Power Quality

Figure 1: JUPITER supercomputer (data centre) © Forschungszentrum Jülich / Sascha Kreklau

Continuous Grid Monitoring in the Data Centre of Forschungszentrum Jülich at JUPITER - Europe's Fastest Supercomputer

Forschungszentrum Jülich operates one of Europe's largest research infrastructures. With JUWELS* and JUPITER, Europe's first exascale supercomputer and currently the fastest computer in Europe**, the requirements for grid stability, availability, and standard-compliant voltage quality have increased significantly. The JUPITER booster reaches 793.40 PFLOPS and is powered by renewable electricity. This power density generates highly dynamic load variations that can directly impact voltage quality. The campus grid at medium- and low-voltage levels integrates research facilities, laboratories, combined heat and power units, PV systems, battery storage, V2G charging stations, and data centres in parallel.

* (Rank 7 of the TOP 500, 2020)
** (Europe: Rank 1 of the TOP500, Worldwide: Rank 4, 2025)

1. Initial situation

Even before JUPITER, more than 120 measuring devices were installed across the campus, including in JUWELS. Among these were **PQI-DA smart** and **PQI-DE** units, featuring centralised evaluation and low-latency data access for simulation servers to create a digital twin of the campus's own MV network.

Initial situation – Summary

- Exascale operation with very high requirements for voltage quality and availability
- Campus grid with mixed load and feed-in profiles
- Over 120 measuring points as a foundation, expandable for JUPITER (additional 17 points)
- Low-latency data access for research and model validation

2. Typical challenges for data centres

Data centres are highly sensitive to voltage dips, flicker, transient events, harmonics, and supraharmonics. GPU-intensive workloads and cooling systems cause rapid load changes. The integration of CHP units, PV installations, storage systems, and V2G charging infrastructure alters load flows and frequency spectra up to 20 kHz. In addition to technical control, standard-compliant measurement and documentation in accordance with IEC 61000-4-30 Class A and EN 50160 are required. At the same time, the monitoring concept must be economically scalable.

Especially in HPC infrastructures such as JUPITER, high-frequency current variations occur due to clock and load transitions in GPU clusters. These can lead to short-term harmonic peaks and frequency-selective coupling effects between the medium- and low-voltage levels. Continuous, high-resolution power quality monitoring enables such transient phenomena to be identified before they affect sensitive IT power supplies or UPS systems.

Challenges – Summary

- High load dynamics due to HPC workloads and cooling
- PQ phenomena up to 20 kHz caused by power electronics
- Obligation for standard-compliant measurement and documentation
- Scalable monitoring with acceptable OPEX

3. Project objective

The key objectives include complete transparency of load flows, validation of simulation and grid models, an effective early-warning system for critical events, and flexibility for future extensions.

Project objectives – Summary

- Transparency, validation, early warning, flexibility, compliance
- 10-minute mean values plus event-based disturbance records
- Precise time base and central, role-based evaluation

The recorded measurement data are used not only for operational monitoring but also directly for validating digital twins of the campus grid. This enables the research centre to realistically simulate response times, voltage stability, and grid interactions, and to compare the results with live data from the PQI systems.

4. Technical solution by A. Eberle

FZJ employs a tiered architecture consisting of **PQI-DE**, **PQI-DA smart**, and **WebPQ®**. **PQI-D**E units are installed at key nodes, offering large displays for direct live access to measurement data. In the deeper network layers, **PQI-DA smart** units are DIN-rail mounted compact, cost-efficient, and optimised for large-scale monitoring. **WebPQ®** consolidates all measuring points, reports, and alarms in a central browser-based interface.

The implemented measurement system is time-synchronised via GPS or NTP-based time servers, allowing precise correlation of events across multiple voltage levels. Such synchronisation is essential for accurately identifying cause-and-effect relationships, e.g. between medium- and low-voltage networks.

4.1 PQI-DE at critical nodes

Figure 2: **PQI-DE** *– Monitoring at critical nodes in the data centre*

PQI-DE – Overview

- Class A measurement for critical network nodes
- Large display for direct access to live data
- Event-triggered disturbance recordings and high sampling rates
- Synchronisation and large local storage

4.2 PQI-DA smart in the field

Figure 3: **PQI-DA smart** *– For scaling measurement points in the lower network levels*

PQI-DA smart – Overview

- Compact design for DIN-rail mounting
- Designed for scalable sub-measurements
- Class A measurement for voltage, current, harmonics
- Economical deployment across the network

4.3 Measurement concept and data path

Across the campus, more than 140 measurement points are active, including around 15 **PQI-DE** units in the JUPITER environment, complemented by numerous **PQI-DA smart** devices at secondary nodes.

4.4 Software platform WebPQ®

WebPQ® – Overview

- Central browser-based analysis with user roles and permissions
- Live data, alarms, compliance reports, exports
- Modbus TCP/IP and OPC UA for system integration

Figure 4: **WebPQ®** *– Central PQ analysis for all measuring points in the JUPITER network*

4.5 IT security in WebPQ®

In the context of high-performance data centres, IT security of the monitoring platform is of critical importance. **WebPQ®** meets the latest requirements for data security and cyber resilience:

- Encrypted communication via HTTPS and TLS
- Role-based user and access management
- Secure authentication mechanisms (including 2FA options)
- Audit trails and tamper-proof logging
- Optional segmentation within protected networks

This ensures that critical PQ data are securely recorded and processed – a must for operators of data centres and research infrastructures. In addition, **WebPQ®** optionally supports integration with existing Security Information and Event Management (SIEM) systems, enabling security-related events and alerts to be integrated into the overall security framework of the research centre – a key aspect in safeguarding critical research and energy infrastructures.

5. Measurement results and findings

5.1 Load flows and trend analyses

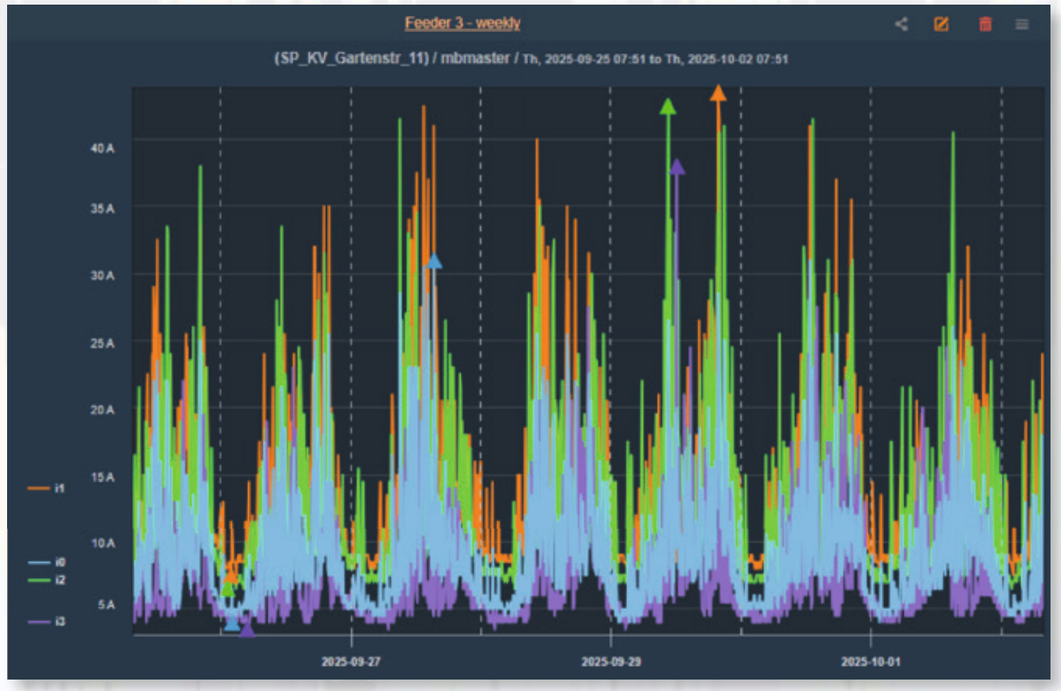

Figure 5a: Current waveforms (I1, I2, I3) in weekly resolution for a selected feeder. The illustration shows typical daily load profiles and characteristic load peaks as observed in HPC operation at Forschungszentrum Jülich.

Figure 5b: Power waveforms (P, Q, S) in monthly resolution. Recurring base and peak load patterns as well as differences in reactive power behaviour are visible – comparable to the dynamic profiles in the JUPITER data centre.

Figure 5c: Voltage waveforms (U1, U2, U3) in monthly resolution. The figure documents typical fluctuations and voltage sags as they occur under strong load dynamics in HPC environments.

The evaluation of current and voltage curves allows precise assessment of network symmetry and phase load distribution. Long-term trend analysis enables early detection of gradual changes in load behaviour, such as those caused by software updates, server expansions, or modified cooling strategies.

5.2 Transients and response times

Figure 6a: Transient recording during the parallel start-up of multiple HPC jobs. A short-term voltage dip and frequency deviation caused by high inrush currents are clearly visible.

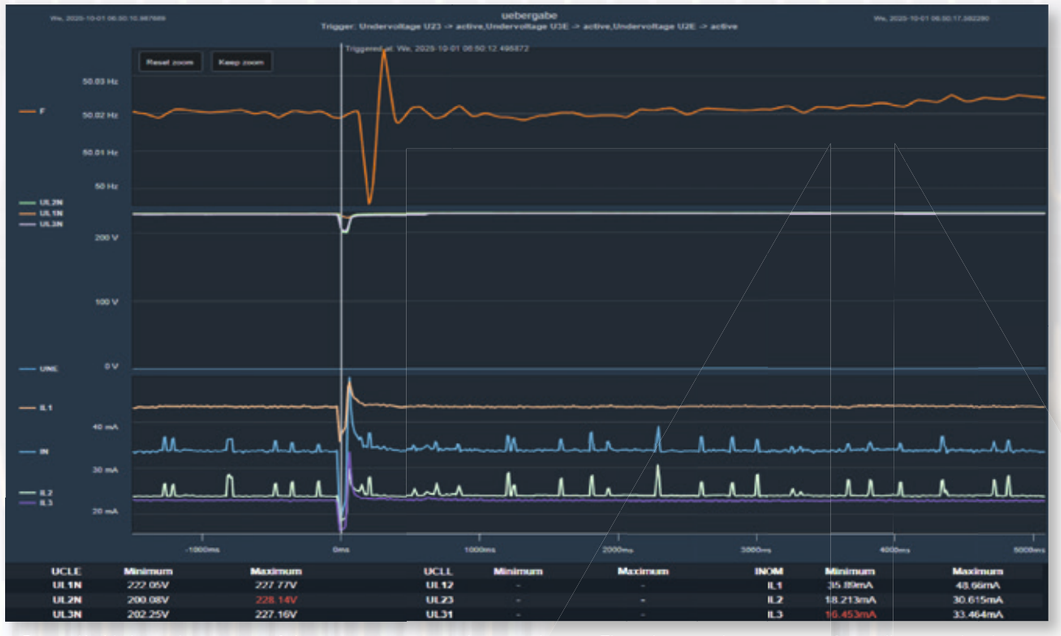

Figure 6b: High-resolution view of the same transient in the time domain. The voltage and current waveforms illustrate the dynamic inrush currents of the server power supplies and demonstrate the network loading during the start-up phase.

The combination of event-triggered recording and high sampling rate (up to 200 kHz per channel) enables voltage dips in the millisecond range to be precisely captured and their impact on downstream UPS systems or sensitive equipment to be quantified.

5.3 Harmonics and supraharmonics

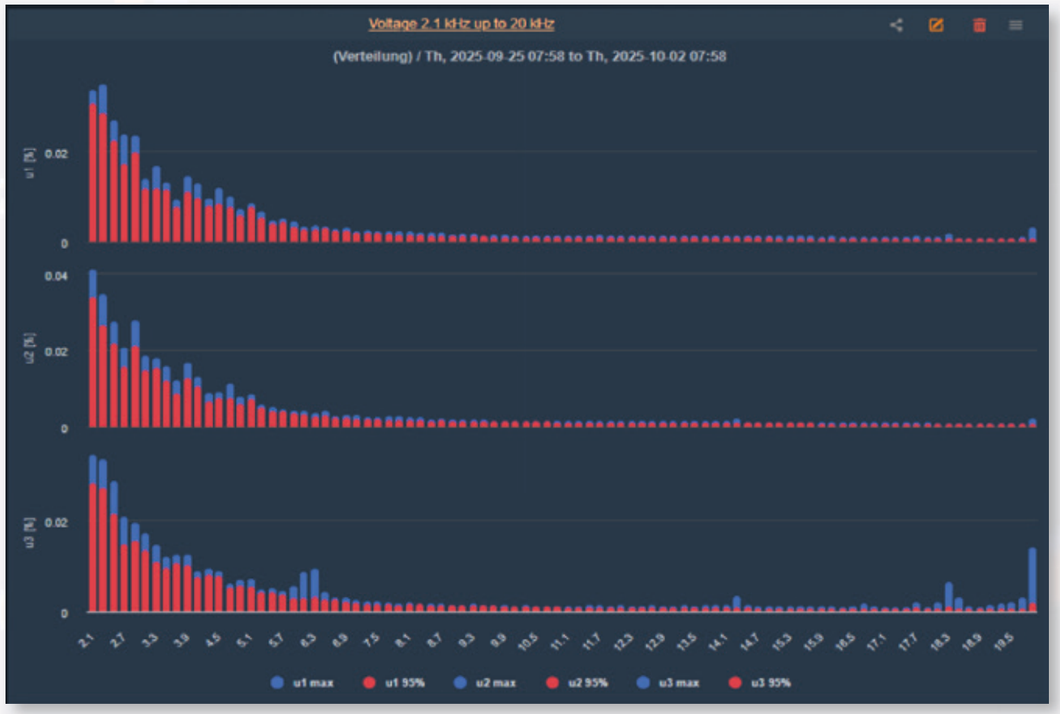

Figure 7: Harmonic and supraharmonic analysis up to 20 kHz. The distributions show spectral peaks caused by the switching power supplies of servers. Frequency-selective effects and possible resonance ranges were identified and are being incorporated into filter and choke design considerations.

Through supraharmonic analysis up to 20 kHz, spectral clusters were identified that correspond to switching frequencies of specific power supplies. These findings serve as a basis for targeted filter dimensioning and EMC optimisation of the power supply system

6. Benefits for the operator

The combined **PQI-DE**, **PQI-DA smart**, and **WebPQ®** concept provides full transparency from the main supply to subdistribution, demonstrates standards compliance, and delivers robust data for informed decision-making.

Furthermore, the system provides valuable KPIs for energy management and capacity planning. Continuous analysis of reactive power and voltage asymmetry enables cost reduction and optimised load operation of network components.

7. Conclusion and outlook

The project demonstrates how exascale requirements and the energy transition can be managed simultaneously: through Class A measurement, a tiered system architecture, and centralised evaluation. The approach can be transferred to other data centres and campus grids.

Next steps include increased automation, predictive analytics, and tighter integration of monitoring, simulation, and control. In the long term, machine learning models within **WebPQ®** could automatically identify recurring patterns and generate early warnings - paving the way for autonomous energy monitoring in high-performance data centres.

8. Standards, measurement methods, and integration into simulation environments

Measurements were conducted in accordance with IEC 61000-4-30 Ed. 4 Class A. Harmonics were measured according to IEC 61000-4-7, flicker according to IEC 61000-4-15, and supraharmonics in the range of 2 to 20 kHz. Documentation followed EN 50160. Ten-minute mean values were used for trend reports, while event-based recordings captured transient events. Accurate time bases and synchronisation ensured consistency across distributed measuring points. **WebPQ®** serves as the central data hub for control room and research integration via Modbus TCP/IP.

Through standardised interfaces (CSV, OPC UA, REST API), measurement data are directly imported into simulation and research environments such as MATLAB®/Simulink® or DIgSILENT PowerFactory®. This enables correlation between real and simulated grid behaviour as well as calibration of load flow and stability models.

9. Product innovation: PQI-LV

The PQI-LV has been recently introduced.

This measuring device is designed to be particularly cost-efficient for low-voltage applications requiring a large number of measurement points with high accuracy and at an attractive price. It complements the existing portfolio perfectly and opens new possibilities for operators aiming to capture power quality comprehensively and economically.

In similar applications, such as in the data centre at Forschungszentrum Jülich, the **PQI-LV** is particularly suitable for complete low-voltage monitoring within server rooms and laboratory areas - where space and budget are limited but precise voltage monitoring remains essential.

Figure 8: PQI-LV – new cost-efficient solution for low-voltage networks

Authors

Fabian Leppich

Product Manager »PQSys«
A. Eberle GmbH & Co. KG

Maximilian Sefz

Head of Marketing
A. Eberle GmbH & Co. KG

Wolfgang Reitmeier

Sales
A. Eberle GmbH & Co. KG

Figure 9: JUPITER supercomputer (data centre) © Forschungszentrum Jülich / Sascha Kreklau

Do you have any questions or would you like advice on our solutions for continuous grid monitoring in data centers, utilities or industrial networks?

Simply scan the QR code or contact us at sales@a-eberle.de

We look forward to hearing from you!

A. Eberle GmbH & Co. KG
Frankenstraße 160
D-90461 Nürnberg
Tel +49(0)911 628108-0
Fax +49(0)911 628108-99
sales@a-eberle.de
www.a-eberle.com

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