Frequency Services for the Electrical Grid from HPC Data Centres.

This report is part of the project “Frequency Services for the Electrical Grid from HPC Data Centres” financed by Vinnova and managed by RISE in collaboration with Vertiv, Vattenfall, KTH, Akademiska hus and EcoDatacenter.

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Summary

This report explores how High-Performance Computing (HPC) data centers can support the Nordic electricity grid, by acting on the ancillary services market such as Fast Frequency Reserve (FFR) and Frequency Containment Reserve (FCR-D).

Balancing electricity production and consumption is crucial for the stability of a power grid. By acting on the ancillary market one can contribute to this stability.

The report starts with an overview of the Nordic electricity grid and explains FFR and FCR-D, two ancillary services well-suited for HPC data centers.

It then covers three power reduction techniques and how they can help HPC data centers meet the requirements of different ancillary services.

1. Job scheduling using the Slurm Workload Manager.
2. Downclocking of server Central Processing Units (CPUs) using the Linux utility CPU power.
3. Using an Uninterruptible Power Supply (UPS) and batteries.

The report investigates how these power reduction techniques can be applied to HPC data centers, with the goal of reducing power consumption during different time intervals. The difficulty of implementing each technique is discussed.

The techniques are then evaluated by how their application can meet the demands for activation time, duration, and capacity. For the software method using Slurm and the downclocking of CPU power, their activation times are assessed in a networked cluster environment. For power systems, the report studies the responsiveness of existing UPS and battery systems.

In conclusion, the report states that a variety of power reduction techniques can meet the rising needs of the ancillary service market in HPC data centers, depending on activation time, duration, and capacity.
1 Conclusion

HPC data centers can act on the frequency market in Sweden, providing that they meet the requirements set for the services. There are special conditions that need to be taken in consideration for each method.

- **Software method**
  A lot of effort needs to be done to be able to use software such as Slurm. To meet the requirements for FFR, all calculations need to be killed, and then restarted from a saved state (checkpointing). This method is fast but might not be acceptable for all customers depending on the type of workload. By using virtual machines, it is possible to pause all calculations at once. However, the use of virtual machines might have a negative impact on performance.

- **Frequency reduction, downclocking**
  There is no issue reaching the demands for activation when it comes to downclocking. However, it is important to control that you can reach the minimum bid size of 0.1 MW. The minimum level which the clock frequency of the CPU can be downclocked to depends on the CPU and must be checked for each type of CPU in the data center. It is also important to understand that all the CPUs might not be used simultaneously.

- **Power reduction via the Power System**
  By using the battery energy storage associated with the UPS as temporary source of energy, the energy consumption of the HPC data centre can decrease with in milliseconds. When calculating the size of the battery energy storage needed, it is important to take into consideration the risk of a power failure short after the service has been activated and hence the remaining battery capacity.
2 Introduction and background

High-Performance Computing (HPC) data centers have high server utilization rates and high-power requirements but typically low availability requirements since they are dedicated to performing a high volume of calculation in a short amount of time. Usually used by universities and research institutes for advanced calculations, but HPCs are increasingly being operated by private businesses as well.

The total electricity output for HPC machines in Sweden are appreciated to be about 10 MW, this assuming that ASIC/GPU clusters for cryptocurrencies are excepted. Cryptocurrencies can use the same methods and are estimated to use about 200 MW in peak power in 2022 in Sweden (RISE - Research Institutes of Sweden, 2023).

The purpose of the project is to show and describe how HPC data centers can act on the ancillary market in Sweden to contribute to the stability of the electricity grid.

The Nordic electricity grid is connected and balanced against a frequency of 50Hz. For the transmission system to work, the frequency must always be kept within tight boundaries. Production must always match consumption to keep the frequency stable. But this is not always the case, which increases the demand for ancillary services. The balance between production and consumption of electricity is a prerequisite for the reliability of the power system.

The Swedish TCO, Svenska Kraftnät (SvK), offers different ancillary services in Sweden listed in Table 1.

<table>
<thead>
<tr>
<th>Service</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast Frequency Reserve (FFR)</td>
<td>Automatic reserve for the initial fast transient frequency change</td>
</tr>
<tr>
<td>Frequency Containment Reserve (FCR-N &amp; FCR-D)</td>
<td>Where N stands for Normal and D for Disturbance</td>
</tr>
<tr>
<td>Frequency Restoration Reserve (aFRR &amp; mFRR)</td>
<td>Where a stands for automatic and m for manual</td>
</tr>
<tr>
<td>Capacity reserve</td>
<td>Strategic reserve procured specifically for power shortage situations</td>
</tr>
</tbody>
</table>

When a deviation occurs and the frequency must be regulated up, either the production needs to increase, or the consumption needs to decrease. This is regulated on the Ancillary service market. Here, the producers and consumers put in bids for which hour of the day they can be activated for the respective ancillary service.

In 2022 a new service, FCR-D Down was established which aim is for down regulation of the frequency. In data center and HPC perspective, this means an offer to increase the use of power, compared to FCR-D Up which is an offer to decrease the use of power.
The provider of the service then gets paid for their bid depending on which service they have signed up for. For FFR, FCR-N and FCR-D the call-off capacity is being compensated. For FCR-N, also the activated energy is compensated. (Svenska Kraftnät, 2023). The minimum bid size is 0.1 MW for both FCR-D and FFR.

The ancillary services have different purposes with different activation and duration time, see Figure 1. (Svenska Kraftnät, 2023) Due to this, the most suitable ancillary services for HPC data centers are FFR and FCR-D.

FFR, which stands for Fast Frequency Reserve is the ancillary service with the shortest activation time and duration. The service must be activated within the range of 0.7-1.3 seconds and duration of either 30 or 5 seconds.

FCR-D, which stands for Frequency Containment Reserve – Disturbance is an ancillary service that has separated up and down regulation services, called FCR-D Up and FCR-D Down. Within 7.5 seconds, 86% should be activated and 100 % within 30 seconds. Both FCR-D Up and Down have a duration time of 20 minutes.

![Figure 1. The activation and duration time for the different ancillary services offered in Sweden.](image)

**2.1 FFR**

FFR, Fast Frequency Reserve, is the fastest service when looking at activation and duration time. The purpose of FFR is to create conditions for handling the initially rapid and deep (transient) frequency changes that can occur in the event of faults at low rotational energy levels in the system.

There are three different activation time limits the provider can choose from.

- 0.7 sec (49.5 Hz)
- 1 sec (49.6 Hz)
- 1.3 sec (49.7 Hz)

With a duration of either 30 or 5 seconds.

The provider needs to be ready for re-activation within 15 minutes.

In the list of documentation for the prequalification application, there are some additional documents needed for energy storage-based resources such as rated power...
for the energy storage, rated energy capacity, energy storage upper and lower limits, and technical description of the controller. (ENTSO-E, 2021)

Since the 2023 procurement no real time data is needed to be provided to SvK. However, the provider should log data continuously and send data monthly to SvK for verification (Svenska Kraftnät, 2022). A list of the signals is listed in Table 2 below. It should be logged and saved with the specified resolution or better.

Table 2. Signals for data logging for FFR (Svenska Kraftnät, 2022)

<table>
<thead>
<tr>
<th>Date and time</th>
<th>Available FFR capacity [MW] (resolution ≤ 0.01 MW)</th>
<th>Measured real power [MW] (resolution ≤ 0.01 MW)</th>
<th>Measured net frequency [Hz] (resolution ≤ 10 mHz)</th>
<th>Activated FFR (0 or 1)</th>
<th>State of charge [%] (resolution ≤ 0.01)</th>
</tr>
</thead>
</table>

2.2 FCR-D

FCR-D, Frequency Containment Reserve – Disturbance has two services, Up and Down regulation which is activate at the interval 49.90-49.50 Hz and 50.10-50.50 Hz respectively.

The activation time limit for both Up and Down service is:

- 86% within 7.5 seconds and 100% within 30 sec
- With a duration of minimum 20 minutes.

The provider should log data continuously and send data to SvK for verification. A list of the signals is listed in Table 3 below. It should be logged and saved with the specified resolution or better.

Table 3. Signals for data logging for FCR-D (Svenska Kraftnät, 2022)

<table>
<thead>
<tr>
<th>Date and time</th>
<th>Measured real power per unit [MW]</th>
<th>Capacity for FCR-D per unit [MW]</th>
<th>Reference value real power per unit [MW]</th>
<th>Measured net frequency [Hz] (resolution ≤ 10 mHz)</th>
<th>State-of-charge [%] (Specific for batteries)</th>
</tr>
</thead>
</table>
3 Implementation

In this project, three methods of power reduction for ancillary services will be investigated and are divided into two parts. The first part covers power reduction via IT systems which involves software methods and frequency reduction methods (downclocking). The second part covers the third method which is power reduction via the power system where the UPS and battery storage system has the main role. In the chapters below, the methods will be described.

3.1 Power reduction via IT systems

Here we have taken a closer look at how quickly it is possible to activate methods that software-wise affect the IT system, as well as what other consequences these may have.

Two methods of implementation have been investigated:

1. **Software method**, by using a job scheduling software to manage batches of computational workloads in a cluster of networked HPC servers.

2. **Hardware frequency reduction methods** by reducing (or increasing) the clock frequency of the Central Processing Unit (CPU), and thus reduce the power consumption of the system.

Both methods can use software that is open-source and free to use.

To meet the demands for ancillary services the HPC cluster management software must be able to pause all workload executions, within the time limits specified by the grid operator, and then resume it again.

In addition to controlling the workloads through cluster management software, there is also the possibility of reducing the power consumption of the server hardware by reducing the clock frequency of the CPU, i.e., downclocking. This method is very fast to activate, and it can be done in a matter of milliseconds. It is commonly used for mobile devices, such as smartphones and laptops, to reduce power consumption and increase battery life.

3.1.1 Software method

HPC clusters are often used for large and compute-intensive workloads, such as training machine-learning/AI (Artificial Intelligence) systems, weather forecasting, seismic analysis, fluid dynamics simulations or financial modeling. Because of their size and complexity, they can take a long time to complete, often several days or even weeks. Clusters must also accommodate multiple workloads at the same time, from multiple users, where each workload may have different hardware requirements (memory usage, hardware accelerators such as GPUs, etc.).

To meet the ancillary service demands, clusters must be able to schedule and manage workloads in a way that ensures that all workloads are completed in a timely manner, while also ensuring that the cluster is not overloaded and that the workloads are not competing for the same resources. This is done by using a workload manager, which is a software that manage the allocation of resources to the workloads. There are several
software suites available for managing workload scheduling. In this project, the Slurm Workload Manager has been investigated.

Slurm is an open-source and scalable cluster management and job scheduling system for large and small Linux clusters. As a cluster workload manager, Slurm has three key functions. First, it allocates exclusive and/or non-exclusive access to resources (compute nodes) to users for some duration of time so they can perform work. Second, it provides a framework for starting, executing, and monitoring work (normally a parallel job) on the set of allocated nodes. Finally, it arbitrates contention for resources by managing a queue of pending work (SchedMD, 2023).

Users interact with Slurm through a **controller node**, which is a server that runs a controller daemon, see Figure 2 below. It is responsible for managing the cluster, and for scheduling and dispatching workloads to **compute nodes**. The controller node provides a set of command line tools that can be used to interact with the scheduler. These tools can be used to submit, cancel, and monitor workloads. The controller node also provides a web interface for the same purpose. All nodes are connected to a common **Network File System** (NFS), which is used to store the output and results from the user workloads.

![Schematic of how Slurm operates.](image)

Using the Slurm controller, it is possible to pause the scheduling for future workloads during times when lower power usage is required. This is done by setting the scheduling state to **drain**. This will prevent any new workloads from being scheduled, but it will not affect any workloads that are already running. The workloads will continue to run until they are completed (not possible for meeting the requirements), canceled (would destroy unsaved progress) or paused.

Slurm does not have any built-in functionality for pausing and resuming arbitrary user defined workloads. However, the Slurm scheduler provides a mechanism for sending inter-process communication signals to running programs, which can be used to pause and resume the execution of a workload. The signals follow the POSIX standard, **SIGSTOP** (stop/pause the process) and **SIGCONT** (continue the process).
This mechanism can theoretically be used to pause and resume user program execution; however, it requires the user to implement the necessary signal handling. This is done by adding a signal handler code to the user program, which is a function that is called when the program receives a signal from the operating system. The user must then be trusted to implement the signal handler correctly, that is, to ensure that execution is halted when the SIGSTOP signal is received, and that execution is resumed when SIGCONT is received. If the signal handler is not implemented correctly, it may cause the program to crash or behave in unexpected ways.

Another possibility is to run the Slurm cluster on virtual machines (VMs), and then use the VM management software to pause and resume all machines simultaneously. The workloads running on the VMs are then automatically paused as a result. This method is much simpler to implement but may not be possible for all hardware configurations. It might also have a negative impact on the computational performance due to virtualization overhead. Additionally, the VM management software may not be able to pause and resume quickly enough to be useful.

There exists another relevant signal that can be used with Slurm, called SIGKILL. This signal cannot be caught or ignored by the user program, and it is guaranteed to cancel the process immediately. This is a simple and reliable method of stopping user program execution, however, any work that has not been saved to disk will be lost. This means that the user program must:

1. Automatically save its internal state to disk at regular intervals.
2. Be able to restart from the beginning.
3. Load a saved state from disk and continue previous work.

Many frameworks for machine learning, such as TensorFlow, PyTorch, and MXNet, can save their state to disk, using so-called checkpoints, and restart from the saved state. Computational fluid dynamics frameworks such as OpenFOAM also have built-in checkpointing functionality. This makes it possible to use the SIGKILL signal to pause and resume the execution of workloads based on these frameworks.

Several unknown issues would need to be resolved before it is possible to use the Slurm scheduler to manage power consumption for all workloads.

1. **Feasibility:** It is unknown if SIGSTOP and SIGCONT (pause and resume) signal handling and/or checkpointing can be implemented for all possible user programs.
2. **Delay:** It is unknown how long it takes to pause and resume the execution of a user program, in all program states.
3. **Enforcement:** It is unknown how to check that pause and resume implemented by a user would prevent the program from using hardware resources. All programs would have to be tested individually.
4. **Performance:** It is unknown if it is possible to implement pause and resume in a way that does not affect the performance of the programs. Automatic checkpointing is very likely to affect the performance of a program that has a large memory usage, as it will require additional disk I/O. Performance may also be an issue if the cluster uses virtual machines.

In conclusion, using the Slurm Workload Manager to reduce power consumption requires that either:
1. The user program can implement a signal handler for SIGSTOP and SIGCONT, and that the signal handler is implemented correctly.

2. The user program can automatically save its state to disk, and to restart from a saved state (checkpointing). SIGKILL can then be used, which would likely satisfy the requirements for FFR (0.7-1.3 seconds). However, this may be a problem for customers because of increased program complexity, and possibly decreased performance from disk I/O overhead.

3. The cluster compute nodes are virtual machines, and the VM management software can pause them quickly enough to meet the requirements for FFR.

### 3.1.2 Frequency reduction (downclocking)

An alternative and/or complementary approach to using a workload scheduler for managing power usage is to reduce the clock frequency of the CPU the workload is running on. This can be done by using the Linux utility `cpupower`. It can be used to set the minimum and maximum CPU frequency or to set an automatic CPU governor.

The CPU governor is a software component that is responsible for controlling the CPU frequency. It can be set to one of several different modes, such as `performance`, `powersave`, `ondemand`, or `userspace`. The CPU governor can also be set to a custom value, which allows the user to enforce a specific CPU frequency in MHz.

As explained previously, `cpupower` can be used to set the CPU frequency to a specific value, or a range of values. It can also be used to set the automatic CPU governor to a specific mode, such as `powersave`, which will reduce the CPU frequency when the CPU is not in use.

Some issues exist with this method:

1. **Minimum frequency**: Each CPU has a minimum frequency that it can be underclocked to. This value is determined by the processor's design and manufacturing constraints. If the CPU is downclocked below this minimum frequency, the system may become unstable or not function at all.

2. **Manufacturing issues**: Individual CPUs may have minor differences in their minimum frequency, due to manufacturing tolerances. This means that the minimum frequency may have to be determined for each CPU individually.

3. **Power management features**: Intel Xeon processors have built-in power management features such as SpeedStep (EIST) and Turbo Boost. When underclocking, these features must be taken into consideration or disabled to prevent interference with `cpupower`. Possibly they must be enabled or disabled in BIOS/UEFI, which requires the system to be rebooted.

4. **BIOS/UEFI limitations**: Some server motherboards may have limitations on CPU frequency adjustments, either due to a locked BIOS/UEFI or limitations in the firmware itself.

5. **Total system power usage**: Even if the CPU is downclocked, the total system power usage may not be sufficiently reduced. This is because the CPU may be idle, but other components such as graphics processing units, memory controllers, network interfaces, and hard drives may still be active. This means that the total system power usage must be measured and monitored to ensure that it is reduced enough to meet the requirements for FFR/FCR.
In conclusion, CPU downclocking is a fast (in the order of milliseconds) and simple method of reducing power consumption, that does not require any changes to the workloads. Using `cpupower` to meet the demands for ancillary services requires that:

- The minimum frequency of the CPU is known, and the CPU can be underclocked to this frequency without causing instability.
- The CPU can be underclocked to a frequency that is low enough to meet the power limitation requirements for FFR/FCR, when combined with the total system power usage.

### 3.2 Power reduction via the Power System

A more proven method is to use the UPS and battery system to act on the ancillary market. There are UPSs on the market today that can reach the activation time requirement of FFR and FCR-D within milliseconds. This is done by running the data center on the stored energy from the batteries. One example is Vertiv’s UPS, Liebert® EXL S1, that can reach the specified power setpoint in less than 500 milliseconds. (Arturo Di Filippi, 2021) Many of the data centers operators have UPSs with battery energy storage system, but might need to expand their capacity to meet the duration demand.

Looking at FCR-D that has both up and down regulation, this can be achieved with this method, depending on how your battery storage system is dimensioned. For FFR and FCR-D up services, when activated, the data center is fed with power from the batteries. For FCR-D down service, meaning that the data center needs to use more power from the electrical grid, the batteries can be charged, or for example the data center can be cooled to a lower setpoint, or both in a combination. An example of battery State of Charge management can be seen in Figure 3 below.

One of the requirements is, as mentioned, a minimum bid size of 0.1 MW, which translates to the minimum requirement for the size of the battery storage. However, a provider does not need to offer all its capacity, as long as it is above the minimum bid size.

![Figure 3. Adjustable State of Charge Range for Grid Services and Critical Load. (Arturo Di Filippi, 2021)]
3.3 Implementation of frequency services at RISE test and demo facility

RISE has a test and demo facility with an experimental data center with a capacity up to 90kW. This is not high enough to act on the frequency market alone. Therefore RISE has in collaboration with Vattenfall investigated if RISE’s experimental data center can together with a partner, act on the frequency market. To be able to do this, RISE needs to have Vattenfall as the Balance Responsible Party (BRP). A process to change this has started.

The prime methods that will be used for acting on the ancillary service market at the RISE test and demo facility is using the battery energy system and the UPS.

Initial work to test a workload manager was implemented. On the project website, there is code written for SLURM that are free to use. The code can be found here: https://www.ri.se/sv/vad-vi-gor/projekt/frekvenstjanster-for-elnatet-fran-hpc-datacenter

3.4 Communication

In addition to this report, a recommendation has been written. The recommendation shall help owners of HPC data centers to take the step to act on the frequency market. The results from this project have also been presented at the industry event DataCloud ESG Summit in Oslo. The implemented methods have also been demonstrated at Vinnova’s demo event. If the UPS is installed at the RISE facility, demonstrations will be made for visitors and customers.

4 Results

HPC data centers can act on the frequency market in Sweden, providing that they meet the requirements set for the services. One example is that a HPC data center with an electricity consumption of 100 GWh/year can earn around 5 000 000–10 000 000 SEK/year. (Vattenfall AB, 2019)

There are several methods of power reduction that can be used to meet the demands on the ancillary service market for HPC data centers. To know what method and which ancillary service to use, one need to look at the activation time, duration, and the available capacity. For example, historically FCR-D is activated more often per year than FFR and requires more energy from the data center since it has a longer duration.

Table 4 below shows a summary of the ancillary service and the methods that can be used.
Table 4: Summary of some of the ancillary services in Sweden and methods that can be used by HPC data centers.

<table>
<thead>
<tr>
<th>Service</th>
<th>Job scheduler</th>
<th>Downclocking</th>
<th>Switching to UPS</th>
</tr>
</thead>
</table>
| Fast Frequency Reserve (FFR)                 | **Activation time:** Depends on the used method. Instant if the calculations are killed, otherwise depending on the size of the calculations.  
**Duration:** All requirements fulfilled.  
**Capacity:** The SLURM controller needs to run during the whole process. Works with all activities that supports checkpoints. Needs a lot of preparations. | **Activation time:** The downclocking can act with in milliseconds.  
**Duration:** All requirements fulfilled.  
**Capacity:** Depends on the type of server. There might be restrictions in the CPU. | **Activation time:** The UPS and batteries are fast and can handle activation well within the activation time for all ancillary services.  
**Duration:** The duration depends on the size of the data center and the size of the batteries.  
**Capacity:** All or a part of the load of the DC can be switched to UPS. |
| Frequency Containment Reserve - Disturbance (FCR-D) | **Activation time:** Depends on the used method. Instant if the calculations are killed, otherwise depending on the size of the calculations.  
**Duration:** All requirements fulfilled.  
**Capacity:** The SLURM controller needs to run during the whole process. Works with all activities that supports checkpoints. Needs a lot of preparations. | **Activation time:** The downclocking can act with in milliseconds.  
**Duration:** All requirements fulfilled.  
**Capacity:** Depends on the type of server. There might be restrictions in the CPU. | **Activation time:** The UPS and batteries are fast and can handle activation well within the activation time for all ancillary services.  
**Duration:** The duration depends on the size of the data center and the size of the batteries. The longer duration, the harder to fulfill the requirements.  
**Capacity:** All or an amount of the DC can be switched to UPS. |

FCR-D is historically activated more often than FFR and require more energy.
5 Discussion

The possibilities to act on the frequency market for HPC-data centers are huge. However, it seems to be quite difficult for the data center owners to understand how to proceed to act on the ancillary market in Sweden and the positive benefits of it for the society. One positive effect for society is that the electricity grid can maintain a stable operation with less amount of plannable power sources. There also seems to be a dread for that these services will increase the risk for the data center owners and customers. To get data center owners to act on the ancillary market, the threshold must be decreased, and the data center industry must be made aware of the possibilities.

The three methods that have been investigated and evaluated theoretically within this project, has all shown great potential to be used for ancillary services. However, we recommend that they are tested and verified in practice before entering the ancillary market.

Further research within this field needs to be done to convince the data center industry to be more active on the ancillary market. For example, develop a stepwise guideline for helping the data center owners in the process to have an active role on the market.
6 References


Through our international collaboration programmes with academia, industry, and the public sector, we ensure the competitiveness of the Swedish business community on an international level and contribute to a sustainable society. Our 2,800 employees support and promote all manner of innovative processes, and our roughly 100 testbeds and demonstration facilities are instrumental in developing the future-proofing of products, technologies, and services. RISE Research Institutes of Sweden is fully owned by the Swedish state.

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