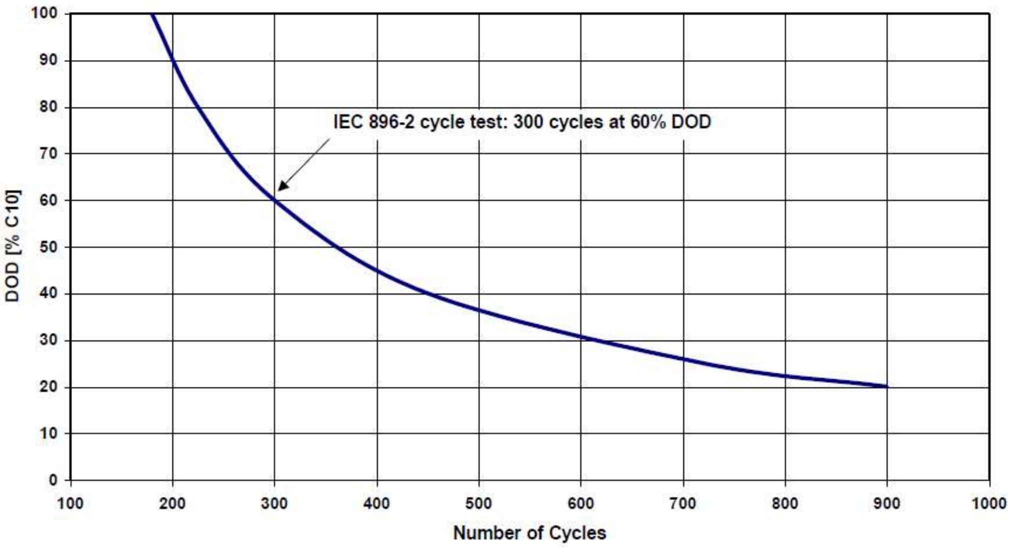

Figure 6. Typical battery cycle life expectancy chart for a valve-regulated lead-acid (VRLA), absorbent glass mat (AGM) battery (Sprinter XP form Exide Technologies), (GNB, 2016).

The simulation program was also modified to include historical market price data and a variable to set the minimum accepted market bid price level. Simulations with several price levels and aggregate combinations were run to gather data on how the set price level and size of the aggregate impact the number of charge/discharge cycles that the UPS batteries are subjected to and also how setting the price limit impacts the achievable revenue.

3.2.2 Results of the background work and simulations

Table 2 provides results of the excess energy investigation for different power protection topologies and example configurations illustrated in Figure 5. The last column shows that as the redundancy level increases from nonredundant systems (N) to parallel and redundant systems (2N+1), also the excess energy in the battery systems increases. This is natural, as the amount of hardware (UPSs and battery systems) increases significantly as the redundancy level increases, but the load and autonomy requirements remain the same. The table shows that the 2N+1 example configuration has a total amount of 1333 kWh of designed energy capacity, while the 10 min autonomy requirement (in normal conditions) with the full 3 MW can be met with 500 kWh, as shown by the equation below:

$$\frac{500\ \mathrm{kWh}}{3000\ \mathrm{kW}} = \frac{1}{6}\mathrm{h} = 10\ \mathrm{min} \tag{6}$$

Table 2. Excess energy amounts inherent to different UPS system topologies (examples).

Design Topology	Number of 1 MW UPSs	Total amount of energy in the battery systems [kWh]	Excess energy in the battery systems [kWh]
N	3	500	0
N+1	4	667	167
2N	6	1000	500
2N+1	8	1333	833

A simulation was run to identify the total energy requirement of the FCR-D activation events and the state of charge behavior of the individual battery systems. The system configuration under investigation was the N+1 configuration, made up of four 1 MW UPS systems according to Figure 5. The simulations were performed with the current Nordic FCR-D requirements and with year 2015 frequency data from the Nordic power system and data from the UK power system.

Figure 7 shows the output charts based on the data provided by the simulation program. The total energy requirement from the simulations is illustrated in Charts A (Nordic) and B (UK). The 167 kWh limit in the figures is the previously identified amount of excess energy capacity in the N+1 example case. Charts C (Nordic) and D (UK) illustrate the state of charge behaviors of the most stressed UPS batteries from the same simulations. The 42 kWh limit in the figures is the amount of excess energy per battery systems (167 kWh divided by four).

The results show that while there were some more energy-demanding events during the year 2015, the average energy demand of the reserve operations was limited, and even the highest demand peaks remained well below the 167 kWh limit; however, the simulation results also show that the limits for the individual battery systems were met several times during the simulated year 2015.

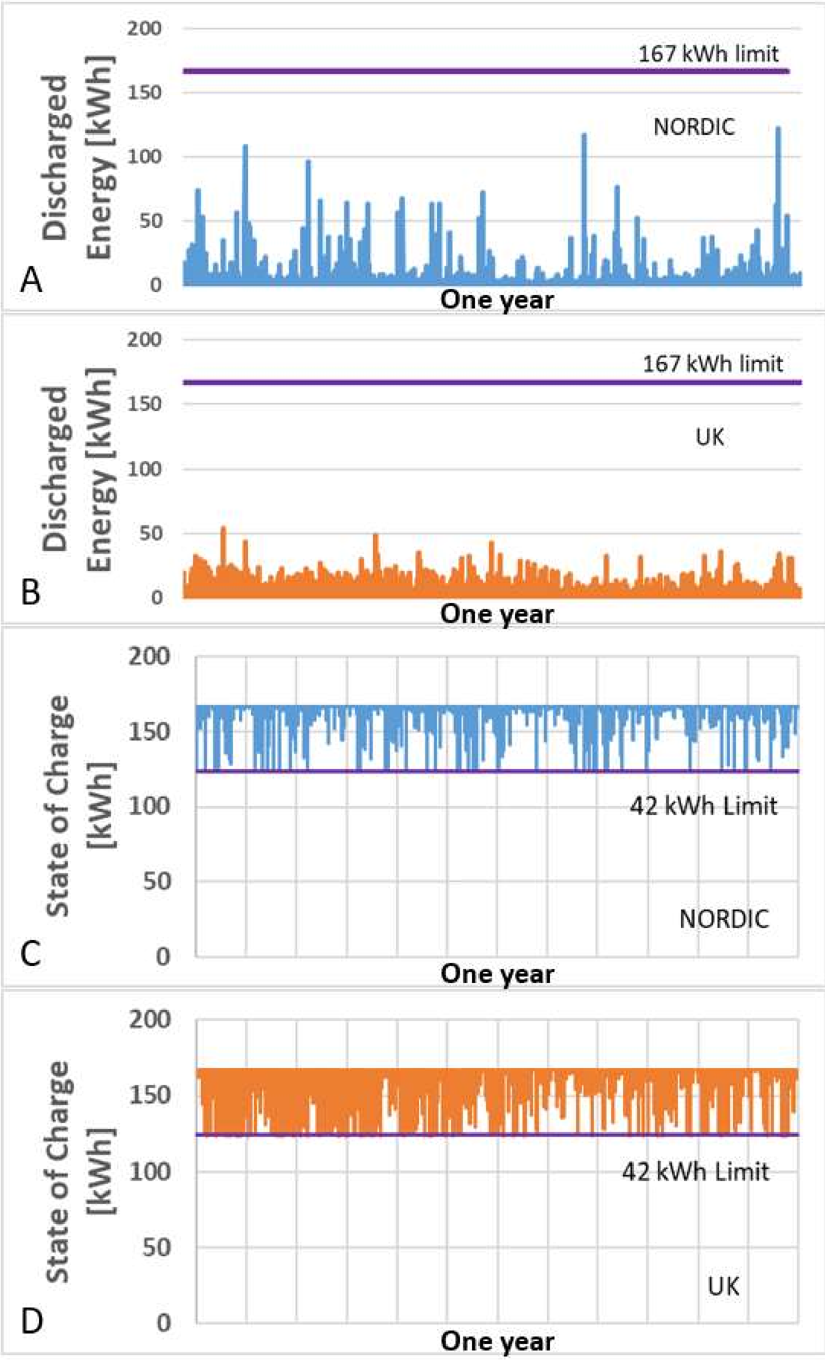

Figure 7. Simulation results for a N+1 (4 x 1 MW) UPS system, total discharged energy amounts with the year 2015 frequency data from the Nordic (A) and UK (B) power systems, and the state of charge profiles of the most stressed UPS batteries Nordic (C) and UK (D).

Further simulations were performed with different price limits and aggregate sizes to investigate their effect on the number of cycles that the battery system is subjected to. The price limits, aggregate sizes, and results (number of cycles for the most stressed battery systems) used in the simulations are gathered in Table 3.

The number of cycles was compared with the cyclic life expectancy characteristics of a commonly used UPS battery type (Figure 6). The depth of discharge (DoD) was limited to 42 kWh, which corresponds to 25% of the 167 kWh limit. Figure 6 shows that the cyclic life expectancy of a typical UPS battery with the DoD of 25% is 700 cycles.

Depending on the local grid stability, in the normal usage, the UPS batteries may encounter a few longer discharges and several shorter ones during a year of operation. This can be assumed to equal ten cycles with the DoD of 25%. The service lifetime expectancy of UPS battery systems normally ranges from seven to eight years. This means that with the expected ten effective annual cycles, the accumulated cyclic usage of UPS batteries (in good grid conditions) is expected to be in the range of ~80 cycles (DoD 25%).

As a result, the UPS batteries can be expected to handle up to 600 cycles of demand response usage in addition to the cycles resulting from the primary operation. This means that the annual (additional) usage should not exceed 75 to 85 cycles (calculated with the seven- to eight-year life expectancy). The colors in the cells of Table 3 illustrate the combinations where the usage stays within the boundaries and is expected not to affect the lifetime of the battery systems. The last column of the table shows the relative income, which is calculated by summing the revenue for all the hours when the market price was above the price limit. The results show that by imposing a price limit, the wear and tear could be controlled while maintaining a significant portion of the market revenue.

Table 3. Simulated number of charge/discharge cycles within one year, with different aggregate sizes, minimum bid prices, and the effect of minimum bid prices on the relative income.

Price limit	Aggregate size: 4 UPSs	Aggregate size: 20 UPSs	Aggregate size: 50 UPSs	Relative income [%]
No limit	205 cycles	130 cycles	122 cycles	100
5€/MW	140 cycles	86 cycles	81 cycles	94
10€/MW	72 cycles	45 cycles	42 cycles	83
15€/MW	58 cycles	37 cycles	34 cycles	79

As a reference, Table 4 provides the calculated revenue estimations for a 1 MW of FCR-D reserve in the hourly markets during the years 2015 and 2018. The revenue estimations have been calculated by

$$R_{est,m} = \alpha * \beta * 8760\text{h} * P_m \, , \tag{7}$$

where α is the bid acceptance rate (100%), β is the asset availability (95%), and P_m is the average market price. The full bid acceptance rate is used, as no price limit will be imposed on the bids.

Table 4. Calculated market income potentials for a 1MW FCR-D reserve unit (Fingrid, 2017).

Year	Average market price [€/MW/h]	Market income for a 1MW FCR-D reserve unit[k€]
2015	14.43	120
2016	5.15	43
2017	3.39	28
2018	5.31	44

3.2.3 Methods and results of laboratory experiments

Several laboratory experiments were performed as part of Eaton's R&D efforts, which included validating the functionality and performance of the UPS systems in demand response usage. Special attention was paid to ensure that UPS would be able to continue protecting the loads even in unexpected situations, including for example a loss of mains during back-feed for demand response purposes and a loss of battery system during demand response operations. The tests showed that UPS systems are able to handle these situations without interruptions in power delivery to the critical loads; however, as the development of the UPS demand response features is not in the scope of this work, the results will not be addressed in detail.

As reaction speed is one of the critical requirements of the selected demand response markets, several tests and measurements were performed to ensure that the UPS systems would meet the market requirements.

A test setup of one of the performed tests is illustrated in Figure 8. In the test, a 93PM UPS system by Eaton was powered from a three-phase AC grid and connected to a battery system and a test load. In addition, a test PC was connected to a CAN interface of the UPS and an oscilloscope was connected to measure the input voltage and current of phase 1 (indicated by the red dot in the figure), the output voltage and current of phase 1 (green dot), the battery current (blue dot), and the CAN signal (grey dot).

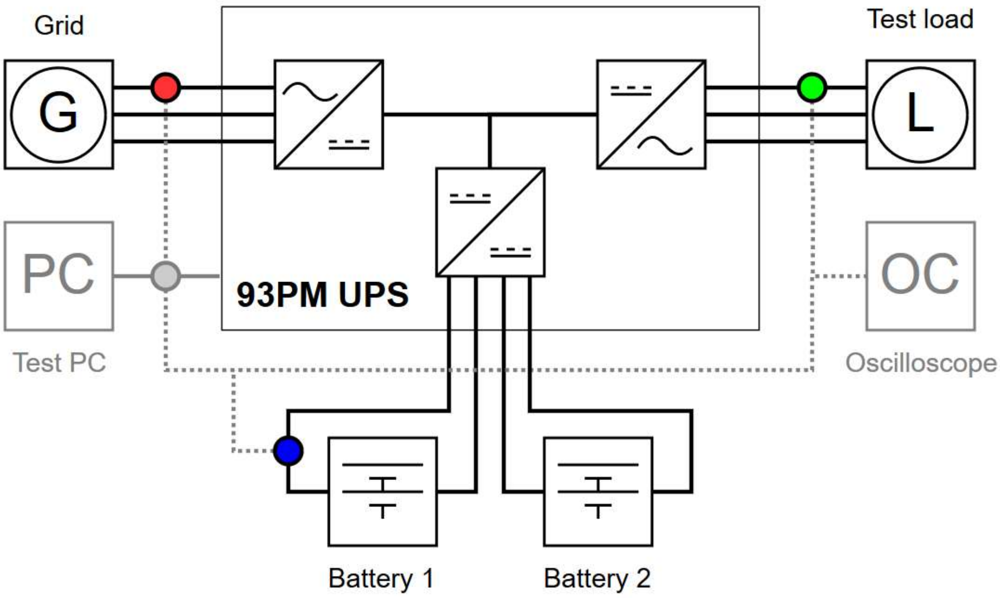

Figure 8. Test setup of reaction speed testing of the 93PM UPS system.

The objective was to see how fast the UPS would respond to a full activation signal given through the CAN interface. Before issuance of the command, the UPS was feeding 100 kW of power to the test load and after the command, the UPS was still feeding 100 kW to the load, but also back-feeding additional 100 kW to the suppling grid.

The results are presented in Figure 9. The figure shows an oscilloscope capture of the activation for the following signals:

- Input voltage (dark blue line)
- Input current (purple line)
- Output voltage (red line)
- Output (or load) current (green line)
- Battery current (cyan line, not in scale)
- CAN pulse (grey line)

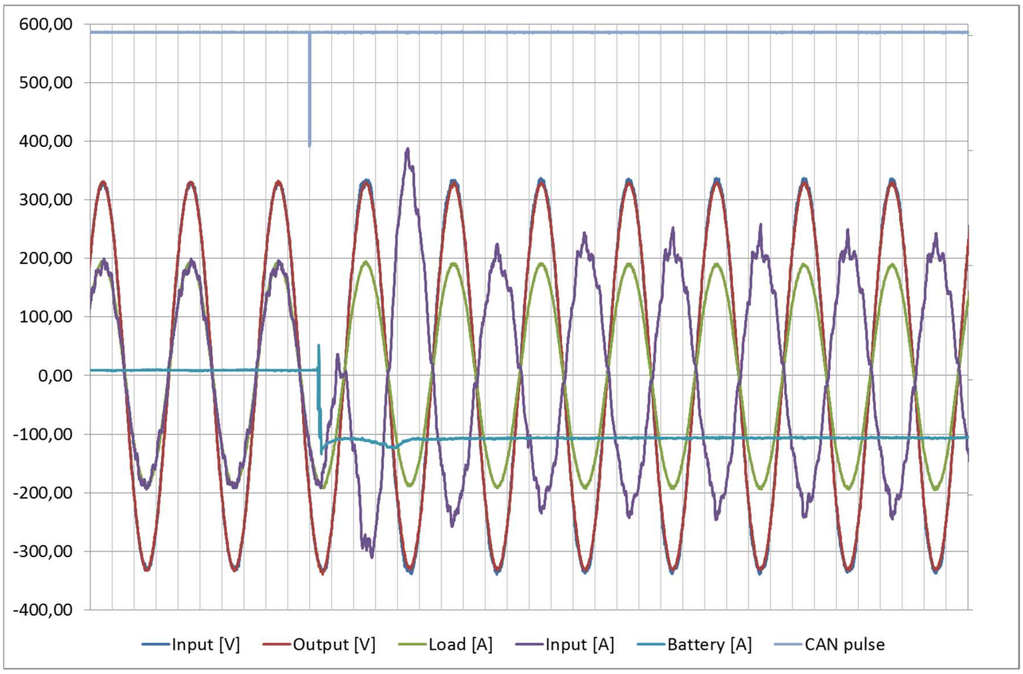

Figure 9. Results of the speed and reaction tests.

The horizontal axis in the figure represents time, and the major grid lines in the chart are presented with 5 ms steps. This can be observed from the 50 Hz oscillations in the voltage and current measurements in the input and the output. The measurements show that the battery current starts to decrease (meaning that current is drawn from the battery systems) in a few ms after the CAN pulse can be observed, and it stabilizes in approximately four steps (20 ms). The input current measurement exhibits a 180° phase shift indicating that the direction of the current changes, and instead of drawing power from the mains, the UPS system starts to back-feed. The change can be observed approximately at one step after the CAN pulse. The (input) current waveform is slightly distorted and overshoots during the first cycle but stabilizes within a few oscillations. In summary, the tests show that the reaction is extremely fast, the batteries start to output current in a few ms, and a steady state is reached in 50 to 100 ms.

3.2.4 Market pilots and results

In order to demonstrate the market viability of UPS systems in demand response, the technology was enrolled and accepted into two market pilots that took place during the year 2018.

The first project was an FCR-D market pilot for demand-side response/energy storages hosted by the Swedish transmission system operator, Svenska kraftnät (Svenska kraftnät, 2018). The second project was an FFR market pilot for demand response hosted by the Norwegian transmission system operator, Statnett (Statnett, 2018).

FCR-D pilot with Svenska kraftnät (SvK)

In the Swedish pilot, a 100 kW Eaton 93PM UPS was installed at Fortum's offices in Stockholm. The system was connected to the Fortum Spring cloud platform, which enabled gathering measurements and issuing market participation commands for the bid (and accepted) hours.

The pilot consisted of three phases:

1) Prequalification of the reserve asset according to the market requirements
2) Bidding and market participation phase
3) Data analysis and reporting phase

The system was prequalified on the 20th of February 2018, according to the FCR-D market requirements of Svenska kraftnät. The main part of the prequalification testing was a step response test where a frequency test signal was introduced to the DUT (device under testing) and the response was measured. The test program included five frequency steps, which could be given once a steady state had been achieved for the previous step; however, the test also required a 15 min dwell time after step 4 (49.50 Hz, full activation) to test that the DUT is able to meet the endurance requirement of the market.

Table 5 presents the applied frequency steps, expected percentages of responses for each step, and results for the stabilization times and power changes in different measurement points. The results show that the UPS responded fast and the response power was as expected. Further, the 15 min dwell time did not cause issues for the system. Figure 10 presents the same results in a graphical form.

Table 5. Applied test frequency steps and measurement results from the FCR-D testing.

Step	Frequency [Hz]	Expected response [% of full scale]	Stabilization time [s]	ΔP in 5 s [kW]	ΔP in 30 s [kW]	ΔP in 15 min [kW]
1	49.90	0%	<1	N.A.	N.A.	N.A.
2	49.70	50%	<1	46.7	46.7	N.A.
3	49.90	0%	<1	0.0	0.0	N.A.
4	49.50	100%	<1	100.4	100.3	100.1
5	49.90	0%	<1	0.0	0.0	N.A.

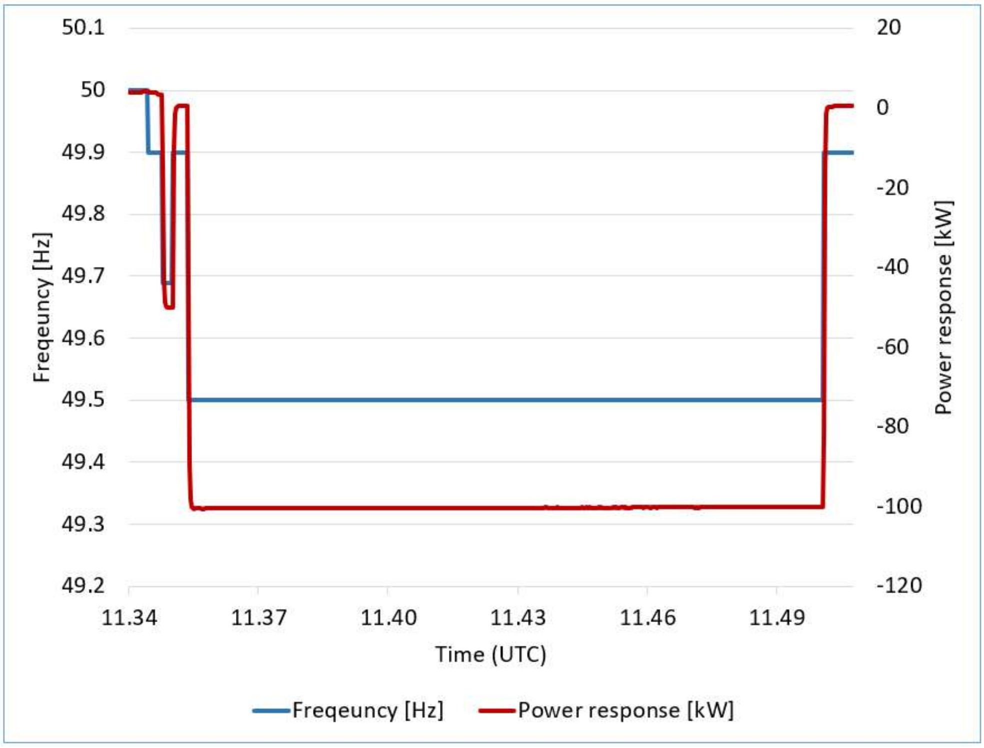

Figure 10. Measurements from step response testing during the SvK prequalification.

Figure 11 presents oscilloscope measurements that validate the reaction speed of the response to be similar to what was achieved in laboratory conditions.

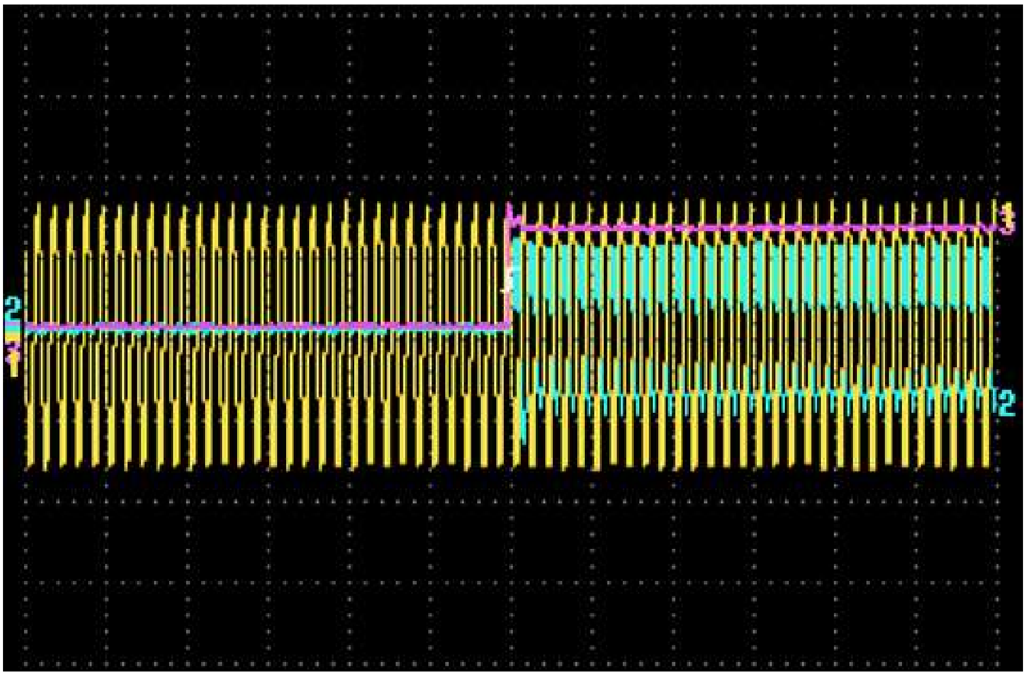

Figure 11. Oscilloscope capture of the UPS during a full activation event in FCR-D testing. The yellow line is the input voltage of the system, the blue line is the input current, and the purple line is the battery current. One horizontal step is 100 ms.

Once the prequalification of the UPS system was approved, market operations were started. During the pilot period, two control methods were tested; a local activation and a centrally controlled activation. In the local activation, UPS system uses internal frequency measurements as a reference for the activations, whereas in the centrally controlled approach, the cloud service of Fortum Spring gives direct power commands based on frequency measurements on Fortum's hydro production sites.

Market operations were performed between the 16th of March and the 30 of May of 2018. During this period the UPS reacted to several frequency events; one such reaction is illustrated in Figure 12. The graph shows that when the measured grid frequency went below the activation limit of 49.90 Hz, the UPS provided a linear response to the frequency deviation.

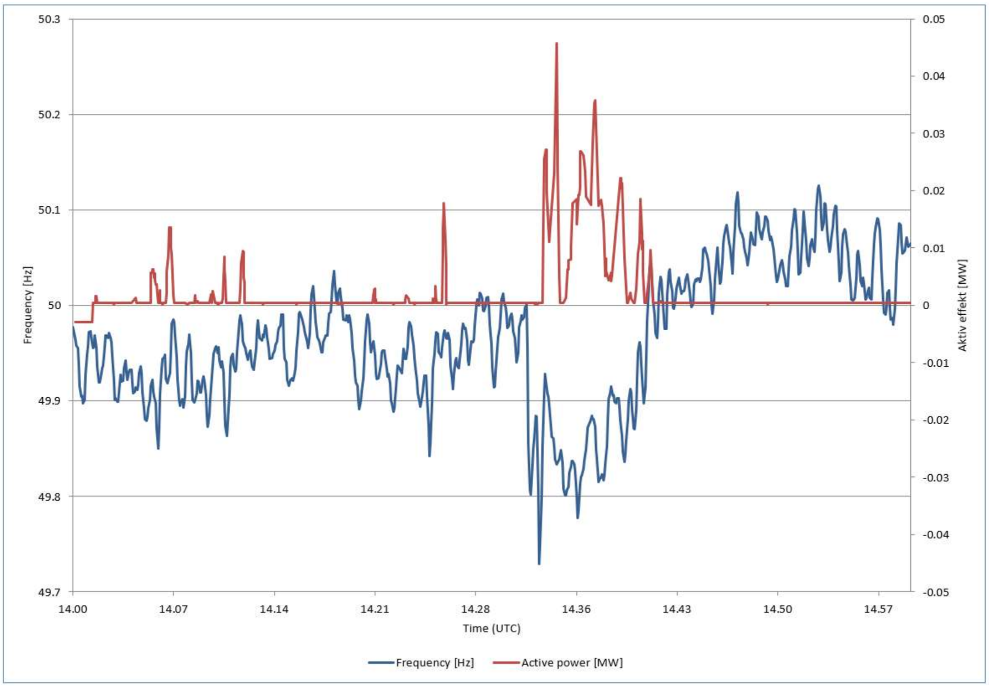

Figure 12. Capture of an FCR-D activation during the SvK pilot.

FFR pilot with Statnett

The Norwegian TSO Statnett hosted a pilot project for the FFR (Fast Frequency Reserve) service during the year 2018. The objective of the pilot was to investigate whether demand-side assets could be used to provide sufficiently fast power response to mitigate situations with low inertia in the grid.

Fortum Spring applied for and was accepted to a pilot with three UPS systems installed into two data centers of BaseFarm AS (a Nordic data center operator) in and near Oslo, Norway. Other accepted technologies were an aggregated fleet of electric vehicles, a hydro power plant, a pump storage, and smelters in aluminum production (Statnett, 2018).

The (pilot) market requirement was that the participating reserve unit would give a full power response within 2 s in case the grid frequency went below the activation limit of 49.60 Hz. The reserve unit should be capable of maintaining activation for 30 s (maximum response time).

UPSs 1 and 2 were 400 kW 93PM units, and UPS 3 was a 550 kW 9395P unit, all manufactured by Eaton. The 400 kW units were able to participate with full capacity (400 kW), but the 550 kW unit had to be limited to a 300 kW response to ensure that power would not be fed back to the distribution grid supplying the data center (as per request of Stanett).

The first part of the project was to prequalify the UPS systems against the pilot market requirements. Figure 13 shows the prequalification measurement results for the three UPS systems. In the tests, a test frequency signal was applied to the UPSs in a similar fashion to the SvK testing described previously in this chapter. The applied frequency signal was 50.0 Hz → 49.70 Hz → 49.60 Hz → 49.00 Hz → 50.00 Hz.

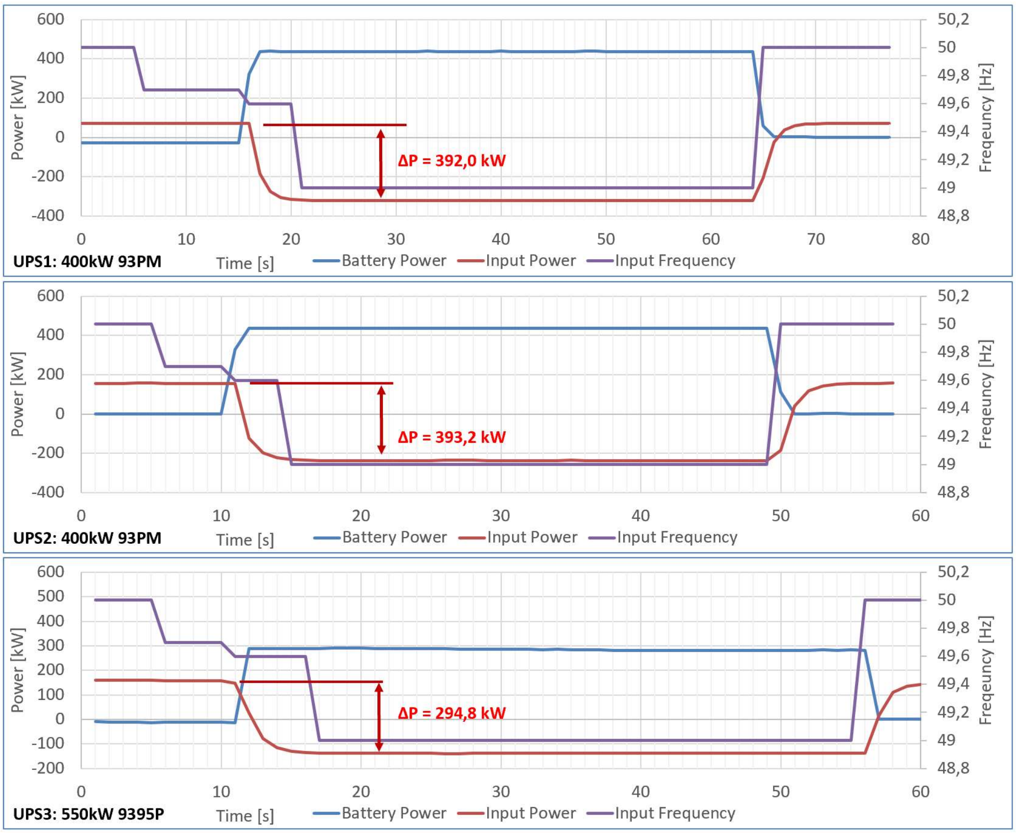

Figure 13. Measurements from the prequalification of the three UPS systems.

Figure 13 illustrates the measurement charts of the battery and input power and the test frequency and shows that all the three UPS systems reacted at step 2 (49.60 Hz), and their steady-state responses were measured to be:

- 392.0 kW (UPS1)
- 393.2 kW (UPS2)
- 294.8 kW (UPS3)

However, the measurements seem to show that there is significant slowness in the power response of the UPS systems. The slowness is explained by the measurement method used in the UPSs to measure the powers. The method uses averaging over a set period of time and is, therefore, not optimally suitable to measure fast dynamics. There is a slight difference in the measurement method for the battery system power and the input power, which explains why the battery power measurement is more “responsive.”

This limitation was known, and to ensure and validate that the actual response would be within the tested technical requirements (100% reaction within 2 s for the frequency disturbance), an oscilloscope was connected to the UPS systems to record the dynamics of the response. The oscilloscope was used to measure the battery input (phase 1) currents of the UPS systems during the activation. Figure 14 shows the charts from the measurements, the yellow line being the input current and the blue line the battery system current. The upper left chart depicts the measurement result from UPS1, the upper right chart represents UPS2, and the bottom chart UPS3. One horizontal step is 100 ms in each of the charts. It can be clearly observed that the response is extremely fast for the UPSs 1 and 2, and a steady state is reached well within one step (response time << 100 ms). The response from UPS 3 takes longer, approximately six steps, to stabilize from the moment at which the reaction started, but still, the response time (≈ 600 ms) is well within the tested market requirement of 2 s. Different reaction times are explained by different types of internal controls on the different UPS types (UPSs 1 and 2 are of the 93PM type while UPS3 is of the 9395P type).

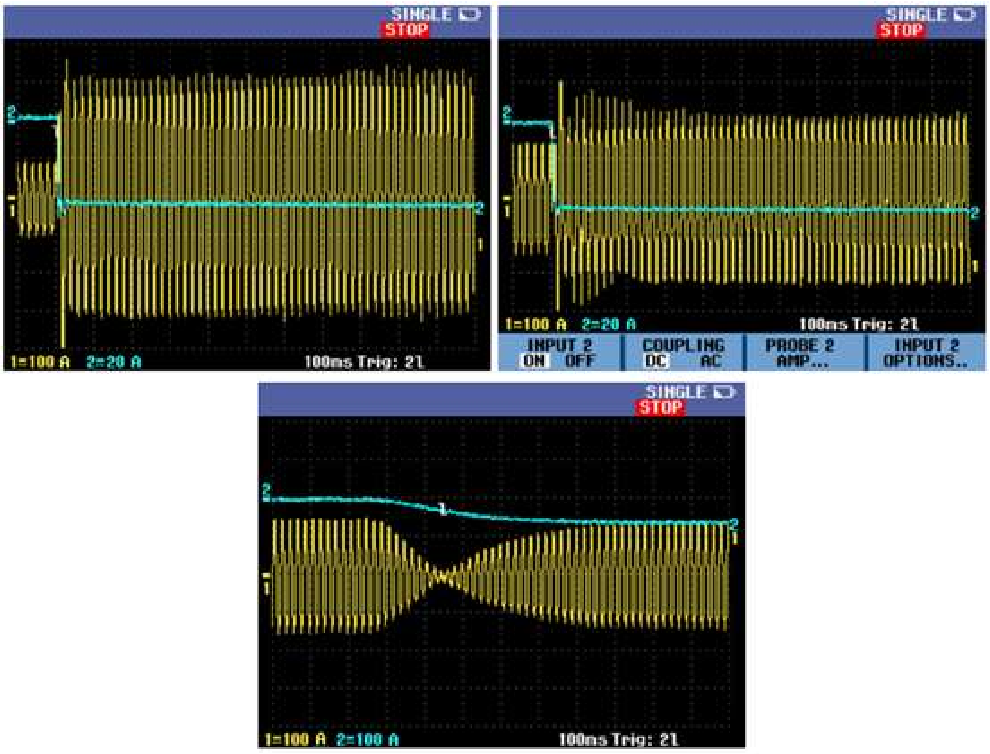

Figure 14. Oscilloscope captures of the battery (blue) and input currents (yellow) of UPS1 (top-left), UPS2 (top-right), and UPS3 (bottom) during FFR reserve testing.

After the prequalification was accepted, the UPS systems participated in the market pilot for four weeks in July–August 2018. During that time, there were two concurrent incidents at Olkiluoto, a Finnish nuclear power plant with two reactors (OL1 and OL2). These incidents caused disconnections of both reactors on the 18th of July 2018. OL2 disconnected at 08:57 (GMT +3) and OL1 at 21:39 (GMT+3) (Fingrid, 2018).

The sudden loss of generation was observed throughout the whole synchronous Nordic power system. The first event caused a frequency dip that was measured by the UPS systems to be 49.57 Hz, whereas during the second event, the lowest measured frequency was 49.61 Hz.

The first event caused activation of the FFR reserve functionality in the UPSs. Figure 15 illustrates the total power response and averaged frequency measurements from all three UPS systems. The chart shows that the UPS systems responded by reducing the grid loading with ~1MW. Unfortunately, because of the above-mentioned reasons, the true reaction time is again not visible from the UPS measurements.

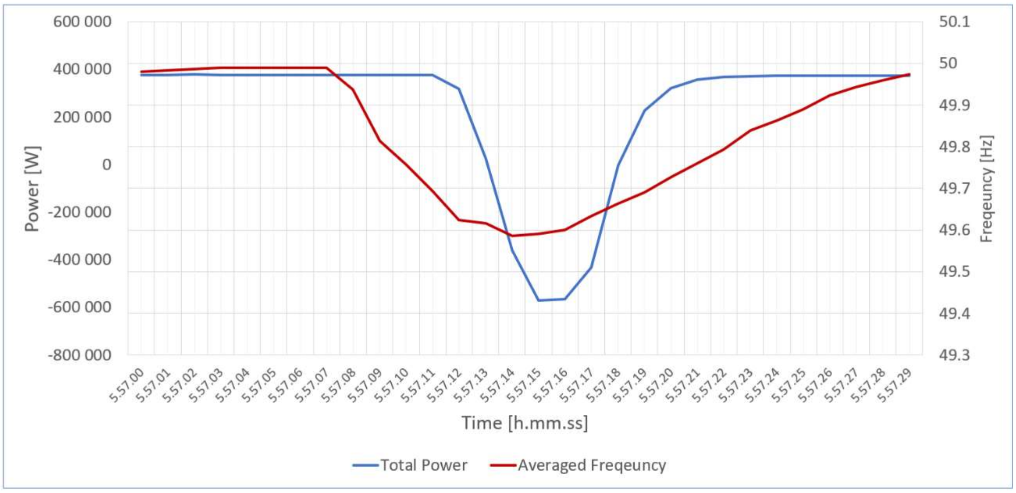

Figure 15. FFR activation of the three UPS systems during the unplanned outage of the Olkiluoto nuclear power plant.

3.3 Data center UPS as a platform for BESS (FCR-N markets)

The starting assumption was that the data center infrastructure and battery energy storage systems (BESS) are mostly constructed by using similar components or at least components that serve similar purposes. The assumption is clarified in Figure 16, which compares components of a BESS- (left) and a UPS-backed-up electricity feed (right). According to the concept, data centers could potentially be good locations to install larger Li-ion battery systems that would utilize the data center infrastructure and would thus offer significant cost benefits over building dedicated battery energy storages.

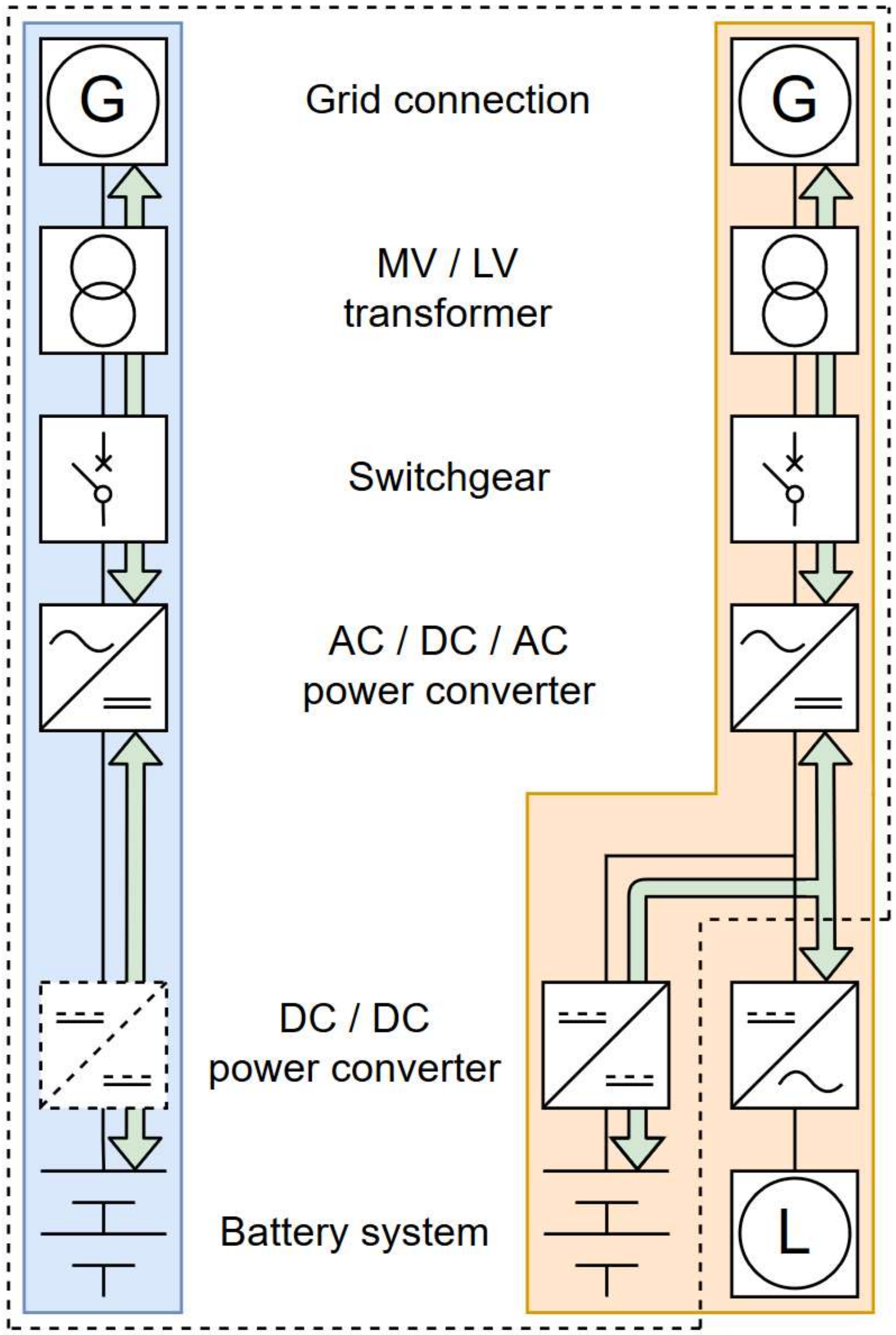

Figure 16. Similar components of the BESS- (blue background) and UPS-backed-up electricity feed (orange background).

3.3.1 Methods of the feasibility analysis

The concept is addressed by studying an example data center setup and analyzing the financial feasibility of the investment case. The example setup is illustrated in Figure 17. The base case (shown on the left) is a typical setup with four 1 MW UPS systems feeding a designed load of 3 MW. The setup is an N+1 topology. This means that under normal circumstances there is (by design) 1 MW of power capacity that is not utilized.

Each of the UPSs is backed up with an 83 kWh (or 5 min autonomy) VRLA battery system. The objective is to study whether an investment in a significantly larger Li-ion battery system would yield positive results with additional income from the FCR-N market. A 1C power to energy capacity ratio requirement is assumed (currently a typical market requirement), and as such, the combined Li-ion capacity (Figure 17, right) of 1.333 MWh is considered. 333 kWh of this would be reserved for backup operations (5 min at full power of 3 MW), leaving 1 MWh available for reserve market usage.

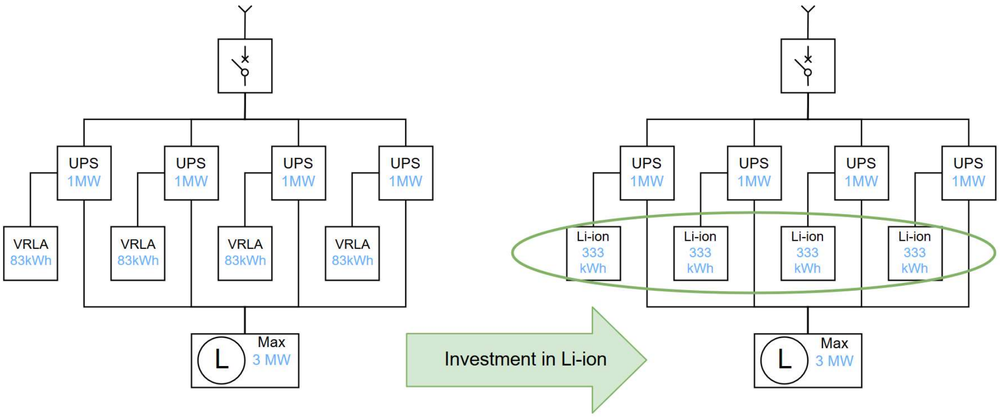

Figure 17. Example data center UPS setup, with a 5 min VLRA battery (left) and dual-purpose Li-ion battery setup (right).

The financial feasibility of the concept is compared against the feasibility of a stand-alone BESS of similar power and capacity (1 MW/1 MWh). The BESS costs are estimated according to the cost structure presented in Table 6 starting from an assumed battery pack cost of 400 €/kWh. For the data center, a slightly higher battery pack cost of 450 €/kWh was used to compensate for the potential added costs of installing four separate battery systems (to four UPSs) instead of one larger system.

Table 6. Cost structure of a 20 MW/20 MWh battery energy storage system project (Rubel et al., 2017).

Cost component	Proportion (%)
Project development	10
Engineering, Procurement, Construction (EPC)	19
Integration	18
Management software	5
Power conversion system (PCS)	13
Battery packs	35

The financial feasibility is investigated by calculating the net present value (NPV) of an example data center and BESS setups in three different markets (Finland, Germany, and UK). The calculation was made using

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_0 \, , \tag{8}$$

where C_t is the net cash inflow during time period t, C_0 is the total investment costs, r is the discount rate (8%), and T is the number of time periods (10 years).

The revenue estimation used as a parameter in the net cash inflow (along with operational expenses) is calculated by (7) that was already previously presented. In the calculation, α is the bid acceptance rate (70%), β is the asset availability (95%), and P_m is the average market price. The average market prices used in the calculations can be found in Table 7, which also gives the calculated revenue estimations for each market in the final column.

Table 7. Average market prices and annual revenue estimation for primary frequency regulation reserves in different markets in 2016 (Fingrid, 2017), (National Grid, 2017), (Regelleistung.net, 2017).

Market	Local product name	Avg. market price [€/h/MW]	Revenue estimation [k€/a]
Finland	FCR-N	23	134
United Kingdom	EFR	12	70
Germany	PCR	16	93

Saulny (2017) lists the following items as the OPEX components of a BESS: energy compensation and imbalance costs, trading and development, operation and management (O&M) on site, transmission costs and taxes, electrical losses and auxiliary power, and an "uncertainty buffer." For a 2 MW/1 MWh system, the OPEX costs were estimated to be in the order of 32 k€/a (Saulny, 2017). As most of these costs are power related, the costs for a 1 MW/1 MWh system can be assumed to be roughly 20 k€/a. For the purposes of this study, the operational costs can be assumed to be the same in both cases, and as such, the exact amount of OPEX costs does not affect the outcome of the analysis.

3.3.2 Results of the feasibility analysis

Table 8 illustrates the costs related to the building of a UPS-based BESS in comparison with a stand-alone system. The figures in the table show that the CAPEX in the example case is 52% of the CAPEX of the stand-alone case. This is quite logical as the starting assumption was that several cost components would not be factoring in the total costs of the UPS-based BESS as they are actually part of the data center infrastructure.

Table 8. Example of a cost breakdown for a 1 MW/1 MWh BESS system and a Li-ion UPS battery system.

Cost component	Stand-alone BESS (k€)	UPS-based BESS (k€)
Project development	114	-
Engineering, Procurement, Construction (EPC)	217	-
Integration	206	-
Management software	57	-
Power conversion system (PCS)	149	-
Battery packs	400	600
SUM	1143	600

Figure 18 presents the NPV calculation results for three different geographical locations; the topmost chart is for a project in Finland, the middle chart for a project in Germany, and the bottom chart for a project in the UK. The results show that data-center-based projects are more feasible than a stand-alone battery energy storage system project. However, based on the calculation, only the data-center-based project in Finland makes financial sense and has a payback within the technical lifetime of the installed systems.

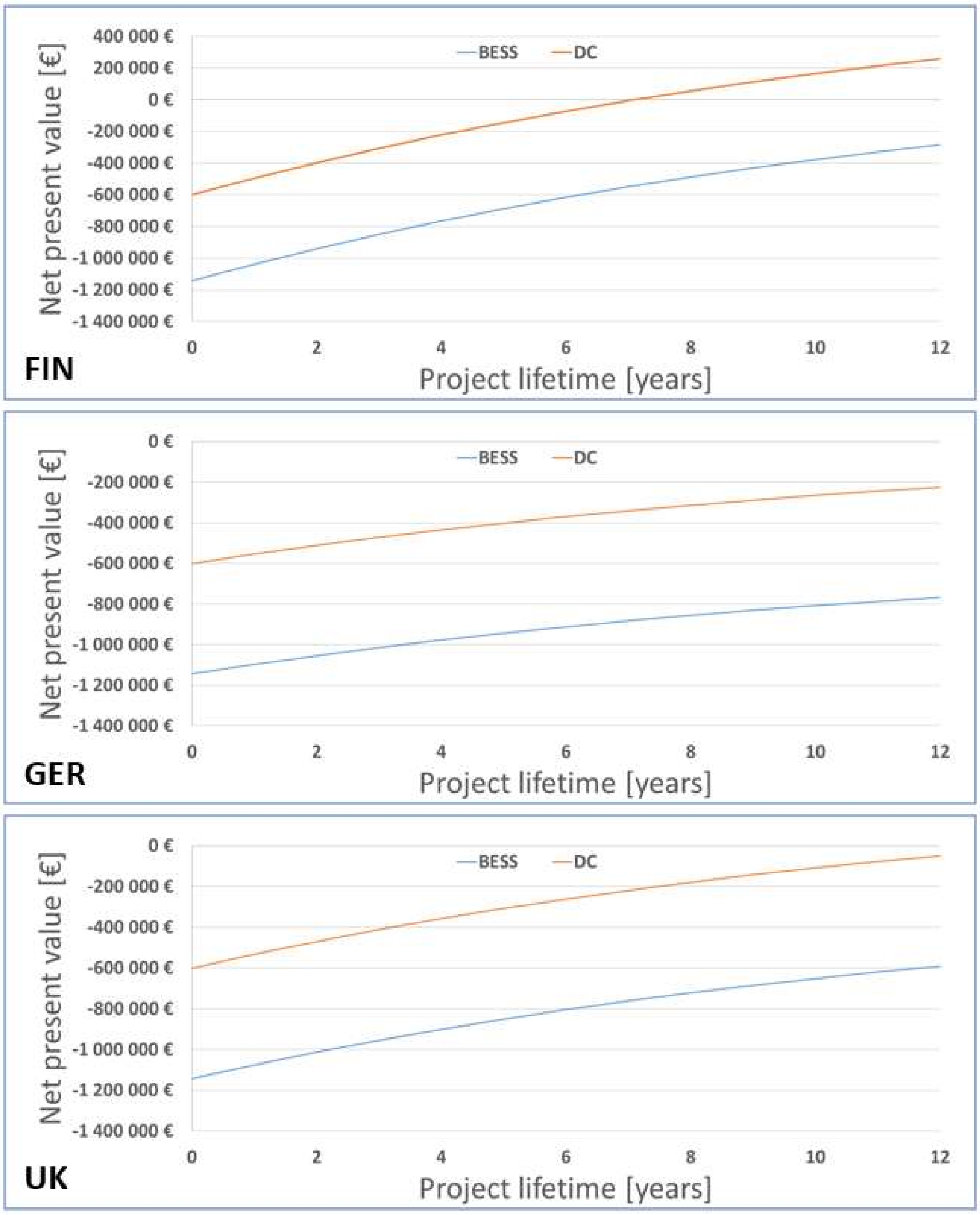

Figure 18. Net present value (NPV) calculation results for data-center-based battery storage systems (orange line) and battery energy storage systems (blue line) for Finnish (upper), German (middle), and UK (lower) markets.

3.3.3 Pilot project

A pilot project on Li-ion batteries and a data center operator has been announced. In the project, an Oulu-based data center operator, Aurora DC Finland Oy, has agreed to pilot the concept with Fortum.

The project aims to install two ~50kWh Li-ion battery systems into Aurora DC's green field data center. The battery systems will be connected to two 200 kW 93PM UPS systems by Eaton. In the pilot, Fortum owns the battery systems and offers Aurora 5 min of battery capacity from each of the systems with a service-level agreement (SLA). The rest of the battery capacity will be used to provide 100 kW of FCR-N service for Fingrid. The concept is illustrated in Figure 19. The schedule is to have the battery systems and the UPSs installed during the summer of 2019.

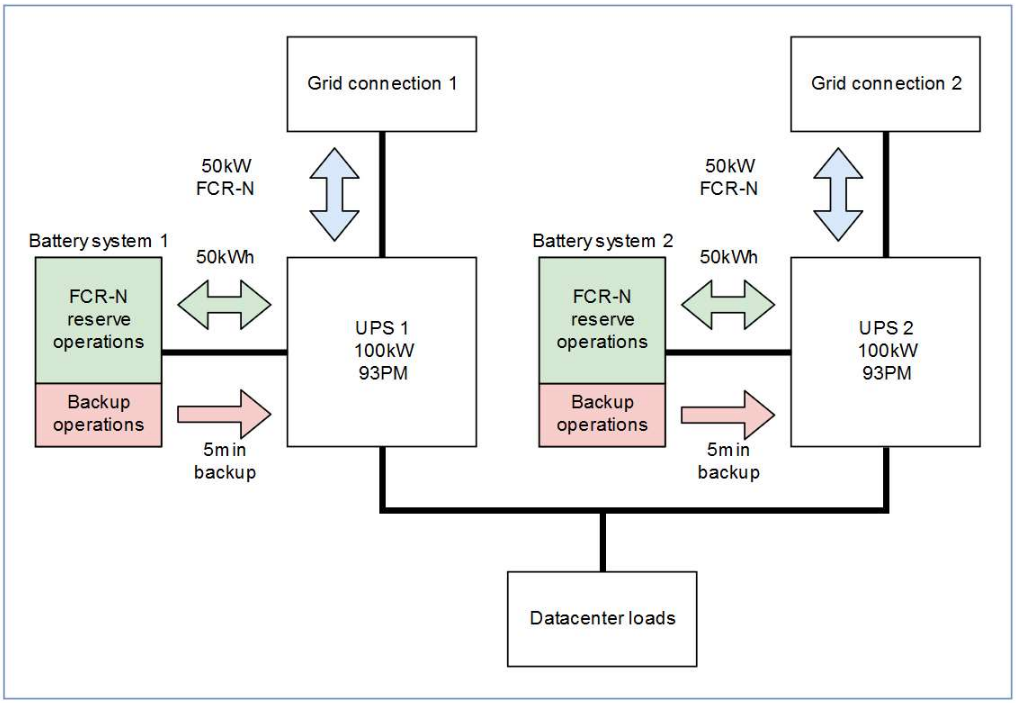

Figure 19. Conceptual drawing of the Li-ion UPS pilot with Aurora DC.

3.4 Discussion

The chapter provided answers to the following research questions (in relation to UPS systems):

1) Can existing battery systems (and the related power protection systems) be used to provide grid services in a technically and economically feasible manner?
2) Can the existing power protection infrastructure (for example in data centers) be used as a "platform" for battery energy storage systems, and what are the limitations and benefits of the approach?
3) Can UPS systems be used to provide fast frequency response (FFR) services?
4) What are the boundary conditions and limiting factors in the above-mentioned cases, and what is their impact on the primary purpose of the systems?

As the results show, UPS systems are technically suitable for providing grid services (specifically FCR-N and FCR-D). Based on the research, typical installations for example in data centers have ample amounts of excess capacity that could be well utilized in the FCR-D reserves as they require limited amounts of energy. Further, the reaction times are suitable for even the fastest reserve types such as the upcoming FFR service.

Depending on the reserve product and the bidding strategy, the effects of grid service participation on the service life of battery systems are shown to range from high (participation in the FCR-D without any price/bidding limit) to basically nonexistent (FFR). Moreover, the effects of the FCR-D participation can be significantly reduced to a level where the additional stress would not affect the service life of the battery systems. This can be achieved by imposing a minimum price limit on the bids. However, optimizing the additional battery stress and the market income will require expertise in the electricity and balancing markets.

In this chapter, technical limitations and boundary conditions were identified in Section 3.1 for both the current (VLRA-based) installations and potential Li-ion-based future installations. Further, the business case analysis showed that under the assumptions, an investment in data-center-based BESS would yield financial benefits over stand-alone installations. However, it should be noted that in the example calculation and the first pilot project, the battery systems were significantly oversized compared with the backup requirements of the data centers. A more economically feasible approach could be to install only a small amount of excess energy capacity to provide the first response to frequency deviations, while having slower (production) assets to back up the energy need (e.g. hydro power). At the moment, assets from production and consumption balances cannot be combined into the same aggregate, but this should be possible in the near future. Fingrid has indicated that it is planning to move to a one-balance system during the year 2020 (Fingrid, 2019).

The pilot projects included in this chapter (FCR-D project with SvK and FFR with Statnett) both yielded very positive results, and both of the TSOs highlighted in their published reports that UPS systems (and data centers) would be highly potential candidates to provide the services.

Data center business is growing at a significant speed, driven by the increasing amount of data enabled by the developments in the ICT (e.g. pending implementation of 5G). Currently, data centers already account for 3% of the global electricity demand, and energy efficiency is among the key items in the agendas of the industry. Heat recovery is gaining general acceptance, especially in the Nordic countries (owing to the existence of heating networks). Demand response is also gaining in significance, and the research conducted in this study assists in enabling more data centers to participate in the grid support markets.

The upcoming FFR services are especially interesting as they require basically no additional investments from the data centers (apart from potential additional metering equipment), and activations will not affect the service life of the systems, nor have any marginal costs.

4 Telecommunications power system demand response

The research around the topic of using telecommunications equipment for demand response is divided into three subcategories: simulation and feasibility background work, laboratory experiments, and piloting with the actual equipment of a Finnish telecommunications operator. This chapter describes the methods used in the study and the achieved results. The subject is covered in Publication IV.

4.1 Feasibility background work and simulations

The objective was to find out whether the current and widely applied telecommunications equipment and the available capacity could be used for demand response. The primary objective was to study the feasibility of providing FCR-D service with the assets.

4.1.1 Methods

The assumption was that current battery capacity installed at the base stations far exceeds the requirements imposed on the telecommunications operators by the regulatory authorities. A further assumption was that by nature, the FCR-D service requires a limited amount of energy when activated.

To test these assumptions, a preliminary study was conducted. In this study, the power protection equipment (rectifiers and battery systems) and power consumption of several dozens of mobile base station sites were investigated.

Additionally, a simulation program was developed to analyze the amount of energy required to perform FCR-D operations with a number of aggregated base stations. The same program was also used to provide information on the additional wear and tear that the battery systems are subjected to. A simplified flowchart of the simulation program is presented in Appendix A.

The program inputs were the characteristics of the power protection systems (battery capacity and charge current), average telecommunication load, number of aggregated base stations, FCR-D market rules, some simulation parameters, and actual frequency data from the Nordic power system. One of the main simulation parameters was the "forced recharge," a parameter that was used to indicate how long the battery system would stay in a "partial" state of charge (in reality as the depth of discharge was so shallow, the battery system state was idle at very close to full charge). Two values of forced recharge were used in the simulations, 24 h and 48 h, indicating that each battery system would be fully charged either 24 or 48 h after initially being discharged. As an output, the program provided simulated state of charge profiles for each of the base stations in an aggregate and a count of number of activations for each base station. The assumed values used in the simulations are gathered in Table 9.

Table 9. Assumed values used in the simulations.

Parameter	Value
Base station load	5 kW
Battery capacity	15 kW (3 h autonomy)
Battery charging power	1 kW
Time resolution	5 s
Number of base stations in the aggregate	20 | 50 | 200 | 2000

4.1.2 Results

In the preliminary study, it was found that base stations have significant amounts of excess battery capacity. The calculated autonomy times of the sites in the study ranged from 3 h 16 min to 7 h 12 min. According to the discussions with the telecommunications operator, the sites in the study are typical examples of its facilities, and it is thus plausible to conclude that similar excess capacity can be found on other sites as well.

The simulation results showed that the impact of performing FCR-D service with base station battery systems has a very limited effect on the autonomy time of the base stations. Figure 20 presents a chart of the state of charge (SoC) behavior of the most stressed battery system in the aggregate when the simulation was performed against the grid frequency data of 2016. The chart shows that the battery system encountered several events during the simulated year, and the maximum amount of energy drawn from the battery system during an individual event resulted in roughly a 0.2% reduction in the SoC of the battery system. The results indicate that the autonomy time of the individual base stations would be practically unaffected by participation in FCR-D operations. The result is well in line with the expectations as the activations of FCR-D service require limited amounts of energy.

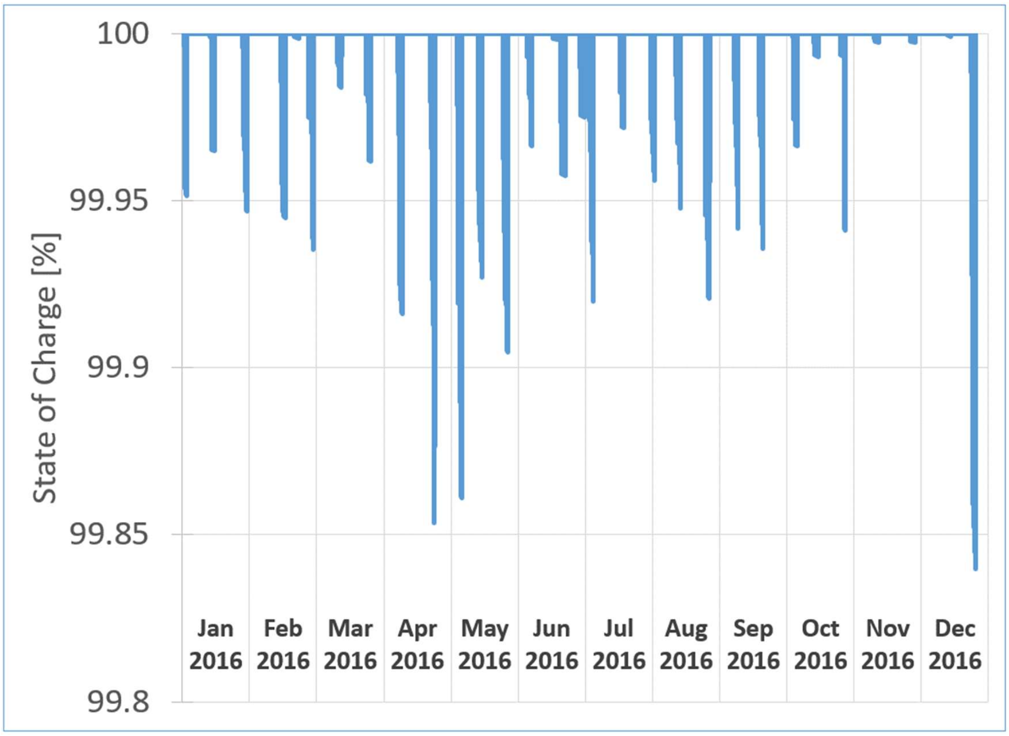

Figure 20. State of charge behavior of the most stressed battery system with the 2016 frequency data and one-day forced recharge.

The simulation also showed that the number of activations for individual base stations remains under reasonable levels, and thus, participation in the FCR-D service is not expected to impact the service life of the battery systems.

Several simulations were run with different forced recharge times (one and two days) and aggregate sizes (20 | 50 | 200 | 2000) and frequency data of different years (2015 and 2016). The results are illustrated in Figure 21, which shows the highest and lowest numbers of charge/recharge cycles during the years of 2015 and 2016 with different aggregate sizes and forced charge parameters. The results indicate that the forced recharge parameter will have a significant impact on the number of cycles, which is quite logical as the amounts of required energy are small and the recharge limits (SoC) are not reached.

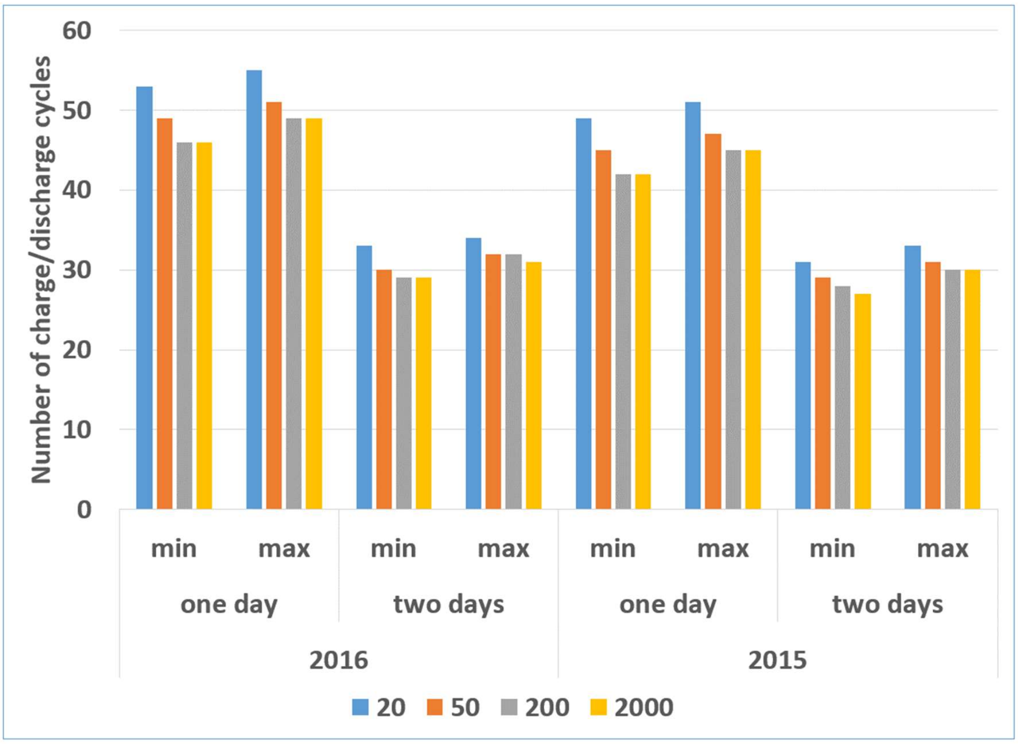

Figure 21. Minimum and maximum number of charge/discharge cycles for different aggregate sizes and maximum activation durations, based on 2015 and 2016 frequency data.

The aggregate size will have a small impact on the number of cycles that the individual battery systems will encounter. This is mostly due to the increased granularity of the aggregate. This is also supported by the fact that there seems to be not much difference between the results of the 200- and 2000-unit aggregates. Table 10 illustrates this point with an example of a 1% percent activation (from the bid size). The table shows that with a more granular array of devices, the aggregated response can be more optimally matched to the grid requirement (i.e., 1% of the aggregate power will be used to provide the required 1% power response).

Table 10. Example of the granularity of the aggregate.

Aggregate size	Bid size [kW]	1% activation [kW]	Activated devices/total number of devices	
20	100	1	1 / 20	5%
50	250	2,5	1 / 50	2%
200	1000	10	2 / 200	1%
2000	10000	100	20 / 2000	1%

4.2 Laboratory experiments

4.2.1 Method

As reaction speed is one of the key requirements of the FCR-D service, it was important to find out how fast the current power protection equipment could react to outside control signals. The current FCR-D service requirement states that the reserve unit must react with 50% of the power within 5 s of the frequency disturbance and must be fully activated (100% reaction) within 30 s (Fingrid, 2017). The specified power frequency relation is further illustrated in Figure 22.

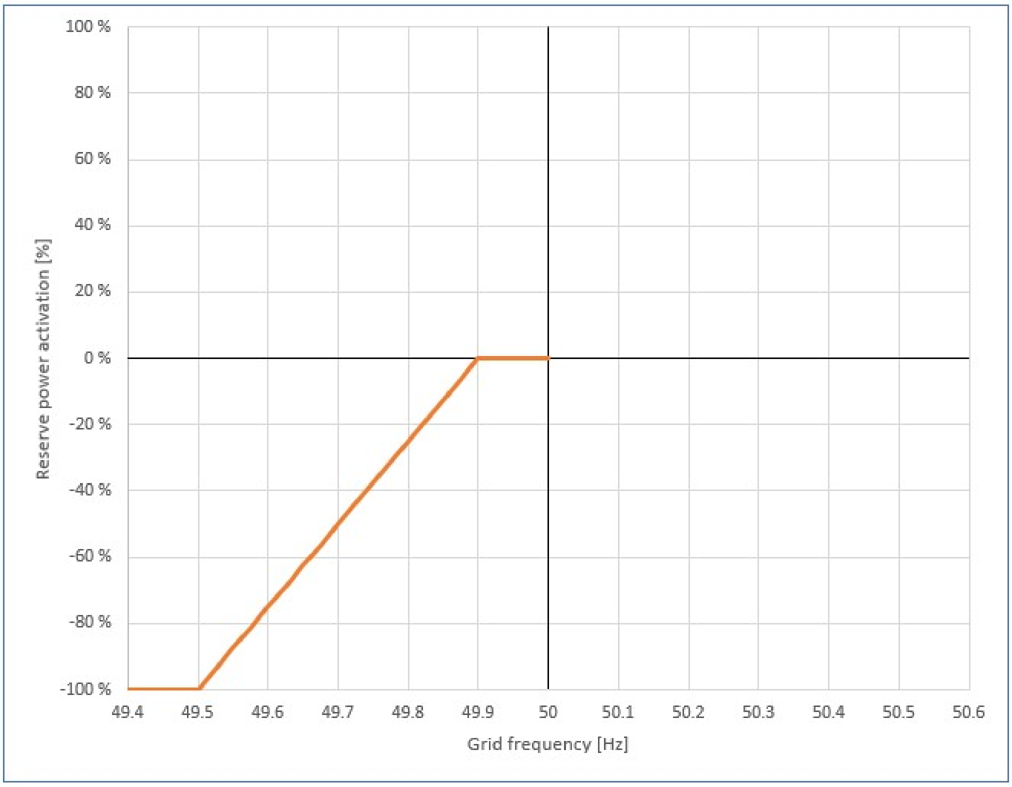

Figure 22. Required FCR-D-activated reserve power, in relation to grid frequency.

A simple setup consisting of a rectifier, a resistive load bank (to simulate the telecommunications loads), and a 48 V battery system was constructed. The rectifier had an Ethernet interface. A laptop computer was connected to this interface, and an SNMP (Simple Network Management Protocol) program was used to send commands to the unit and to receive measurements. The concept was to use the inbuilt battery test functionality of the rectifier to achieve the response (i.e., reduction in the input power drawn by the setup by diverting the loads from the grid-fed power to the battery power). The rectifier achieved this by reducing its output voltage below the voltage of the battery system so that loads would then draw current from the battery system instead of the rectifier. Figure 23 illustrates the test setup and power flows during regular and demand response operations. An SNMP command to start the battery test was sent from the laptop and the response was observed from the input power measurements gathered by the same SNMP protocol. The test was repeated several times, and the results were analyzed and averaged.

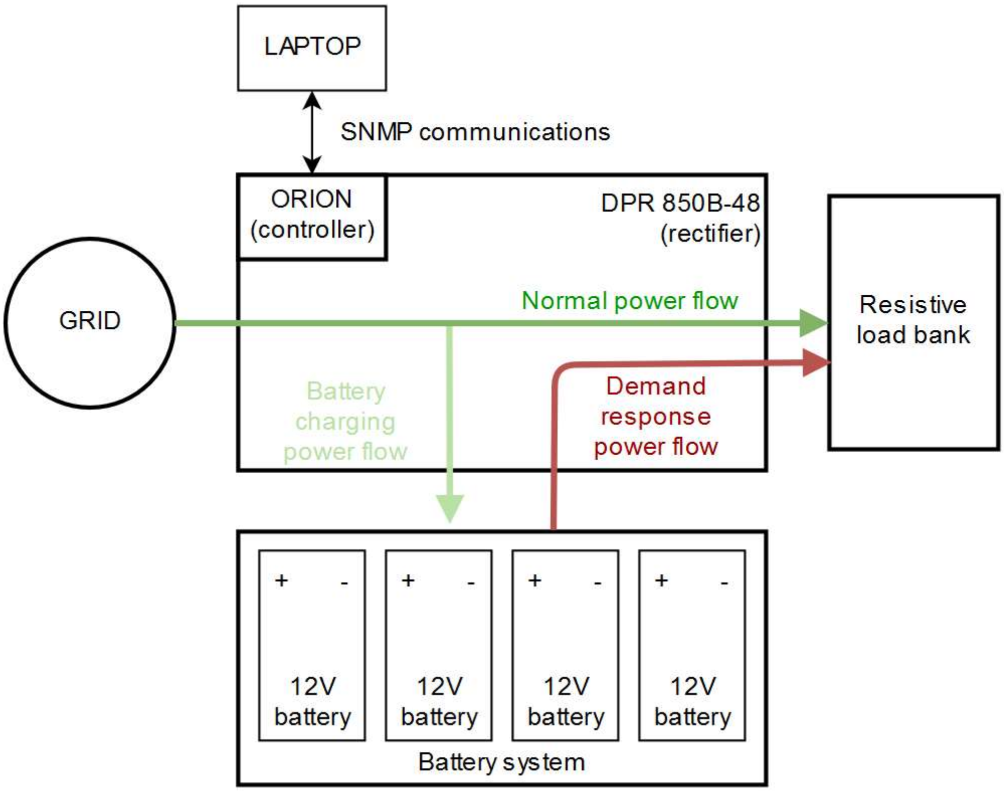

Figure 23. Laboratory setup and power flows during normal and demand response operations.

4.2.2 Results

The reaction time was observed to be 3.75 s on average to reach a 50% reduction in power. This was slower than expected and explained by the fact that the rectifier had an inbuilt limitation of how fast the output voltage was reduced when the battery test was initiated. 100% activation was always reached well before the 30 s limit, on average in 6.6 s. The results for ten consecutive tests are gathered in Table 11.

Table 11. Results of the local activation speed testing.

Test #	50% reduction [s]	100% reduction [s]
1	4.4	7.3
2	3.5	5.4
3	3.0	7.0
4	3.6	6.6
5	4.4	6.5
6	3.7	7.8
7	2.7	5.2
8	4.5	6.6
9	3.3	5.1
10	4.4	8.4

4.3 Pilot case

In the pilot, a simple communications gateway device was installed to dozen base stations in the capital region of Finland. The device enabled centralized control of the base station assets from a cloud platform (the setup is illustrated in Figure 24). The gateway used SNMP communications towards the rectifier and protected 2G communications towards the cloud platform that was used to issue the commands and gather and store the measurements. An activation command was sent by the cloud platform to all the systems simultaneously, and the response was observed from the incoming measurements (reduction in the input power).

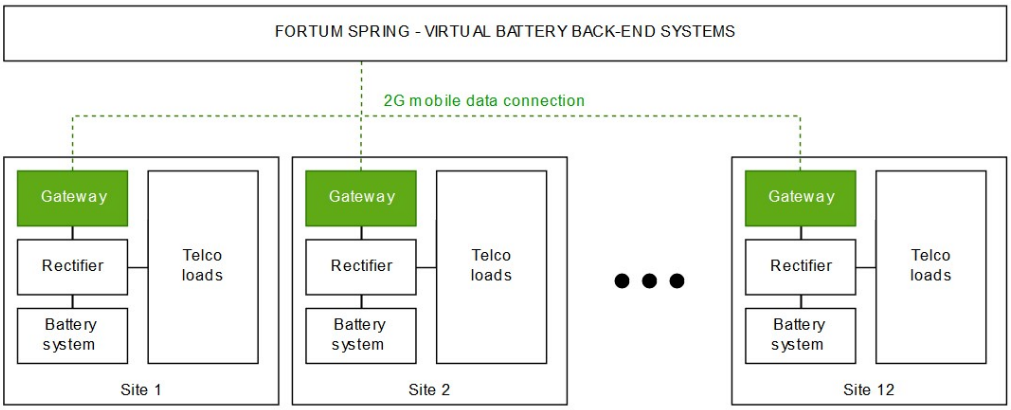

Figure 24. Pilot setup.

4.3.1 Results

Three tests were performed; owing to some connectivity issues, seven out of the twelve gateway devices were online during the first test and nine out of twelve during the second and third test. The results illustrated in Figure 25 show that during each test, the aggregate was struggling to reach a 50% power reduction in 5 s; this was achieved only during the first test. Full response (100% reduction in power consumption) was, on the other hand, reached well before the 30 s limit. The results also show that the power consumption of the rectifier increased for a few seconds after the grid loading started to decrease. This, however, can be a measurement error or caused by the inefficiency of starting to draw power from the battery system. Nevertheless, the phenomenon was not investigated further.

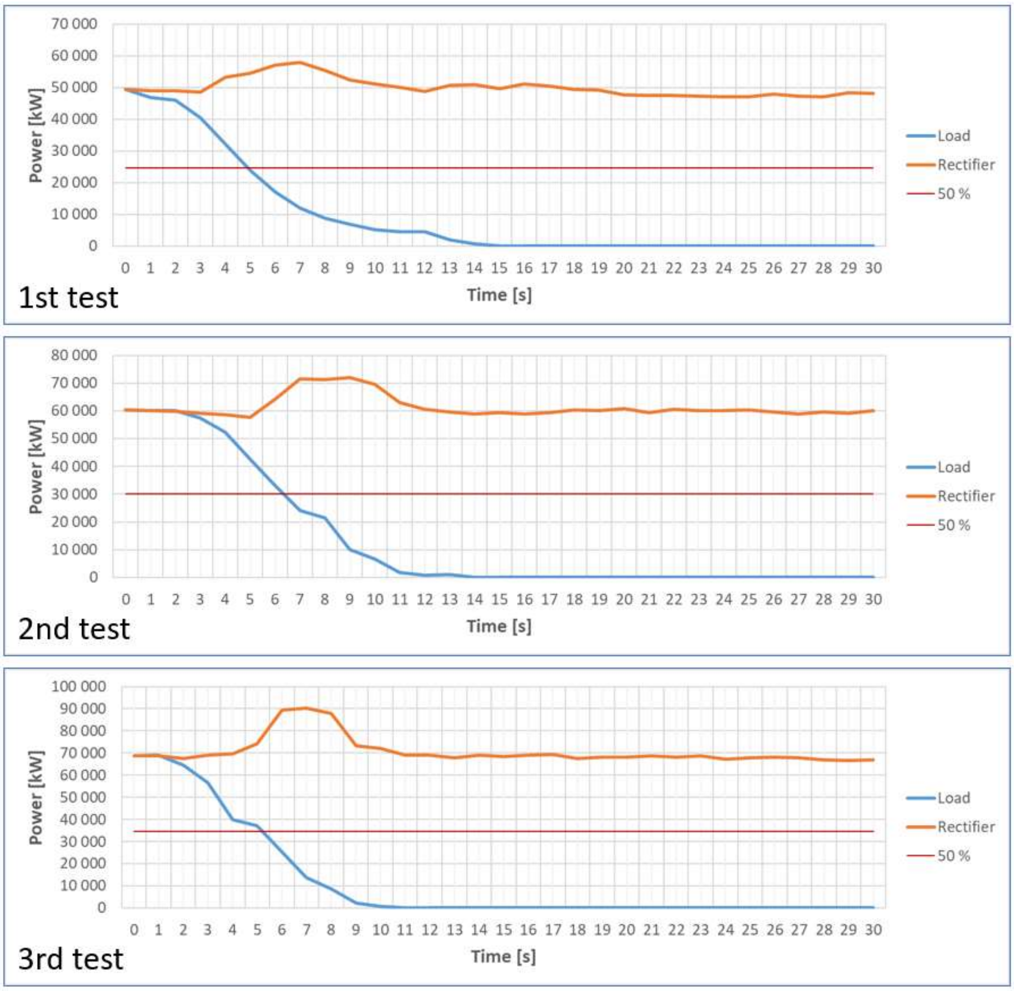

Figure 25. Results from three aggregate reaction tests. The blue line indicates the grid load power measurement, the orange line the rectifier power measurement, and the red line the 50% reduction level from the starting values.

4.4 Discussion

The chapter provided answers to the following research questions (in relation to the telecommunications equipment):

1) Can existing battery systems (and the related power protection systems) be used to provide grid services in a technically and economically feasible manner?
4) What are the boundary conditions and limiting factors in the above-mentioned cases, and what is their impact on the primary purpose of the systems?

As shown in the results above, the current battery systems in the base stations could easily provide the capacity required for the FCR-D application. Further, the additional cycles would not cause premature aging of the battery systems. The time that the battery systems spend in a state of partial discharge may be an important factor as VRLA batteries do not typically tolerate prolonged times while not fully charged. However, as the results show, batteries would be subjected to extremely shallow discharges (in the range of 0.2% DoD), basically having the same effect as dropping the battery systems from a float charge to idle, a procedure that some power electronics manufacturers have actually incorporated into their products as an energy saving method (periodically float/idle batteries to save energy).

The reaction time would pose more challenges, at least when considering the systems tested in the pilot. In order to ensure that the systems are able to meet the current market requirements, the firmware of the rectifier controllers should be modified to enable a faster response.

A large-scale rollout to existing base stations is probably not economically feasible, as the unit benefits for the FCR-D participation are marginal. For example in 2018 (based on the data in Table 7, Chapter 3), a 5 kW reserve unit providing the FCR-D service (as part of a larger aggregate) would have ideally accumulated €220 in market revenue. Travel, labor, and connectivity hardware costs per site would be significant compared with the financial benefits potentially available.

However, a fully viable scenario is that as the rectifier manufacturers increasingly start to include “smart-grid” and connectivity functionalities in their products as standard options, the costs of making the rectifiers connected and available as assets of demand response of virtual power plants will decrease considerably.

5 Value stacking of distribution system batteries

Benefits of the battery systems in the distribution networks have been identified and discussed in the current scientific literature as was presented in the literature review in Chapter 2. The benefits are listed in Table 12.

Table 12. Identified DSO benefits.

Application	Short explanation
Reduction in regulatory outage costs (ROC)	By providing backup energy from the BESS during an outage, SAIDI and SAIFI can be lowered, which will impact the ROC incurred to the DSO.
Congestion management	By providing power from the BESS during a congestion, the technical or contractual (power) limit of the grid can be maintained.
Reactive power management	By providing either reactive or inductive power with the power conversion systems in the BESS, the effects of reactive power in the grid can be managed.
Voltage support	The power conversion system of the BESS can provide voltage support and increase the voltage in the network.
Investment deferral	Related to congestion management, by providing congestion management with a BESS, network reinforcement investments can be deferred.

However, the current regulation model prohibits the DSO from owning battery systems on a large scale. Figure 26 presents the framework prepared by the CEER (Council of European Energy Regulators), which states that if there is a commercial offering of battery services and that if the DSO cannot justify (with a cost/benefit analysis) that it should carry out the activity, it is not allowed to own and operate the battery system.

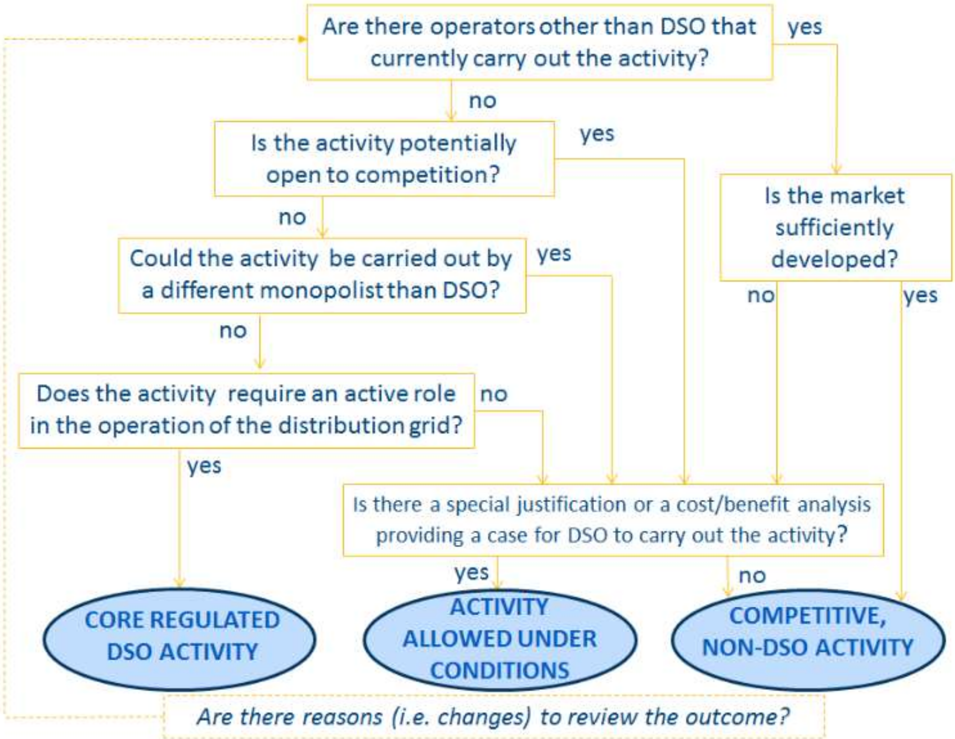

Figure 26. Logical framework regarding DSOs owning batteries for “grey areas” (Council of European Energy Regulators, 2015).

In the present research, the objective was to find a business model that would allow a third-party company to own a battery system and provide local flexibility services from the system under a service-level agreement (SLA) to the DSO.

The research project focused on looking into the characteristics of the needs of the DSO for local flexibility and finding out whether it would be feasible to provide such services from a battery energy storage system, while simultaneously maintaining the economic viability by operating the battery system in the frequency regulation market.

The project was conducted in close cooperation with a Finnish DSO, Elenia. The company had previously done internal research in which it had quantified its regulatory outage costs (ROC) and the location causing these costs in its network. Based on this analysis, a site selection process was conducted to find an optimal location for the battery system and the potential ROC savings that the battery system would generate. The site selection gave a technical framework of the characteristics that the battery system should meet. These included sizing of the energy capacity, converter power, transformer, and grid connection.

A business model development was carried out based on the expected ROC savings and estimated FCR-N market revenue. Additional benefits that the system could provide were also listed in the process, but as the financial value for most of them was difficult to quantify, the business model was constructed based on two revenue streams mentioned above. The related investment calculations were performed by a net present value analysis.

5.1 Pilot case Elenia

A pilot project was started with the objective to source, install, and commission the battery system. During the site selection process, it became apparent that in order to reach a financially feasible case, the battery system would have to support several low-voltage (LV) grids. Consequently, a decision to place the system on a medium-voltage (MV) feeder branch was made.

The selected area has ten low-voltage networks with more than 100 customers in total, and the average power consumption in the branch is 71 kW (based on measurements from 2018). Figure 27 illustrates the location of the battery system in Elenia's network and the area protected by the battery system. The location is in Kuru, central Finland (about 70 km north-northeast from the city of Tampere).

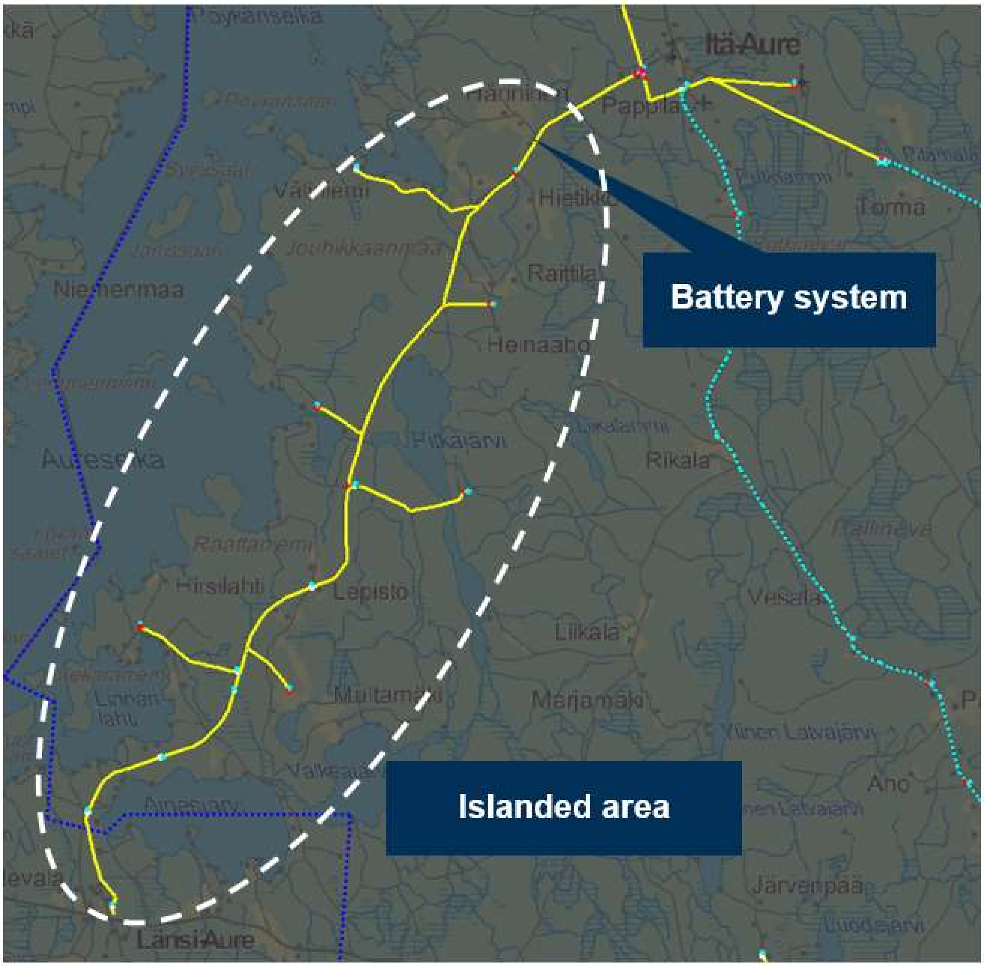

Figure 27. Location of the battery system and illustration of the area that the battery system will protect.

The technical concept and ownership lines were agreed as illustrated in Figure 28. In the project, Elenia makes the investment in the grid components and the power conversion system, and Fortum makes the investment in the battery energy storage components.

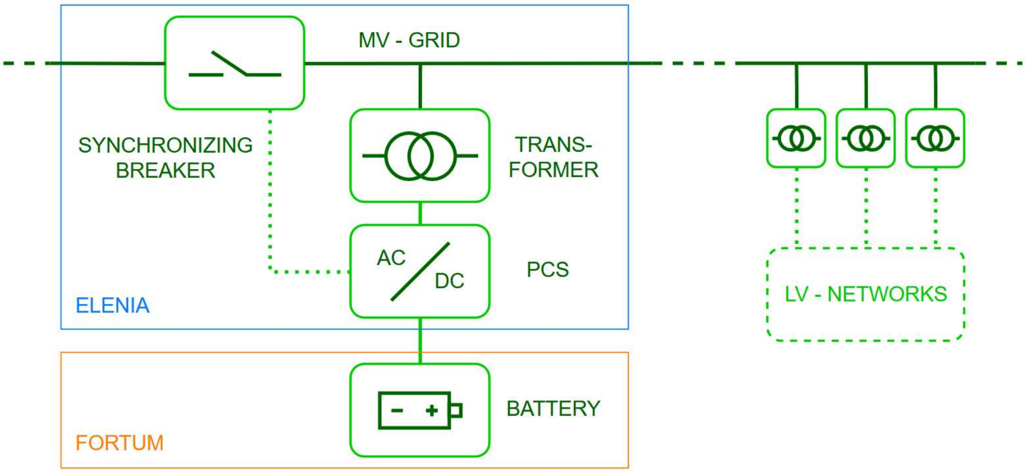

Figure 28. Conceptual drawing of the battery system and ownership lines.

The concept is that in case of a failure (such as storm damage) of the feeding MV grid, the battery system will island a part of the grid downstream from the point of connection and feed energy to the consumers in that part of the grid from the energy stored in the battery modules.

The business model was agreed to be as illustrated in Figure 29. In the model, companies make the above-mentioned investments, Fortum provides Elenia with the security of supply service (SoSS) and Fingrid with the FCR-N service and receives revenues from them respectively. The revenue for the SoSS is twofold, consisting of a service-level agreement (SLA) payment part and a reservation part. Naturally, other services such as FCR-D could have been considered, but currently, FCR-N provides the best economic benefit. This will be further elaborated on in Chapter 6.

The SLA payment is a service payment for the battery system to be operated and maintained in the location chosen by Elenia. During normal operation, the battery system is used to provide the FCR-N service, and as a result, the SoC of the battery system varies based on the frequency behavior of the grid. In case of a sudden and unexpected disturbance, Fortum does not guarantee a specific level of SoC.

However, Elenia can commission for a reservation time, which can be done for example when it has received a weather forecast notice indicating that there is a high likelihood that the area protected by the battery system will face distribution issues. Upon receiving a request for reservation, Fortum will not bid the battery system to Fingrid but will charge the battery system to full charge and make the battery system wait for potential grid issues. For this service, Elenia compensates Fortum with the reservation payments, which are hourly based.

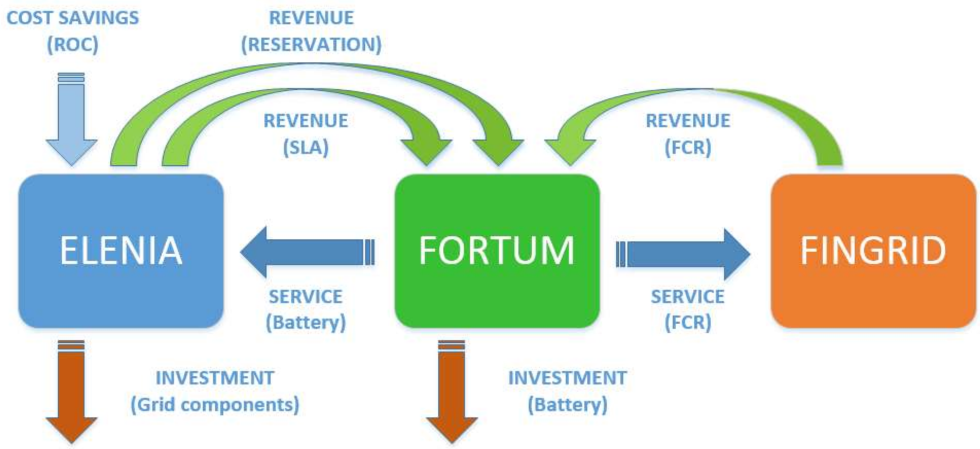

Figure 29. Business model with revenue streams and services.

Figure 30 is a photograph taken from the installation and commissioning of the battery system.

Figure 30. Battery system being installed and commissioned.

Figure 31 illustrates the measurement data during one hour of FCR-N operations. The charts show that the battery system responds quickly and accurately to the frequency changes and as such has not issues with meeting the market requirements, which is illustrated in Figure 31.

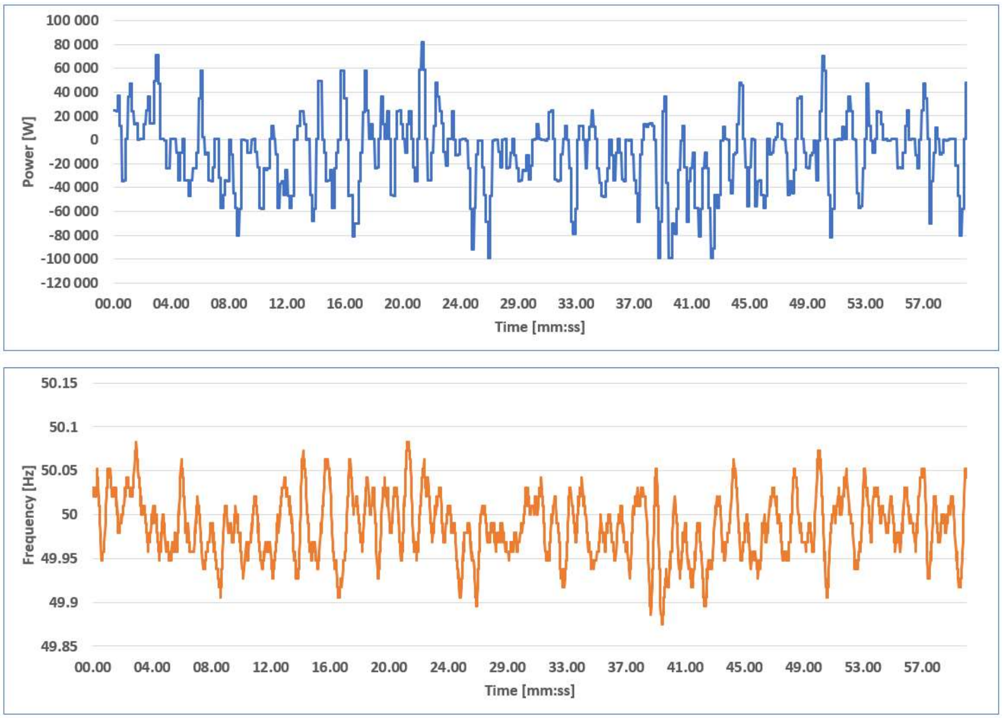

Figure 31. Data from the battery operations in the FCR-N. The chart above shows the power response from the battery system (blue line) and the chart below the measured grid frequency (orange line).

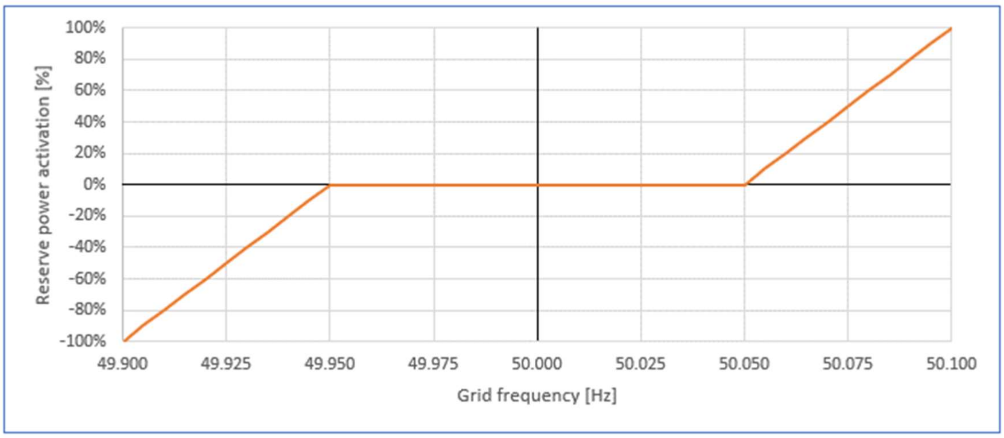

Figure 32. Required FCR-N-activated reserve power, in relation to grid frequency.

5.2 Discussion

This chapter answered the research question 5 of whether a third-party company can find an economically feasible business model that would enable it to offer batteries as a service to the distribution company.

A technical concept was presented and implemented in a pilot project. A business model was also presented where the DSO would be able to get benefits from a local energy storage system without actually owning or operating the system.

Generally, the DSO’s need for local flexibility will be restricted to congested hours that typically (at least in the current Nordic context) occur during times of cold weather, as most peak power consumption will be required by heating systems. Another identified need is during grid outages, caused by issues (e.g. storm/snow damages) in the overhead power lines (pilot case Elenia).

Both of the needs are periodical, limited, and (somewhat) forecastable; that is, congestion is highly likely during morning peak hours of cold days and grid outages are likely in the case of high winds and heavy snow loads. In case a DSO invested in a battery system purely for these applications, for most of the year the system would not be used and would thus not generate value for the investor. Therefore, a model that will allow the battery system to be utilized more and be able to generate more value will always be beneficial to investors and more socio-economically preferable as electricity distribution is a socialized cost.

The ownership of the battery systems by the DSOs is a hot topic across different forums within the EU, as well as a general topic of local flexibility. There are several development projects aiming to establish a marketplace for local flexibility. The research provides a potential solution and has aroused significant interest especially among the Swedish DSOs, who are facing significant capacity issues in and near larger cities, such as Stockholm and Gothenburg.

6 Discussion

The research conducted and documented in this doctoral dissertation focused on investigating how different existing and potential future install bases of battery systems in different applications could be used to provide ancillary services to stabilize the grid. The research was conducted within the confines of the current regulation and ancillary market design. However, the power systems are globally going through a major transformation, which will have a significant impact on how the power systems will be operated and managed in the future.

A commonly shared view within the industry and related academia is that enhanced grid flexibility will be paramount to operate and manage a sustainable and reliable electrical power system in the future. Increasing renewable energy generation will cause issues in maintaining both the short- and long-term grid stability and balance of electricity generation and demand. Different kinds of battery systems are most likely going to be used to provide systems with increased short-term to maximum mid-term flexibility, solving stability issues within periods of a few milliseconds to potentially a few days. Long-term flexibility needs, while technically viable, will most likely not be mitigated by electrical energy storages, let alone stand-alone battery systems, because of the vast energy capacities required, which will make the economic feasibility virtually impossible to achieve. Instead, seasonal balancing of electricity systems will be (and partially already is) handled for instance by hydro (pumped and traditional) and power-to-gas technologies.

This work focused on specific types of ancillary services; FCR-D and FFR for assets with lead-based battery systems, and FCR-N for Li-ion-based battery systems. In the current regulation and market landscape, this kind of an approach is fully justifiable. The FCR-D reserve is roughly (on average) priced around ~5 €/MW/h in the hourly markets hosted by Fingrid, while FCR-N is (on average) in the range of ~20 €/MW/h, again, in the hourly markets by Fingrid. In Sweden, a similar difference in the market prices can be observed; however, the gap is smaller between the two reserves. Thus, if a unit can technically perform both services, it is nearly always advisable to enroll in FCR-N. To complicate this reasoning, different reserve products have different price profiles, and therefore, to actually maximize the market income, the aggregator has to take into account different prices of various products, which also means to look outside from the power-based products into energy-based ones such as aFRR and mFRR or even intraday or day-ahead electricity trading. For clarity, the analyses in this work typically addressed one reserve product at a time, but for example UPS systems could technically be used to provide the full spectrum of services, ranging from the fastest FFR to day-ahead electricity trading. However, economic feasibility would be highly questionable for most of these services.

The underlying logic in this research was that the studied battery systems are nearly never actively used and that there should be plenty of opportunities in dual-purposing the battery system of the ancillary services, provided that the participation does not cause premature aging of the battery systems that were initially purchased for example to back up critical data handling processes. The research and the simulation have shown that the exerted additional stress can be kept within acceptable boundaries and should help to mitigate the concerns of potential stakeholders, who are thinking about joining different aggregators or market schemes to benefit from their investments.

The future role of ancillary services is an interesting topic and the future of different reserve products, not to mention that the future market prices are quite vague and difficult to forecast. However, the short-term view is fairly straightforward and will include balancing product unification within and between different synchronous systems, such as the power systems of the Nordic countries and Central Europe. This can already be seen from different projects, such as MARI and PICASSO led by ENTSO-E, which aim to create a platform for mFRR (MARI) and aFRR (PICASSO) products, and the FCR Cooperation project, the objective of which is to establish a common FCR marketplace for Central European transmission system operators. The product unification will have an impact on how the findings of this dissertation can be utilized in real-life applications. At the moment, the FCR-D type of a balancing product can be considered a Nordic curiosity, and for example the Central European markets do not have a similar product. This will basically limit the direct application of the research findings (related to the use of lead-based batteries in FCR-D) to the Nordic markets. On the other hand, FFR is one of the products that could potentially be introduced also to other systems. The current development and research work related to FFR is led by a work group consisting of Nordic TSOs, yet inertia-related issues are definitely not limited to the Nordic countries, but will be (and are) experienced also by other systems, and penetration of renewable energy will only increase the need. When discussing application of Li-ion battery systems, such as the example covered in Chapter 5, market unification will make the geographical expansion significantly easier, even to a point where cross-border flexibility trading will enable the provision of balancing services to neighboring countries, even without actually having physical assets in these specific countries.

Another highly relevant topic is the role of regulation. As stated previously in this dissertation, the market access of explicit demand response is still not provided in most of the areas around the globe. Basically, only some countries in Europe have implemented market structures and regulation that allow demand response to participate in the ancillary services markets. Additionally, there are also several open questions about the roles that the different stakeholders will and should take in the markets, one of these being the question of third-party aggregation (i.e., offering balancing services without having the balance responsibility for the assets offered). Enabling third-party aggregation will again make the geographical expansion easier. Currently in a country where third-party aggregation is not allowed, should a datacenter operator want to use their systems to support the grid frequency, they would have to find an energy retailer that is also capable of offering aggregation services. Typically, electricity supply contracts for these kinds of customers are negotiated for fixed periods (several years), and therefore, changing them midterm to enable demand response participation is probably not very feasible. Thus, from the customers' point of view, allowing third-party aggregation would enable them to benefit from different opportunities regarding demand response. On the other hand, incumbent electricity retailers might prefer to hold on to the limitation of not aggregating assets that are not in their balance, as it would allow them to develop service product offerings tailored to attract new electricity customers, but also (potentially more importantly) to defend their existing customer base against new market players with light organizations, smaller overheads, and new business models. Future introduction of a market role called a balancing service provider (BSP), an actor between the balance responsible parties (BRPs) and service providers (aggregators), is a method of clarifying the different roles and responsibilities of different market parties, as well as a method of providing third-party access to the balancing markets.

A further issue related to balances is how the production and consumption balances are handled. At the moment, for example in Finland, it is not possible to issue a bid combining assets from production and consumption balances. In the Nordic countries, this, in particular, would be a highly interesting option for actors with access to a hydro power plant. Cross-balance optimization would enable market participation of very limited capacity battery systems backed up with (in this context) infinite energy amounts of hydro power. In the concept, battery systems would have the responsibility of providing initial response promptly and accurately, followed by an energy response from a hydro power increase, in case a longer reserve activation would be required. This would have several benefits including significantly reduced wear and tear of hydro turbines, a faster and more accurate initial response, and a reduction in the battery capacity requirement. For example, the battery systems in Section 3.3 were significantly oversized in order to independently meet the one-hour capacity requirements of the current markets. If the systems could have been combined with production assets (for example hydro power), the battery sizing could have been much closer to the customers' requirement of 5-min autonomy. Naturally, the concept would require much closer analyses to determine the optimal size of the battery system in such a case, factoring in parameters such as valorization of the reserve capacity of the hydro power. Fingrid has already indicated that they aim to move to one balance (combined production and consumption balances) during 2020.

Regulation will also have to define the different roles and responsibilities of the established market parties such as the TSOs and the DSOs. These companies are good candidates to benefit from emerging technologies such as demand response and advanced (and increasingly cheaper) battery technologies, but as natural monopolies, their role must be clear and different from the actors that are operating commercially in the electricity sector. One such example was covered in Chapter 5. The chapter presented a business model where the DSO could benefit from a battery system, without having to purchase it. This makes socio-economic sense, as the duration of the needs of the DSO is highly limited, and it would not be cost effective to invest in a battery system and have the system basically idle for most of the time. How these kinds of tools are valued by the regulation models of the DSOs is also a major topic of discussion and one that could certainly be updated. Currently, DSOs are incentivized to invest in CAPEX, as OPEX-based solutions are not treated equally in the regulation models, which typically relate the DSO's allowed profits to the accumulated regulatory asset base (e.g. invested CAPEX).

Building viable business models that will benefit all the parties will be crucial to enable a large-scale roll-out of demand response. For larger assets, such as data center UPS systems covered in Chapter 3, it is easier to find suitable business models. This is due to their significant unit potential to generate market revenue. For example, retrofitting control equipment to existing UPS systems, or investing in a battery system for a green field data center can be fully feasible (technically and economically) and cover both the initial investment costs and the operational costs. However, for smaller units, such as the base stations discussed in Chapter 4, finding profitability will require a different approach. For example, the upcoming implementation of 5G networks might provide interesting opportunities. The suppliers of network infrastructure and their equipment manufacturers might want to brand their products “demand-response-ready” and sell this as an optional feature for the network operators, who could then use these features themselves to increase the profitability of their investments or have an aggregator to do this for them. All this will lead to increased flexibility in the grids and should benefit society in general, both directly by lowering the costs of grid balancing and indirectly by increasing the capacity of the electricity system to accommodate inherently variable renewable energy.

7 Conclusions

This doctoral dissertation studied the use of a battery system (either existing or future installations) to provide grid support as a secondary application. The focus of the research was on three different application areas of battery systems, viz. data centers and telecommunication networks that are currently the major users of battery systems, and distribution systems that might be among the most potentially growing application areas of battery energy storage systems in the near future.

The research focused on applying current technology to perform grid support functions and investigating the related boundary conditions. Nevertheless, the study did not go into details about the specific functionalities of the technologies (UPS, battery storage, and rectifiers).

Further, batteries in electrified transportation (electric vehicles) were not included in the study. While electric vehicles offer a significant flexibility potential, the topic is widely covered in the current academic literature.

The research was structured around five research questions:

1) **Can existing battery systems (and the related power protection systems) be used to provide grid services in a technically and economically feasible manner?**

   Based on the results presented in this doctoral dissertation, the existing battery systems can be used to provide grid services.

   Findings in Chapter 3 show that UPS systems in data centers have the sufficient capacity to provide FCR-D and FFR types of a grid service. The research also shows that the response times of the systems are well within the requirements of the markets and that participation in the reserve operations will not have a significant impact on the service life of the systems, provided that attention is paid to how the reserve participation is performed.

   The research question is further answered in the reports published by Svenska kraftnät and Statnett, where the TSOs state that UPS systems (in data centers) are technically feasible assets in the FCR-D and FFR markets.

   Findings in Chapter 4 show that battery systems in telecommunication base stations could also provide the FCR-D service without a significant impact on the service life of the system. However, the reaction time may become an issue (which would at least limit the amount of reserve capacity). This could be addressed by updating the rectifiers in the base stations. As stated in the discussion section of Chapter 4, it might not be economically feasible to initiate such a project, but the update will most likely take place during the end-of-life replacements of the equipment.

2) **Can the existing power protection infrastructure (e.g. in data centers) be used as a “platform” for battery energy storage systems, and what are the limitations and benefits of the approach?**

   Based on the results presented in this doctoral dissertation, the existing power protection infrastructure could be used as a platform for battery energy storage systems. Section 3.3 covers the technical and economic feasibility analyses of the concept. Basically, as shown, by investing in a larger Li-ion type battery for the UPS system, the data center could provide BESS-type grid support functions, with reduced CAPEX compared with a stand-alone BESS.

   The approach would, however, have some limitations that are addressed in Chapter 3. The limitations or boundary conditions are mainly related to the sizing of the (power) infrastructure and the battery system.

3) **Can UPS systems be used to provide fast frequency response (FFR) services?**

   As covered in the discussion on the pilot cases in Section 3.2.4, UPS systems were tested in an FFR pilot project hosted by Statnett. The results indicate that UPS systems are very well suited for such services, which is also the conclusion presented in Statnett’s report of the pilot project.

4) **What are the boundary conditions and limiting factors in the above-mentioned cases, and what is their impact on the primary purpose of the systems?**

   The boundary conditions and limiting factors are addressed in detail in Chapter 3. They are mainly related to the battery capacity and available power. Further, an important factor is whether the back-feed into the supplying grid is allowed or not.

   As discussed in Chapter 3 (for UPSs) and Chapter 4 (for telecommunications equipment), the impact on the primary purpose of the systems is limited, provided that the systems are used reasonably and that the additional incurred stress is monitored.

5) **Can a third-party company (e.g. an aggregator) find an economically feasible business model that would enable it to offer batteries as a service to the distribution company?**

   A model for such purpose is presented in Chapter 5. In the model, a third-party company (here Fortum) makes the investment in the battery system and the DSO (here Elenia) for the grid components. The DSO will get the benefits from the battery system for their needs of limited duration, while the third-party company is able to generate value with the battery system in the FCR-N markets when the battery system is not used for the DSO's purposes.

As shown, the research presented in this doctoral dissertation reduces the knowledge gap identified in the literature review. The scientific contributions of the dissertation include: 1) Covering participation of data centers and telecommunication base stations in explicit demand response and specifically to primary frequency regulation. 2) Identifying the boundary conditions and analyzing the potential impact of the participation. Finally, 3) presenting a battery as a service business model so that the benefits of the battery systems could be maximized in compliance with the current regulatory framework.

Future research into the topic could include studies of different storage technologies, in addition to lead- and lithium-based battery systems (covered in this doctoral dissertation), such as supercapacitors, which might provide very interesting opportunities owing to their extremely high cyclic lifetime performance.

Further, empirical investigations into the aging effects of grid support participation would be an interesting research field, but would require several years of recorded usage data, which is the reason why different modeling and simulation approaches are preferred in the current literature.

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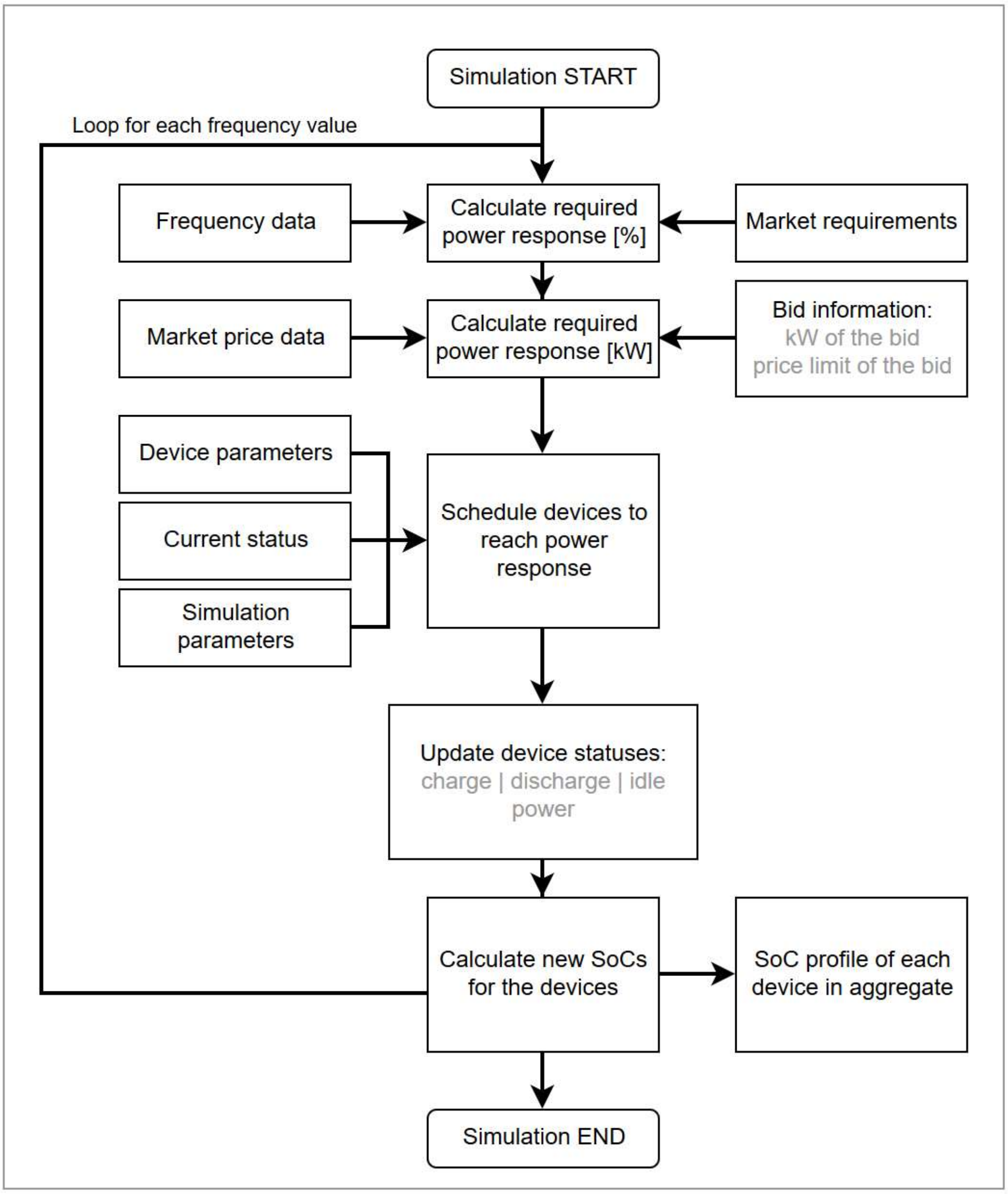
Appendix A: Simulation program flowchart



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Data centers as a source of dynamic flexibility in smart girds

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HIGHLIGHTS

- Data centers have a lot of excess capacity due to their redundant design.
- This capacity can be used to provide ancillary services, such as primary regulation.
- UPS systems are technically and economically viable in primary regulation.
- Additional stress to battery systems is within battery specifications.
- Participation to primary regulation can create significant revenue for data centers.

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ABSTRACT

Data centers have a significant potential to become a major source of flexibility in smart girds. They consume currently roughly 3% of all the electricity produced globally and are expected to only increase their consumption as the world becomes more connected and digitalized.

As data centers are required to operate without any interruptions, they use power protection systems and energy storages. This paper investigates the technical and economic feasibility of dual-purposing these power protection systems, the uninterruptible power supplies, and their batteries in data centers to perform primary frequency regulation services. While the topic of data centers and demand response has been extensively covered in the current scientific literature, the focus has been on the demand response enabled by server workload shifting or hardware-enabled peak shaving. Based on an extensive literature review, there is a knowledge gap in the literature concerning primary frequency regulation and dynamic response enabled by modern power electronics systems in data centers. In this paper, this knowledge gap is bridged by suggesting a novel approach of taking advantage of the bidirectional operations capabilities of the uninterruptible power supply systems, thereby enabling them to provide dynamic power response from their battery systems.

The feasibility of this approach is examined with the proposed method, which includes (1) an analysis of the required energy for primary regulation and the availability of this energy in a typical data center, (2) a simulation of activation events and their impact on the service life of the battery systems, (3) reaction speed and reliability considerations of the operations, and (4) an economic feasibility and balancing market analysis.

The results show that as primary frequency regulation is an energy nonintensive service and data center battery systems are by design oversized for redundancy reasons, typical data centers have more than ample amounts of energy to participate in the primary regulation without jeopardizing their own processes. The results also show that by maintaining reasonable levels of usage, the battery systems can be operated within their specifications, and the demand response operations will not cause premature aging of the battery systems. The reaction speed of the power electronics is found to be very high and easily meet the current market requirements.

While the achievable revenue from the primary regulation service is small compared for example with the electricity costs of the data centers, it is still significant as there is little to no impact on the daily business of the data centers.

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1. Introduction

As the amount of renewable and intermittent energy increases in electrical power systems globally, also the need for flexibility increases [1]. This flexibility has been traditionally provided by large power plants, but now, as an increasing proportion of production is becoming difficult or even impossible to adjust, new sources of flexibility are needed. Attention is turning to flexible consumption, and the topic of demand response has been addressed in multiple scientific publications. For example, Muhssin et al. and Xu et al. studied the usage of aggregated household consumption assets, such as refrigerators and heat pumps, as sources of ancillary services in [2,3], and Jia et al. investigated the usage of electric vehicles (EVs) in frequency regulation in [4]. Batteries and energy storages and their feasibility in grid support applications, such as primary regulation, have been extensively studied both in academic literature and commercial demonstrations. For example, Zheng et al. analyzed the economic and environmental benefits of different dispatch strategies of a large number of residential energy storage systems in [5], Shi et al. analyzed multipurpose usage of battery systems for peak shaving and frequency regulation in [6], and Cheng et al. and Brivio et al. covered the combined use cases of primary frequency regulation and energy arbitrage in [7,8]. The demand response potential of power-intensive industries has also been studied lately; Otashu et al. proposed a metric of analyzing the available load reduction in the industry in [9], and Ramin et al. presented a case example of a metal casting process in [10].

Data centers are the power-intensive industry of the modern age. They are highly redundant digital factories and among the largest energy consumers in the world, and their power consumption is expected to increase significantly over the following decades. This development is driven by increasing digitalization and a growing amount of data being transferred and processed [11,12]. To achieve the high uptime requirements, data centers are designed with significant amounts of inbuilt flexibility in the form of electrochemical storage (i.e. batteries) and redundant power electronic systems. These design choices and significant power consumption make data centers attractive candidates for demand response participation.

Currently, there are few data centers participating in grid support activities, and while some companies have already begun to commercialize these activities [13,14], the majority of the data center flexibility potential still remains an untapped resource. The participation of data centers in demand response has also been covered in the scientific literature. For example, Mamum et al. addressed the topic in [15,16], where demand response was studied from the perspective of performing peak-shaving with Li-ion batteries, while Li et al. focused on demand response enabled by IT load shifting in [17]. However, as the extensive literature review (presented below) shows, there is a knowledge gap in the current literature concerning data center participation in primary frequency regulation. In particular, the key questions still unanswered are: how data center power protection systems could enable dynamic regulation, and what is the technical and economic feasibility of such an approach.

This paper presents a novel way for the data centers to participate in grid support (specifically in primary frequency regulation) by actively using their uninterruptible power supply (UPS) systems and batteries to balance the grid, instead of shedding their loads by off-gridding their systems, or performing workload shifting. The technical and economic feasibility of this approach is analyzed methodologically from several viewpoints.

The main research questions of this paper are: could a data center with a battery system perform primary frequency response in an economically feasible way without significant risks to their primary business, and how much additional stress would be exerted on the existing batteries during these grid support operations.

The structure of the paper is the following: The results of a literature review are presented in the second section. The third section introduces primary frequency regulation. The fourth section explains typical UPS topologies and their inherent excess capacities deployed in data centers through selected example configurations. The fifth section explains the key differences between the commonly applied method of providing grid services and the proposed approach. The sixth section investigates the technical feasibility of performing dynamic upwards regulation with an UPS system. The seventh section presents results from a frequency analysis and a simulation model to estimate the additional stress exerted on the UPS systems and their batteries while participating in primary regulation, and references it to typical battery cycle life characteristics. The eighth section provides discussion, and conclusions are drawn in the final section.

2. Literature review

The subject of demand response (DR) in the data center space is extensively covered in the current scientific literature. The research can be divided into two main categories; (1) DR enabled by "IT knobs" (basically workload management of the servers) and (2) DR by data center hardware (e.g., UPS systems, air conditioning, generators, and additional on-site generation). By far, the majority of the research focuses on the first case, that is, server management, and specifically, how to enable implicit demand response. The term 'implicit demand response' refers to (1) optimizing the electricity consumption of a data center for example by peak shaving to reduce grid connection costs, (2) limiting server power consumption during periods of high electricity prices, or (3) spatial workload shifting to gain savings from regional price differences. Li et al. [17] modeled the effects of spatial and temporal spreading of IT workloads to take advantage of electricity price differences between different price regions and times of the day. Similar research was presented by Ruddy et al. in [18], where they introduce a methodology for shifting global demand and calculate the resulting cost and CO_2 emissions savings and potential DR revenue from capacity payments in the Irish electricity markets. Further, in [19], Liu et al. proposed several algorithms for optimizing electricity cost and the usage of renewable energy for data center operations.

A more extensively studied subtopic has been the role and potential of multitenant or colocation (colo) data centers, especially in emergency demand response (a type of ancillary service, where independent system operators (ISOs) contract resources to respond to their DR signals, dispatched when a grid power balance is in jeopardy). Tran et al. have investigated the subject and related topics in multiple publications; in [20], they presented a simulation model and related results for cost optimizing EDR activations in a mixed-use building with data center (server) loads (workload management), HVAC systems, and backup generators. In their other publications they have studied how to incentivize the colo tenants to participate in the EDR by proposing different schemes and analyzing their convergence rates [21,22]. Similar research was presented by Kishwar et al. in [23] and Sun et al. in [24]. Guo et al. also examined how to incentivize colo tenants' participation in the EDR and applied the Nash bargaining theory to coordinate the tenants' participation and revenue gain in [25]. Again, Zhan et al. [26] proposed (and mathematically proved) a pricing model for colo data center operators that would include a reward component for tenants with flexible processes. The colo operator would benefit from reduced grid tariffs (resulting from peak load reduction). There are also several conference publications on the topic of using server management for DR, each with a slightly different focus. Wang et al. presented a DR framework model (server workload management) in [27], and further, they introduced an electricity cost optimization algorithm in [28], which is much similar to the work presented by Baharm et al. in [29,30].

In addition to the above-mentioned work related to server load management, there are several extensive papers that address the topic of using hardware systems in data centers to perform demand response operations. The most relevant research with respect to the scope of this paper has been conducted by S. Gonvindan, A. Sivasubramaniam, B. Ungaokar, A. Mamun, I. Narayanan, and H. Fathy. These authors have published several high-value papers, such as [15], where they provide an in-depth study on the option of using learning algorithms to determine the aging process of lithium-ion batteries in data centers performing demand response operations. In [16] they studied the optimization of cost savings generated by performing peak shaving and Li-ion battery degradation as a result of constant usage and cycling. They also presented related research results in [31], where they extended the above-mentioned optimization to include physics-based models for battery performance and degradation in combination with stochastic models of data center demand. In [32] they posed a question: “Should we dual-purpose energy storage in data centers for power backup and demand response?” As the title suggests, they investigated whether it would make economic (in terms of total cost of ownership) and technical sense to dual-purpose UPS battery systems to perform demand response (peak shaving) alongside their primary function of providing backup power. Their conclusion is that provisioning lead-acid batteries for peak power load needed to handle power outages (backup power usage) already comes with a sufficient energy capacity to also handle DR operations. Furthermore, they have published several conference papers that study the subject of dual-purposing data center batteries for peak shaving, such as [33,34]. What is common for all the papers mentioned above is that they focus solely on implicit demand response (price signal driven).

Cupelli et al. investigated in [35] how a combination of a battery energy storage system (BESS; here a UPS battery system), HVAC, and IT workload management could be used in price- and incentive-based (implicit/explicit) DR. However, the incentive-based demand response uses a three-stage control signal, which is, by nature, significantly different from primary frequency regulation. Li et al. examined integrated power management of data centers and electric vehicles (EVs) in [36]. Their work features explicit DR operations, specifically frequency regulation. However, the addressed frequency regulation differs from the primary frequency regulation we have studied in this paper, as the one covered by Li et al. is an ISO-based control signal rather than a requirement to react to the grid frequency. Moreover, their paper focuses on presenting a control framework to incorporate different assets, rather than on the specifics of data center UPSs in frequency regulation.

Apart from the last few publications, the focus of academic research has so far been on implicit demand response, specifically peak shaving. The lack of research on explicit demand response, and particularly, primary frequency regulation, can mainly be explained by the fact that explicit demand response markets are still in the development phase, and active, commercially available markets can be found only in a couple of European countries and a few other locations globally [37–39].

Based on the above literature review, it can be concluded that to the authors’ knowledge, there is a significant knowledge gap in the scientific literature concerning primary frequency regulation enabled by data center hardware, such as UPS systems and their batteries. In this paper, we aim to bridge that knowledge gap by providing a technically and economically feasible method for data center participation in primary frequency regulation services with the batteries of UPS systems.

3. Primary frequency regulation

The global market size for uninterruptible power system (UPS) batteries is estimated to be worth $5.5 billion annually [40]. Data centers represent a significant proportion of this market as they are one of the major UPS end users. For most of the time, these batteries are sitting at full charge, standing by for a grid disturbance or failure, during which they will deliver energy for the critical loads protected by the UPSs. The nature of the primary application (i.e., rare events with a short duration) of UPSs could allow them to be dual purposed for other applications, one of them being primary frequency containment reserves.

Primary frequency response (or frequency containment reserves, FCR) is a type of an ancillary service intended to mitigate the imbalances between electricity production and consumption on short timescales from a few seconds up to several minutes. In case of a longer disturbance, these primary reserves will be gradually replaced by slower reserve types (secondary and tertiary reserves). Typically, the grid operators (transmission system operations, TSOs, in the European power system) are responsible for upholding or acquiring these reserves [41–43].

3.1. Normal operations reserve and disturbance reserve

Primary regulation reserves can be divided into two main types; a normal operations reserve and a disturbance reserve. Normal operations reserves are intended to handle small deviations in frequency and are constantly active to prevent frequency from drifting away from the nominal window of operations. Disturbance reserves are intended to handle sudden changes in the balance between power generation and consumption, such as unexpected losses of electricity production of a power plant or disconnection of a major transmission line. These reserves are specified to be activated when the frequency has already deviated significantly from the nominal, and for that reason, the activation must be faster than that of the normal operations reserves. When normal operations reserves have to be activated within minutes, the disturbance reserves have to be activated within seconds [43,44].

The currently dominant battery technology (lead-acid based batteries) in data centers is not technically capable of providing normal reserve operations because of the cycle-life limitations and intolerance to operate at a partial state of charge (PSoC) [45]. However, Li-ion batteries have been a constant topic of discussion in data center forums for several years, and are forecasted to gain a significant market share in the future [46–49] mostly owning to their several technical advantages, such as a smaller footprint, a longer service lifetime, and a lower operations and maintenance cost. The discussion section presents the idea of using lithium-ion-based batteries with intent to provide normal reserve operations. To this end, the market requirements and market prices for normal reserves are briefly addressed in this article.

3.2. Primary frequency regulation in the Nordic Countries

For example, in the Nordic power system, the primary frequency regulation reserves are divided into two products; frequency containment reserves for normal operations (FCR-N) and frequency containment reserves for disturbances (FCR-D). FCR-N is a bi-directional normal operations reserve, whereas FCR-D is an only upwards regulating disturbance reserve.

The current regulation states that FCR-D starts to activate at 49.90 Hz and should be fully activated when frequency reaches 49.50 Hz. Activation between 49.90 Hz and 49.50 Hz is expected to be linear. The reaction speed is defined as 50% reaction within 5 s from a frequency deviation and 100% activation within 30 s [44,50].

FCR-N is defined to be active when the grid frequency is between 49.90 Hz and 50.10 Hz. Thus, the reserve is regulating with a full upwards power at 49.90 Hz and with full downwards power at 50.10 Hz. Current regulation defines the reaction speed requirement to be full activation within 3 min of a frequency change [44,50].

FCR-N is basically constantly activated, whereas FCR-D is activated only if the frequency goes below 49.90 Hz. Historically, frequency has been quite good in the Nordic power system; for example, the frequency was outside the nominal limit (49.90–50.10 Hz) for 14000 min in year 2016. 6500 min of these frequency anomalies were underfrequency situations (i.e., times when FCR-D would have been activated). It should be noted that while the frequency does go outside the nominal limits, large deviations are rare (i.e., FCR-D is activated, but with a limited power required). For example, the grid frequency in the Nordic

Table 1
Average market prices for primary reserves in the Nordic markets in 2017 [52,53].

Market	Normal Reserve		Disturbance Reserve	
	Local Market	Price [€/MW/h]	Local Market	Price [€/MW/h]
FIN	FCR-N	20.87	FCR-D	3.39
SWE	FCR-N	23.52	FCR-D	7.43

system went below 49.70 Hz (requiring an activation of 50% or more from FCR-D) eight times during 2016, with an average event duration of 6.43 s and a maximum event duration of 11.90 s [51].

3.3. Market prices

As transmission system operators acquire these reserves from open electricity markets, the market prices are subject to variation depending on supply and demand. Table 1 presents the average hourly market prices in the Finnish and Swedish markets in 2017. The Finnish market also has a year market, with a slightly lower price (2.8€/MW h in year 2017) [52]. These prices are later used to illustrate the level of revenue that the primary frequency regulation can provide.

4. Data center UPS topologies and their excess capacity

Data centers are designed to have a maximal uptime. This is achieved (for example) by building redundant power protection systems within data centers. As a result, data center power protection systems are significantly overdimensioned during normal operations.

4.1. Different topologies

To consider the amount of excess capacity (energy and power), it is necessary to understand different power protection topologies in data centers. Typical topologies deployed in data centers are N, N + 1, 2N, and 2(N + 1) (Fig. 1). In order for a data center to receive a tier III (or higher) classification from the Uptime institute, a redundant power delivery path is required, meaning that the at least a 2(N + 1) UPS topology should be implemented [54,55].

4.1.1. N – Topology

In the N topology there is practically no redundancy or excess capacity. A critical fault in the UPS will jeopardize the power supply of the critical loads.

4.1.2. N + 1 Topology

A N + 1 system is designed so that a failure of a single UPS device will not endanger the ability of the system to supply electricity to the critical loads. An example configuration in Fig. 1 shows a N + 1 system consisting of four 1 MW UPSs. This system can supply 3 MW of power at the maximum to IT -loads, even if one of the UPS devices encounters a critical failure.

4.1.3. 2N Topology

A 2N system has two independent power delivery paths that are supplying the critical loads. The loads will not lose power even if one path is compromised. The example configuration in Fig. 1 has two systems, each with three 1 MW UPSs supplying 3 MW of critical loads.

4.1.4. 2(N + 1) Topology

In the 2(N + 1) topology, two independent and redundant power delivery paths are supplying critical loads. The example configuration in Fig. 1 is a 2(N + 1) system made of two independent N + 1 systems (each with four 1 MW UPSs). This system is able to supply a maximum of 3 MW of power to the critical loads even in an event where another power path is out of commission and one device from another power path simultaneously encounters a critical failure.

4.2. Excess energy in different configurations

This subsection uses the above-mentioned system examples and illustrates the available excess energy in these systems. This excess energy is a result of redundancy. During normal operations, all the UPSs are online and the combined energy stored in their battery systems is larger than the load requirement.

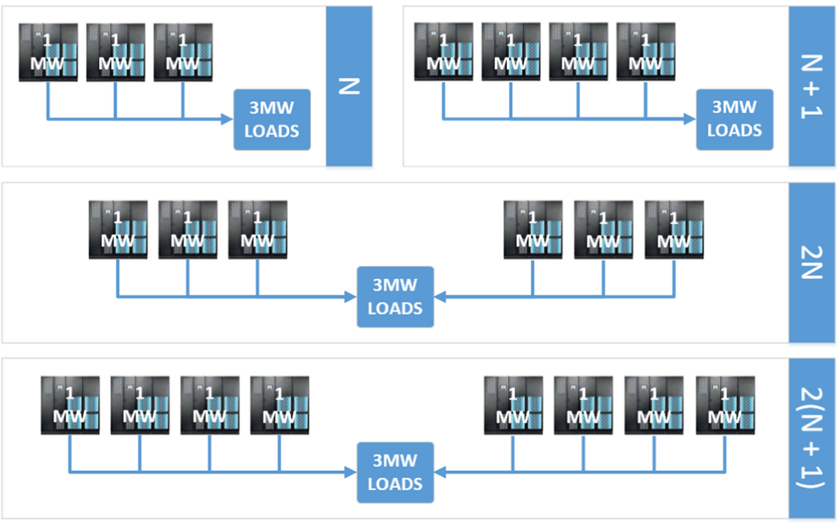

Fig. 1. Typical UPS topologies deployed in data centers [56].

Table 2
excess energy amounts inherent to different UPS system topologies (examples).

Design Topology	Number of 1 MW UPSs	Total amount of energy in the battery systems [kWh]	Excess energy in the battery systems [kWh]
N	3	500	0
N + 1	4	667	167
2N	6	1000	500
2N + 1	8	1333	833

To illustrate this, each UPS system is assumed to have a battery system with 10 min of autonomy time (a typical design value in data centers). For the purpose of this paper this is assumed to correspond to 167 kWh of energy (1 MW ∗ 10 min). For the critical loads expected to require full power autonomy for this 10 min, this is assumed to correspond to 500 kWh (3 MW ∗ 10 min). The third column in Table 2 presents the sum of energy in all the battery systems in each topology and the excess energy (4th column) is calculated by subtracting the energy requirement by the load from the sum.

It should be noted that the actual amount of energy available in lead-acid batteries depends on the discharge current (the higher discharge current, the less energy available), this relation is in accordance to well-known Peukert's Law [57]. For frequency response operations, the available energy amount is expected to be greater as typically the required discharge current that the batteries are subject to is less than in the main UPS application.

5. Different ways of using data center UPSs for primary regulation

5.1. Data center islanding

The most straightforward way for a data center to participate in primary frequency regulation is to install a frequency-controlled breaker after the grid connection point. If the frequency goes below a set threshold, the breaker will open and UPSs will feed energy to the critical loads until the on-site generators (genset) have had sufficient time to start.

The grid will see an upwards regulating effect, of the size of the power consumption of the critical loads, as they no longer get their power from the grid, but from on-site systems. In this case, the functionality of the power protection systems is the same as during a grid outage event. Fig. 2 illustrates the concept and the related energy flows. Doing this would allow the data center to participate in upwards regulation as a step-activated reserve.

Most, if not all, data centers currently participating in grid support activities apply this method. Some use a physical breaker in the critical power path, others take an activation signal from a frequency relay and use that information as a trigger for automation systems to perform the similar operation.

5.2. Dynamic upwards regulation

In dynamic upwards regulation, the UPS system would be used to modulate the power consumption from the grid with the help of a battery system. In case of a frequency disturbance, the UPS system will discharge energy from the battery system. Depending on the current power requirement of the critical loads and the regulation need, this discharged energy will be either consumed fully by the on-site loads or, if the regulation need exceeds the power consumption of the loads, power will be fed back to the grid. The UPS system has to be compatible with the functionality; mainly the rectifier has to be able to perform two-way operations to enable feeding back power to the grid. In case of a longer disturbance, the on-site back-up generators could be used to provide additional energy if the battery state of charge level is approaching the state of charge (SoC) level allocated for ancillary services. Fig. 3 illustrates the concept and the related energy flows.

The main difference from data center islanding is that in this approach the regulation power is not limited to the load power, but full UPS capacity can be utilized.

5.3. Potential market income of different data center topologies and participation methods

Table 3 illustrates the level of revenue that primary regulation could provide for data centers and how the revenue depends on the UPS topology (i.e., the level of redundancy). The revenues in the table are calculated for a 3 MW data center according to the example used in the previous section. Full availability and bid acceptance are assumed, and thus, the annual revenue is calculated simply by multiplying the available UPS power (P) with number of hours in a year (8760) and the average market price (p) (Eq. (1)).

$$Annual\ \ revenue = 8760 \times p_{avg.market\ \ price} \times P_{UPS} \tag{1}$$

6. Technical feasibility and reaction speed considerations

For a data center to participate in dynamic regulation, the UPS system has to be able to adjust its power consumption as described previously (i.e., the rectifier of the UPS needs to be able to perform bidirectional operations). Most of the modern UPS systems use IGBT (insulated gate bipolar transistor) based power electronics, which, at least in theory, are capable of performing these operations. It is more a question if these functions have been implemented in the control software of the UPS.

As an example, Fig. 4 presents the measurement results from a FCR-D prequalification measurement performed according to the Swedish TSO's (Svenska kraftnät) specification. The device under test (DUT) is a 100 kW 93PM UPS from Eaton. The UPS was subjected to a test signal (the orange line in Fig. 4). The test signal was a series of frequency values first going down from 49.90 Hz with 0.05 Hz steps, and once the frequency reached 49.50 Hz, upwards frequency steps of 0.05 Hz were

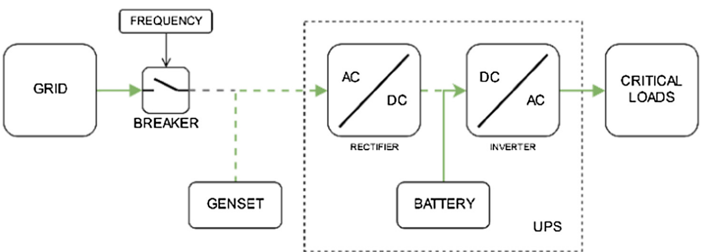

Fig. 2. Off-grid or islanding demand response power system configuration and the related power flows.

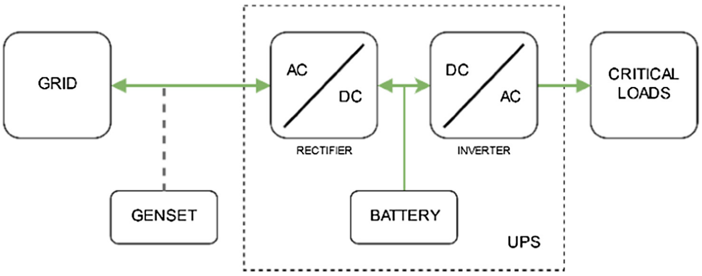

Fig. 3. Dynamic upwards regulation configuration and the related power flow.

Table 3
example of potential market revenue for a 3 MW data center with different UPS topologies in the Finnish and Swedish markets.

	Data center islanding		Dynamic regulation	
	Fin [k€/a]	Swe [k€/a]	Fin [k€/a]	Swe [k€/a]
N	90	195	90	200
N + 1	90	195	120	260
2N	90	195	180	390
2(N + 1)	90	195	240	520

issued until 49.90 Hz was reached. The blue line in the figure shows the UPS response, which is in compliance with the FCR-D activation requirements. It should be noted that the UPS was not connected to loads during the test, and thus, all the power was fed back to the grid.

6.1. Reaction speed

While the results of the prequalification test show that reaction to frequency changes is very fast, additional tests were performed under laboratory conditions in Eaton's facilities to thoroughly investigate the speed of reaction (among several other things). Fig. 5 is an oscilloscope capture from one of these tests. Voltage and current waveforms for the UPS input and output were recorded (one phase) along with the battery current. The communications channel (CAN) to issue the activation command was used as a measurement trigger. The DUT was a 200 kW 93PM UPS by Eaton. The UPS was loaded with a 100 kW constant load, and the activation signal that was given requested a full 200 kW activation.

The results show that the output waveforms (current and voltage) of the UPS remains unchanged during the event, indicating that operations have no impact on the critical loads. Before the CAN burst (top of the figure), the input and output currents are synchronized and uniform and the battery current is close to zero, as would be expected (i.e., UPS is feeding energy through the conversions to the loads and no energy is being drawn from the batteries). Quickly (in approx. 5 ms) after the CAN burst has been issued, the battery current changes followed by a change in the input current. The UPS starts to draw energy from the battery systems (shown by an increase in the battery current) and instead of drawing 100 kW from the grid and feeding that to the loads, the UPS is actually drawing 200 kW from the batteries and feeding 100 kW of it to the loads and 100 kW back to the grid. This can be observed from the 180-degree phase shift in the input current (and unchanged output current). The measurements show that it takes two to three

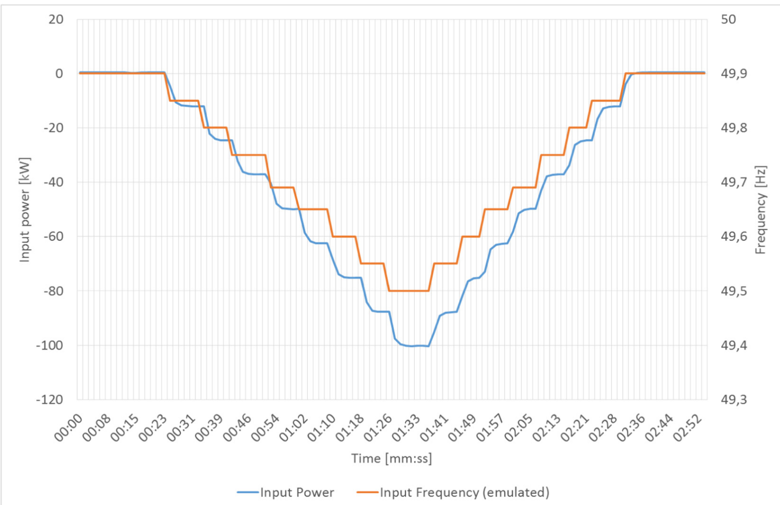

Fig. 4. Results of the linearity of the reaction tests.

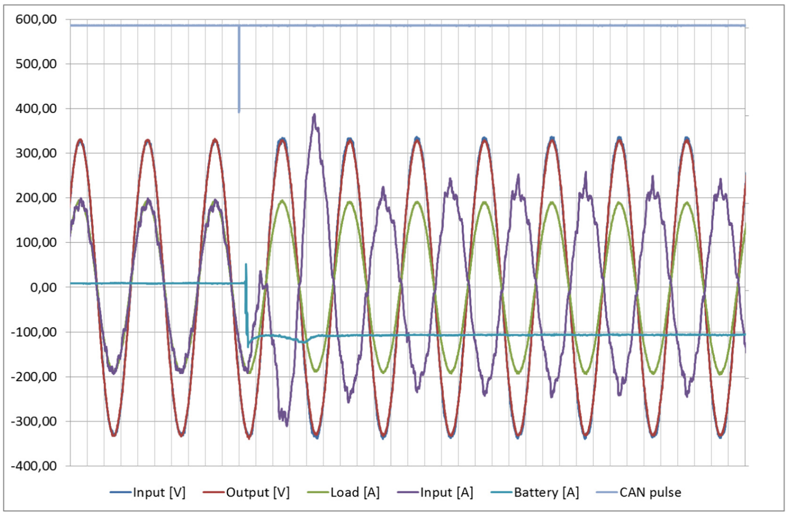

Fig. 5. Results of the speed of reaction tests.

cycles (50 Hz) for the UPS input to fully stabilize, but the UPS is outputting energy well within one cycle from the issuance of the command.

7. Frequency analysis, simulation model and results

7.1. Frequency analysis

A frequency analysis was conducted to investigate how sufficient the previously identified excess capacity would be in relation to the energy demand for primary regulation. Frequency data were analyzed and the energy demand (according to the FCR-D requirements) for each activation (an event where the frequency went below 49.90 Hz) was calculated. Frequency measurement data from the Nordic power systems (year 2015) were used as the input data. For reference, a similar analysis was also conducted for frequency data from the UK power system (year 2015). The regulating power was assumed to be 4 MW according to the N + 1 configuration presented previously.

The results of this preliminary analysis are presented in Fig. 6. The results show that the identified excess capacity (167 kWh limit in the figure) would have been more than enough in relation to the discharged energy and that the generators would have not been needed to start. The upper chart in Fig. 6 shows that for a Nordic data center the most energy requiring continuous activation in the year 2015 would have discharged 122 kWh from the battery systems. The lower chart shows that the corresponding discharged energy for a UK-based data center would have been 53 kWh. The discharged energy amounts are less than the value presented for the excess battery capacity in the previous sections (167 kWh). Thus, there would have not been a technical need to start the generators during these discharges.

7.2. Simulation model

A model was developed to simulate the state of charge (SoC) behavior of the batteries. The simulation input and outputs are described in Fig. 7. This model is modified based on the model presented in [58] so that it is more suitable for the case of the data center UPS. The SoC behavior information was used to study the additional stress exerted on the batteries while performing primary regulation operations.

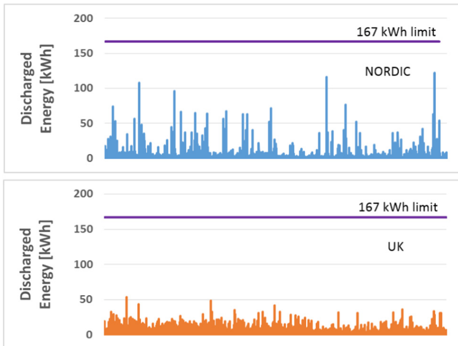

Fig. 6. Calculated discharged energies per activation for a N + 1 (4 × 1 MW) UPS system with the Nordic (above) and UK (below) frequency data from 2015.

7.3. Study of additional stress exerted to battery systems

The upper chart of Fig. 8 shows the SoC behavior of a single UPS battery system for a N + 1 (4 × 1 MW UPS) configuration, simulated with frequency data from year 2015 from the Nordic power system. In the simulations, the depth of discharge (DoD) was limited to 42 kWh (the excess capacity for a N + 1 UPS system according to Table 2 divided by the number of UPSs in the system). The simulation result shows that the UPS would have encountered roughly 200 charge/discharge events during that year. The corresponding results for a data center in the UK are presented in the lower chart of Fig. 8 showing approximately 270 charge/discharge cycles annually.

While the discharges are shallow (limited 42 kWh out of 167 kWh ~ roughly 25% SoC), the number of cycles throughout the expected service life of the battery systems would add up to significant figures in relation to the cyclic life expectancy: approx. 750 cycles with the DoD of 25% (Fig. 9) [59]. Limiting these cycles would be mandatory

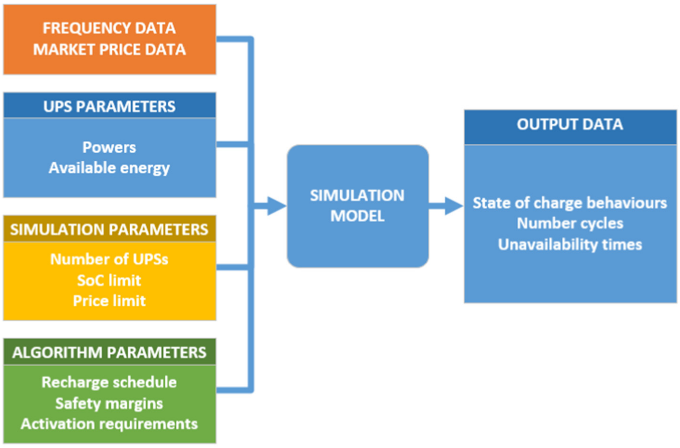

Fig. 7. SoC simulation model.

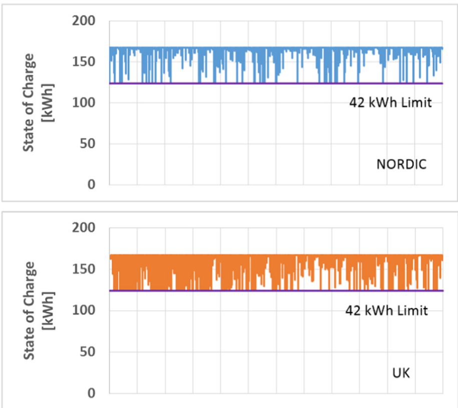

Fig. 8. State of charge behaviors of the most stressed UPS batteries, simulated with the 2015 frequency data from the Nordic (upper) and UK (lower) power systems.

to ensure that demand response participation would not significantly shorten the service life of the batteries. Depending on the target market structure, the cycle count can be effectively limited with aggregating several UPS and even data centers under one bid, thus reducing the stress for a single battery system. Another way to limit the cycle count is to bid for the hourly markets and to issue a limit price for participation.

Table 4 gathers the simulation results for different aggregate sizes and minimum bid prices. The effects of implementing different minimum bid prices for the relative market income are also studied. Price information used in the simulation is the hourly FCR-D prices for the year 2015 [52].

The results show that implementing minimum bid price levels will have a significant effect on the number of charge/discharge cycles that the batteries are subjected to by demand response operations. Implementing these minimum price levels will also have an effect on the relative market income, but as shown below, the decrease is moderate. Combining several UPSs into an aggregate will have a significant effect on the additional stress applied to individual battery systems. Additionally, the experienced cycle count can be significantly reduced if the market allows a selection of lower participation frequency (e.g., 49.80 Hz instead of 49.90 Hz).

A typical service life expectancy for a UPS battery system (VRLA, AGM, 10-year design life) is roughly between seven and eight years. In data center usage, these batteries are expected to encounter a very limited number of charge/discharge cycles a year; a design rule of thumb is that batteries will encounter an equivalent of one to two full discharge cycles a year, and thus, the batteries could be cycled significantly more without affecting the service life. As an example, adding 45 annual cycles with a DoD of 25% (per simulated result with 20 UPSs and a price limit of 10€/MW/h) would mean approximately 360 additional cycles during the service life of the battery system, still well within the specifications for cyclic performance, even considering the cycles the batteries will endure as a result of their primary operations.

8. Discussion

While data centers have multiple alternative ways to participate in demand response for example by managing IT loads, this paper focuses on primary regulation enabled by the inherent redundancy and energy storages in data centers. The purposed approach allows data center participation to demand response without impacting the power consumption profiles or the servers.

As shown in the paper, data centers can have a lot of underused assets that could be used for primary regulation. The exact amount of excess capacity depends heavily on the applied topology and the redundancy level of the data center. The figures presented in the paper serve as an example, but are highly related to real-life data center topologies and their power and back-up energy capacities. Further, in general, the more redundancy a data center has, the more excess capacity it will have to offer to the demand response markets.

The performed frequency analysis showed that the required amount of energy to perform primary regulation is limited, and the example configurations would have had more than ample amounts of excess energy capacity to participate in primary regulation and to have sufficient energy to support the critical loads at all times. Another important finding was the level of additional stress exerted on the batteries by the DR operations. It was found that by limiting the participation times (issuing reasonable price limits for the bids), the additional stress could

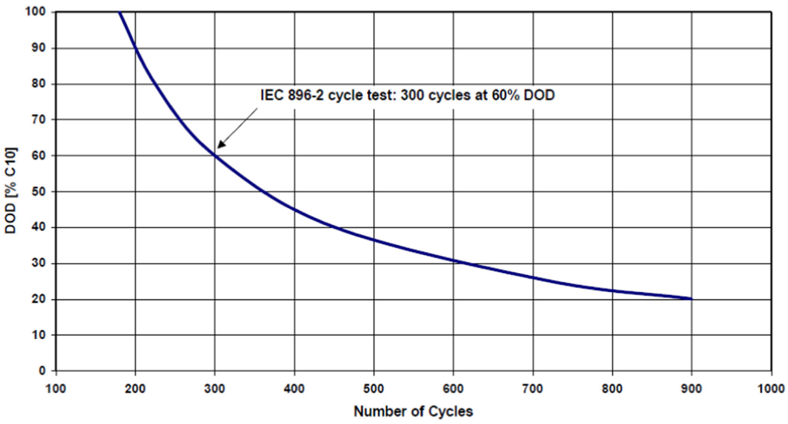

Fig. 9. Typical battery cycle life expectancy chart for a valve-regulated lead-acid (VRLA), absorbent glass mat (AGM) battery (Sprinter XP form Exide Technologies) [59].

Table 4
simulated number of charge/discharge cycles with different aggregate sizes, minimum bid prices and the effect of minimum bid prices on relative income.

Price limit	Aggregate size: 4 UPSs	Aggregate size: 20 UPSs	Aggregate size: 50 UPSs	Relative income [%]
No limit	205 cycles	130 cycles	122 cycles	100
5€/MW	140 cycles	86 cycles	81 cycles	94
10€/MW	72 cycles	45 cycles	42 cycles	83
15€/MW	58 cycles	37 cycles	34 cycles	79

be maintained within nominal specifications of the generally applied battery technology. The reliability aspect of participation was also investigated by several experiments in the laboratory, simulating various kinds of fault situations that could occur during DR operations. The simulation results show that, from the perspective of data centers, the suggested approach is technically feasible, and thus, answer the primary research question. The performance characteristics of the UPS systems are more than sufficient to provide response fast enough (~100 ms) to meet the requirements for primary frequency regulation in the observed markets (< 5 s). Based on this and the prequalification results from the tests performed for Svenska kraftnät, the suggested approach meets the technical requirements of the markets.

The economic feasibility of the approach was investigated by examining the potential market revenue in the Finnish and Swedish markets and comparing it with revenue from data center islanding. As the regulation power is independent of the data center power consumption, it will provide better economical results than data center islanding. The amount of revenue naturally depends on market prices, but for the example configurations, potential revenues (with 2017 prices) ranged from 90 k€ to 240 k€ in the Finnish markets, and from 200 k€ to 520 k€ in the Swedish markets. As previously shown in this paper, there are no significant additional investments and no additional wear and tear of the equipment, and thus, economic feasibility can be assumed.

This paper focuses on data centers with existing battery systems that apply the currently dominant lead-acid battery technology. While these batteries have been identified (in this paper) to be feasible in the upward-regulating primary disturbance reserve (FCR-D), they are not suitable for the more common and economically more valuable bidirectional normal operations primary reserve (FCR-N). This is mostly explained by the limited cycle life and inability to operate in a partial state of charge. UPSs equipped with a different battery technology, such as lithium ion (Li-ion), could be used in the normal operations reserves to provide better market access and higher revenue. For some time now, Li-ion batteries have been suggested as a replacement for traditional lead-acid batteries, but so far, only a few data centers have implemented them. Recent developments in the prices of lithium-ion batteries [60–62] alongside potential additional revenue from primary regulation could actually make a feasible business case for the data centers to change over from lead-acid batteries to lithium-ion ones. This is a subject of future work by the authors and will be covered for example in the forthcoming conference publication by the authors [63].

Recently, there has been a lot of discussion about the need to generate virtual inertia in order to compensate for the diminishing natural inertia on both the production and consumption sides of electricity generated by grid-connected rotating machinery [64]. This has led to debate on the role of primary frequency regulation, the adequacy of the current regulation, the possible need for tightening the reaction speed requirements, and demand for development of a new, faster market. New Zealand, for example, has a balancing product requiring a reaction time of one second or less [64]. Furthermore, the Norwegian TSO (Statnett) has recently announced a fast frequency reserve (FFR) pilot, which aims at investigating the feasibility of a fast-responding balancing product to support the grid during times of low inertia. The market requirement is full activation of the resource within 2 s [65].

It is noteworthy that at the moment, demand-side participation in primary regulation with aggregated assets is possible only in a few market areas in Europe (and the rest of the world), but recently, more and more markets have been opening up; more information on the development in Europe can be found for example in [37]. Further, there is a market unification process going on to uniform the FCR in Europe and a major market restructuring in the UK [66,67]. In addition to national regulation, there may be distribution-grid-related limits and/or regulation that may prohibit a data center from participating in the operations, as in some cases the data center might be inputting energy to the grid.

9. Conclusion

This paper investigates the technical and economic feasibility of data center participation in primary frequency regulation by adopting an approach where the UPS systems of the data centers are used to dynamically adjust the grid loading with energy from batteries.

Our research shows methodologically that the approach is technically feasible from the perspective of the data center, and it meets the requirements of the balancing market. Data centers have the required capacity, and further, the excess stress exerted on their systems and batteries can be maintained within the nominal operational limits. Reliability and security considerations have been taken into account, and the approach has been vigorously tested. The applied UPS technology has also been used for several years as part of autonomous battery test functions in the UPSs. The response speed of the UPSs is significantly faster than the current and foreseeable future market requirements.

As the suggested approach requires no significant additional investments and has practically no impact on the service and maintenance costs, while providing reasonable revenue stream, its economic feasibility can be demonstrated.

The knowledge gap identified in the literature on data centers and their participation in primary frequency regulation is addressed by presenting a technically and economically viable solution of using UPSs with lead-acid batteries. As discussed above, the dominant battery technology, however, limits the operations to a specific type of primary frequency regulation. Nevertheless, the price and technology development of Li-ion batteries will create new usages for the proposed approach and the applied technology. Therefore, future work on the topic is considered to include a study of the feasibility of Li-ion battery systems in data centers with intent of dual-purposing them for primary frequency regulation, as well as an analysis of opportunities in the area of inertia compensation (i.e., synthetic or virtual inertia) enabled by the extremely fast response of the power electronics.

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Publication II

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Dual-purposing UPS batteries for energy storage functions: A business case analysis

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Abstract

The increasing amount of renewable energy in power systems poses challenges for the system operators to handle the volatility of power generation. Demand response and lithium-ion (Li-ion) based battery systems have been suggested as a promising solution to provide balancing services to address this challenge. In the paper we investigate the economic feasibility of providing primary regulation services with dual-purposed Li-ion batteries in the power protection systems of data centers. This is also compared with investments in dedicated battery energy storages. Our analysis shows that investments in dual-purpose data center batteries have a higher profitability, even if this means that the battery capacities in the power protection systems have to be oversized with respect to the data center backup time requirements.

Keywords: Batter energy storage; data center; demand response; primary regulation; lithium batteries

1. Introduction

As the amount of renewable energy increases in a power system, adequate provision of ancillary services (AS), such as frequency regulation, becomes challenging. This is due to two main reasons: 1) The increasing amount of volatile renewable energy requires more grid balancing reserves, and 2) traditionally, AS have been provided by

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conventional generation assets, which are now being replaced by renewable energy sources with a limited ability to provide these services [1] [2]. Battery systems, mainly lithium-based batteries, have been suggested as one of the most promising solutions to provide these services. In the spring of 2017 there were about 1000 electrochemical battery projects in the world, representing 3 134 MW of power capacity in various AS markets [3–5].

Primary regulation or frequency containment reserves is an example of a service that the transmission system operators (TSOs) are responsible for upholding. These reserves are used to maintain the stability of the electrical grid by balancing the electricity production and consumption. Primary regulation reserves are the first ones to react to any deviations in the grid frequency. They are intended to maintain the grid frequency within nominal operating limits.

In deregulated markets, service providers can make agreements with TSOs to adjust the energy production or consumption of the assets based on the grid frequency and current market requirements. In the case of a production asset, the asset is required to increase its production if the grid frequency goes below the nominal limit (upwards regulation) and decrease production if the frequency exceeds the limit (downwards regulation), and vice versa in the case of consumption [6]. In their previous work [5], the authors show that it is technically and economically feasible to provide AS by using redundant, voltage-regulated lead-acid (VRLA) battery capacity in uninterruptible power supply (UPS) systems of data centers. This paper goes deeper into the topic by studying a business case of investing in new Li-ion batteries in data center UPS systems, and compares the profitability of these investments with investments in standalone battery energy storage systems (BESS).

While the topic of data centers and demand response (DR) has been extensively covered in the current literature, most of the published papers focus on slower, energy-based AS and shifting consumption from the time of high electricity cost to more inexpensive consumption hours and/or DR enabled by server workload throttling. For instance, Mamun et al. have extensively studied the usage, optimization, and aging of Li-ion batteries in DR usage in data centers in [17] and [18], but with the focus on peak shaving. Again, in [19], Cupelli et al. have studied how a combination of different data-center-based assets could be used in incentive-based DR; however, the usage and operations of incentive-based three-level control signals differ significantly from primary frequency regulation. Moreover, Li et al. have studied spatial and temporal shifting of IT workload to enable DR and cost savings from lower electricity prices in [19]. Based on the literature review and to the authors' knowledge, the presented business case is novel and the usage of lithium-based data center batteries specifically for primary regulation has not been covered in detail in the literature thus far.

To keep the analysis simple, the paper focuses on revenue generated solely by primary regulation. Although other balancing products, value stacking from multiple revenue sources, and potential grid fee and electricity cost savings could be more profitable, they do not change the main conclusion of this paper, as both the BESS- and UPS-based systems could be used in a similar fashion to achieve similar financial benefits.

The structure of the paper is following: the second section introduces primary frequency regulation. In the third section, the relevant characteristics of battery energy storages and UPS systems are examined. In the fourth section, these characteristics are compared. Section five presents business case calculations and analysis. Conclusions are provided in the final section.

2. Components of BESS and power protection systems in data centers

2.1. Battery energy storage system

The main components of a BESS are a battery system and a power conversion system (PCS). A BESS is typically connected to the medium-voltage grid through switchgear and a transformer. The battery system consists of battery packs, racks, and a battery monitoring system (BMS). The PCS connects the battery system to the grid and converts the alternating current (AC) in the grid into direct current (DC) used to charge/discharge the batteries. Furthermore, a BESS requires management software, which ensures that the BESS is operated according to the current application. Further, both indoors and outdoors, the system has to be placed inside a dedicated enclosure, which results in additional costs. Table 1 shows the cost structure of a BESS project. Even though the cost of the battery packs constitutes a significant proportion of the total project costs, the cost is still limited to 35 % (for a system with 1 C capacity).

Table 1. Cost structure of a 20 MW/—20 MWh battery energy storage system project [7]

Cost component	Proportion (%)
Project development	10
Engineering, Procurement, Construction (EPC)	19
Integration	18
Management software	5
Power conversion system (PCS)	13
Battery packs	35

2.2. UPS-based power protection systems in data centers

While there are multiple UPS topologies, the currently dominant topology in the data center space is double-conversion. The main components of a double conversion UPS system are a rectifier, a battery system, and an inverter. In addition to the UPS, data centers have additional upstream equipment, such as switchgear and transformers [8][9].

In the double conversion topology, the first conversion stage, the rectifier, is fed with AC power from the grid. The rectifier converts this power into DC to feed the second conversion stage, the inverter. The inverter converts DC into AC, which is used to feed the protected loads. The battery system uses the DC from the rectifier to charge the battery systems. During a grid failure event, the inverter is fed with the DC power that is stored in the batteries. This topology ensures that the critical loads are protected from any grid disturbances, including power quality issues and total grid blackouts [5][8].

3. Dual-purpose data center power protection systems to provide ancillary services

When compared, a BESS system and a UPS system share plenty of similar components. A simplification is that a BESS system is a UPS system without the second transformation stage. However, to dual-purpose a UPS system for BESS functions, the inverter has to be able to perform bidirectional operations. The majority of modern dual-conversion UPS systems are designed using insulated gate bipolar transistors (IGBTs) as core power electronics components in the converters. They enable bidirectional power flows in the components with modified control algorithms. Some UPS manufacturers use these features to enable discharging of battery systems to the grid to perform battery load tests without external load banks. A UPS manufacturer Eaton has developed a UPS DR feature based on the above-mentioned technology [10].

In addition to appropriate hardware and control algorithms in the UPS, the battery system has to have sufficient energy to perform these services and to have reserve energy for the needs of critical loads. In the case of primary regulation, the battery system has to be able to perform high cycling operations. For this application, the UPSs have to be equipped with Li-ion batteries instead of the commonly used voltage-regulated lead-acid (VRLA) batteries, which have an inferior cyclic performance [11].

3.1. Energy flows and restrictions

During normal operations of a double conversion UPS system, the power of the critical loads is fed through the UPS. This means that both the conversion stages are under constant load. This load is directly proportional to the critical loads that the UPS is supplying. The fact that the rectifier is constantly loaded reduces the ability of the UPS to perform BESS functions. For example, let us assume that a UPS with 1 MW rated capacity (both conversion stages are rated at least for 1 MW) is feeding 500 kW of critical loads. The rectifier is constantly loaded with 500 kW (the loading is slightly higher because of conversion inefficiencies within the UPS, but they have been omitted for simplification in this paper).

This will limit the ability of the UPS to absorb energy from the grid (downwards regulation) to 500 kW.

Nevertheless, this will not limit the ability of the UPS to perform upwards regulation (reduction of loading that the grid sees or injection of energy to the grid). However, as the primary regulation markets tend to require bidirectional and symmetrical activations (i.e., similar amounts of upwards and downwards regulation), limiting either direction will effectively limit the market-regulating power that the UPS can provide.

The requirement for high availability of data center operations and the resulting redundancy requirements for their power protection equipment ensure that the UPSs are never fully loaded, and that there is significant power capacity to perform these operations. For example, in a 2N data center topology, the maximum loading for the UPSs under normal conditions is 50 %. Different UPS topologies and their excess power capacities have been analyzed in detail in the previous work by the authors [5].

4. Business case analysis

In this section, investment costs for a 1 MW/1 MWh BESS project are compared with the costs of performing similar operations with a UPS system of a data center. A net present value (NPV) analysis is conducted to study the feasibility of the investment. The NPV analysis gives information on the total profitability of the investment when subjected to uncertainty and inflation. The same calculations are also used to determine the payback time of the investment (i.e., the length of the period when the cumulative discounted cash flow remains negative). The analysis is a rough estimation with several assumptions (given and justified below) aiming to clarify the financial motivation of investing in data centers instead of dedicated battery systems.

4.1. Assumptions

The time horizon of the analysis is set at 12 years; this is to match the expected lifetime of a battery energy storage system (12.2 years) evaluated in [4]. The discount rate used in the NPV calculations is selected to be 8 %.

4.1.1. Data center UPS topology and battery systems

The data center UPS topology is assumed to be N+1 with four 1 MW UPSs feeding a maximum of 3 MW of critical loads. This UPS system can feed the critical loads even if one of the 1 MW UPSs has a critical malfunction. In a maximally loaded situation, each UPS will be operating with 75 % loading (4 x 750 kW = 3 MW) [5]. This results in 1 MW (minimum) of usable regulating power.

As the "excess" power capacity is split between the four UPSs (250 kW each), the 1 MWh battery capacity will also be split between the four UPSs (250 kWh each). To ensure that the critical loads are always protected, the full battery capacity cannot be utilized for primary regulation, but a certain proportion has to be reserved for the backup functionality, and therefore, each battery system will be designed with additional 83 kWh (to provide 5 min autonomy with the maximum loading of 1 MW). This yields a total battery capacity of 1333 kWh.

4.1.2. Li-ion battery capital and operational costs

In recent years, Li-ion batteries have undergone a significant cost reduction, and this trend is expected to continue. McKinsey & Company, for example, analyzes that the Li-ion battery pack price will be in the range of 100 to 200 USD/kWh in 2020 and even below 100 USD/kWh in 2030 [12]. Other analytics providers such as The Boston Consulting Group [7] and The Economist [13] have also made similar price predictions.

Table 2 describes the cost breakdown of a 1 MW/1 MWh BESS system. The costs are calculated based on the percentages in Table 1 starting from the assumption that the cost for the battery packs is 400 €/kWh.

The right-hand column of Table 2 holds the related costs for a BESS system placed behind UPSs in a data center. The assumption is that the battery capacity will be sourced as a part of the UPSs, and therefore, there are no additional costs in the project development, EPC (engineering, procurement, and construction), or integration as these costs are already covered in the UPS procurement process. There are also no additional costs for management software or inverters, as the UPS will perform these functionalities with the internal features and hardware as described above.

The cost for the battery packs is higher in the latter case as the total amount of energy is greater to enable the backup functionality (1 MWh vs. 1.33 MWh). Further, because the battery system will be separated into four units (one for each UPS), the related costs can be expected to be higher than in a case of a single battery system. Therefore, a cost of 450 €/kWh has been used for Li-ion batteries in the data center.

It should be noted that dual-purposing of the data center UPSs to perform BESS operations will require significantly more energy capacity than pure backup operations would require. However, the actual additional space requirement is limited because of differences in the volumetric energy densities of typical voltage-regulated lead-acid batteries (VRLA) (approx. 100 Wh/l) and Li-ion batteries (approx. 250 Wh/l) [11].

Table 2. Example of a cost breakdown for a 1 MW / 1 MWh BESS system and a Li-ion UPS battery system

Cost component	Standalone BESS (k€)	UPS-based BESS (k€)
Project development	114	-
Engineering, Procurement, Construction (EPC)	217	-
Integration	206	-
Management software	57	-
Power conversion system (PCS)	149	-
Battery packs	400	600
SUM	**1 143**	**600**

Saulny [4] lists the following items as the OPEX components of a BESS: energy compensation and imbalance costs, trading and development, O&M on site, transmission costs and taxes, electrical losses and auxiliary power, and an "uncertainty buffer" [4]. For a 2 MW/1 MWh system, the OPEX costs were estimated to be in the order of 32 k€ [4]. As most of these are power related, the related costs for a 1 MW/1 MWh system can be assumed to be roughly 20 k€. For the purposes of this paper, the operational costs can be assumed to be similar in both cases, and as such, the exact amount of OPEX costs does not affect the outcome of the analysis.

4.1.3. Market revenue

Market revenue is defined by market price, bid acceptance, and asset availability. Average market prices for primary reserves in several market areas are given in Table 3. The fourth column of the table presents the estimated annual market revenues calculated for a 1 C (1 MW/1 MWh) system. The revenue estimations (RE) for each market were calculated using equation 1. In the calculations, a 70 % bid acceptance rate (α) was use along with a 95 % asset availability rate (β) and the market prices from Table 3.

$$RE_{market} = 8760\ h * Price_{market} * \alpha * \beta \quad (1)$$

Table 3. Average market prices and annual revenue estimation for primary frequency regulation reserves in different markets in 2016 [14][15][16]

Market	Local product name	Price (€ / h / MW)	Revenue estimation (k€ /a)
Finland	FCR-N	23.1	135
United Kingdom	EFR	12	70
Germany	PCR	16.2	94

5. Case study results

NPV is made using the equation 2 where C_t is the net cash inflow during period t, C_0 is the total investment costs, r is the discount rate (8 %) and T is the number of periods. Calculation results for selected years are presented in Table 4. The results show that the majority of cases fail to yield net positive results over the projected 12-year lifetime. The results also show (as expected) that investments in UPS Li-ion batteries are significantly more profitable than investments in BESS systems, under the assumptions made in this paper. The only case that yields positive results is the investments in UPS Li-ion batteries in Finland. The project reaches the break-even point in eight years.

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_0 \quad (2)$$

Table 4. NPV calculation results in k€ for UPS and BESS investments in different countries over the projected lifetime

Year	UPS FIN (k€)	UPS UK (k€)	UPS GER (k€)	BESS FIN (k€)	BESS UK (k€)	BESS GER (k€)
0	-600	-600	-600	-1 143	-1 143	-1 143
1	-494	-554	-531	-1 037	-1 097	-1 074
7	-4	-340	-213	-546	-883	-756
8	59	-313	-172	-484	-856	-715
12	264	-224	-39	-279	-767	-582

6. Conclusions

Based on the analysis results presented in this paper, investments in dual-purpose Li-ion battery systems in data centers are significantly more profitable than investments in standalone BESS systems. This is because the related investment costs would be significantly lower as the data centers already have most of the cost components of a BESS covered in their infrastructure and UPS projects. Therefore, in fact, this approach would not be per se about dual-purposing of the UPS batteries for BESS functions, but using existing assets and infrastructure development projects in data centers to avoid most of the investment costs related to the BESS.

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Publication III

Alaperä I., Honkapuro S., Paananen J., Dalen K. and Hornnes K.
Fast frequency response from an UPS system of a data center, background and pilot results

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Fast frequency response from a UPS system of a data center, background, and pilot results

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***Abstract*— Power systems are going through fundamental changes including an increase in renewable energy production, phasing-out of traditional generation, and increased energy efficiency of consumption. These changes will influence the system inertia and will hinder the ability of the system to maintain frequency stability during large and sudden imbalances. Fast frequency reserves (FFR) have been suggested as one of the possible solutions to improve frequency stability. During 2018, Statnett organized a pilot for the FFR, testing a small-scale market arrangement during normal system operation. A data center operator was selected as one of the participants. Three uninterruptible power supply (UPS) systems of a data center operator were updated to enable FFR services. The results of the pilot indicate that data center UPS are capable to provide FFR response according to the requirements defined in the pilot.**

***Index Terms*— Data center, Fast frequency response, Future energy system, Inertia response, UPS**

I. Introduction

In an electrical power system, a constant balance must be ensured between electricity production and consumption. Any imbalance will cause a frequency deviation and power system inertia contribute to short term frequency stability the first seconds after e.g. a generation trip. Balance is further achieved by adjusting the electricity production in large power plants.

However, current technical and economic developments are changing this scenario. The increasing penetration of renewable energy sources into power systems is displacing traditional power generation from time to time and limiting its ability to balance the grid and stabilize the frequency. To make it worse, a majority of this added renewable energy is produced with systems using power electronic converters that offer little to no inertial response as there is no kinetic energy involved. Additionally, energy-efficiency-driven advancements in deployment of variable speed drives to control heavy machinery are effectively decoupling these machines from the grid, thereby reducing the amount of rotational energy in the grid. The rotational energy (or inertia) has traditionally acted as a natural first response to frequency deviations in the power systems, effectively acting much faster than the deployed frequency control mechanisms.

Current academic research has focused on finding alternative sources for inertia, generally referred to as virtual or simulated inertia. In an in-depth review article [1], current methods of generating frequency response listed, and their effectiveness and implications are analyzed through several examples. The article discusses frequency response and its possible role as an ancillary service. It specifically mentions modern data centers as a potential, but underutilized source for this.

This paper goes deeper into the subject of using data center power protection systems as a substitution for grid inertia, giving a response that will reduce the frequency nadir in the early phase of a frequency drop. The research builds on previous work of the authors on the subject [2] [3]. The technical feasibility of using uninterruptable power supply (UPS) systems to mitigate frequency drop, as an ancillary service is being studied through a pilot project organized by the Norwegian transmission system operator (TSO), Statnett.

The structure of this paper is as follows: Chapter 2 provides the readers with background information about grid inertia, effects of reducing inertia to power systems, and current solutions to address low inertia situations. The technical concept of using UPS systems as fast-acting demand-side resources (DSR) are presented in Chapter 3. The Norwegian FFR pilot and the related results are addressed in Chapter 4, and discussion and final conclusions are presented in the last chapter.

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II. Power system inertia

The European Network of Transmission System Operators for Electricity (ENTSO-E) [4] defines inertia of a power system in their future system inertia reports as follows: "Inertia of a power system is defined as the ability of a system to oppose changes in frequency due to resistance provided by kinetic energy of rotating masses in individual turbine-generators." Fig. 1 illustrates an example where the amount of kinetic energy in the power system has an effect on the depth and duration of a frequency disturbance [5].

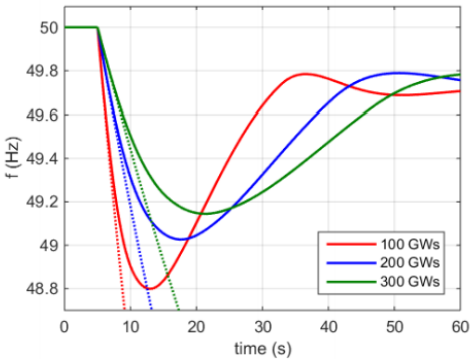

Figure 1. Frequency response with different levels of kinetic energy in the system. The dotted lines indicate the initial RoCoF (Rate of Change of Freqeuncy) [5].

A. Frequency containment reserves (FCR) and FFR

Frequency containment reserves are a type of primary regulation reserves that the TSOs are responsible for upholding. They are intended to handle the small variations in the grid frequency (normal control, called FCR-N in the Nordic power system) or to help the power system recover from larger disturbances, such as sudden loss of generation (disturbance reserve, called FCR-D in the Nordic countries).

FFR is a future tool intended to reduce the frequency nadir. This is to mitigate the effect of low inertia in the grid, which will result in faster and larger oscillations in the frequency.

Responses of different products are illustrated in Fig. 2. The figure shows that synchronous inertial response (i.e., response from the rotating masses) is the first to react, followed by synthetic inertial response, FFR, and lastly, FCR-N and FCR-D. It should be noted that both “Proportional response” and “Temporary power boost” can be considered FFR products, only with a different activation profile (stepwise and dynamic).

The theoretical details of the FCR and FFR have been extensively covered in [4], [5] and in the current academic literature.

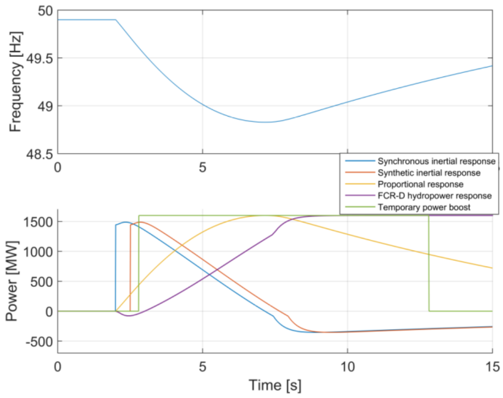

Figure 2. Responses of different products to mitigate frequency disturbances [5].

III. UPS system as a source of FFR service

A. Technology

This paper focuses on static UPS systems, which consist of power electronic converters and energy storages, typically batteries, and have been designed to protect the critical loads against disturbances of the feeding power grids. There are different topologies for a static UPS, providing a varying level of protection against grid-related disturbances. The majority of high-power UPS systems used in data center applications are based on a double conversion topology, where the first conversion stage converts alternating current (AC) from the grid into direct current (DC), which supplies the battery converter and the second conversion stage. The second conversion stage converts the DC back into AC, which feeds the critical loads. In the case of a blackout on the feeding grid, the power is drawn from the battery systems and fed to the loads.

By using appropriate control algorithms, the UPS system can react to external signals in order to reduce (or increase) the power consumption from the grid. Additionally, if the converters are capable of bidirectional operation, UPS can feed energy towards the grid. Different power flows are illustrated in Fig. 3. A more detailed description of using UPS systems in explicit demand response operations, such as primary frequency reserves, can be found in the previous work by the authors, for instance [2] and [3].

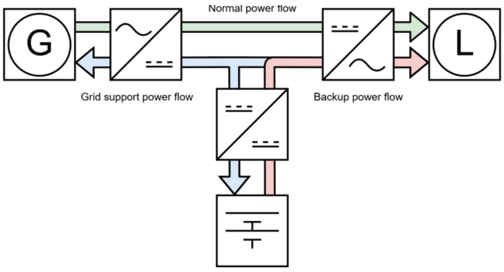

Figure 3. Different power flows between the grid (G), the UPS (3 converters) battery system, and the critical load (L).

B. Energy capacity and effects on the battery lifetime

The FFR service is intended for situations where the grid frequency has declined severely from the nominal. In the Statnett pilot, the activation threshold was set to 49.60 Hz. Naturally, the number of activations depends on the grid frequency stability. Historically the Nordic frequency has been quite stable and events leading to grid frequencies under 49.60Hz have been rare and short lasting. The numbers of times that FFR service would have activated and their average durations have been gathered in Table 1 [6].

The data in the table shows that with the piloted market rules, the battery systems would be subjected to a very limited number of discharges (≤4/a). Participation in the FFR has a negligible impact on the battery aging due to the limited number and depth of the discharge cycles. No additional costs are incurred by the owners of the UPS systems, implying that there is no marginal cost in offering FFR services with a UPS system.

TABLE I. NUMBER OF FREQUENCY EVENTS THAT WOULD HAVE LED TO FFR ACTIVATION AND THEIR AVERAGE DURATIONS BETWEEN THE YEARS OF 2012 AND 2017

Year	Number of activations	Average duration [s]
2017	1	2.90
2016	2	4.35
2015	3	5.50
2014	2	5.35
2013	21	2.34
2012	3	5.23

IV. STATNETT PILOT AND RESULTS

Among four other technologies (aggregated fleet of electrical vehicles, hydro, pump storage, and smelters in aluminum production), three UPS systems of a Norwegian datacenter operator BaseFarm AS were selected to participate in the FFR pilot [7].

As all three UPS systems were able to feed energy back to the supplying grid, the response was not limited by the loading of the UPSs (i.e., the power consumption of the IT loads), but rather by the installed power capacity of the UPS systems. The maximum demand response capacities of the systems are given in Table 2.

Feeding power to the grid would have required a concession from the Norwegian regulator and was outside the scope of this pilot. Hence, to avoid feeding power back to the local distribution grid, the total electricity consumption of the sites, behind the point of grid connection, was studied. As a result, the demand response capacity of UPS3 was reduced from 550 kW to 300 kW.

The concept is illustrated in Fig.4 and (1) and (2). Basically, in order to keep the input power flow (Ptot) of the site positive (from grid to site), the sum of consumption by UPSs and auxiliary systems not participating must be larger than the sum of reverse power from the participating UPSs (1). The amount of power fed back to the grid is related to the demand response capacity of the UPS and the current loading (2). In the equations, P_i denotes power consumption of the UPS i, P_{FBi} is the fed-back power of the UPS i, P_{Cj} is the power capacity of the UPS j, and P_{Lj} is the power consumption of the load j.

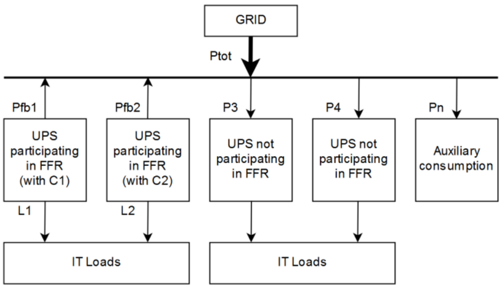

Figure 4. Example of a data center electricity system where a few UPSs participate in the FFR markets and some do not. The power consumption of HVAC and other systems not directly related to the protected server power consumption is illustrated as "Auxiliary consumption."

$$\sum_{i=2}^{n} P_i \geq \sum_{j=1}^{2} P_{FBj} \quad (1)$$

$$P_{FBj} = P_{Cj} - P_{Lj} \quad (2)$$

A. Prequalification

During the prequalification, the power response, activation length, and the reaction speed of the reserve assets were studied.

1) Power response and activation length

Power response was tested by giving a series of frequency references to the UPS through a service tool. The followed sequence was 50.00 Hz–49.70 Hz–49.00 Hz–50.00 Hz.

The response was monitored by using UPS internal measurements and captured by using a service software. Fig. 5 is an illustration of the power response testing performed on the UPS1. The measurements yield 392.0 kW as the full response of the unit. In addition to the input power (red), the chart also shows the introduced frequency reference (purple) and the measured battery power (blue). As the results show, the UPS was able to provide the response for the required 30 s. Results for the other units are gathered in Table 2.

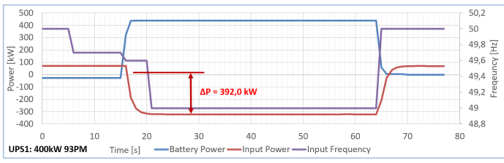

Figure 5. Measurement results of UPS1 during power response testing.

When considering the test results shown in Fig. 5, it should be noted that the UPS internal power measurements were sampled and averaged over a period, and as such, they do not provide accurate information on the reaction speed of the UPS. Further, the measurements of the battery power and the input power were treated differently, which explains the smoothing on the input power measurement, while the battery power measurement is quite linear.

TABLE II. MAXIMUM AND MEASURED POWER RESPONSE OF THE UPS SYSTEMS PARTICIPATING IN THE PILOT

UPS	Maximum response [kW]	Measured response [kW]
UPS1	400	392.0
UPS2	400	393.2
UPS3	550	294.8

2) Reaction speed

According to the requirement (of the FFR pilot by Statnett), the reserve units had to be activated fully within 2 s. During the prequalification process, this was confirmed by using an oscilloscope. A test signal was introduced, and the resulting oscilloscope captures are presented in Fig. 6. The light blue line is the battery current measurement and the yellow line is the input voltage measurement of the UPS.

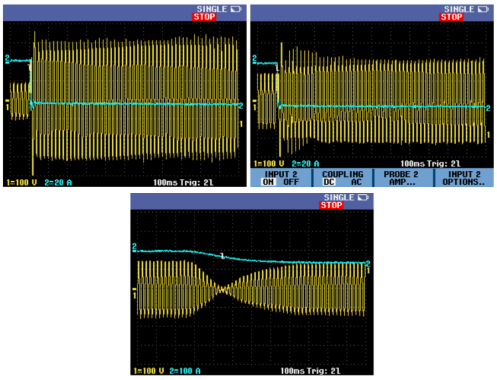

Figure 6. Oscilloscope captures of battery current (blue) and input voltage (yellow) of UPS1 (up-left), UPS2 (up-right) and UPS3 (below) during FFR reserve testing.

For UPS1 and UPS2, the measured (battery) current value drops instantly after the issuance of the command, indicating that current is being discharged from the battery system. There is also a significant change in the waveform of the input voltage measurement, indicating that the UPSs start to feed power back. As one division in the chart is 100 ms, it can be observed that these systems react and reach a stable state in roughly 30 to 40 ms.

The reaction speed performance of UPS3 is slower, which is explained by the facts that UPS3 is a different model than the other two and that in this model the demand response control is not as fast. However, the reaction speed is still well within the specifications of the pilot project with a significant margin (reaction and steady state achieved within 500 ms).

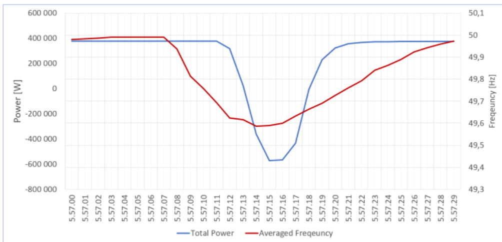

Figure 7. Averaged frequency measurement (red line) and sum of the UPS power response measurements (blue line) during the first event on the 18th of July 2018, the horizontal axis is GMT.

B. Activation

During the 4-week pilot in July–August 2018, there were two concurrent incidents at Olkiluoto, a Finnish nuclear power plant with two reactors (OL1 and OL2), which caused the disconnection of both reactors on the 18th of July 2018. OL2 disconnected from the grid at 08:57 (Finnish summertime, GMT +3) and OL1 at 21:39 (GMT +3) [8]. The amount of lost production was not disclosed, but the capacities of the reactors are 880 MW (OL1) and 890 MW (OL2) [9] [10].

As the Nordic power system is a unified synchronous area, a sudden loss of generation was observed throughout the system. During the first event the UPS systems (in Oslo, Norway) measured the grid frequency to be as low as 49.57 Hz, and during the second event the lowest measured frequency value was 49.61 Hz.

The UPS systems were programmed to have an activation frequency of 49.65 Hz and to provide full response at 49.60 Hz, resulting in a slight ramp to prevent rapid and high oscillations of power in the local electrical system.

Fig. 7 illustrates the average frequency data from UPSs and the total sum of power response from the three UPSs. As previously explained, the power measurements are averaged and as such not fully capable of capturing dynamic events. However, the measurements show that the UPS systems were promptly activated once the frequency fell below the threshold value and that during the event the UPS power consumption was reduced by 949 kW (from 377 kW to -572 kW).

V. CONCLUSIONS

Fast frequency response from the UPS system of data centers is technically feasible. The speed and availability of UPS's has a good fit for the FFR-product. Furthermore, the expected number of activations due to frequency is low. Thus, providing FFR should be a good business case for data center owners. Yet, in order to assess the full business potential, TSO market requirements and national regulation for grid use and connection must be considered.

FFR requirements are currently being developed in the Nordics. The requirements in the pilot project are foreseen to be close to future Nordic harmonized FFR requirement, which are under development. These requirements will include technical requirements as well as requirements for prequalification. As an example, Norway currently has numerous bottlenecks in the distribution grid, and therefore the local grid situation of the data center would need to be assessed during the prequalification process. Market participation will also be affected by the relationship between the service provider of FFR and the supplier of electricity, the balance responsible party. Although FFR is a product with close to no energy volume, this relationship must be clear and established. Furthermore, if the service provider wants to aggregate multiple resources, this adds complexity to the entire value chain. Suppliers must deliver technical solutions for monitoring of availability, activation and verification of response. Solutions with local measurement and local activation can give a higher availability, than centralized solutions with a need for communication.

To sum up, a data center is well suited to provide FFR response. The activation time is short, and the number of data centers is increasing. The pilot demonstrated a potential technical specification and paved the way to a possible market solution. The local grid company and balance responsible party must also be considered as parts of the value chain for accessing the market. Altogether, response from data centers may give a valuable contribution to frequency stability in the future.

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Publication IV

Alaperä I., Manner P., Salmelin J. And Antila H.

Usage of telecommunication base station batteries in demand response for frequency containment disturbance reserve: Motivation, background and pilot results

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Usage of telecommunication base station batteries in demand response for frequency containment disturbance reserve: Motivation, background and pilot results

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***Abstract*—Electrical power systems are undergoing a major change globally. Ever increasing penetration of volatile renewable energy is making the balancing of electricity generation and consumption challenging, forcing transmission system operators to spend increasing amounts of money for ancillary services. This creates interesting opportunities for demand side assets, that would be able to adjust their power consumption.**

Paper focuses on the potential and feasibility of using existing battery systems in telecommunications base stations as an aggregated and highly distributed asset for frequency containment disturbances reserve.

Potential for base stations to participate in demand response was found to be high, due to the characteristics of reserve type (e.g. predicted number of activations, required activation length and power) and the simulation results from a prepared model that indicated a negligible impact that performing these operations would have on the battery systems, their expected lifetime and ability to protect the critical telecommunications loads.

***Keywords*—demand response, telecommunication base station, power system, primary regulation, frequency regulation, frequency containment disturbance reserves, distributed loads, aggregation**

I. INTRODUCTION AND MOTIVATION

Our electrical power systems are undergoing a major change globally. Renewable and intermittent energy is penetrating the systems with an increasing pace. Fig. 1 shows, how the energy production is expected to radically change within the EU. Figure shows that renewable energy generation is expected to increase significantly and that conventional generation with fossil fuels (solids, gas and oil) will be displaced by it. Renewable energy production is forecasted to quadrable from ~100Mton in 2005 to ~400Mton by 2050 while fossil fuels are expected to decline from ~550Mton to <200Mton in the same timeframe [1].

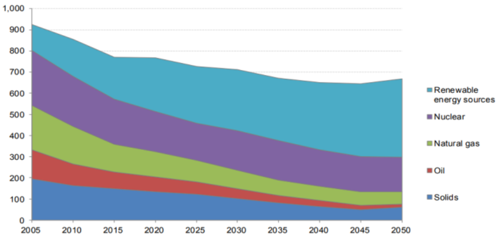

Fig. 1. Forecast of energy prodction mix in EU (form 2005 to 2050 in Mton) [1]

One of the challenges in electrical power systems with a high penetration of renewable energy is the provision of ancillary services. Traditionally these services have been provided by conventional generation, but as power from renewable sources (wind and solar) displaces conventional generation, new providers of ancillary services are needed [2].

Instead of generation, focus for these services, will alternatively turn to demand. Theoretically generation and demand have the equal potential to contribute to ancillary services, such as frequency containment reserves (FCR) [3] and their capability has been proven in several publications [2, 3, 4]. At very high levels of renewable penetration demand side flexibility will be crucial to realize a fully sustainable and reliable electrical power system as generation assets are not anymore able to provide the required services.

This increasing need for demand side flexibility will create interesting business opportunities that could be realized by for example using already existing backup energy in different applications to provide these ancillary services.

II. BACKGROUND

In electrical power systems operation, the system frequency provides an indication of the momentarily balance between the supply and demand [4]. While this paper focuses on the frequency regulation and specifically frequency containment reserve for disturbances (FCR-D), as it is identified as the most financially and technically feasible ancillary service for the batteries in the base stations, distributed demand side assets can be used for other grid support services in both the transmission system level as well as in the distribution system level.

Also, while focus of this paper is in the balancing markets in the Nordic power system (specifically in Finland) balancing markets and/or balancing programs with similar requirements can be found in other frequency areas and electrical power systems around the world. There is also an ongoing unification process in the balancing markets, that is going to open possibilities for distributed demand side assets in multiple countries. As an example, European Network of Transmission System Operators for Electricity (ENTSO-E) is running a public consultation on "FCR cooperation" for potential market design evolutions [5].

A. Requirements for FCR-D in Finland as defined by the national transmission system operator (Fingrid)

FCR-D is defined as an upwards regulating reserve type that starts to activate if frequency goes below 49,90Hz and should be fully activated when frequency reaches 49,50Hz. Activation should be linear or consist of several small steps as shown in Fig. 2 to mimic linear behavior. Required speed of reaction is defined by Fingird as follows: During 5 seconds from the frequency deviation 50% of the assigned reserve power should be activated and full activation is required within 30 seconds from the initial deviation [6].

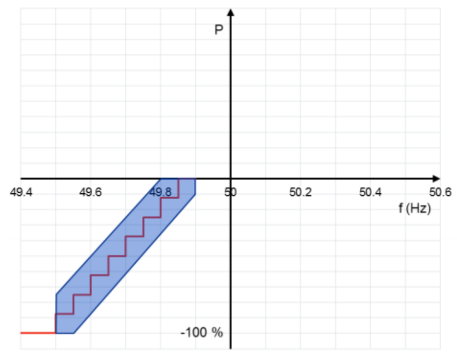

Fig. 2. Frequency response requirements for the FCR-D per Fingrid [6]

B. Length and the power requirement of the activations

As the required FCR-D response is determined solely by the frequency deviation the number, length and relative power requirement of the activations can be determined by analyzing historical frequency data. An analysis was conducted for the frequency data from 2015 and 2016. While there is a significant number of activations in the FCR-D, most of them are relatively short in their duration and the relative power requirement is small. Meaning that the frequency will go under 49.90Hz, but seldom stays there for prolonged times. Also, frequency never went as low as 49,50Hz, meaning that the full FCR-D reserve was never used. Based on analysis that was conducted, the duration of 95% of the activations was 152 seconds or less, in the year 2016 and 154 seconds or less in the year 2015. Power requirement was less than 10% in 90% of the activations during both years.

C. Telecommunication base station as an asset to frequency containment disturbance reserve

The protected power system of a telecommunications base station consists typically of a rectifier and a battery system that are feeding telecommunications loads (radios, routers, etc.). From demand response's point of view, base stations can be considered as controllable loads. The rectifier can be controlled to limit the energy consumption from the grid and instead feed the loads with the backup energy stored in the batteries. This creates an upwards regulating effect that is directly proportional to the current power consumption of the base station.

D. Power consumption of telecommunication base stations

The power consumption of a base station depends on the configuration of the telecommunications equipment that the backup power system is supplying (i.e. quantity and type of different radios). Power consumptions of different radio technologies are listed in Table 1. Base stations are usually equipped with multiple radios and based on pilot findings, the power consumption of a typical base station can be roughly estimated to be around 5kW.

TABLE I. THE POWER CONSUMPTION PER RADIO CONFIGURATION [7]

Site technology configuration	Psite (W)
GSM/EDGE	2145
Combined GSM/EDGE and UMTS	1855
UMTS/HSDPA	1028
HSPA+ double carrier MIMO 2 × 2	1572
HSPA+ double carrier MIMO 4 × 4	2643
LTE Multi Standard Radio MIMO 2 × 2	794
LTE Multi Standard Radio MIMO 4 × 4	1388

E. Battery characteristics of mobile base stations

Currently the main battery technology used in mobile base stations is valve regulated lead acid batteries with absorbed glass mat constructions (VRLA/AGM). A typical battery system for a mobile base station consists of 2 to 4 strings of four 12V batteries ranging between 100Ah to 200Ah in capacity.

Telecommunication authorities (in Finland) define minimum autonomy time requirements for base stations, depending on the classification and importance of the base station, these requirements vary, but typical requirement is 3 hours of autonomy time. Base stations tend to have excess capacity, due to oversizing, reservations for future added loads or redundancy requirements. As an example, the base stations that were included in the pilot had expected autonomy times (with the current loads) between 3h 16min and 7h 12min.

F. Potential and scale of mobile base stations in demand response

While the regulating potential of a single base station is limited, there is a lot of potential using them as a centrally controlled distributed resource that can be scaled to reach MW levels of flexible reserve.

Energy consumption of radio access networks for one mobile operator (MO) with 33,3% market share in Finland was estimated to be 79,2GWh in H1/2011 [7]. Even considering the radio network deployment scenarios presented by M. Katsigiannis and H. Hämmäinen [7] that would reduce the bi-annual consumption down to 51GWh for this MO by the year 2015, total energy consumption for Finnish mobile base stations could be estimated to be in the range of 300GWh. This would result in ~30MW of average power consumption by the mobile base stations in Finland.

Market potential for the 30MW of base station loads can be calculated to be 1,2M€ (year 2017) based on figures presented in Table 2. This represents 6,5% of the total Finnish FCR-D market (year 2017).

TABLE II. FCR-D MARKET PRICES AND MARKET SIZE BETWEEN 2014 AND 2017 IN FINLAND [6]

Year	FCR-D market price [€ / MW / h]	FCR-D market size [MW]
2017	4,70	456
2016	4,50	367
2015	4,13	298
2014	4,03	319

III. PRINCIPLE OF OPERATING TELECOMMUNICATION BASE STATION BATTERIES AS FREQUENCY CONTAINMENT RESERVE FOR DISTURBANCES

During normal operations, the power flows in the base stations protected power supply per Fig. 3. This power flow can be modified to provide an upwards regulating effect. One possibility to achieve this is to lower the output voltage of the rectifier to shift the current flow to load from rectifier to the battery system (Fig. 4). This functionality is much like generic battery test operations in the rectifiers.

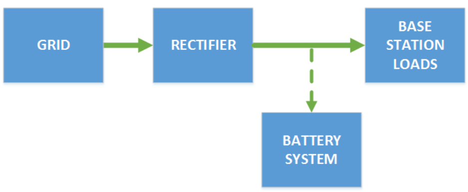

Fig. 3. Mobile base stations power flow during normal operations

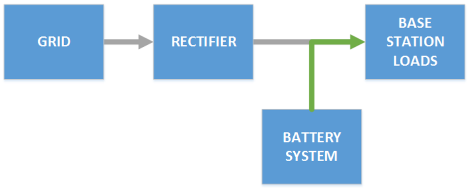

Fig. 4. Mobile base stations power flow during FCR-D activation

Shifting the load from the rectifiers (grid fed) to the batteries (backup) creates an upwards regulating effect directly proportional to the current power consumption of the rectifier.

A. Aggregation vs localized control

To create a regulating effect of significant level, multiple base stations need to be bundled together. This can be done by aggregating a centrally controlled fleet of base stations or by using locally controlled base stations. The main advantage of using an aggregate over multiple locally controller devices is that aggregating a fleet of base stations will allow advanced load balancing and greatly reduces the expected stress for the participating battery systems.

Performing demand response operations with such an aggregate requires a platform to handle the algorithms, logic and measurements, that are used to determine the current balancing power, bid that power to the balancing markets and to dispatch resources based on grid frequency and bid acceptance. Required interconnections are clarified in Fig. 5.

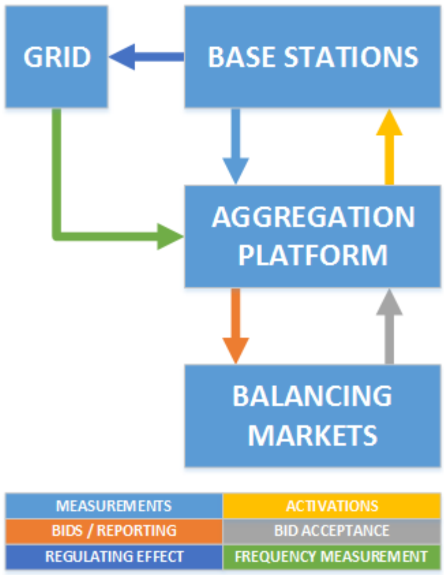

Fig. 5. Conceptual drawing of required connections, data and command flow

B. Reaction speed considerations

One of the major challenges to overcome in using distributed aggregated resources for primary regulation, such as frequency containment disturbance reserves is the required speed of reaction. Table 3 lists the different delays associated.

TABLE III. DIFFERENT DELAYS AND THEIR RELATIVE SIGNIFICANCE IN OPERATING DISTRIBUTED AGGREGATED RESOURCE FOR PRIMARY REGULATION

Delay	Explanation	Significance
Frequency measurement delay	Delay between the frequency deviation and the detection it	Minor
Platform delay	Delay it takes for the platform to send dispatch commands to individual devices per the frequency deviation	Minor
Network delay	Delay of the network connecting the devices and the platform	Minor / Major
Device delay	Delay on the reaction of the device, time between receiving the command and dropping grid consumption to 50%	Major

Frequency measurement delay as well as platform delay can be considered as minor, as they are something that can be controlled by the aggregator, by designing their systems and algorithms to be fast and efficient.

Network delay is highly dependent on the selected approach, if the assets in the aggregate are controlled with interface devices, that are wirelessly connected to the platform, delays will be significant compared to cases where the assets will be interfaces through fixed networks. Although introduction of 5G networks will change this.

Device delay can be considered to have a major significance since it is a characteristic of the device and cannot be controlled externally. Basically, this is the limiting characteristics of the device, as if it has the potential to be used as assets for primary regulation. Investigating this was one of the main objectives for the pilots conducted during the project along with the investigation of the additional stress that the battery systems would be subjected to.

IV. SIMULATION

A simulation model has been developed to investigate how individual battery systems within base stations would be used as a part of a larger aggregate, consisting of several thousand base stations.

The model takes historical frequency data as input along with several calculation and device related parameters and provides simulated state of charge behaviors of each battery system in the aggregate along with several other parameters as outputs.

A. General assumptions

- Base station load was assumed to be 5kW
- Battery capacity was assumed to be 15kWh (3h autonomy)
- Battery recharging power was assumed to be 1kW for each base station.
- Simulation was performed on 5 second steps to match aggregates reactions to reality with non-instantaneous reactions to commands and frequency deviations

B. Principle of operation

Simulation loops through each input data frequency value (one frequency value per five seconds) and the algorithm assigns a state for each battery system in the aggregate, these states are: idle (battery system in float charge), recharge, holdSoC (not charging nor discharging) and discharge. By setting these states the algorithm adjusts the activated reserve power to match the frequency deviation to simulate an upwards regulating effect.

Simulation models the effect of the states to the battery systems (i.e. increments or decrements the charged or discharged energy of the battery system based on its state and calculates the current SoC of the battery system).

Algorithm is designed to cycle the batteries to balance the number, length and depth of the discharges for each battery system in the aggregate.

C. Results

Simulations were run with several different parameters and frequency data from years 2015 and 2016. Increasing the number of devices in the aggregate did not have much impact on the stress (number of charge/discharge cycles) encountered by individual battery systems (Fig. 6). Most impactful input parameter was maximum duration of an activation (discharge and/or hold SoC). By allowing battery system to stay at very shallow partial state of charge for maximum of two days instead of one, charge/discharge cycles for a battery system can be decreased from roughly 48 cycles (Fig. 7) to 30 cycles (Fig. 8).

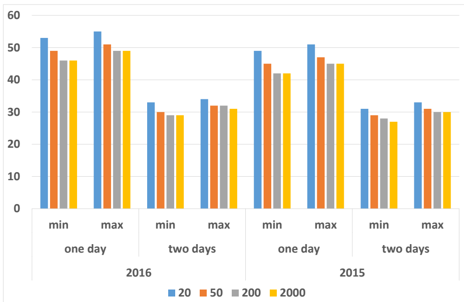

Fig. 6. Minimum and maximum number of charge/discharge cycles for different aggregate sizes and maximum activation durations, based on 2015 and 2016 frequency data

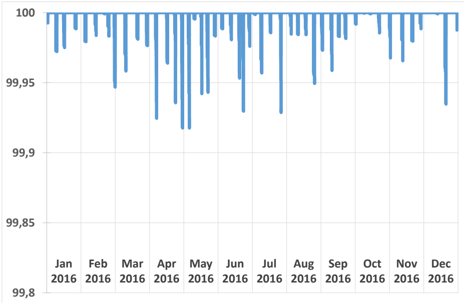

Fig. 7. State of charge behaviour of a most stressed battery system with 2016 frequency data and 1 day forced recharge

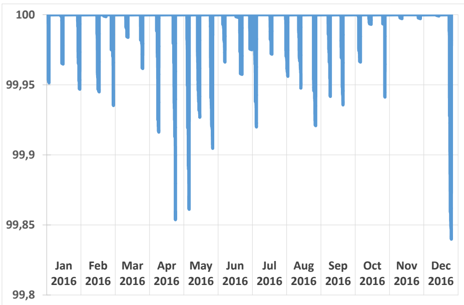

Fig. 8. State of charge behaviour of a most stressed battery system with 2016 frequency data and 2 day forced recharge

D. Simulation conclusions and estimation of the effects for the lifetime of the batteries

Based on the simulation results, VRLA batteries in the base stations would seem to be potentially suitable to be used as frequency containment reserves, if they would be aggregated in a large enough volume to enable uniform distribution of charge/discharge cycles of reasonable length and count.

Simulation results also showed that, batteries would be subjected to less than 50 charge discharge cycles per year, with very shallow depth of discharges (DoD). Battery manufacturers don't generally provide data for the effect of these kind of cycles for the batteries. What can be found are cycle life expectancies for as low as 20% DoD, these vary between 900 [9] and 1300 [10] cycles (30% DoD). For DoD's well below 1% (yielded by the simulations) cycle life would be significantly longer.

Reduction of 0,2% SoC (at maximum) means that the autonomy times of the battery systems would be practically unaffected by the participation to the demand response operations.

Other aspect of the proposed usage is the fact that batteries would not be at float charge all the time, but would be subjected to short periods (max 24h/48h) of "dynamic mode", where the power flow from and to battery system would be minimized. Due to very shallow discharged energy and limited time, this should not be an issue for the lifetime of the batteries. VRLA batteries are, for example, subjected to similar types of mission profiles in uninterruptible power supply (UPS) systems that have periodical charging for the batteries. Effects of periodical charging have been discussed in several publications [11,12] and have been applied by some UPS major manufacturers.

V. Pilot

A. Laboratory setup

A simplified base station power system setup was put together to test the control and reaction speed of the rectifiers. The setup consisted of a telecommunications rectifier (common type and model that can be found at mobile base station sites), four 12V (65Ah) VRLA batteries and a resistive load to simulate the telecommunications loads typically connected to the power systems.

The controller on the rectifier used SNMPv3 protocol and after enabling the protocols and creating a user account with SNMP read/write access rights the rectifier could be controlled using the protocol via a connected laptop sending the SNMP requests.

Reaction speed of the rectifier was tested. A set of 10 activations was performed and the input current of the rectifier was measured to investigate how fast the rectifier reacts to commands. On average 50% reduction in input current (and power) was reached in 3,5s from sending the command. Rectifiers were quick to start reacting (about 1 seconds), but it took over 2 seconds for the output voltage to decline enough to allow more than 50% of the load current from the batteries instead of the rectifier.

Next step was to establish a connection between the rectifier controller and the backend of the cloud platform running the aggregation algorithms. A 2G based communications device was connected to the rectifier that would act as a gateway between the SNMP interface on the device side and the MQTT interface on the cloud side.

A command to shift the loads was send from the backend and the input current of the rectifier was measured to investigate how fast the rectifier reacts to the commands. A set of ten activations was performed and on average 50% reduction in input current (and power) was reached in 8,2s.

B. Field testing

Similar communications equipment was installed to 10 rectifiers in mobile base stations, located in the Southern Finland. Several tests have been planned and will be conducted during the H2 of 2017 to investigate how they will react as an aggregated fleet.

C. Pilot results

The laboratory setup proved that the rectifier can react as per required and that the internal functions work as supposed and that the power flow can be controlled. The speed of the reaction (3,5s to reach 50% on average) was more than expected, but still tolerable. When sending the commands from the platform backend via 2G connection the delay was over 8 seconds, but using faster interfaces and updating the backend algorithms should remedy this.

During the field tests measurements for the input power was read with the SNMP from the rectifier. However, there was a 3 second internal measurement cycle in the rectifiers so the exact reaction times were not obtainable. Depending on the requirements for the local transmission system operator a separate measurement with 1 second resolution might have to be arranged.

VI. Conclusions

Mobile base stations have a lot of potential to be used for ancillary services. They tend to have excess capacity that can be utilized, if the usage is well controlled and that it will not cause too much stress and strain on the battery systems in the base stations. There are also significant economic benefits for the owners (usually mobile operators) of the base stations.

FCR-D type of the reserve is one of the most potential ancillary services that current base station batteries can be used for, while there are multiple daily activations the duration and required power for the activations is limited and an aggregated fleet of base stations batteries will be able to spread out the additional stress so that batteries will not be prematurely aged.

Reaction speed requirement is one of the most critical issues to overcome, this can be mitigated by the usage of fixed networks or advanced radio technologies over 2G/3G communications. Also, the rectifiers in the base stations might need modifications to allow fasted reactions.

Future developments in battery technology and the pending implementation of the 5G networks will create interesting opportunities in aggregated demand response. Smaller cell size of next generation 5G radios will require significantly more base stations and ever diminishing prices of li-ion batteries could create a paradigm shift from lead based batteries to li-ion. A highly-distributed fleet of li-ion battery backed up base stations could be used to provide constant bi-directional regulation around the nominal frequency that would be economically much more interesting than FCR-D.

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Publication V

Alaperä I., Hakala T., Honkapuro S., Manner P., Pylväläinen J., Kaipia T. and Kulla T.
Battery system as a service for a distribution system operator

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BATTERY SYSTEM AS A SERVICE FOR A DISTRIBUTION SYSTEM OPERATOR

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ABSTRACT

Benefits of battery systems in the distribution networks have been widely identified, but current regulation model prohibits the distribution system operators (DSOs) from owning and operating these systems. This paper presents a novel business model where an aggregator company makes the investment to the battery system and offers the system as a service for the DSO.

This business model, and related different revenue streams and cost savings required to make the business case viable, are defined in this paper. The suggested model creates a market place for the DSO, where they can purchase reservation time from the battery, which enables them to technically and economically benefit from the battery system. This service and business model are compatible with the current regulatory environment.

INTRODUCTION

One of the main tasks that distribution system operators (DSO's) have is to ensure the security of supply to electricity customers within their networks. Current developments in renewable energy penetration and increasing utilization of electrical vehicles (EVs) are globally increasing the need for stronger, flexible and more reliable distribution grids.

As a result of lower lithium-ion (Li-ion) battery prices [1], batteries have become one reasonable solution to improve the supply reliability of the branch lines of the medium voltage (MV) network in the rural area. The battery system also enables management of peak loads, reactive power compensation and other DSO level services (see for instance [2]), and thus reduces the potential network reinforcement needs of the future (due to, for example, solar panels and EVs).

However, as these batteries could be used to provide also services in the electricity and balancing markets there has been significant controversy whether the DSO should be allowed to purchase, install and operate these batteries. One of the main topics in the discussions (e.g. in the Clean Energy package by the European Commission) is that since DSOs are highly regulated monopolies, they should not be allowed to participate to unregulated electricity markets. Additional challenges arise, as in some area's DSOs are still vertically integrated to electricity supply business [3].

This paper presents a technical concept and a business model, in which the battery is offered as a service (service level agreement, SLA) to Elenia (a Finnish DSO). The underlying concept is that both the occurrence and duration of the DSO's needs for the battery are very limited. Rest of the time the owner of the battery, in this case Fortum (a Nordic energy company), would be able to utilize the battery in other applications, such as primary frequency regulation service – frequency containment reserves (FCR), offered for the national transmission system operator (Fingrid). This combination allows actors to build a positive total business case in relation to current Li-ion prices. Anticipated revenue streams are two folded; 1) market income from the primary frequency regulation, and 2) the reduction in DSO's regulatory outage costs (ROC).

Novelty value here lies in new kind of business concept, which incorporates the value of a single battery storage from two different applications. Our work (and this project) aims to show that such a project can be economically and technically feasible and fully compatible with the current regulatory framework.

Structure of the Paper

Introduction chapter of this paper offers motivation and background for the paper. A short description of the battery system's design and placement within the DSO's network is given in Chapter 2. Two main applications are described in Chapter 3. Chapter 4 explains the basics of the business model. The principle of usage is described in Chapter 5. In addition to a novel business model, the major contribution in this paper is the final discussion chapter, providing insights on how the concept developed in the project can be used to form a DSO-level service market within the boundaries of current regulation.

BATTERY INSTALLATION LOCATION AND DESIGN

Location

As the DSO's benefits in this project are solely dependent on the local grid needs such as ROC avoidance, finding an optimal place for the battery system in the DSOs network was crucial for making a positive business case for this project. Several individual LV-networks were studied, but the ROC reduction estimations from those networks were not enough (with current battery system prices) to make a viable business case, even with additional revenue from primary frequency regulation. The costs of the battery, its grid connection and the components enabling the island use are too high compared to the ROC avoidance of one LV network.

Battery system was decided to the be installed in medium-voltage grid. The location was selected to be 31 kilometres from the supplying primary substation and at the start of a MV-branch feeding electricity to several LV-networks. This offered significantly better ROC reduction potential over LV-network installation as benefits from multiple LV-networks could be combined.

In addition, these LV-networks have been subjected to several interruptions and the related ROC history is well known by Elenia. These types of costs have been also previously discussed in other publications co-authored by Elenia personnel such as [4] [5].

Battery system design

The designed battery system consists of battery packs, a power conversion system (PCS) (i.e. a grid-tie DC/AC converter system) and a management system. To connect the battery system to the MV-network and to have it perform the required operations in accordance to local regulation a MV/LV transformer, MV-breaker and related protection equipment are also required. The battery is synchronised with the AC grid by the grid-tie converter. The MV breaker is controlled by a protection relay that includes a synchronisation check function. This prevents asynchronous interconnection in case of a failure in the control system of the grid-tie converter. Figure 1 shows the main components of the battery system and the point of connection (PoC) of the battery system in relation of the MV branch and the LV networks downstream. Ownership lines are also illustrated in the Figure. Basically, the concept is that the DSO offers the service provider a DC-grid connection and invests to the components to enable that connection. The service provider procures and installs a DC battery system to the defined connection. Figure 2 shows a picture taken from the battery packs to be installed.

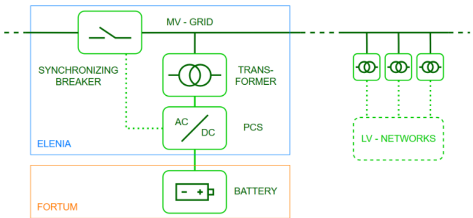

Figure 1, Conceptual drawing of the battery system and ownership lines

Figure 2 Picture of the battery system

Main design characteristics

The decision to connect the battery system to MV-grid over LV-network caused several design challenges mainly related to automatically islanding and resynchronisation the MV-branch downstream from the PoC, electrical safety, environmental conditions at installation site, and implementation of the multi-objective control. In relation to islanding, a major design point was to ensure that the battery system could supply enough short circuit current while the branch is isolated from the rest of the network. The short-circuit current is limited by the PCS and thus has to be fully controlled to prevent converter failures. In addition to current limitation also the duration of supply is controlled based on the identification of the fault type. To ensure the safety, the entire system will be stopped in case of a fault within any of the end-user's installations if the protection of the end-users installation does not operate within the required time. Several network simulations were performed to evaluate the required short circuit current capability and to ensure that even the furthest fuse could be tripped according to local regulation in an isolated state.

In addition to the short circuit capability, the basic battery system parameters such as power and capacity needed to be sized to fulfil the desired operations. The output power of the system was sized to meet the combined peak power of the LV-networks downstream with sufficient margin. Battery systems capacity was a compromise between ROC reduction and cost of the battery system (i.e. the more energy the system has, the longer interruptions it can handle, but battery system costs are heavily affected by capacity).

To enable ease of usage for Elenia, the MV-network equipment was designed to enable the battery system to island the downstream network autonomously and in the longer run to synchronize and reconnect the islanded part to the grid without operator interactions once the upstream failure has been cleared. The PCS control system and the local protection system must operate seamlessly together to enable both automatic and rapid initiation of the island operation as well as uninterruptible resynchronisation of the islanded branch with the rest of the power system. The latter requires active control of the phase sift, frequency and voltage of the island with respect to the power system in the PoC.

During the power system interconnected operation, the PCS will participate in distribution network Volt-var control. It will control both the reactive and active power flows according to the applied control strategy within the boundaries of system temperatures and current limits as well as in the limits due to PoC and battery pack voltages. Thus, multiple overlaying and parallel control loops have been implemented.

APPLICATIONS

During the initial phase of the project, it was found out that in order to reach feasible business case, several revenue streams or cost saving applications would need to be combined, since a single application such a primary frequency regulation or frequency containment reserve (FCR) usage would not be economically feasible. This finding is supported by similar results of other researchers [6]. This is also one of the reasons why such a co-operation model has been selected for further studies.

Elenia's main application for the battery system was identified to be the reduction of the customer interruption times and thus reducing ROC.

From Fortum's point of view, the main application for the battery system will be primary frequency regulation. The market name for this type of service is frequency containment reserve (FCR) in the Nordic power system.

Regulatory Outage Cost (ROC) avoidance

Financial regulation of DSOs in Finland is based on the Electricity Market Act [7], in which is stated that pricing of the DSO's should be reasonable. Foundation of this financial regulation is the calculation of reasonable returns; regulatory asset base is present value of distribution network and Energy Authority define the reasonable return on capital based on WACC (Weighted Average Cost of Capital) method. ROC has impacts on the quality adjustment of the regulation model, and it can increase or decrease the DSO’s reasonable return up to 15% [4]. ROC parameters are presented in table 1.

TABLE I. REGULATORY OUTAGE COST PARAMETERS (I.E. UNIT PRICES) FOR 2018 IN FINLAND [4] [7]

Unexpected interruption		Planned interruption		Delayed Automatic Reclosing	High--- speed automatic reclosing
€/kWh	€/kW	€/kWh	€/kW	€/kW	€/kW
13,44	1,34	8,31	0,61	1,34	0,67

Figure 3 sums up the proportional size of different interruption types and durations and their effect to ROC in Elenia's network [4]. Figure shows that a significant portion of the ROC costs occur from interruptions with short to medium duration. These interruptions are the ones that the battery system is designed to limit. As the battery system will not be used as an uninterruptible power source (UPS) (i.e. all the downstream power will not be fed through it) it will not be able to react fast enough to limit the high-speed automatic reclosing (HSAR) related costs. However, the system limits the delayed automatic reclosing (DAR) and longer interruptions. Also, the battery system will have limited energy capacity and thus it will be unable to handle the longest of interruptions. The average time that the system is capable to maintain the island mode is approximately 3 hours based on the average power of the MV-branch.

In addition to the ROCs, the Electricity Market Act defines strict maximum duration limits for outages, 6 h within urban areas and 36 h outside of them, which DSOs have to meet in their entire area of responsibility by the end of 2028 [7]. The battery system will limit the blackout durations experienced by the consumers, and effectively give Elenia more time to solve the issue in their networks.

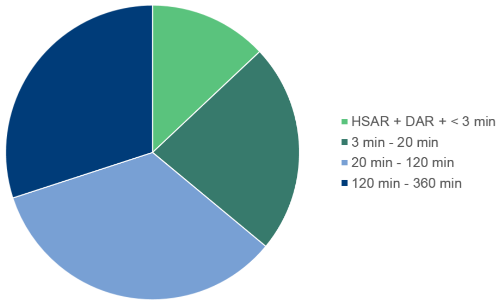

Figure 3 Total ROC per different interruption durations [4]

Frequency containment reserves

Frequency containment reserves are primary frequency regulation tools that are automatically activated when frequency deviates from nominal limits. National transmission system operators are responsible of upholding or acquiring their reserves from the markets. There are currently two types of primary reserve with in the Finnish markets, called frequency containment reserves for normal operations (FCR-N) and frequency containment reserves for disturbances (FCR-D) [8]. Li-ion batteries are technically suitable for both of these markets, but FCR-N is by far economically more interesting, at least in the current market environment.

When participating to FCR, the asset owner / operator makes an agreement with the Fingrid to adjust the power production or consumption of the asset based on the grid frequency. FCR-N activation requirement is illustrated in Figure 4.

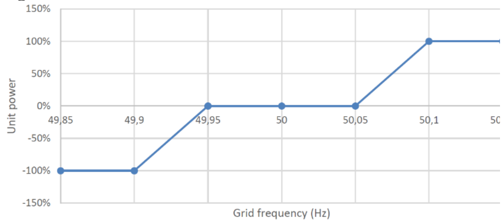

Figure 4 Operation of a reserve unit in primary frequency regulation according to minimum frequency requirements by Fingrid [8] [9]

These reserves are acquired from hourly and yearly markets, the related average prices for the years 2013-2017 are presented in Table 2. Achieved market revenue depends on the hourly / yearly price, bid acceptance and availability of the resource.

TABLE II. AVERAGE HOURLY AND YEARLY PRICES FOR FCR-N BETWEEN 2013 AND 2017 [10]

	Average hourly price [€ / MW / h]	*Yearly price [€ / MW / h]*
2017	20,87	13,00
2016	16,80	17,42
2015	22,32	16,21
2014	31,93	15,80
2013	36,33	14,36

BUSINESS MODEL

In the upon agreed business model (Figure 5), Elenia invests in the equipment related to grid protection and islanding. Fortum makes the investment to grid connection and to the battery system. Fortum then offers the battery system as a service to Elenia with a fixed annual service cost. In addition to the fixed service cost, Elenia can purchase reservation time with a fixed hourly price.

Fortum will receive revenue from the services fees paid by Elenia. These fees include the service level agreement (SLA) related payments (for the battery-as-a-service) and the reservation-based fees. In addition, Fortum will get revenue from Fingrid from the FCR services the battery system is used to provide.

Elenia will get ROC savings from reduced amount and duration of serviced interruptions experienced by the electricity consumers in the LV-networks downstream the PoC.

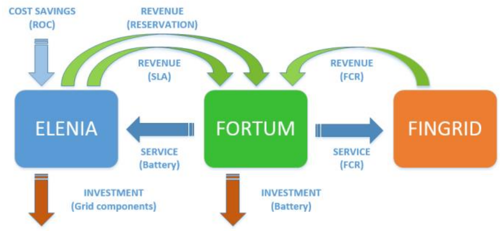

Figure 5 Simplified business model illustration

PRINCIPLE OF OPEARTION

During normal operations Fortum will offer the battery system and its capacity to the hourly FCR-N markets. In the case of a grid failure upstream of the PoC, the related automation and protection equipment will isolate the MV-branch downstream from the PoC and the remainder battery capacity will be used to supply the island network. However, as the battery system will be constantly offered to the FCR-N markets the momentary state of charge (SoC) of the battery system depends on the grid frequency behavior. For this reason, Fortum won't guarantee any capacity for this application. Historically the frequency behavior in the Nordic frequency area has been quite stable and long lasting downwards activations of FCR-N (that would totally deplete the battery capacity) have been relatively infrequent, so there is a high statistical likelihood that there will be at least some energy in the battery system in the case of an unexpected service interruption upstream from the PoC.

However, the co-operation model is designed to give Elenia an option to purchase reservation time. For example, in the case that Elenia has reviewed a notification on potential grid disturbance such as storm fronts etc. they can issue a request for reservation. Fortum will then recharge the battery and seize any operations to the battery. Basically, ensuring that the battery system will be at full SoC ready to supply energy to downstream customers to minimize the effects of the grid disturbances to the end users and simultaneously limiting the ROC. Most of the interruptions occur during exceptional weather conditions, so the timing of interruptions is reasonably well predictable.

DISCUSSION

As described in the article, DSOs (along other actors in the electricity systems) have identified that battery systems could provide them technical and financial benefits. Especially if the battery systems price development continues as it has been forecasted by several analysts (including [1] [11] [12]). However, due to the specific and regulated role of the DSO's, owning and operating battery systems can be interpreted as something that could distort the energy markets. Current regulation states that the DSO cannot own the batteries, but it can buy the services of battery capacity from the market.

The suggested business model answers to that need. In the model Fortum can make a commercially viable business case to own and operate the battery system and also to offer its services to the local DSO.

The model creates a market place for the DSO to purchase backup power services, enabled by the battery system, without participating to the energy markets as such. This model allows DSOs to utilize the battery that is also used in the electricity market (by Fortum). Thus, the battery can be utilized as efficiently as possible thereby improving the cost efficiency of the battery system. This makes the model profitable for both Fortum and the DSO.

While the model relies currently heavily on the market revenue from primary frequency regulation and ROC these are not the only revenue streams that have been identified to be accessible during the lifetime of the battery system. Feasibility of other (DSO and TSO) level services, such as reactive power compensation in the DSOs network, will be investigated later in the project.

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