White paper

Grid-interactive data centers: enabling decarbonization and system stability

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Summary

Data centers are one of the fastest growing loads on the electric grid. Since they use energy storage as backup in the Uninterruptible Power Supply (UPS), the growth in data center loads will result in growth in energy storage capacity. As the penetration of intermittent renewable resources increases, the electric grid requires energy storage to maintain grid balances and system stability. Data centers can offer a unique opportunity to help maintain grid balance. This paper will discuss how data centers can monetize existing assets with no negative impact to customers and support to improve grid stability, which enables the integration of more renewables.

Introduction

Data center as a data plant

Although data centers are considered as loads for the electric grid, every megawatt (MW) of data center capacity includes megawatts of power generation from utilities, megawatts of power generation as a backup system and energy storage system in the UPS. Hyperscale data centers like Microsoft's are effectively data plants with power plants and energy storage plants next to the data center. Thus, a data center will be an asset to the grid in future, given distributed energy assets are the core components of its design (e.g., backup generators, UPSs), and these distributed energy resources (DER) can provide services to support grid decarbonization.

Transition to low-carbon energy systems

Organizations and society are moving away from fossil-based fuels to cleaner energy sources to help battle climate change and reduce our environmental impact. This decarbonization of energy systems is mainly based on the use of variable renewable energy (VRE) such as solar and wind power generation, but the transition toward low-carbon power systems is creating new challenges for system operators.

Managing the availability of the energy and variations in renewable power generation are subjects commonly discussed with the potential congestion in power systems caused by increasing energy consumption in quickly developing areas.

Powering Business Worldwide

Another equally important challenge is the management of the power system reliability in a grid with reduced inertia and a high level of non-synchronous power generation. This may lead to the curtailment of renewable power generation and force us to have more traditional generation based on fossil fuels until enough fast reserves are available to manage the contingency events and maintain system frequency.

Thus, as the penetration of uncertain and intermittent renewable resources increases, energy storage systems are critical to the robustness, resiliency and efficiency of energy systems.

Ancillary service market

Electricity is not a singular product, but a service consisting of several products that can be classified generally as energy, i.e., reliable transmission of electrons over time; capacity, i.e., the availability of power if and when it is needed; and ancillary services, i.e., a broad range of services that includes managing the frequency in the grid and providing fast response to changes in either supply or demand. Given the increasing penetration of renewables across the globe, the value of capacity and ancillary services will rise, and the opportunities associated with DER and energy storage will increase. Thus, the ancillary service market is one of the attractive electricity markets for energy storage systems, providing premium services to the grid to maintain the system stability.

In this paper, various versions of frequency regulation as examples of ancillary services are described. Then, the structure of advanced UPSs as a source of frequency regulation is presented, including two case studies. Technical and economic aspects of data center energy storage versus traditional energy storage are also discussed.

Frequency regulation

In the electric grid, transmission operators have a need and obligation to maintain the grid balance and reliability, and the frequency within defined limits. The frequency deviation from the nominal frequency, i.e., 50 Hz or 60 Hz, is the function of mismatch between supply and demand. When the demand is greater than supply, the frequency decreases, and when the supply is greater than demand, the frequency increases. Maintaining system frequency means matching supply and demand while maintaining system frequency of 50 Hz or 60 Hz and tracking moment to moment. This is achieved through proactive balancing of the system by acquiring the correct amount of generation capacity based on demand and supply forecasts and frequency regulation, typically composed of mandatory frequency regulation by large production units and frequency containment reserves as part of the ancillary services market. Frequency regulation is a corrective (reactive) method to maintain the frequency within defined boundaries, operating based on real-time frequency.

Based on stability definition in the power system, frequency stability can be divided in short- and long-term stability. Long-term stability is affected by factors such as demand and supply forecasts, small imbalances in the system, balancing services and primary frequency regulation; the time frame of long-term frequency regulation is in the order of several minutes. In the high penetration of the renewables, unpredictable DER can introduce further instability to the grid.

Short-term stability is affected by factors such as load shedding, generator controls and response, protection devices and system inertia, with time frames in the order of one to several seconds following a large disturbance. Because of that, grid operators require additional reserves to maintain system stability and provide rapid response to restore system balance, which can be composed of generation, energy storage or interruptible loads.

While traditional demand-side response, such as peak shaving or load shifting, is energy-intensive, frequency regulation is more about the availability of power to regulate. Frequency containment reserves, especially the ones against disturbances, often have requirements to operate for a relatively short duration, and use less energy.

There are several programs developed by utilities and grid operators in Europe, North America and Australia for frequency regulation using an energy storage system and allowing demand-side loads to participate in this market. Therefore, the deployment of grid-connected energy storage systems for ancillary services is increasing, including stationary battery projects in California and Australia.

System inertia

Inertia in the power system means all the spinning mass that is directly coupled to system voltage and frequency. This is created by traditional power generation with synchronous generators and directly connected electrical motors in the industry.

As the amount of non-synchronous power electronic interface-based generation such as solar and wind increases, the power grids are facing new challenges, since higher penetration of VRE sources also reduces the inertia in the power system. Besides this, changes in industrial loads with electrical motors connected through variable frequency drives (VFD) are contributing to the reduction of grid inertia.

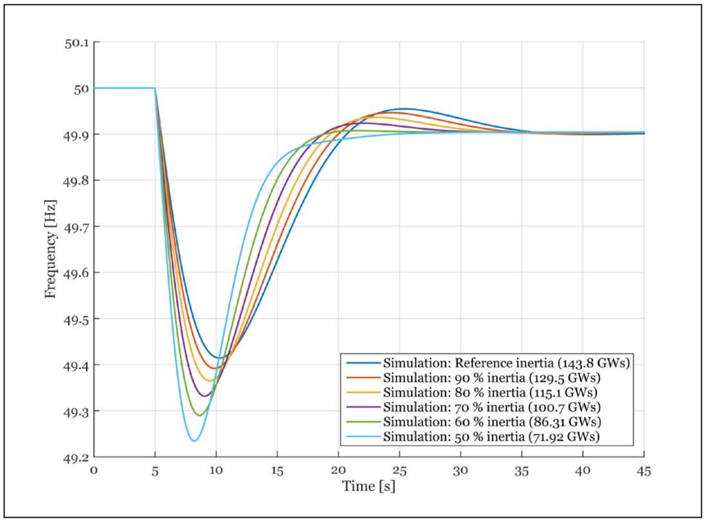

Figure 1. Impact of system inertia to frequency variation. (Entso-e, Nordic report Future System Inertia V1).

If there's a demand-supply imbalance and the frequency in the system goes up or down, the spinning mass either absorbs or releases energy, and essentially increases or reduces demand (on the load side) from the grid. This has a dampening effect to frequency variations.

In the grids with high penetration of VRE and low inertia, the frequency variations caused by momentary imbalances are higher and faster. This is causing challenges to maintain system stability and reliability during the disturbances, since traditional frequency regulation may not provide fast enough response to keep the frequency within specified limits. Large and fast frequency deviations, as a result of contingency events, can jeopardize the system stability and may result in automatic under-frequency load shedding and disconnection of parts of the grid. In a worst-case scenario, the result is a grid-wide blackout — which can significantly impact businesses and society in general.

One of the solutions to mitigate low system inertia has been curtailment of non-synchronous generation, such as wind. In practice, all the available clean energy is not used, and some of it is replaced with traditional fossil-based fuels. Another method has been limiting the size of a dimensioning incident by reducing the output of largest generation units, such as a nuclear power plant. While it is effective, it may increase cost significantly to compensate for the lost revenue from the energy market. Also, using spinning reserves running on fossil fuel is an option with obvious negative environmental impact and cost. The most prominent solution has been Fast Frequency Response (FFR), used in selected markets in Europe and proposed for ERCOT in the U.S. The FFR provides very fast response to large frequency deviations during contingency events, helping to contain the frequency within acceptable limits, and providing time for traditional, and a bit slower, reserves to react.

Reserves against disturbances

The purpose of frequency containment reserves against disturbances (FCR-D) is to provide the primary response to sudden frequency variations, typically low frequency, caused by a contingency event in the power grid. As the system inertia is reducing in many synchronous areas, even faster reacting reserves are required to tackle the low inertia situations. FFR is an example of these new faster type reserves coming to ancillary markets. The market names for reserve types vary along with the exact technical requirements.

As a general principle, once the frequency drops below the defined threshold value, these reserves will give a response by reducing demand, or feeding power to the grid, to contain the frequency within an acceptable range. Typically, these reserves are self-deployed based on the local system frequency measurement and regulate only when frequency is outside defined limits. Once frequency is restored, they cease regulating. Required reaction time varies from below one second (FFR) to a few seconds (FCR-D).

Depending on the market and reserve type, the power response to frequency deviation can be static and provide a constant response once activated, or dynamic, using a defined droop curve, where the power response is proportional to actual frequency deviation. Figure 2 shows a generic droop curve to participate in dynamic frequency regulation. Required response can be to either or both directions (frequency up and down regulation).

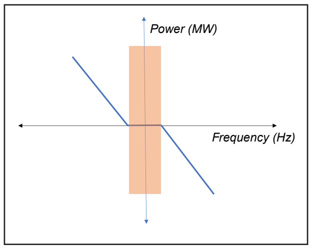

Figure 2. Generic droop curve for frequency regulation.

Reserves for normal (continuous) operation

There are other sets of frequency regulation services to balance load and generation, with the exact technical approach varying between markets. For example, a regional transmission organization (RTO) in the U.S., PJM, is using an Automatic Generator Control (AGC) to derive a response for regulation. Dynamic regulation signal (RegD) and traditional regulation signal (RegA), used in PJM's market, are examples of this type of frequency regulation. The AGC is centrally calculating the required response based on the real-time system balance and frequency, and the regulation signals are sent to the participants through an external signal. Figure 3 shows 40 minutes of PJM's RegD signal for FFR. In this specific market, AGC sends a signal every two seconds, and the payment is proportional to the accuracy with which the DER can follow the regulation signal.

FCR-N would be equivalent to PJM's strategy in Europe, with the exception of using local frequency measurement and regulation. Dynamic and symmetrical frequency regulation like RegD or FCR-N requires continuous charging and discharging, while FCR-D or FFR are based on the activation due to larger but more occasional deviation in the grid frequency.

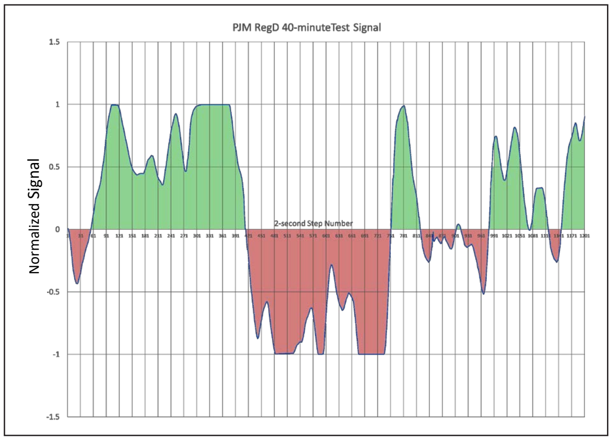

Figure 3: PJM's test signal for FFR.

Data centers and UPSs as sources of FFR

A typical data center has backup generators and UPSs depending on the electrical design and availability requirements at the server level. Many data center operators have already offered their power generation capacity for the ancillary services market as secondary reserves. Due to the associated emissions and startup time, they are not the primary answer to tackle the fast frequency variations in the grid, whereas a modern static UPS with bidirectional converters and built-in control features can provide a fast response to support FFR. Figure 4 illustrates how a modern UPS can increase or decrease demand from the utility to respond to the power setpoint while supporting the critical load.

With correct control algorithms and the capabilities of modern UPS technology, the use of energy from batteries can be seamlessly controlled while remaining connected to the power grid. There's no need to disconnect the grid from a UPS to provide a demand response; this can be done by controlling battery discharge (or charging) in parallel with the grid.

With a bidirectional rectifier, power can be fed to the grid by operating in regenerative mode; the response given can be controlled and is independent from the UPS load level. The energy management of the UPS and battery can respond to the active power setpoint, calculated either by a secondary controller or built-in controller in the UPS, to respond to the frequency deviation.

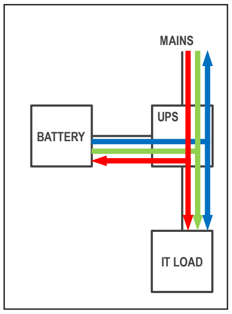

Figure 4. Modern UPS and energy management. UPS can increase demand from grid through charging (red), reduce the demand by power sharing (green) or even feed power back to grid (blue) while supporting the critical loads.

Case study 1

A modern UPS with the appropriate supporting features can easily provide a fast-enough response to meet the needs of transmission system operators for frequency containment. This new UPS technology has been field tested for FCR-D and FFR reserve types in the Nordics by Eaton, a local aggregator and energy company (Fortum) and local transmission system operators (Svenska Kraftnät and Statnett). An Eaton UPS in Dublin, Ireland is used to provide a FFR for the Eirgrid DS3 market as part of aggregator's (Enel X) virtual power plant, and local data centers in Stockholm and Oslo have participated in the new FFR market with Eaton UPSs. Figure 5 shows how the UPS is providing fast response to frequency deviation in Ireland by reducing buildings' demand from the grid.

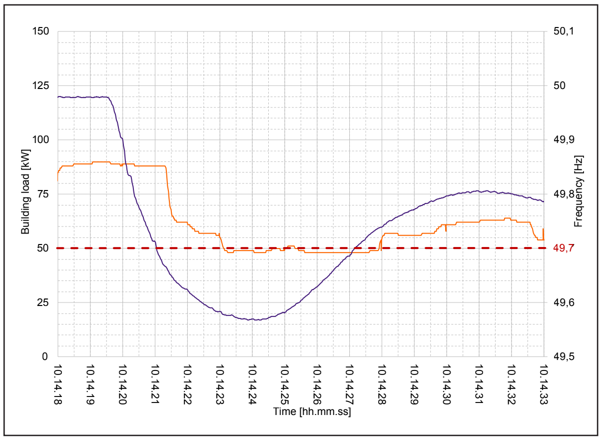

Figure 5. UPS providing fast response to frequency deviation. Response (static 25 kW) activated through external signal once frequency drops below threshold value (49,70 Hz). Power grid frequency (purple) and building load (orange) plotted during one event.

Case study 2

A UPS with grid-interactive function for dynamic frequency regulation has also been field tested for RegD signal in one of Microsoft's eastern U.S. data centers, collaborating with the UPS supplier (Eaton) and the regional transmission organization (PJM). The external signal by PJM has been communicated to the UPS, and the UPS will follow an external signal considering all the constraints and available capacity of the battery allocated for the frequency regulation. Figure 6 shows the two hours of the test of the RegD signal and the response of the UPS.

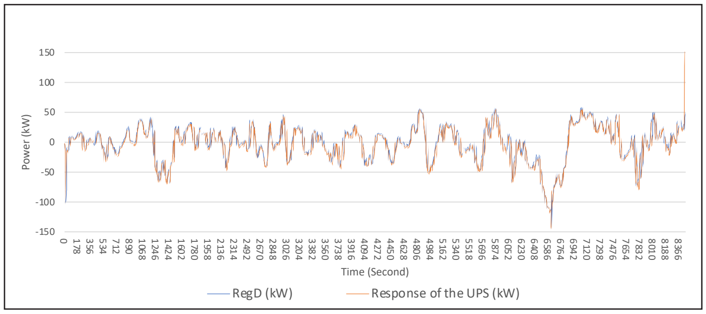

Figure 6: PJM RegD signal (blue) and the response of the UPS to RegD (orange).

Critical load protection

Using a UPS for a secondary application such as frequency regulation or demand response naturally raises some concerns, such as:

- What happens if a battery fails?
- How can you ensure enough backup time for critical loads?
- What if there is a problem in a UPS or it is not suitable for the business to perform demand response?

A data center's generator's and battery's first job are to ensure continuous power to the Information Technology (IT) critical load. Current UPS architectures must be enhanced to allocate the capacity needed to protect the data center IT loads in the case of utility outage and generators must be adapted to start fast.

These concerns can be mitigated by the UPS technology with correct control methods and control algorithms. When using their batteries in parallel with the power grid, UPSs can revert full power back to the rectifier, or batteries, should the other circuit fail. Equally, a UPS can estimate the remaining energy in batteries and allocate enough capacity for the critical load, preventing the batteries from being discharged beyond defined limits.

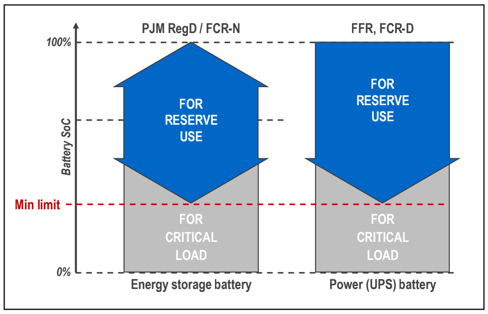

Figure 7. Allocating battery energy in a UPS for primary and secondary application.

When external signals are used to control the power and state of charge (SoC) of batteries, the failures in communication or external controllers must be detected and managed properly by a UPS. In case of abnormal conditions (alarm) in a UPS, the UPS will fail-safe to a normal operation mode, focusing solely on load protection.

Being a part of virtual power plant as a route to market typically offers additional flexibility to use assets as it fits the owner's schedule. Also, the ancillary services markets can offer flexibility, with hourly bidding plans allowing the choice of the exact time (hours) of participation.

Data center energy storage economics

In general, there are various ancillary services in the electric grid, such as peak shaving, frequency and voltage regulation, virtual inertia, FFR, etc., which have a premium value compared to the energy market. This premium value makes ancillary services a profitable market for DER or energy storage owners or operators to participate in. The time duration required for each service and the number of required activations and technical requirements vary for each electricity market. Since the UPSs are part of the core design of most of data center infrastructure, there is only a marginal cost of making UPSs compatible for ancillary services, while other DER companies should get a return on the full project cost. Also, there are other non-cost factors that could potentially benefit the data center — using less resources, lowering carbon use, and supporting the environment while providing the same services. Figure 8 shows conventional versus data center energy storage economics.

Comparing a battery energy storage system (BESS) and a data center UPS shows commonalities in the power infrastructure. About 50% of the cost for >1 MW BESS is coming from batteries and the converter system. The other half is related to grid connection, property, building, etc. When leveraging the mandatory UPS installation to provide additional value through grid support, the related investment for energy storage can be highly reduced.

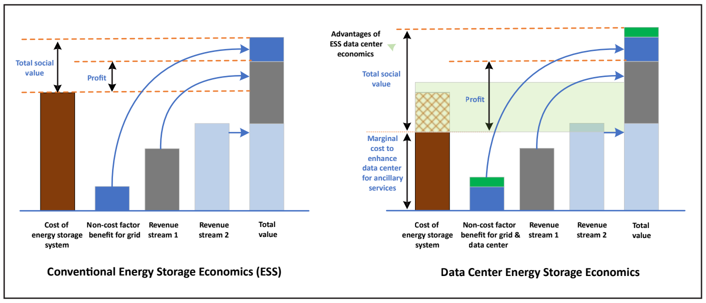

Figure 8: Conventional versus data center energy storage economics.

This concept can offer various collaboration models, since it provides commercial benefits for aggregators operating in ancillary markets through reduced investment, and for asset owners through new revenue streams or savings. The investor (funding) and owner of batteries and converters can vary as well as the models for revenue sharing.

In European energy markets open for consumers to participate in ancillary services, the typical revenues vary between tens of thousands up to over 100,000 euros per MW per year. Exact earnings depend on market prices, application and implementation (technology) and will be studied case-by-case.

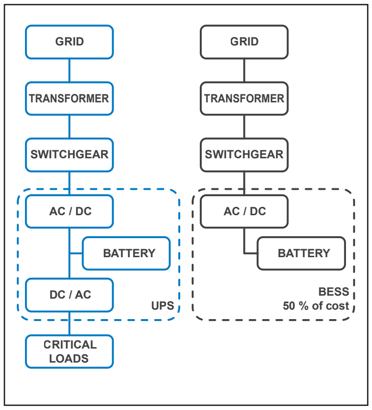

Figure 9. High-level UPS and BESS infrastructure comparison.

Battery impact

One of the key factors in the operation cost of the grid-interactive services is the degradation cost of the battery. In general, the lead acid battery used in a UPS may not be suitable for many of the applications in the ancillary services market. In some markets, such as in Ireland and the Nordics, grid-interactive operation can have a minimal impact on battery degradation due to the operation plan and payment method, while in electricity markets such as PJM in the U.S. or in continental Europe, the battery degeneration has a significant impact on the total cost of ownership. Battery degradation modeling is challenging and requires detailed development and several experimental tests, verified by a third-party laboratory, to define the degradation curves.

Li-ion is an established technology to advance UPS technology, but there are many more nascent chemistries under evaluation. Lower cost, minimizing degradation and extending ride-through time are some of the key attributes to be considered to select the battery.

A key element for the battery is to understand the market requirements, such as activation frequency, the local frequency quality indicating how often the battery is used and what the depth of discharge is. Historical grid frequency data is often provided for download and analysis by TSOs and can be used to gain this understanding. Figure 10 shows an example of annual battery use for frequency regulation with different activation frequencies.

With a new installation, selecting a battery suited for more aggressive use may allow participation in more lucrative markets or gaining higher savings through energy management, but it comes with a higher price. It's important to know market requirements, values, foresights and technical data to achieve an understanding of opportunities as well as required (additional) investments, potential revenue and payback times.

Conclusion

In the future, an "energy-aware UPS" or "grid-interactive UPS" is not only protecting the load against voltage and frequency anomalies, but intelligently leveraging the connected energy storage to manage power and the flow of energy. It can also help optimize energy usage, reduce cost of energy through demand response activities and support the grid to allow higher penetration of renewables.

New markets for ancillary services and faster reserve types are introduced to support the future decarbonized power grid and renewable power generation. More and better means to support the grid will be accomplished not just in UPSs, but in demand-side generally, improving the grid-responsiveness of the buildings. This new flexibility is necessary to enable grids with high levels of renewable power generation and reduce greenhouse gas emissions. Once the stored energy in the buildings and systems is leveraged to provide flexibility, optimization and services, it becomes an asset, increasing its value.

Breaking the silos, coupling the sectors and considering everything as a grid by using existing and multi-purpose assets to provide the essential flexibility and services for future low-carbon energy system are reducing the need for additional investments and systems. As a result, less natural resources and energy will be consumed to build the required flexibility, while making the transition to low-carbon energy systems more affordable for all.

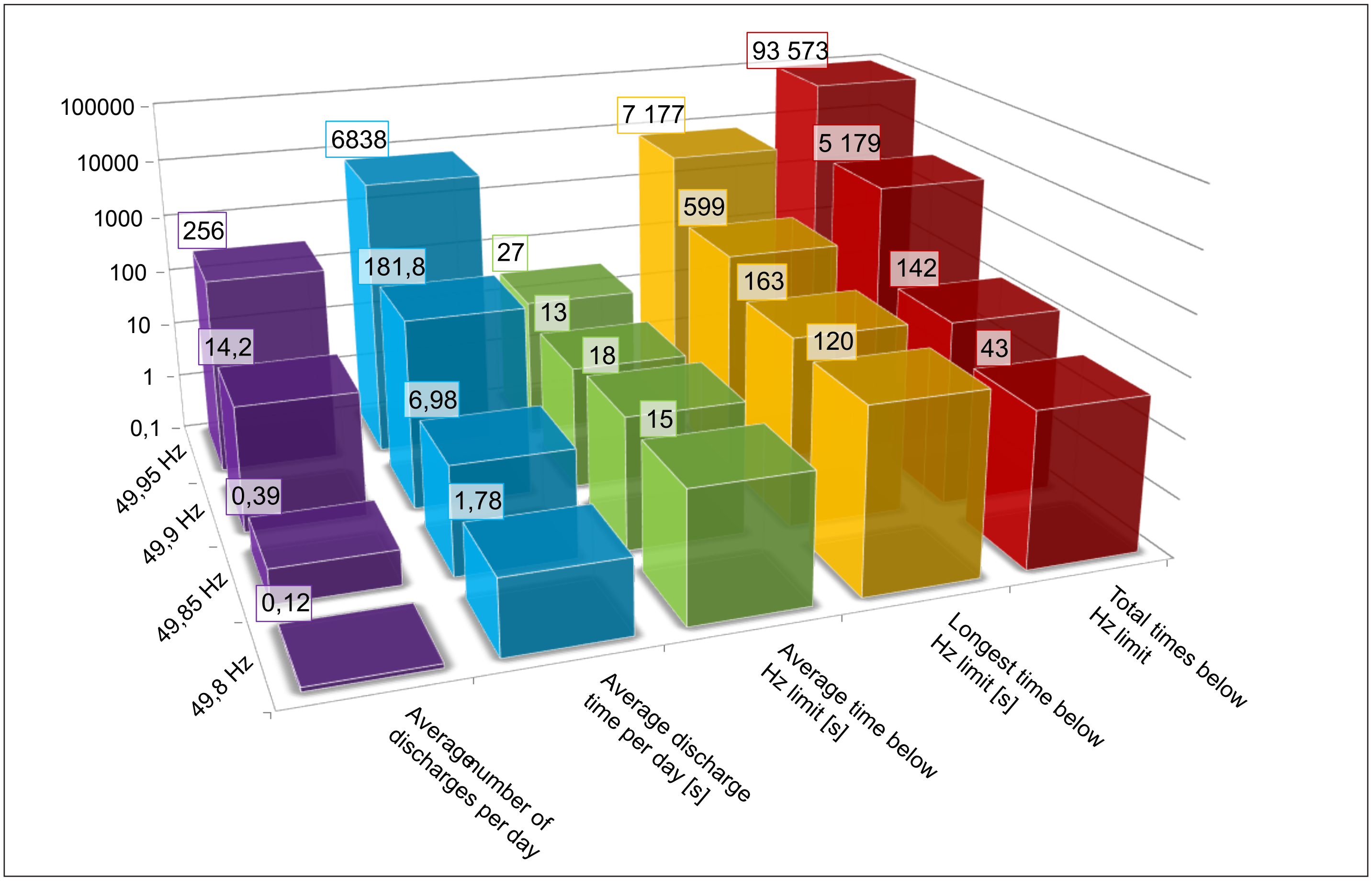

Figure 10. Annual battery use in frequency regulation with different activation frequencies (regulation band); based on Irish national grid frequency data from 2016.

About the authors

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Based in Espoo, Finland, Janne Paananen is technology manager in the Critical Power Solutions organization for Eaton EMEA.

Janne specializes in large UPS system solutions for data centers and special applications. He has 20 years of experience with large three-phase UPS products and has been working in after- and pre-sales organizations providing tailored UPS solutions, support and in-depth product trainings for Eaton's personnel and customers world-wide.

Janne is also a guest lecturer for educational institutes and participating in the international standardization work around data centers and low-voltage electrical installations.

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Further reading

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