Data Centers – A Good Grid Citizen

July 11, 2025

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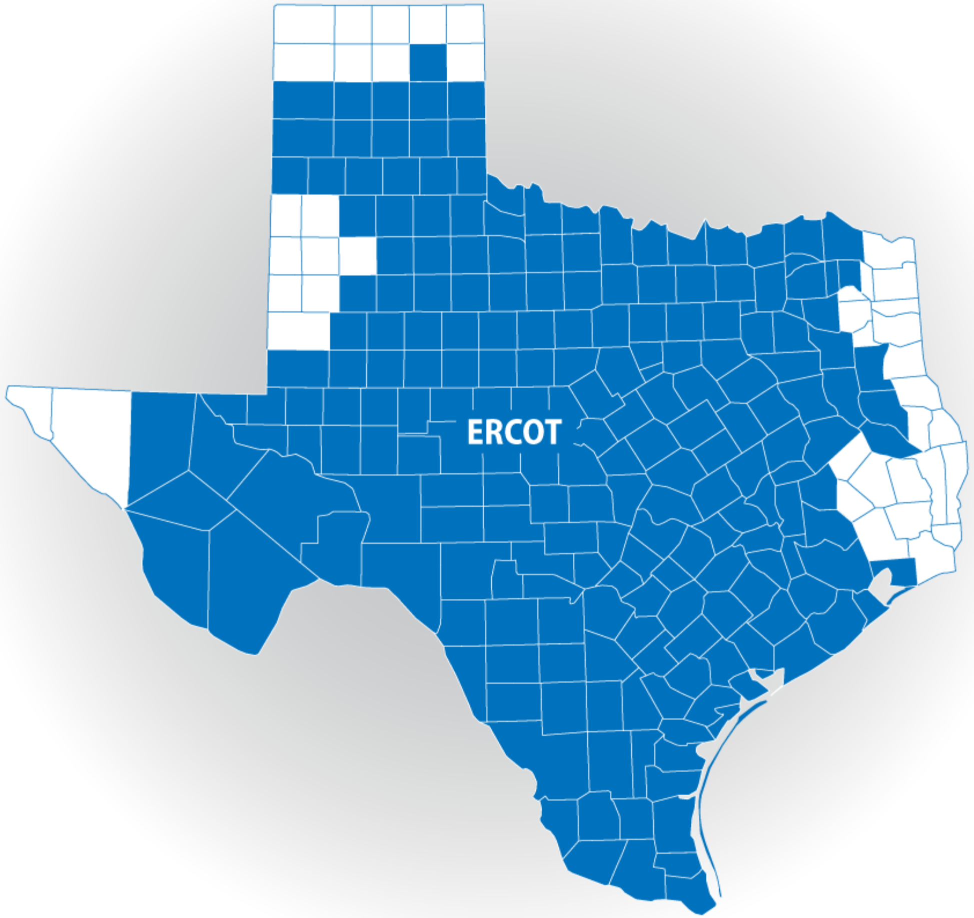
New challenges for electrical grid



- Data center share of overall power demand is increasing, and campuses are getting bigger
- High concentration of demand in certain areas
- Potential impact to grid power quality, stability, and reliability
- Multiple system operators have identified issues relating to large consumers and sensitive power electronic loads
- During momentary voltage disturbances large share of demand can disconnect resulting severe system imbalance
- New regulations and practices are needed to better predict and control large load behavior

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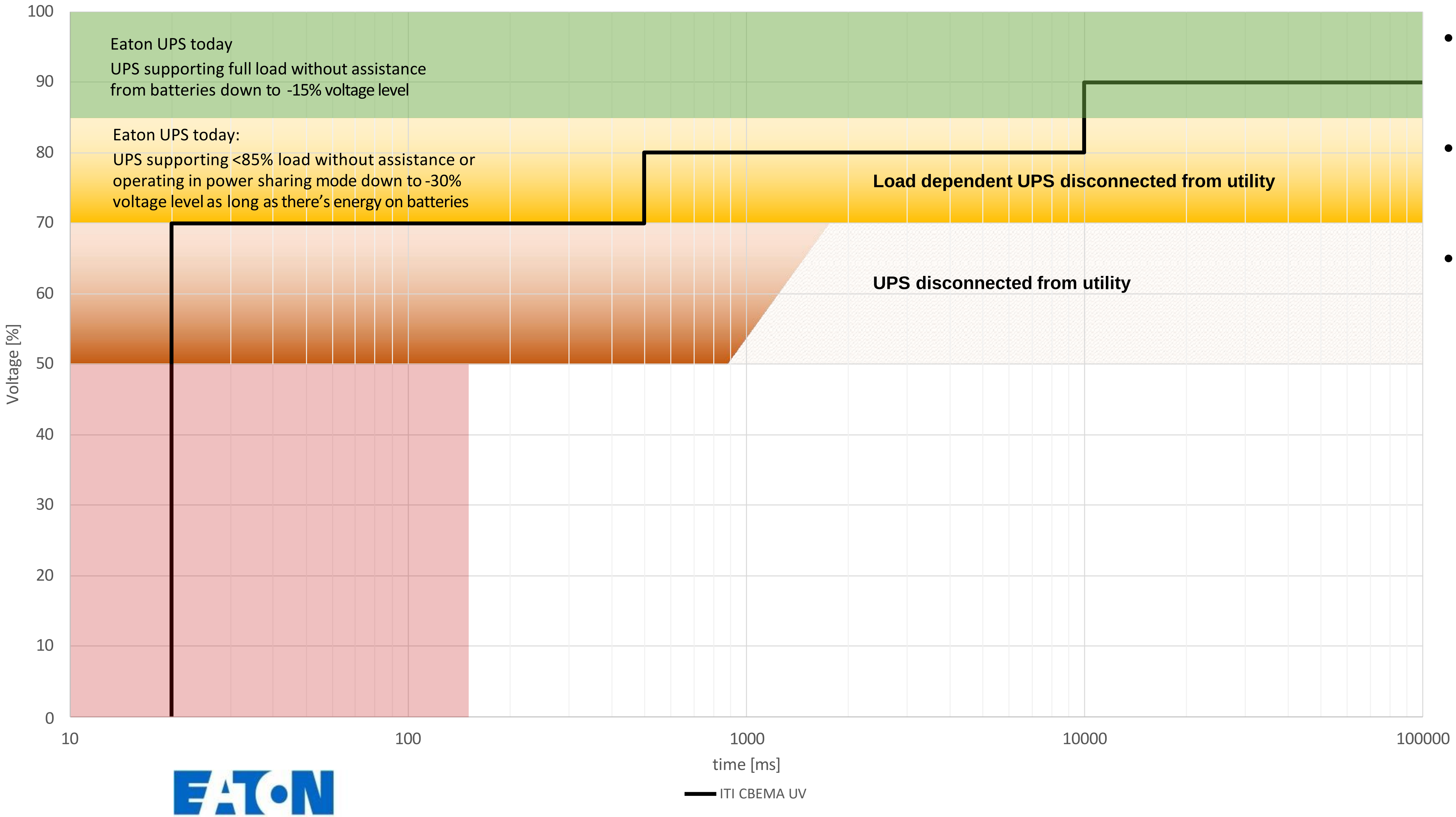
Typical Static UPS

UPS Operation - Typical



- Designed to protect critical load from power anomalies
- Disconnect from utility and use batteries to support load
- Reconnect to utility or generator when voltage/frequency stabilized

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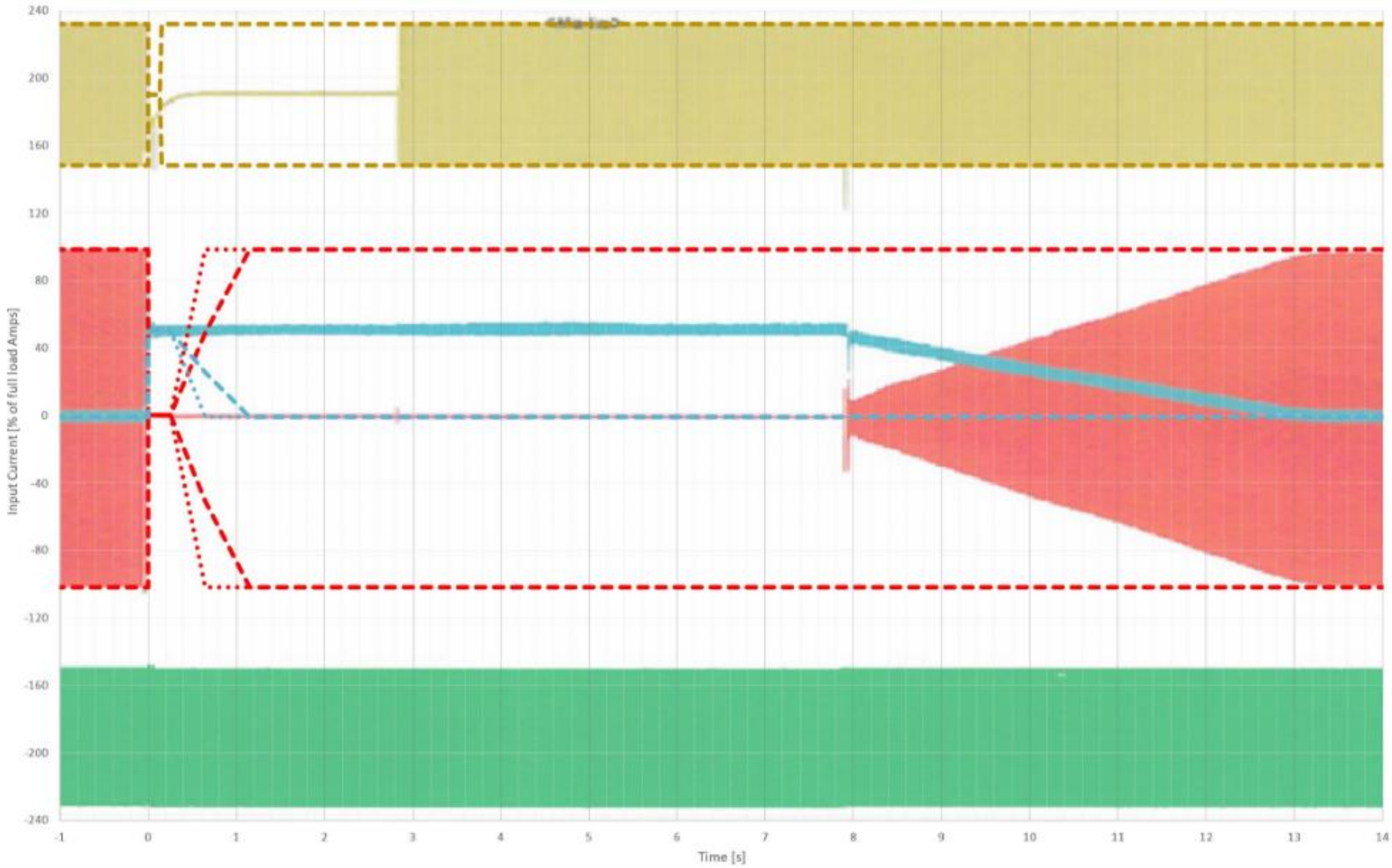
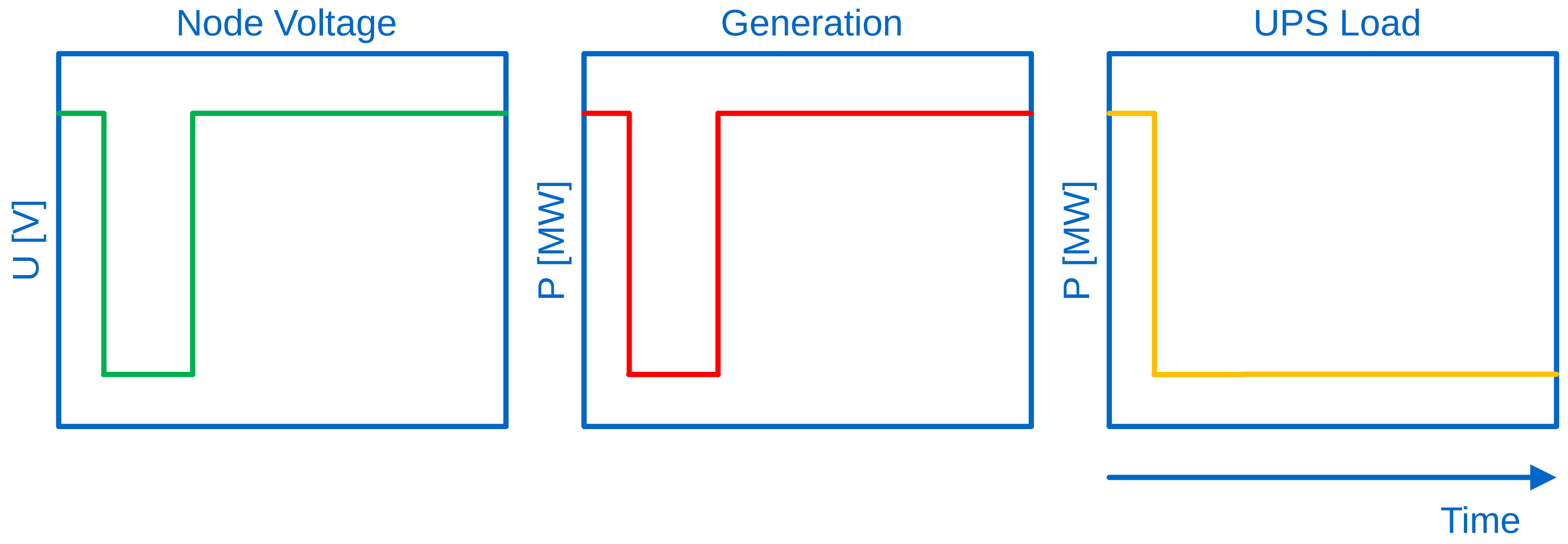


- Input voltage (yellow)
- Input current (red) and battery current (cyan)
- Output voltage (green)

Grid-interactive UPS for FRT & PFAPR

Voltage Induced Frequency Rise – Step Through *

Transmission System Fault
↓
Voltage Dip
↓
Initial Generation and UPS Load Reduction
↓
Fault Cleared
↓
Generation Output Recovers
UPS Load Reduction Sustained
↓
Power Imbalances Causes Frequency to Rise



* Modified from: Eirgrid industry webinar 22 October 2024: Fault Ride-Through Requirements for Demand Facilities

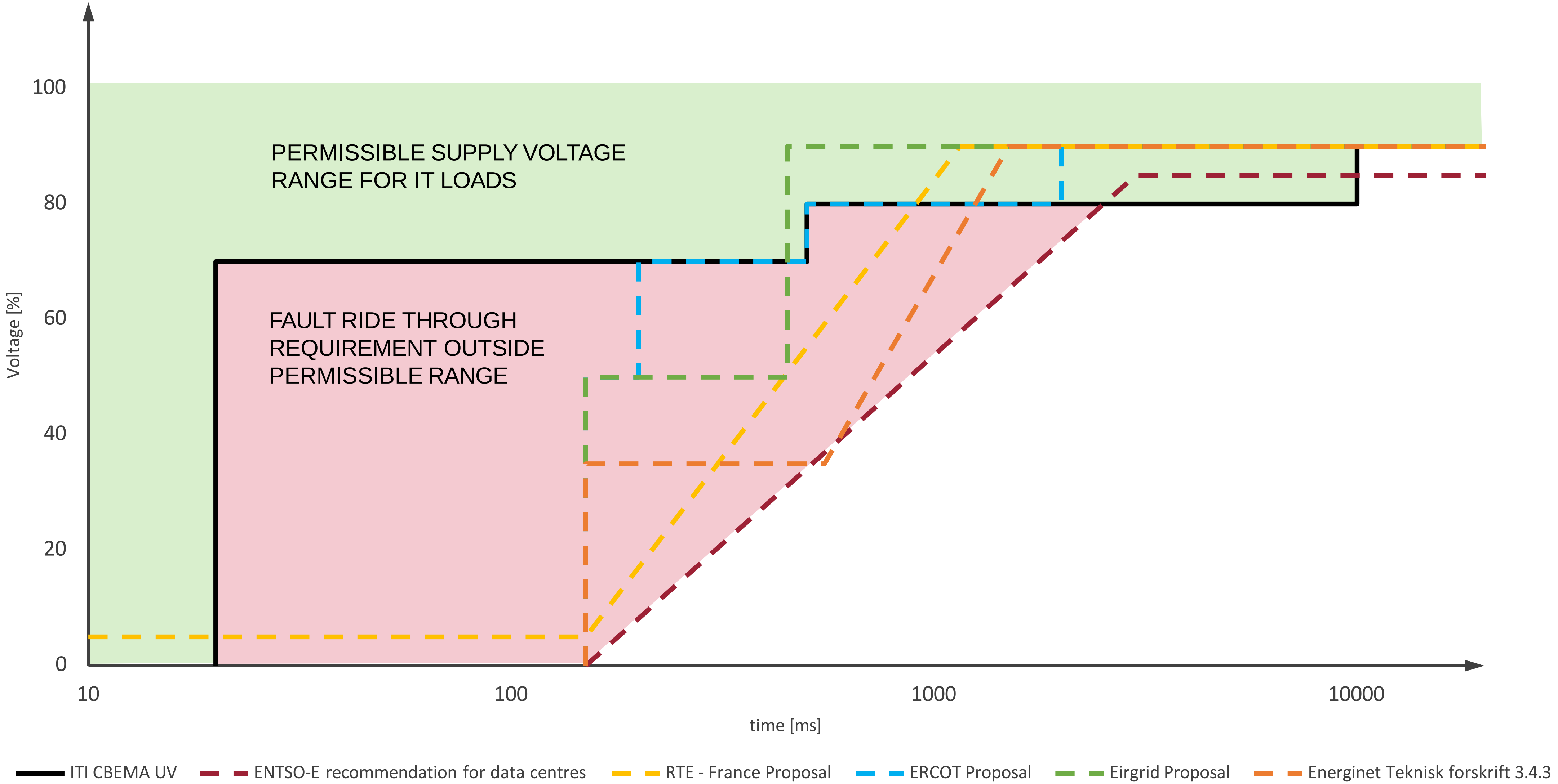
Fault Ride Through of generators and existing loads

- For generating assets, such as traditional power generation, wind turbines, photo-voltaic and BESS systems, a requirement to perform Fault Ride Through exists today
  - Purpose is to avoid disconnection of generation capacity from the grid during short momentary (<150 ms) voltage interruptions, that would cause total collapse of electrical grid
  - Generating assets will remain connected during under voltage (<150 ms), and feed constant current to help to sustain voltage (if technically possible)
  - Once fault is cleared and voltage recovers, generators quickly restore their output power to pre-fault level (often rereferred as Post Fault Active Power Recovery, PFAPR)
- Actively working on requirements for large loads
- Power electronic converters and other electronic loads can be problematic as they typically **tolerate limited voltage variations and interruptions**, and turn off when these limits are exceeded
- Loads **do not quickly restore the demand** after system voltage recovers, causing a significant system imbalance when occurring in large enough capacity

New grid connection requirements for converter-based loads

- Various system operators (Fingrid, Eirgrid, Energinet, Rte France, AEMO, ERCOT and ENTSO-E) have identified potential issues relating to large consumers with sensitive power electronic loads
- New requirements to be introduced, such as **Fault Ride Through** (FRT) and **Post Fault Active Power Recovery** (PFAPR)
- Generally, **more focus on impact to power quality and system stability** during permitting and more stringent limits for power factor, harmonics, flickering etc.
- **Simulation models** (PSCAD, PowerFactory, PSS/E) of (converter-based) loads will be required during permitting process
- Possible harmonic, inter-harmonic and harmonic impedance data up to the 50th order

Proposed Fault Ride Through Requirements



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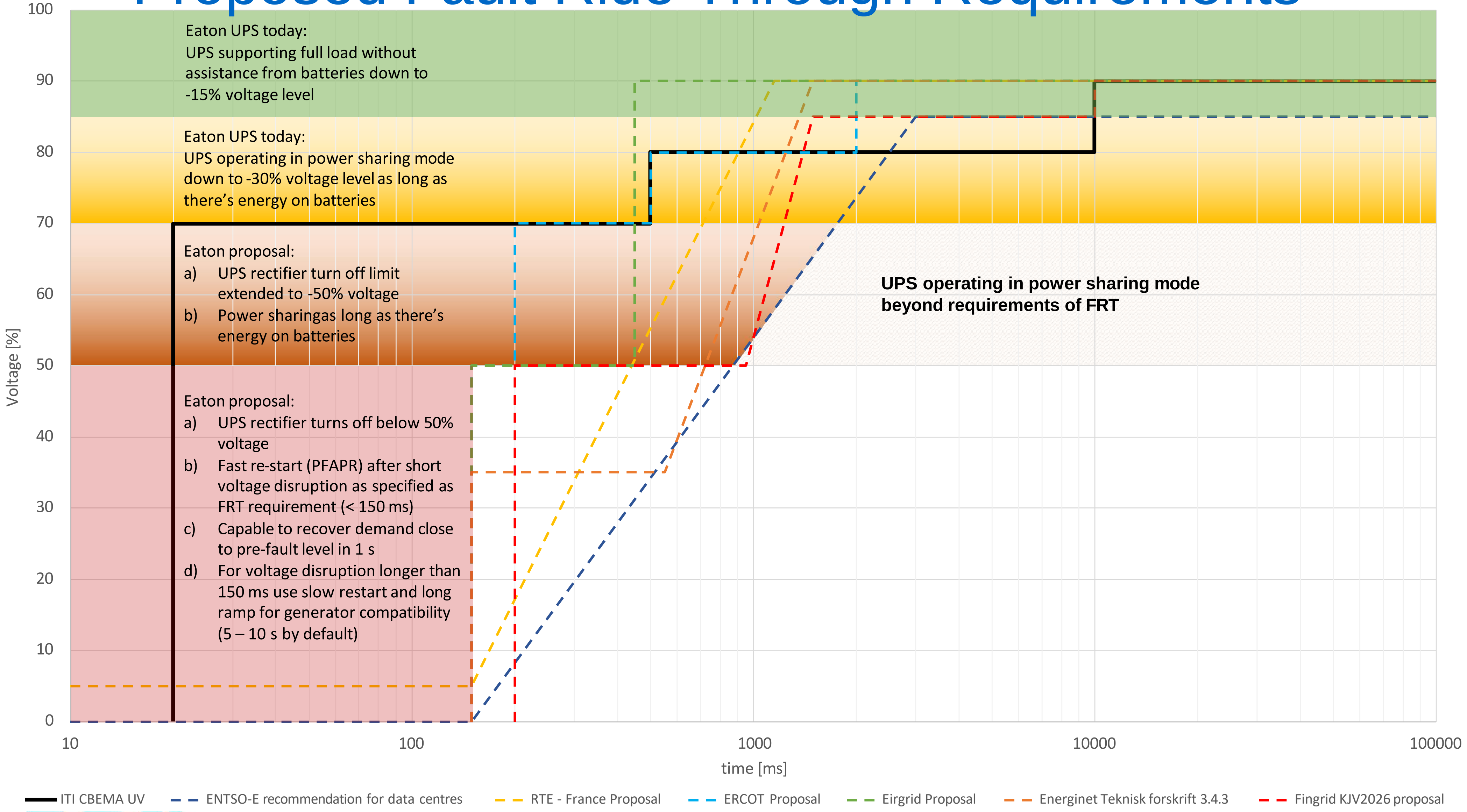
Proposed Fault Ride Through Requirements



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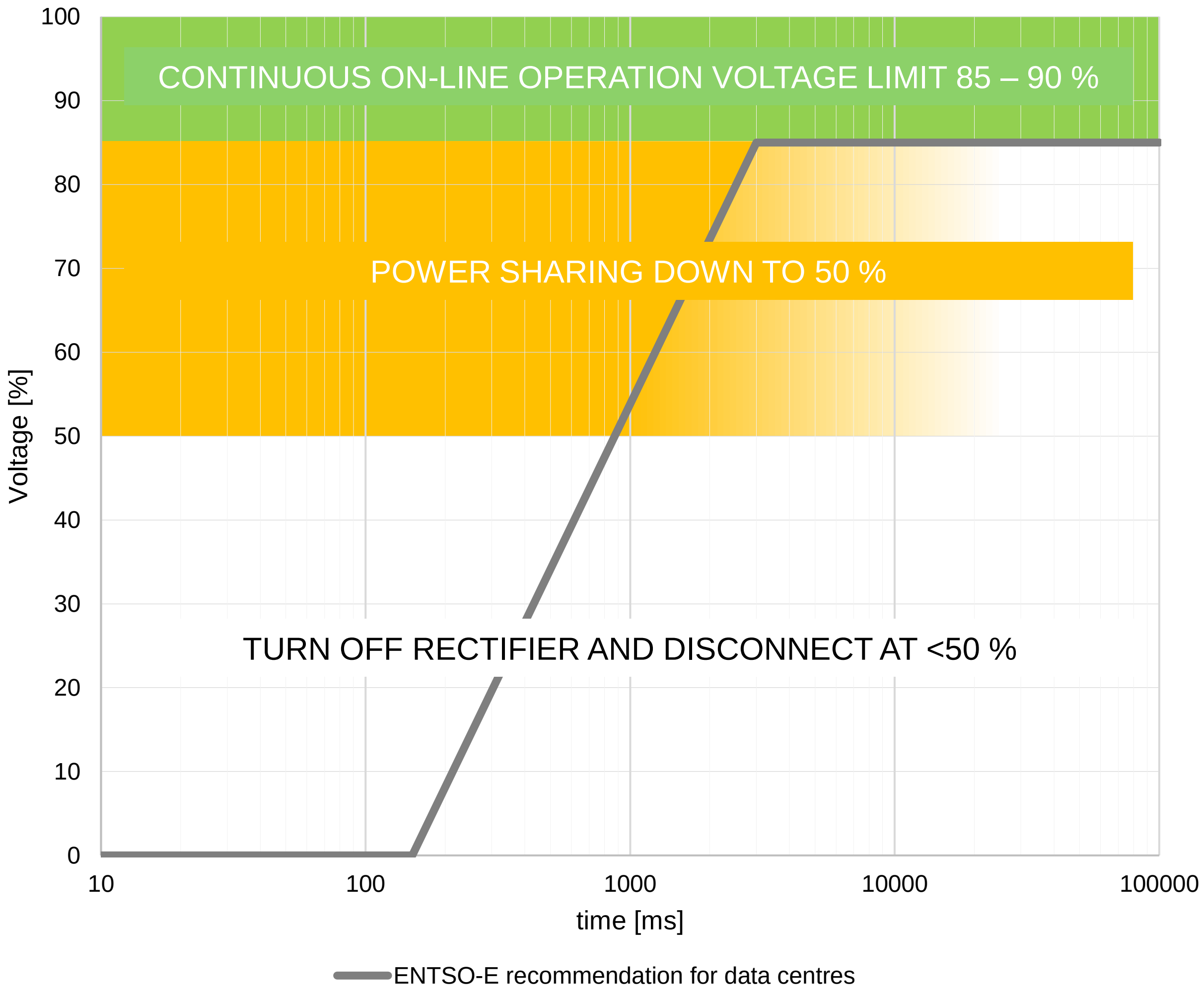
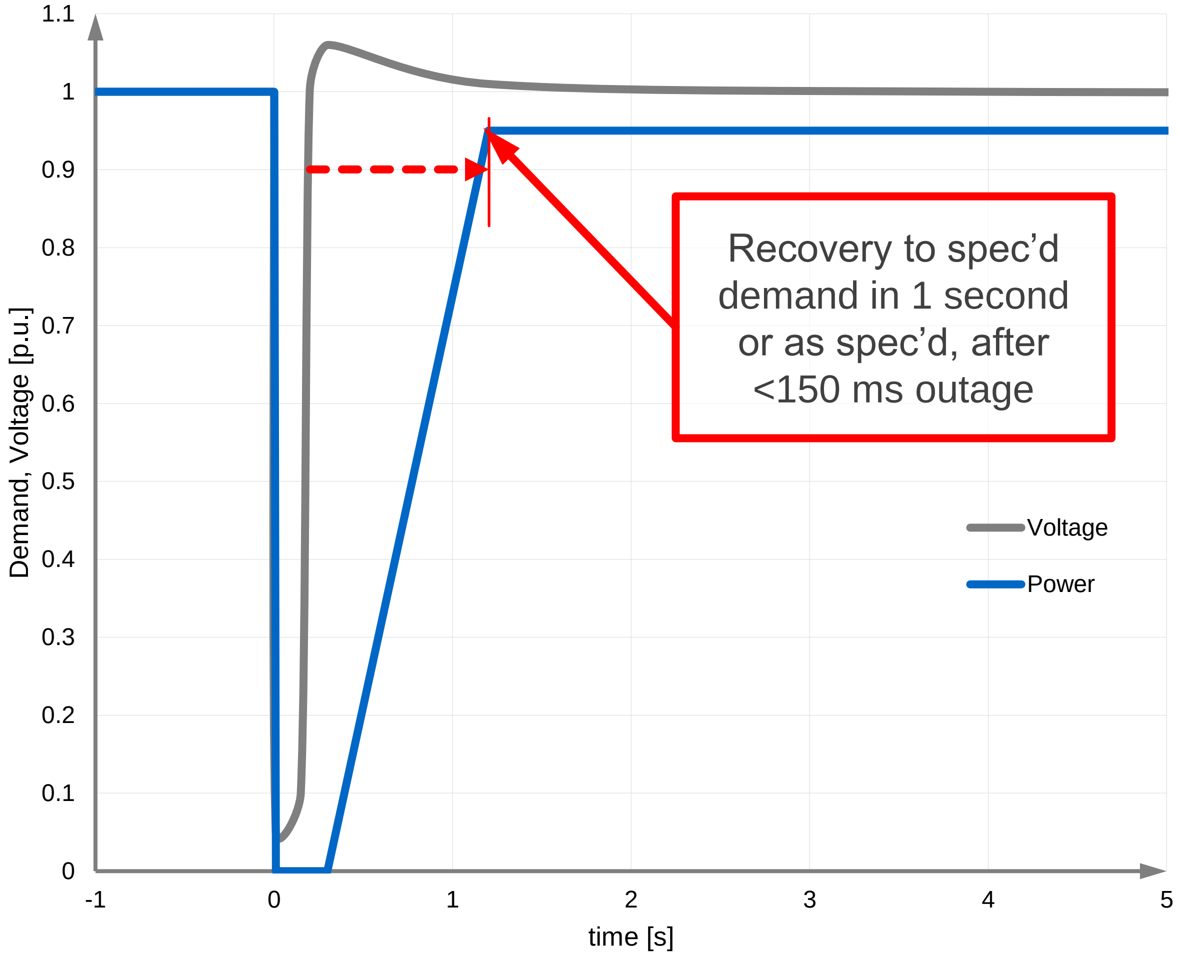
Eaton proposal for data center FRT and PFAPR





Eaton recommendations for FRT and PFAPR

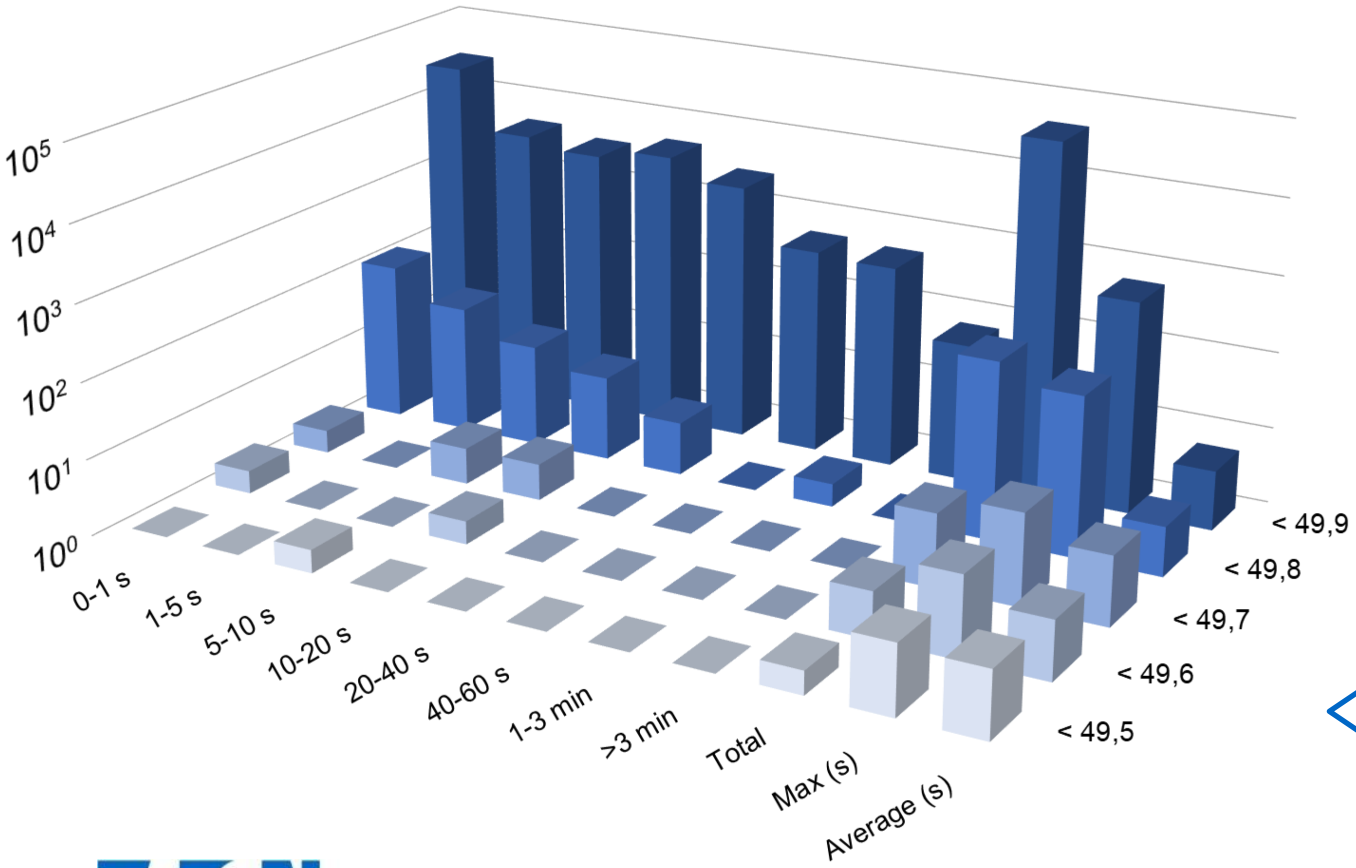
- Improve fault tolerance and implement Fault Ride Through (FRT) functionality into a UPS :
  - Rectifier on-line and power sharing down to 50 – 70% load level at least for minimum required duration (FRT) or longer.
  - Below above-mentioned voltage level, allow to completely turn off UPS rectifier and open input relays. Support all loads from energy storage device(s). This helps to avoid high over-voltages at rectifier input, that are common to occur after a fault in HV grid is cleared and could risk critical load protection.
  - If voltage disturbance is within limits, for voltage and duration, of FRT specification, minimize all restart delays and restore input active power demand to pre-fault level within specified time and ramp. (Rte France specifies 50% / s)
  - Limit PFAPR demand restoration time requirement to minimum of approx. 1 second.
- Above helps restore demand once voltage has recovered and to maintain system balance while being relatively easy to implement to existing UPS technology

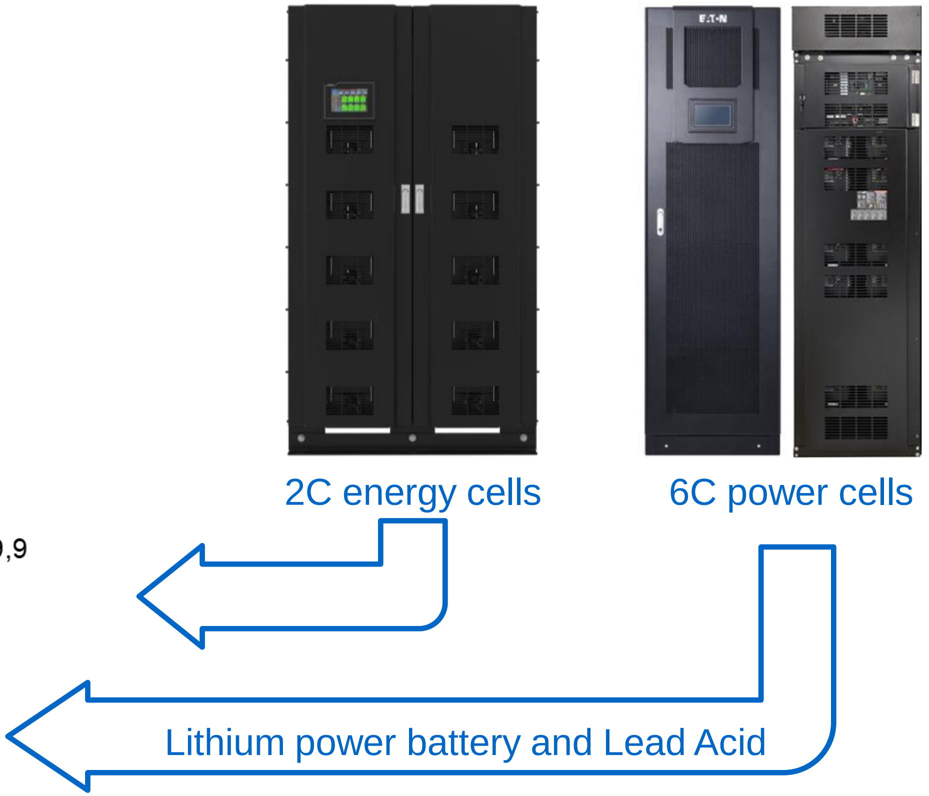
Grid-interactive UPS for FFR & UFLS

Grid support and batteries

Grid support can be performed with all types of batteries, but other application are more demanding that others. Today, most of grid-interactive deployments with Eaton UPS are using lead acid batteries and participating in Fast Frequency Response (FFR).

https://www.fingrid.fi/globalassets/dokumentit/fi/tiedotteet/lehdistotiedotteet/frequency-quality-analysis-2023.pdf





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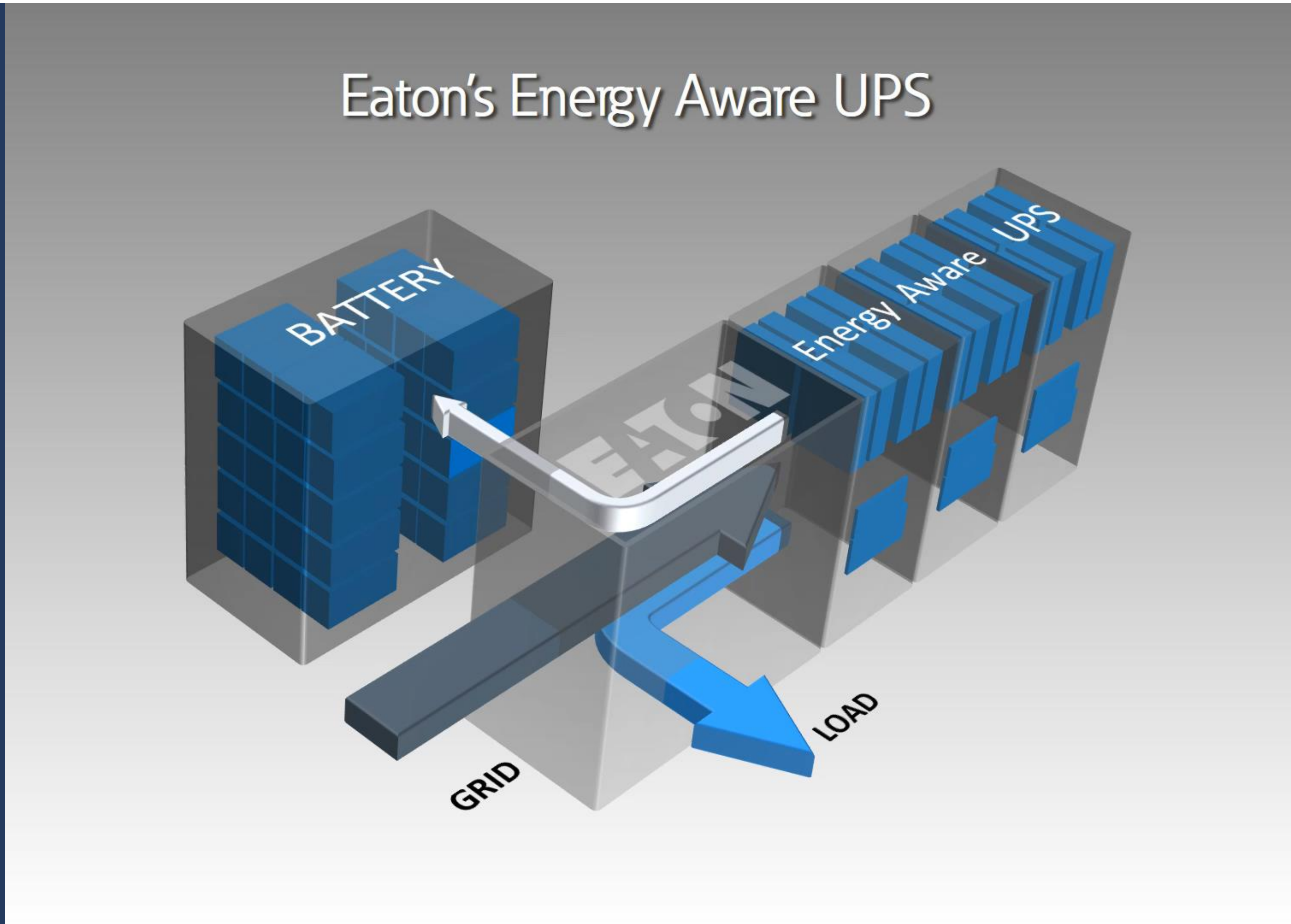
Grid-interactive UPS

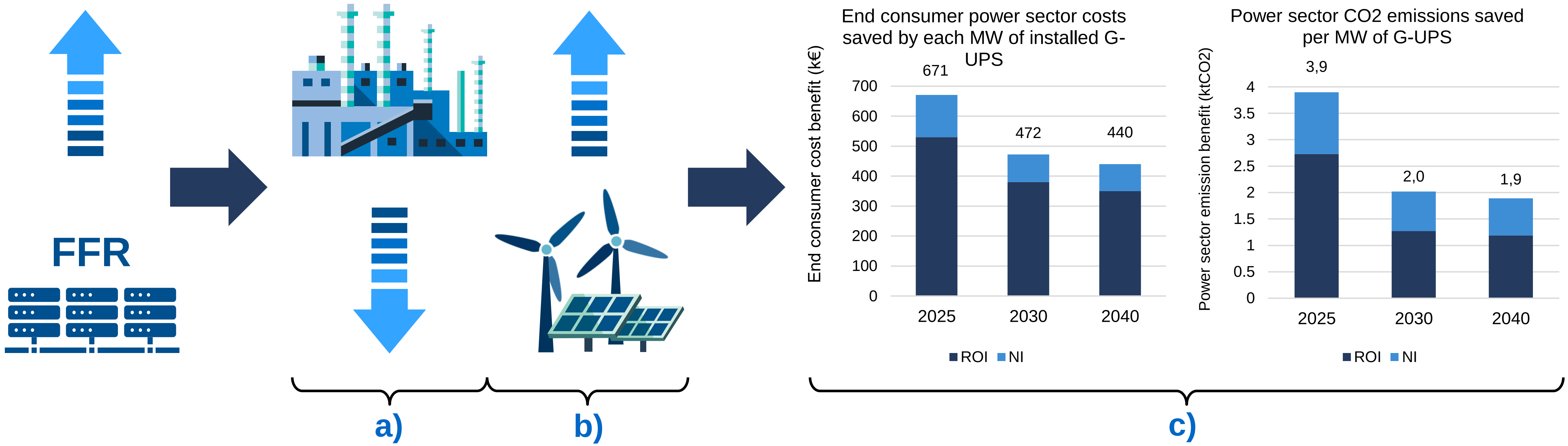
Seamless control of stored energy enables:

- Energy management, grid services and flexibility bringing additional revenue streams and savings for asset owner
- Supporting grid to allow higher penetration of non-synchronous generation and avoid curtailment of renewable energy
- Support on-site power generation to manage load transients and ramping
- Filter harmonics, power factor and fast load variations to eliminate power quality issues
- To comply with new requirements such as Fault Ride Through and Under Frequency Load Shedding



Grid-interactive UPS socioeconomic impact

Fast frequency response allows to **a)** reduce inertia floor and retirement of traditional generation and **b)** higher penetration of renewable energy and reduces curtailment that **c)** reduces emissions and operating cost of the system



1) Baringa: Irish decarbonisation and consumer benefits of Grid-Interactive UPS https://www.baringa.com/contentassets/8771b5d7c2ee4f1598d746b5ceafbcd3/baringa_irish_decarbonisation_g-ups_study_report_v4_0.pdf
2) EirGrid and SONI: Shaping our electricity future, 2021. http://www.eirgridgroup.com/site-files/library/EirGrid/Full-Technical-Report-on-Shaping-Our-Electricity-Future.pdf
3) System Services Future Arrangements Scoping Paper SEM-20-044, A Submission by EirGrid plc. & SONI Ltd. 2020. https://www.semcommittee.com/sites/semc/files/media-files/SEM-20-074a%20-%20EirGrid%20and%20SONI%20Response%20to%20SEM-20-044.pdf

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Grid-Interactive UPS journey

- **2014**: UPS for rural area LV distribution network to improve power quality
- **2015**: Collaboration starts with Fortum
- **2015**: Discussion with TSO in relation to a UPS, data centers and ancillary services
- **2016**: Introducing concept to market in a major data center event in London
- **2017**: Starting firmware development in HPO
- **2017**: Collaboration starts with **Enel X** and **Multigrid (Primrock)**
- **2018**: Svenska Kraftnät and Statnett pilots with **Fortum** (SWE & NOR)
- **2018**: **Microsoft Lab** pilot success (US)
- **2019**: **Eaton House** UPS (93PM) goes live to DS3 market (IRE)
- **2020**: **Bahnhof AB** entering FFR market (SWE)
- **2020**: **Basefarm DC** entering FFR market (NOR)
- **2021**: Grid-interactive data center collaborative white paper with **Microsoft**
- **2022**: **Microsoft** Dublin & Quincy go live with EnergyAware (IRE & US)
- **2023**: Piloting with TasNetworks and go live to market (AUS)
- **2023**: **Digital Realty** goes live with EnergyAware in Dublin

- Alaperä, I., Honkapuro, S. & Paananen, J. 2018. Data centers as a source of dynamic flexibility in smart girds. In journal Applied Energy 229, 69 – 79. https://doi.org/10.1016/j.apenergy.2018.07.056
- Alaperä, I., Honkapuro, S., Tikka V. & Paananen, J. 2018. Dual-purposing UPS batteries for energy storage functions: A business case analysis. In journal Energy Procedia 158, 5061 – 5066. https://doi.org/10.1016/j.egypro.2019.01.645
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- Hansson, M. 2019. Virtual inertia from UPS systems. Master thesis. Lappeenranta University of Technology. http://urn.fi/URN:NBN:fi-fe201903057128
- Paananen, J. 2022. Grid-interactive UPS and Data Centre potential to provide Fast Frequency Response and role in a low carbon energy system. Master thesis. JAMK University of Applied Sciences. https://urn.fi/URN:NBN:fi:amk-2022060816628

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Alternative fuels and power generation technology

Transition from diesel back-up generators to gas engines. Impact to data center power distribution topology, central powerhouse vs. distributed generators for each stream. Opportunity for solutions to manage poor load acceptance with a UPS (Dynamic Generator Support) [1,2].

Transition from diesel back-up generators to gas and steam turbines for back-up and on-site (off grid) generation. CHP, small modular nuclear reactors (SMR), etc. Opportunity for Grid-Interactive UPS & Dynamic Generator Support [1,2].

Replacing diesel back-up generators with hydrogen engines, turbines or fuel cells as a direct generator replacement or using hydrogen fuel cells as alternative energy source for a static UPS. Approach impacted by data center power distribution topology, available space and site layout, etc.

Replacing back-up generators with large multi-MW scale grid-forming BESS as a direct generator replacement. Alternatively having large battery for a static UPS. Centralized BESS may have significant cost impact on MV distribution, this is eliminated with UPS having a large battery.

UFLS Data center without gensets in locations giving enough nines with utility supply only. Pushing for 15 – 60 minutes battery solutions. European Commission regulation requiring implementation of UFLS, challenge for hyper-scale DC connected to transmission system. UFLS could be managed with a UPS [3]

1) *FREQUENCY REGULATION IN AN AC POWER SUPPLY SYSTEM.* https://patentscope.wipo.int/search/en/detail.jsf?docId=WO2022233457
2) Karjalainen, A. 2021. Power System Frequency Regulation with UPS Rectifier. Master thesis. Tampere University. https://urn.fi/URN:NBN:fi:tuni-202104273700
3) *Autonomous Under Frequency Load Shedding functionality of an uninterruptible power system.* https://www.ipo.gov.uk/p-ipsum/Case/ApplicationNumber/GB2301299.0

Dynamic generator support

Initial RoCoF in a power system depends on system inertia constant and relative size of load transient.

Example gas engine generator:
3150 kW, 1500 rpm, ~300 kgm^2, 50 % load step

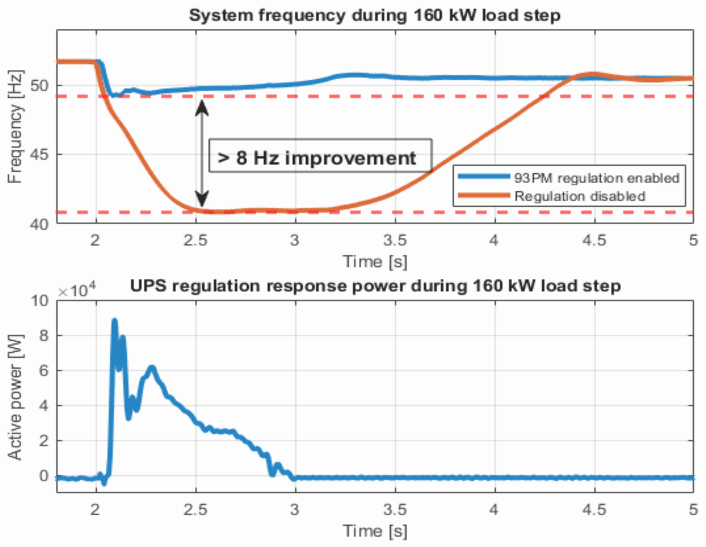
$$H = \frac{1}{2}\frac{300 \times (2\pi \times 25)^2}{3\,150\,000} = 1.17s \qquad RoCoF = \frac{50}{2 * 1.17} \times \frac{1575}{3150} = 10.7\ Hz/s$$

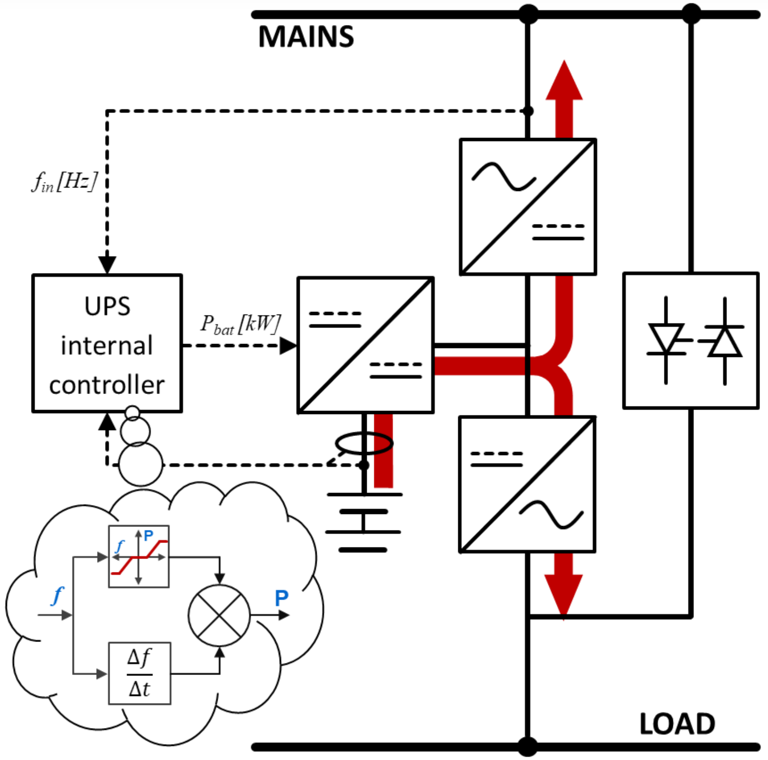
Fast transient requires extremely fast response**,** cannot rely on external devices or control signals

UPS detects load transients by **monitoring incoming utility frequency**

- Sub-cycle frequency measurement based on a **digital synchronous reference frame PLL implementation**
- UPS **calculates the power response at ~5 ms rate** based on the *frequency deviation (Hz)* and *RoCoF (Hz/s)*

Load is shifted on batteries and/or power is injected upstream **to manage load transients** in power system





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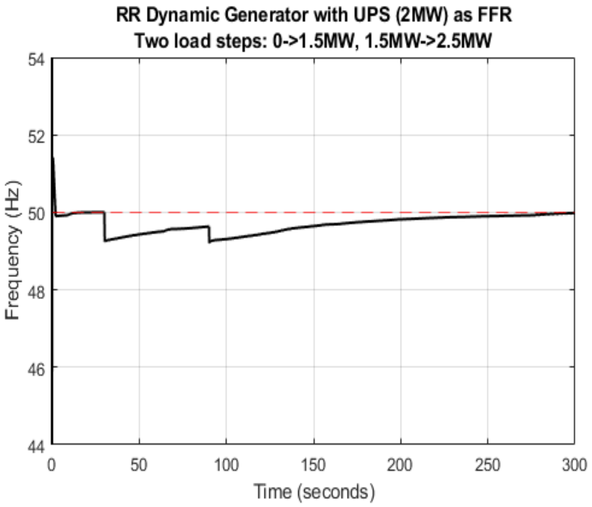
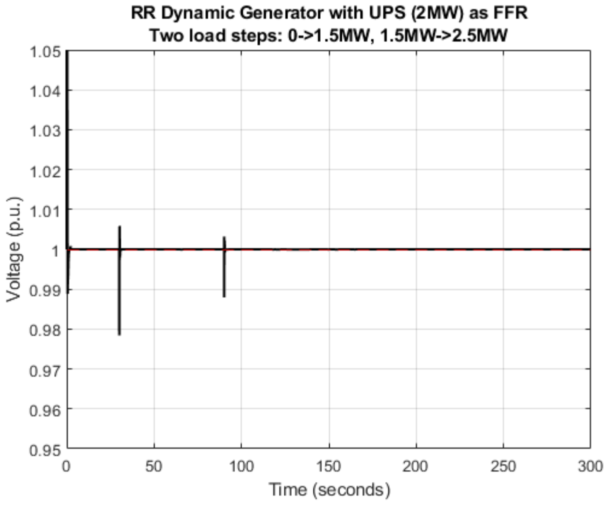
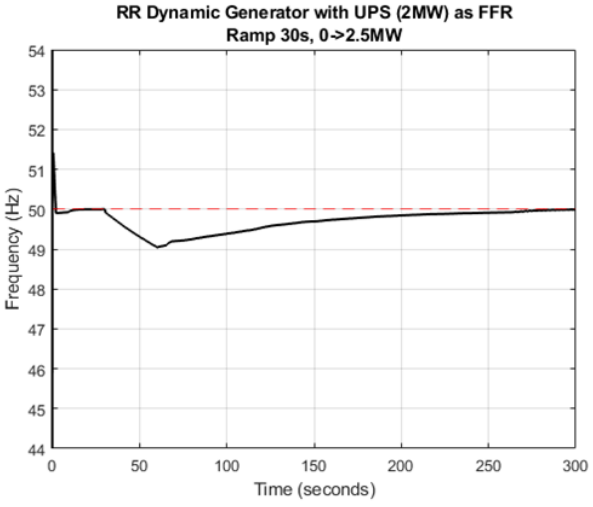
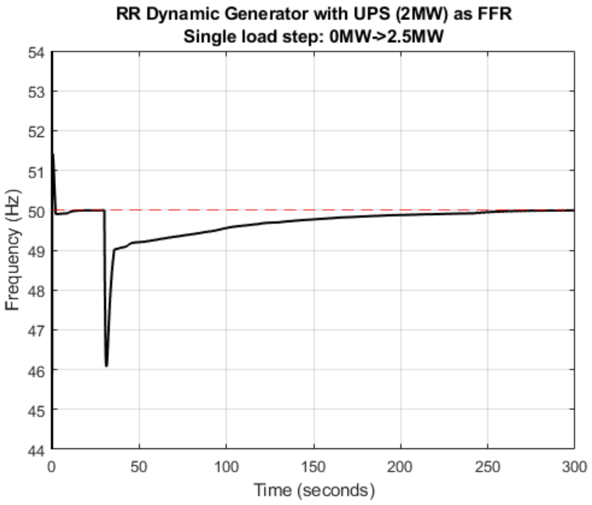
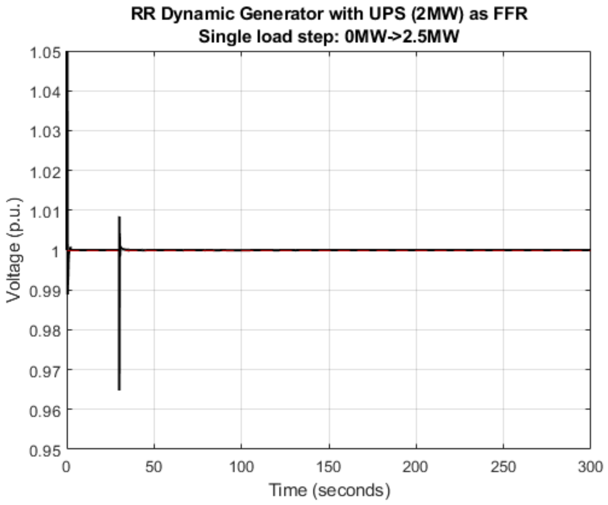
Simulation results with 2.5 MW gas engine generator

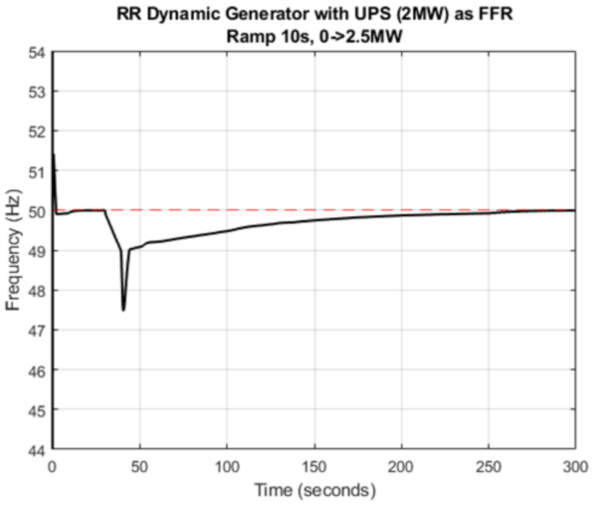












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Under Frequency Load Shedding (UFLS)

- **Transmission-connected demand facilities** and distribution networks shall disconnect part their demand when frequency drops below defined limits [1,2]
- Purpose to act as **a last resort to restore balance** in the system and recover the frequency after primary frequency regulation contain the frequency
- Demand reduction is performed in discrete steps following declining frequency
- Participation is mandatory and done with UFLS relays **disconnecting demand by tripping circuit breakers** on high or medium voltage feeds
- Reconnection of demand allowed only after a permit is received from transmission system operator (TSO)

28.11.2017 EN Official Journal of the European Union L 312/85

ANNEX

Automatic low frequency demand disconnection scheme characteristics:

Parameter	Values SA Continental Europe	Values SA Nordic	Values SA Great Britain	Values SA Ireland	Measuring Unit
Demand disconnection starting mandatory level: Frequency	49	48,7 – 48,8	48,8	48,85	Hz
Demand disconnection starting mandatory level: Demand to be disconnected	5	5	5	6	% of the Total Load at national level
Demand disconnection final mandatory level: Frequency	48	48	48	48,5	Hz
Demand disconnection final mandatory level: Cumulative Demand to be disconnected	45	30	50	60	% of the Total Load at national level
Implementation range	± 7	± 10	± 10	± 7	% of the Total Load at national level, for a given Frequency
Minimum number of steps to reach the final mandatory level	6	2	4	6	Number of steps
Maximum Demand disconnection for each step	10	15	10	12	% of the Total Load at national level, for a given step

ANNEX from Commission Regulation (EU) 2017/2196 http://data.europa.eu/eli/reg/2017/2196/oj

1) COMMISSION REGULATION (EU) 2017/2196 of 24 November 2017 establishing a network code on electricity emergency and restoration http://data.europa.eu/eli/reg/2017/2196/oj
2) COMMISSION REGULATION (EU) 2016/1388 of 17 August 2016 establishing a Network Code on Demand Connection http://data.europa.eu/eli/reg/2016/1388/oj

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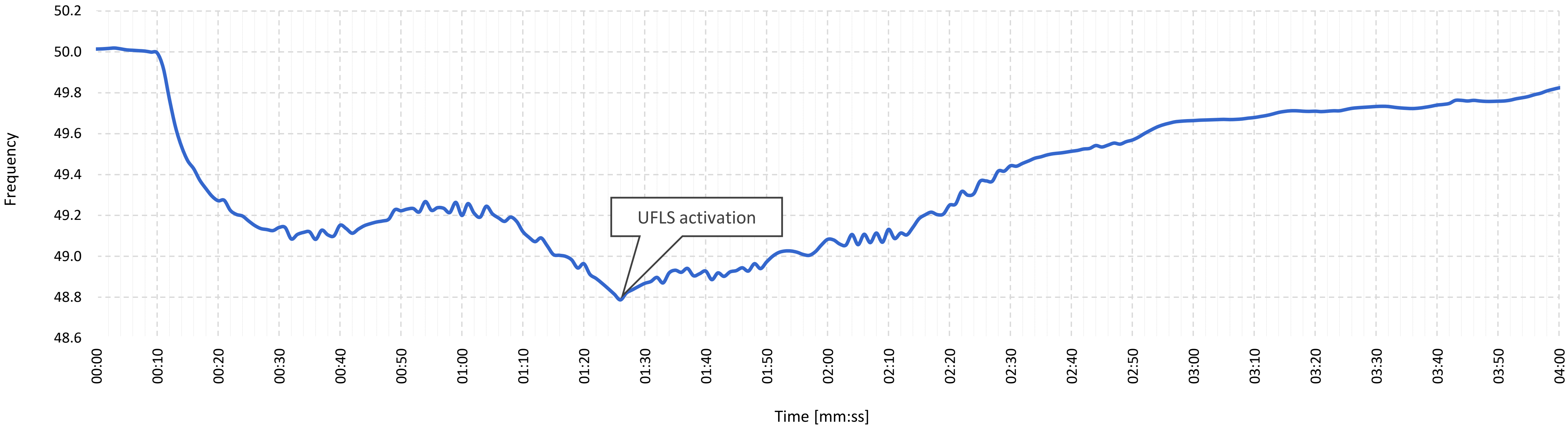
Under Frequency Load Shedding (UFLS)



UK power outage on 9 August 2019:

- DI was 1000 MW and 1481 MW of generation capacity was lost following a lightning strike, additional 210 MW tripped after frequency stabilized in 49,2 Hz
- Once frequency reached **48.8 Hz**, stage 1 (of nine) automatic LFDD (UFLS) was triggered
  - 1.15 million consumers and approx. 4% of national demand (892 MW) was disconnected from the grid
  - Net demand reduction in transmission system reported later by NG ESO was 350 MW indicating that 550 MW of embedded generation was lost as a result of LFDD
- After ULFS activation frequency started to recover and additional frequency response reserves were activated. Frequency returned to 50 Hz within 5 minutes of the fault.

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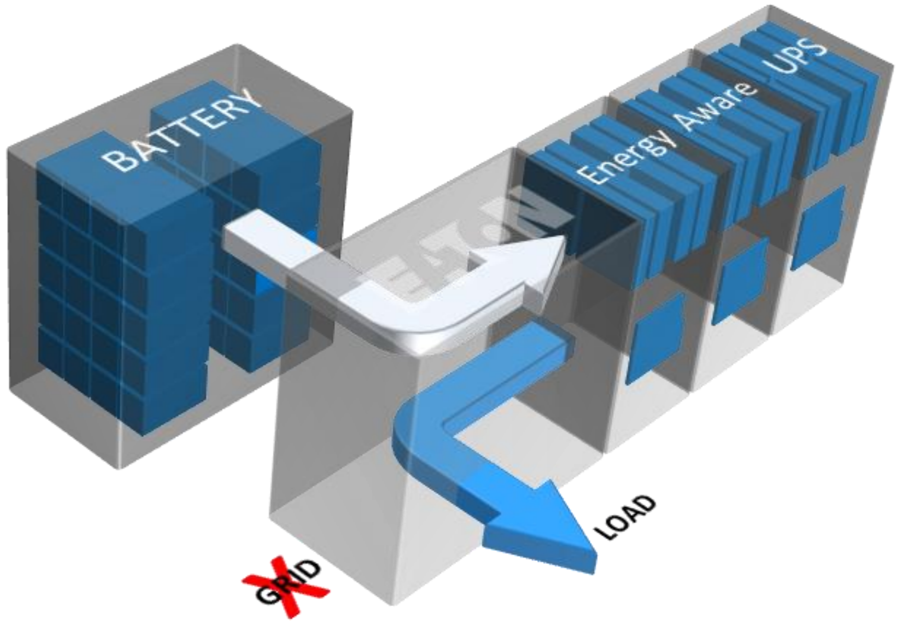
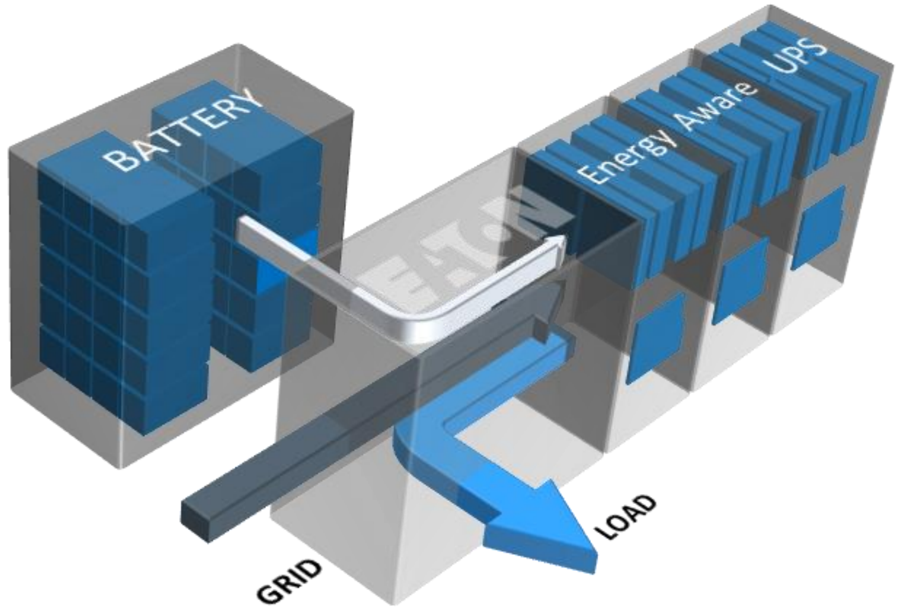
UFLS in a data center





UFLS relays to trip MV feeders:

- In-built redundancy adds complexity
- Whole sub-system demand fed from batteries until shutdown
- Reclosure of feeders after receiving a permit from TSO

Autonomous UFLS function in a UPS:

- UPS's provide demand reduction according actual load
- Feeders remain closed and UPS power shares up to several hours
- Stop UFLS after a receiving permit from TSO or automatically once frequency has recovered

https://www.ipo.gov.uk/p-ipsum/Case/ApplicationNumber/GB2301299.0

Benefits of Grid-Interactive UPS for FFR & UFLS

- Dynamic generator support brings benefits by supporting back-up generation to better manage:
  - Sudden load transients
  - Transitions between grid connected and island mode
  - Fault conditions (tripping a generator etc.)
- Supports transition to new cleaner fuels and power generation technologies as a back-up or primary power source in critical applications and islanding power systems
- Supports green data center designs and abandoning fossil fuels
- Reduces operational risks associated with major grid events and improves reliability of generator-free and alternative back-up power designs
- Reduces complexity in redundant designs as response follows the load and is proportional to actual UPS load on a given moment
- More accurate, predictable and intelligent method for UFLS allowing automatic demand restoration once frequency is restored
- Allows to perform UFLS while having on-site power generation available for grid
- Patent pending, https://patentscope.wipo.int/search/en/detail.jsf?docId=WO2022233457

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High Performance Computing

Typical AI load profile

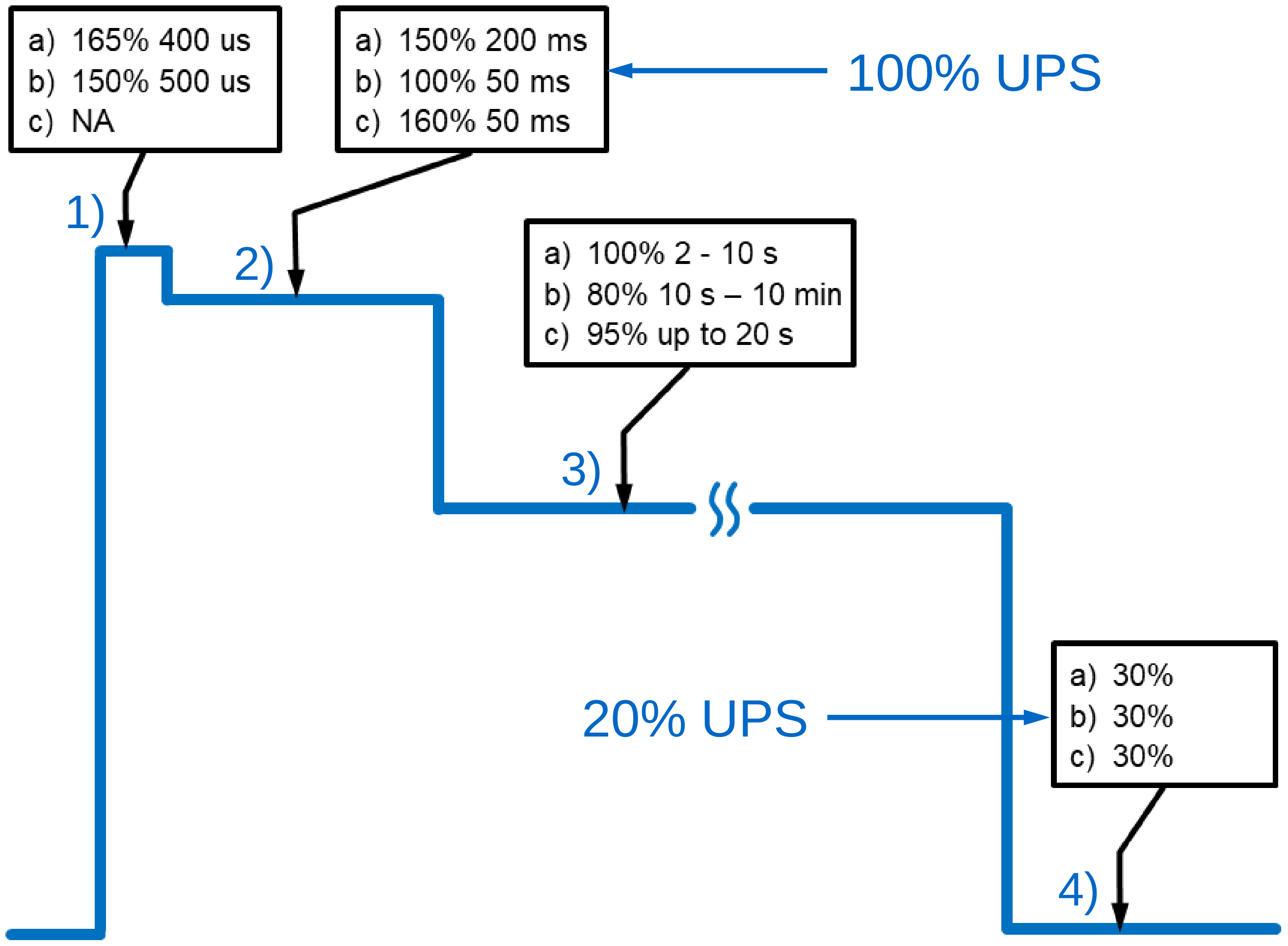
1) GPU input may have <1 ms power burst that is filtered by PSU and not visible on AC side

2) Overload peak at beginning on cycle varying from tens to couple hundred milliseconds

3) Steady state load lasting from couple seconds up to minutes, depending on GPU workload

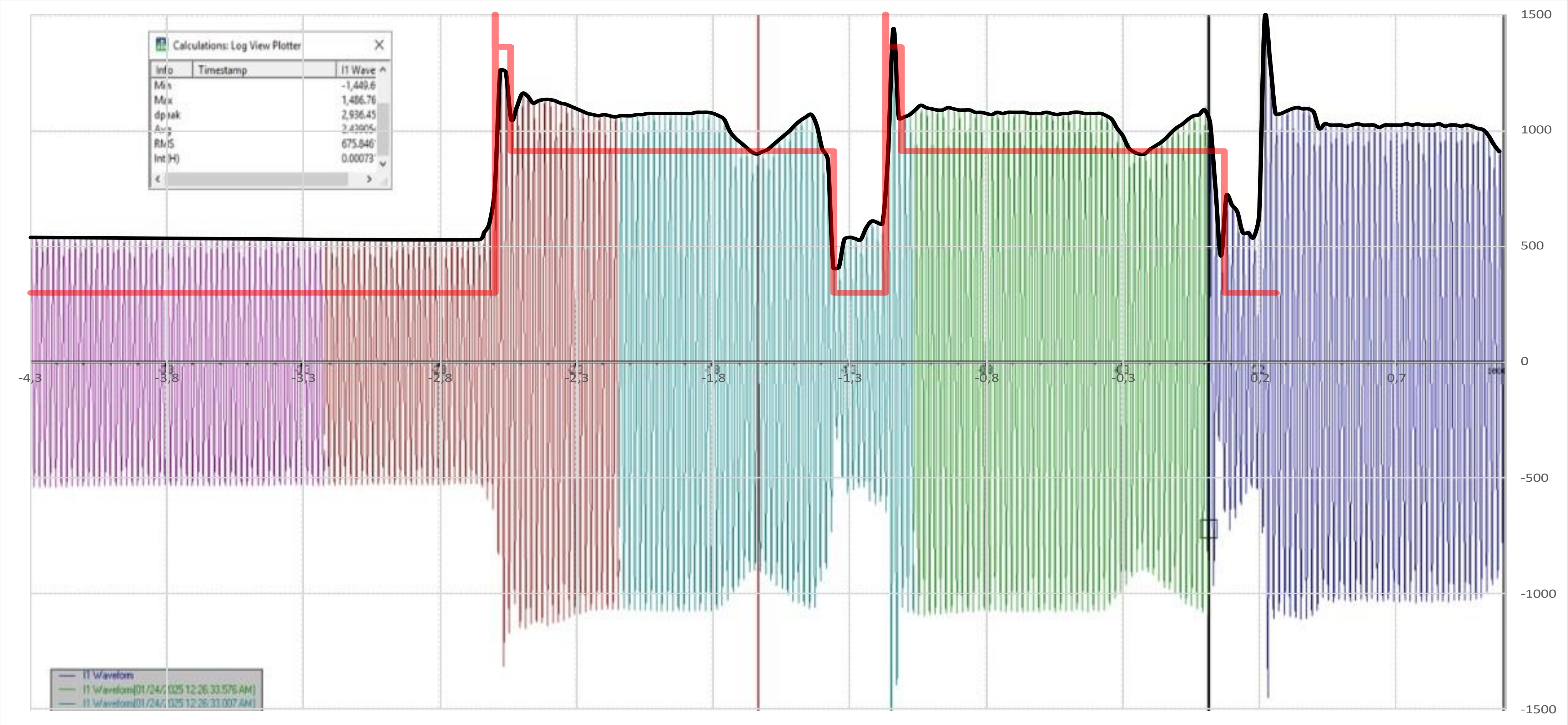
4) Idle power between cycles 30%, idle period is short and duty cycle is high

Based on this UPS will see load between 20% and 100% *(150% in graph equals 100% to UPS and 30% in graph equals 20% to UPS)*



GPU input power in AI application. Source: Various discussions with a GPU manufacturer

AI load profile on AC-side

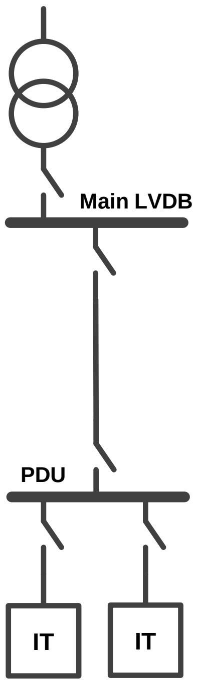


GPU load profile on AC-side

- Fastest load transients created by GPU are filtered with PSU
- Current waveform on AC side remains sinusoidal with fast momentary fluctuations in amplitude
- No abnormally high di/dt on AC current that could cause additional stress to filtering components of a UPS
- Dynamic performance of a standard UPS inverter is not an issue, voltage quality is maintained in UPS output
- Number of load variation cycles can be from thousands to millions per year causing continuous charging and discharging of energy storage devices
- Supercapacitors most likely solution to manage short and frequent discharge cycles
- If not filtered, could cause flickering and other power quality issues for electrical grid
- Case-by-case studies (with simulation models etc.) needed as local grid conditions and characteristics impact the situation

HPC data center power distribution

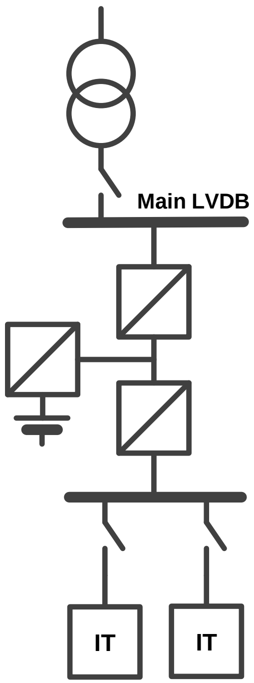
Solution for AI without a UPS



High Power Computing (HPC) fed directly from utility:

- AI learning (and HPC in general) has high and fast load swings or “bursts”
- Grid is exposed to these power bursts that may lead into power quality issues
- Any brownouts in the grid may cause IT systems to end-up in uncontrolled state, some equipment may shut off and others may not
- Recovery can take up to several days
- IT equipment doesn’t tolerate under-voltages (max one cycle) and turns off in the case of near-faults in distribution or transmission system
- This can cause voltage and frequency instability
- High power feed into white space and high fault currents and energies
- How to manage incident energy and safety?

Solution with a UPS



HPC servers fed with a UPS:

- UPS with batteries or supercapacitors can smoothen the power bursts towards the grid
- UPS filters utility voltage variations and cuts the power cleanly after full discharge of the batteries
- IT system end-state is known and predictable
- UPS can perform FRT and PFAPR making data center stable load for the grid
- Grid-interactive UPS can also provide grid services
- Data center doesn’t cause power stability or quality issues for the grid and can help to manage contingency events etc.
- Converter-based sources limit fault current and incident energies
- Safer working environment for IT personnel

Data Centers - A Good Grid Citizen

Data center - a good grid citizen

- Efficiently recycles waste heat to provide for example district heating to decarbonize heat production and networks
- Provides flexibility and services to electrical grid to enable higher penetration of renewable energy sources and to reduce system emissions and balancing cost
- Supports electrical grid and helps to manage contingency events to improve grid reliability
- Does not negatively impact electrical grid power quality, stability or reliability