Assessment of Power Quality in an Industrial Facility: A Case Study at DESY Hamburg

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ABSTRACT This article presents a comprehensive assessment of power quality (PQ) disturbances in the industrial power network of the Deutsches Elektronen-Synchrotron (DESY), a leading research facility for particle physics. The study leverages high-resolution measurements (7-days) from Fluke 435 Series II and long-term monitoring data (6-months) from Janitza UMG 512 analyzers to characterize PQ issues. Measurement data were collected from various substations and Points of Common Coupling (PCC) to evaluate harmonics, voltage fluctuations, flicker, and transient events. The high-resolution data (sampled at 500 ms) revealed voltage deviations of up to $\pm 4\%$, current unbalance exceeding $\pm 10\%$, and flicker spikes reaching 0.63 Pst, all attributed to nonlinear load dynamics and switching events. In total, 17 voltage swell events and 12 dips were recorded, along with 6 transient disturbances linked to PETRA's 12-pulse converter operations. Also, voltage and current total harmonic distortion (THD) levels peaked at 3.6% and 7.5%, respectively, breaching IEEE 519 thresholds under dynamic loading. These findings highlight the necessity of coordinated PQ monitoring strategies and support the development of predictive, data-driven PQ management frameworks tailored to mission-critical industrial networks.

INDEX TERMS Medium-voltage (MV) networks, power electronic loads, power quality (PQ) measurement, predictive diagnostics, total harmonic distortion (THD), transients.

I. INTRODUCTION

THE INCREASING complexity and reliance on electricity in modern industrial facilities have made power quality (PQ) a critical concern. The proliferation of nonlinear loads, such as power electronic converters, variable speed drives, and arc furnaces, coupled with the growing integration of renewable energy sources, introduces new challenges to maintaining acceptable PQ levels [1], [2]. These factors contribute to a range of PQ disturbances, including harmonic distortion, voltage sags/swells, voltage flicker, transient overvoltages, and frequency variations [3]. The disturbances can have significant impacts on industrial operations, leading to equipment malfunction, premature aging of components, increased power losses, reduced efficiency, production downtime, and ultimately, substantial economic losses [4], [5].

In particular, industries with highly sensitive equipment, such as semiconductor manufacturing, data centers, and research facilities like the Deutsches Elektronen-Synchrotron (DESY), which specializes in particle accelerators and detection instruments, are particularly vulnerable to PQ variations. Even minor deviations from nominal voltage and current waveforms can disrupt critical processes, compromise data integrity, and lead to costly delays. The DESY in Hamburg, Germany, provides an ideal case study for investigating and addressing PQ challenges in a complex medium-voltage (MV) industrial power network. As a leading research center for particle physics, DESY operates large-scale pulsed loads such as 12-pulse converters and fast-switching magnetic power supplies, which introduce synchronized harmonic bursts and voltage fluctuations. These loads differ

significantly from conventional industrial settings such as arc furnaces or drives, which generate more continuous and random disturbances. The facility's diverse electrical load profile, ranging from linear resistive loads to highly nonlinear and dynamic loads associated with accelerator operations, creates a complex PQ landscape. This diversity, combined with the stringent PQ requirements of the scientific equipment employed at DESY, makes it a good example of a modern industrial setting facing evolving PQ challenges.

Understanding and mitigating PQ issues at DESY not only safeguards its scientific mission but also provides valuable insights and best practices applicable to other complex industrial environments. Unlike conventional industrial systems, DESY's load profile includes synchronized pulsed converters and fast-switching magnet supplies that cause periodic harmonic bursts and voltage fluctuations. These dynamics demand tailored PQ analysis beyond standard continuous or stochastic load assumptions. Traditional mitigation approaches to PQ management have often been reactive, addressing PQ problems only after they have occurred and caused disruptions. However, this approach is no longer sufficient in the face of increasing grid complexity and the growing sensitivity of industrial equipment. A proactive approach to PQ management is essential, which involves anticipating potential PQ problems before they manifest and implementing preventive measures to minimize their impact [6]. This proactive strategy relies heavily on accurate PQ forecasting, enabled by advanced data analytics and modeling techniques [6], [7]. By predicting the occurrence, severity, and timing of PQ disturbances, industrial operators can take timely actions to mitigate their effects, preventing costly downtime, equipment damage, and production losses.

Despite significant advancements in PQ research, several critical gaps persist, particularly concerning comprehensive, long-term, field-based studies in highly specialized industrial facilities with unique and dynamic loads. While many studies focus on general PQ assessment or specific disturbance types, there is a scarcity of research that integrates high-resolution transient analysis with long-term trend monitoring in environments characterized by complex pulsed loads. Existing literature often relies on synthetically generated data or short-term measurements, which may not fully capture the intricate PQ dynamics induced by such specialized equipment. Furthermore, the implications of these disturbances on system reliability and sensitive equipment in mission-critical industrial networks are not always explicitly addressed, and the development of concrete, data-driven frameworks for proactive PQ management remains an active area of research. These gaps highlight the need for a more holistic and practically grounded understanding of PQ phenomena in advanced industrial settings. This article presents the findings of a comprehensive PQ data measurement conducted within the DESY MV power network. The study is focused on comprehensively characterizing the existing PQ landscape and identify specific areas of concern. Beyond simply identifying existing problems, this study also proposed

a framework for a proactive PQ management at DESY. Furthermore, we discuss the broader implications of our findings for industrial PQ management and highlight the importance of proactive strategies and data-driven decision-making in ensuring the resilience and reliability of modern industrial power systems. To address the identified research gaps and provide a more focused investigation, this study aims to answer the following research questions.

1) What are the characteristic PQ disturbance patterns (e.g., harmonics, voltage fluctuations, flicker, and transients) observed in a high-demand industrial facility with significant pulsed loads, such as the DESY particle accelerator complex?
2) How do the unique operational characteristics of pulsed loads (e.g., 12-pulse converters and fast-switching magnet power supplies) at DESY influence the severity, frequency, and waveform characteristics of PQ disturbances compared to those typically found in conventional industrial settings?
3) How effective is a dual-layer PQ monitoring strategy, combining high-resolution short-term measurements and long-term continuous monitoring, in comprehensively characterizing both transient and steady-state PQ phenomena in such a dynamic industrial environment?
4) What are the implications of the identified PQ disturbances for system reliability, operational continuity, and the performance of sensitive research equipment at DESY, and how can these findings inform the development of proactive PQ management strategies?

The primary contributions of this article are summarized as follows.

1) We implement a dual-layer PQ monitoring strategy, combining high-resolution 500ms mobile measurements (Fluke 435 II) with long-term Class A monitoring (Janitza UMG 512).
2) We establish a structured and repeatable workflow for PQ evaluation in a MV systems, covering planning, measurement setup, multidevice synchronization, data acquisition, and compliance analysis.
3) We provide a detailed field-based analysis of PQ disturbances at DESY Hamburg, reporting significant current unbalance (up to $\pm10\%$), elevated current total harmonic distortion (THD) (peaks of 7.5%), voltage dips/swell events (29 occurrences), and flicker levels (up to 0.63 Pst).
4) We show the need for a tailored PQ analysis and proactive management strategies to address the unique challenges posed by dynamic load profiles in a mission-critical industrial networks.

II. LITERATURE SURVEY

Measurements of PQ disturbances and mitigation have been extensively studied in recent years. Traditional measurement methods, such as those using oscilloscopes and multimeters, have been supplemented by more advanced techniques,

including wavelet analysis, Fourier analysis, and machine learning (ML)-based approaches [8]. The IEEE Standard 1159-2009 provides guidelines for monitoring electric PQ, emphasizing the importance of accurate measurement and characterization of disturbances [9]. Recent studies have also explored the use of IoT-based sensors and smart grid technologies to enable real-time monitoring and measurement of PQ disturbances. Despite these advances, there are challenges to developing measurement techniques that can accurately detect and characterize complex disturbances in real time [10].

Researchers have explored advanced signal processing techniques and novel classification methodologies to better detect and characterize disturbances PQ disturbances. For example, Poisson et al. [11] utilized continuous wavelet transform (CWT) methods for the accurate detection and classification of voltage sags and transients. This offers improved time-frequency resolution compared to classical methods. Amariapadath et al. [12] provided a comprehensive review of PQ disturbances in smart grids, with a particular focus on suprarharmonics and the measurement configurations required for their analysis. Ferrero [13] emphasized the growing challenges in accurately measuring PQ under the increasing penetration of nonlinear and time-variant loads. Golkar in [14] further classified various PQ disturbance types and highlighted trends in advanced monitoring equipment needed for their detection. Priyadarshini et al. [15] conducted an in-depth comparative study on Fourier Transform, short-time Fourier transform (STFT), CWT, and discrete wavelet transform (DWT), identifying strengths and weaknesses of each method in resolving PQ disturbances across different domains. Yang et al. [16] proposed a multiple impact factor-based accuracy analysis using wavelet lifting and redundant lifting transforms for improved PQ disturbance detection. Moreover, Ali et al. [17] offered a comprehensive study on the application of key PQ devices and AI-based methods for mitigating harmonic-induced overheating in modern grids, emphasizing the ongoing shift toward AI-driven PQ management strategies.

A recent review by Choudhury et al. [18] in 2024 specifically analyzed various PQ monitoring methods in industrial distribution systems. The study emphasizes the increasing complexity of industrial networks due to variable speed drives, PWM inverters, and distributed energy resources. The authors discuss different techniques, including CBEMA curves, EN 50160 reporting, and waveform capture, and underscore the importance of analytics for identifying disturbance sources to enable effective corrective actions. Samanta et al. [19] provided a comprehensive review of artificial intelligence and ML techniques for PQ event classification. Their review highlights that AI/ML techniques, particularly hybrid approaches like dual-tree wavelet packet transforms combined with extreme learning machines, can achieve classification accuracies as high as 99.94%. This article emphasizes the growing complexity of PQ disturbances due to renewable energy sources and nonlinear

loads, making traditional analysis methods insufficient. They also outline future research directions, focusing on hybrid models, explainable AI systems, and real-time adaptability to dynamic grid conditions. Chinthaginjala et al. [20] proposed a novel hybrid approach for PQ improvement using semiconductor devices integrated with ML and deep learning (DL). Their research addresses key PQ challenges like voltage sags, swells, harmonics, and transient disturbances through a data-driven framework. They found that DL models, especially long short-term memory (LSTM), were more accurate and dependable in identifying and forecasting PQ issues compared to traditional ML models. The study highlights the promise of hybrid systems that combine traditional and data-driven control strategies for adaptive and dependable PQ management in smart grid applications.

Also, several studies have utilized AI architectures to enhance classification accuracy and forecasting reliability in PQ research. Hong et al. [21] proposed a novel classification framework based on confidence-enhanced guided multilabel learning (CEGML), integrating convolutional and recurrent neural networks with attention mechanisms to handle complex and multilabel PQ disturbance scenarios. This represent a promising direction that aligns with the use of hybrid intelligent models for PQ analysis. Liu et al. [22] proposed a multidimensional ensemble feature-driven model based on a convolutional neural network (CNN) combined with bidirectional gated recurrent units (Bi-GRUs), demonstrating robustness against typical power system disturbances such as DC offsets, frequency variations, and phase jumps. Similarly, Zhao and Milanović [23] and Abed et al. [24] employed artificial neural networks (ANNs) and Sequential ANNs for predicting harmonic distortions at critical points in industrial and transmission networks, particularly under scenarios of sparse monitoring. These works collectively underscore the potential of neural networks in capturing complex PQ dynamics across diverse grid environments. In addition to neural-based models, hybrid and optimization-based approaches have also been explored to enhance PQ monitoring and control. Yang et al. [16] introduced a hybrid forecasting model combining LSTM networks and adaptive neuro-fuzzy inference systems (ANFISs), achieving dependable forecasts for harmonics in renewable energy systems. Likewise, Lopez et al. [25] applied a moth-flame optimization (MFO) algorithm to effectively reduce THD in multilevel inverters, while Elgammal and Ramlal [26] demonstrated the efficacy of a multiobjective particle swarm optimization (MOPSO) procedure for enhancing active power filter performance in photovoltaic-wind-based smart grids. Lopez et al. [27] further employed the Taguchi method for optimizing voltage THD in multilevel inverter applications, highlighting the diverse set of optimization techniques used in contemporary PQ research.

Despite the advancement highlighted in the reviewed literature, challenges remain in developing measurement techniques that can accurately detect and characterize complex disturbances in real-time. Unlike most studies in which

FIGURE 1. Layout of DESY Hamburg Research Center.

FIGURE 2. Single line diagram of DESY Hamburg power system structure.

synthetically generated data is used, this study aims to quantify and characterize PQ disturbances induced by DESY complex pulsed loads, which cannot be adequately assessed using conventional PQ indicators or standard observation windows. The results of this study will provide valuable insight into the characteristics of PQ disturbances in an industrial setting like DESY Hamburg and contribute to the development of more accurate and reliable measurement techniques for PQ disturbances.

III. METHODS

In this methodology section, we describe the comprehensive measurement setup, equipment used, data acquisition process, and analytical techniques employed to assess PQ at DESY Hamburg. Our approach is designed to provide a holistic understanding of PQ phenomena in a complex industrial environment, moving beyond conventional monitoring practices through a dual-layer strategy.

A. DESY RESEARCH FACILITY LAYOUT

The area view of DESY research facility campus in Hamburg, Germany, covering an area of approximately 57 hectares is shown in Fig. 1. The figure highlights the positions and layout of DESY's major accelerator facilities withing the campus. As shown in Fig. 1, DESY Hamburg site hosts several major accelerator facilities, each serving a unique role in generating and delivering high-energy particle beams. PETRA III is the largest, with a 2.3 km storage ring that accelerates electrons to 6 GeV and provides extremely bright X-ray light for research. DESY II, a smaller 293 m synchrotron, cycles electron and positron beams up to 6.3 GeV at 12.5 Hz, acting both as a test beam facility and as the injector for PETRA III. Upstream of DESY II is Linac II, a linear accelerator that accelerates primary electrons to about 400 MeV and produces secondary electrons and positrons for injection, using 3 GHz S-band traveling-wave structures. Together, Linac II and DESY II create the high-quality particle beams needed for PETRA III operations. In addition to these injector systems, DESY also operates FLASH, a superconducting linear accelerator and free-electron laser (FEL) producing intense, ultrashort pulses of extreme-ultraviolet and soft X-ray radiation. FLASH's
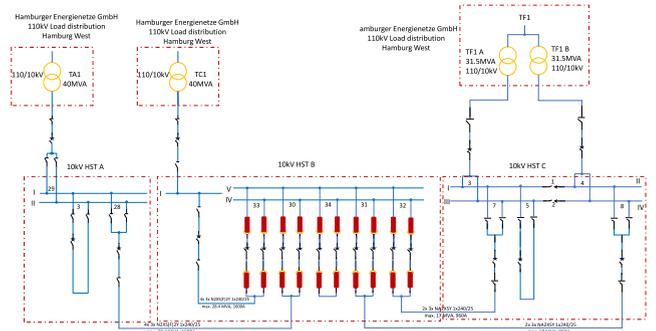
superconducting RF cavities accelerate electrons up to 1.35 GeV along its roughly 320 m beamline before they pass through undulators to generate laser-like light. This combination of synchrotrons, linacs, and FEL technology makes DESY Hamburg a versatile research hub, offering scientists a wide range of photon energies and beam characteristics for experiments in physics, chemistry, materials science, and biology.

Maintaining good PQ at DESY is critical because its accelerators and supporting systems rely on highly stable, distortion-free electrical power to operate within tight tolerances. The facility hosts numerous power-electronic converters, magnet power supplies, RF systems, and cooling infrastructure, all of which can both generate and be affected by harmonics, flicker, and voltage disturbances. Even small deviations in voltage or frequency can disrupt beam stability, reduce experimental uptime, or damage sensitive equipment. Measuring PQ events in such a complex network is challenging due to the wide range of nonlinear loads, fast transient events, and distributed nature of the system. This makes systematic monitoring through the dual-layer PQ monitoring developed in this research essential.

B. DESY POWER NETWORK

The DESY facility is operated on a complex power network architecture connected to a public network of Hamburger Energienetze GmbH via three 110 kV feeds. The overview of the MV Power System architecture of DESY is shown in Fig. 2.

Fig. 2 shows the DESY three independent 110 kV feeds from the public utility Hamburger Energienetze GmbH. These feeds connect to three high-voltage/MV step-down transformer stations, TA1, TC1, and TF1 (comprising TF1 A and TF1 B), with individual ratings of 40 MVA for TA1 and TC1, and 31.5 MVA each for TF1 A and B. Each transformer reduces the voltage from 110 kV to 10 kV and supplies one of the three main DESY MV supply stations; HST A, HST B, and HST C. These stations form the point of common coupling (PCC) between DESY and the public power grid. Within these substations, more than 22 MV circuit breakers per station ensure operational flexibility and protection. The 10 kV MV buses feed over
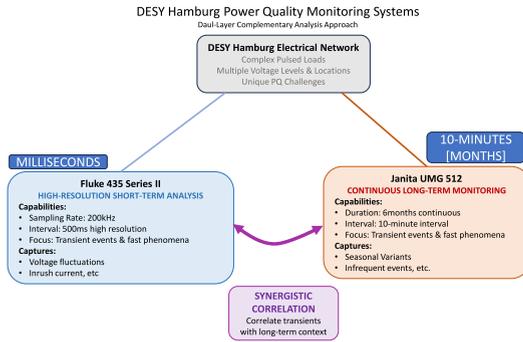
FIGURE 3. Dual-layer measurement approach.

120 distribution transformers (10 kV/400 V), which are connected to corresponding low-voltage main distribution boards that supply experimental halls, laboratories, RF power sources, klystrons, and infrastructure services throughout the DESY facility. The network is structured to ensure redundancy and operational reliability, with parallel feeders, ring configurations, and sectionalizers. This robust and scalable power system is designed to meet the stringent PQ requirements of DESY's advanced particle accelerators, including PETRA, FLASH, and the European XFEL.

C. DUAL-LAYER PQ MONITORING STRATEGY

To ensure a comprehensive assessment of PQ across the DESY Hamburg electrical network, the study utilized two complementary PQ analyzers (Fluke 435 Series II and the Janitza UMG 512). These devices served distinct but synergistic roles in the measurement, enabling both detailed short-term analysis of transient events and long-term trend monitoring across various voltage levels and locations within the network. This dual-layer approach highlighted in Figure 3 represents a methodological advancement over traditional single-layer monitoring, which often relies on either continuous, low-resolution logging or short-term, high-resolution spot checks. Our strategy bridges this gap, providing both the breadth of long-term data and the depth of high-resolution captures, which is essential for understanding the unique PQ challenges at DESY. The Fluke 435 Series II, with its high internal sampling rate (up to 200 kHz for waveform capture) and 500ms data capture duration for high-resolution events, is used to capture granular fast-changing phenomena and transient events. This allows for detailed understanding of voltage fluctuations, inrush currents, and high-frequency transients characteristic of pulsed loads. The Janitza UMG 512, is used to capture six months of continuous data aggregated at 10-min intervals for long-term trends, seasonal variations, and infrequent events. This is used for the purpose of holistic understanding of DESY PQ landscape. Both measurement perspective allows us to correlate transient events observed in the high-resolution data with their broader context within the long-term trends. Thus, allowing for a more accurate characterization of PQ issues induced by complex pulsed loads, which are not adequately assessed by conventional PQ indicators or standard observation windows. The data from the combined approach enables a deeper understanding of the cause-and-effect relationships between specific operational events at DESY and their impact on PQ.

D. MEASUREMENT EQUIPMENTS AND SPECIFICATION

Given the fast transient behavior and high harmonic sensitivity at DESY, a sampling interval of 500 ms was selected for short-term measurements, alongside Class A 10-min logging for long-term trends. PQ indicators such as Pst, THD, and waveform distortion up to the 63rd harmonic order were prioritized. These settings which exceed standard industrial requirements are selected to reflect the need for precision diagnostics in environments with critical timing and signal integrity constraints.

1) SHORT-DURATION MOBILE HIGH-RESOLUTION MEASUREMENT USING FLUKE 435 SERIES II

The Fluke 435-II PQ and Energy Analyzer was utilized for high-resolution, short-duration data acquisition. The device was installed at the PCC location in the DESY power network. This location was strategically selected to ensure representative measurement of PQ parameters, including voltage and current RMS values, frequency, active and reactive power, power factor, THD of voltage and current (THD-V and THD-I) up to the 50th harmonic order, individual harmonics, voltage sags, swells, interruptions, and flicker indices (Pst and Plt). The device is specified by the manufacturer to maintain a maximum relative error of less than 0.5%, for the purpose of high measurement fidelity across voltage and current parameters. This provide a high level of confidence in the acquired data. The analyzer was configured to record measurements with a temporal resolution of 500 milliseconds.

The analyzer was equipped with flexible current probes (i430-Flex-TF) and standard voltage test leads supplied by the manufacturer. Data was continuously logged using the built-in Logger Function and stored on an SD memory card for subsequent analysis with Fluke PowerLog software. Waveform capture was performed with a sampling rate of up to 200 kHz, enabling the detection of millisecond-scale transients. A recording window of 500 ms was configured to capture short-duration events associated with pulsed and fast-switching loads.

2) LONG-DURATION PERMANENTLY INSTALLED MONITORING SYSTEM USING JANITZA UMG 512

To facilitate long-term PQ assessment and historical data analysis, the Janitza UMG 512 Class A PQ Analyzer was permanently deployed at DESY. The device was selected due to its high measurement accuracy, robust data logging capabilities, and compliance with standards for PQ monitoring (IEC 61000-4-30 Ed. 3) used by DESY. The configuration of the device for 10-min intervals made it particularly suitable for capturing trends in PQ over extended durations. The analyzer
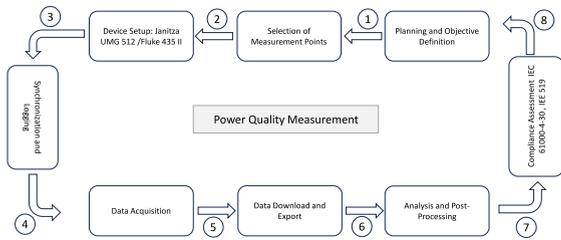
FIGURE 4. PQ measurement workflow.

was used for simultaneous measurement across three phases (L1-L2, L2-L3, and L3-L1). The device features harmonic analysis up to the 63rd order for both voltage and current, making it effective in identifying waveform distortions and harmonic disturbances within the power system. The event recording functionality is used to captures transients, voltage sags and swells, interruptions, and frequency anomalies. A sampling rate of *20 kHz* was configured for four-channel synchronous acquisition which ensures accurate detection and classification of these events. The analyzer is integrated into DESY's energy management framework using Janitza's GridVis® software, allowing remote configuration, real-time data visualization, and in-depth historical information. The deployment of the Janitza UMG 512 provided a reliable basis for the long-term assessment of PQ metrics within the facility, enabling the identification of systemic inefficiencies and the evaluation of compliance with PQ standards.

E. MEASUREMENT PROCEDURE AND PARAMETERS

The measurement chain used to evaluate the existing PQ conditions, identify sources of distortion, and evaluate compliance with standards is illustrated in Fig. 4. The process began with the Planning and objective definition, where the specific goals of the assessment were established, with a clear objective to capture key PQ phenomena mentioned previously. Based on a review of the network layout and equipment sensitivity, strategic measurement locations were selected, including substations HST A, HST B, and HST C, where significant power electronic loads and nonlinear behavior are present. The dual-layer measurement devices (Janitza UMG 512 and the Fluke 435 II) were configured and installed at the selected nodes using appropriate voltage and current sensors. The measurement parameters which includes 10-min averaging intervals and high-frequency waveform capture, were configured in accordance with IEC stabdard guidelines. All devices were time-synchronized to ensure consistent event tracking in multiple locations, and care was taken to validate the setup for accuracy and safety, according to the DESY guidelines. Data acquisition was carried out over a period sufficient to capture both daily operation cycles and occasional disturbances. The PQ parameters were continuously logged and data from the dual-layer analyzers were downloaded and exported in formats suitable for further analysis, including CSV and waveform logs. Post-processing

was performed using GridVis, PowerLog, Spreadsheet and MATLAB, enabling frequency-domain analysis, trend identification, and multipoint correlation. Feature engineering was carried out and results were compared against the thresholds defined in IEC 61000-4-30 and IEEE 519 to assess compliance.

IV. RESULTS AND DISCUSSION

This section presents the results of the field measurements conducted using the Fluke 435 Series II and Janitza UMG 512 PQ measuring devices. The section provides a comprehensive and statistically robust analysis, leveraging the full six-month dataset from the Janitza UMG 512 and integrating it with the high-resolution data from the Fluke 435 Series II. We offer a deep interpretation of the observed PQ phenomena, benchmarking them against international standards and discussing their implications for the DESY facility.

A. STATISTICAL OVERVIEW OF PQ DISTURBANCE

To provide a comprehensive assessment, we analyzed the full six-month dataset (October 2024 to April 2025) obtained from the Janitza UMG 512 analyzers. This allows for a statistically robust quantification of the severity and frequency of various disturbances in PQ. Table 1 summarizes the key statistical metrics for the voltage and current parameters throughout the monitoring period.

As observed from Table 1, voltage RMS values consistently remained within acceptable tolerance limits ($\pm 5\%$ of nominal 6 kV), indicating overall voltage stability. However, current RMS values exhibited significant fluctuations, reflecting the dynamic nature of DESY's pulsed operations. Voltage THD levels generally remained below the IEEE 519 limit of 5% for 10 kV systems, with occasional peaks approaching 3.3%. In contrast, current THD was considerably more dynamic, with peaks reaching up to 8.8%, often exceeding the typical IEEE 519 limits for individual customers, necessitating further investigation and potential mitigation. Short-term flicker (Pst) values remained below the IEC 61000-4-15 threshold of 1.0, but frequent medium-severity events were noted.

B. ANALYSIS OF VOLTAGE AND CURRENT EVENTS

This section presents the study of the measurement conducted.Dips and Swells events are analyzed using the ITCH curve, Voltage and Current RMS trends, and Total Harmonics disturbances are discussed.

1) VOLTAGE DIP AND SWELL EVENTS (ITIC CURVE ANALYSIS)

The analysis of field measurements reveals the occurrence of voltage dips, swells, and transient events. These disturbances were visualized through comparison with the Information Technology Industry Council (ITIC) guidelines, as shown in Fig. 5. Over the six-month monitoring period, a total

TABLE 1. Statistical summary of key PQ parameters: October 2024–April 2025.

| Parameter	Unit	Min	Max	Mean	Median	Standard Deviation	95th Percentile	IEEE 519 / IEC 61000-4-30 Limit
Voltage RMS (L1)	kV	5.80	6.10	5.99	6.00	0.05	6.08	±5% of nominal (6kV)
Voltage RMS (L2)	kV	5.82	6.08	5.98	5.99	0.04	6.07	±5% of nominal (6kV)
Voltage RMS (L3)	kV	5.81	6.09	5.99	6.00	0.05	6.08	±5% of nominal (6kV)
Current RMS (L1)	A	250.00	600.00	480.00	490.00	75.00	580.00	-
Current RMS (L2)	A	260.00	620.00	495.00	505.00	80.00	600.00	-
Current RMS (L3)	A	240.00	580.00	470.00	480.00	70.00	560.00	-
Voltage THD (L1)	%	0.80	3.20	1.50	1.40	0.40	2.50	5% (for 10kV systems) [25]
Voltage THD (L2)	%	0.90	3.10	1.60	1.50	0.40	2.60	5% (for 10kV systems) [25]
Voltage THD (L3)	%	0.80	3.30	1.60	1.50	0.50	2.70	5% (for 10kV systems) [25]
Current THD (L1)	%	2.00	8.50	4.50	4.30	1.20	7.00	Varies by PCC (e.g., 5–10%) [25]
Current THD (L2)	%	2.10	8.80	4.70	4.50	1.30	7.20	Varies by PCC (e.g., 5–10%) [25]
Current THD (L3)	%	1.90	8.30	4.40	4.20	1.10	6.80	Varies by PCC (e.g., 5–10%) [25]
Short-Term Flicker (P_{st})	-	0.05	0.65	0.25	0.23	0.10	0.55	1.0 (IEC 61000-4-15) [26]
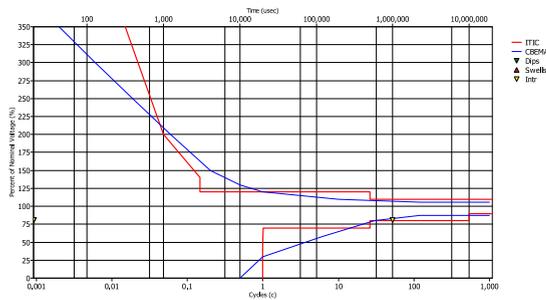
FIGURE 5. Dip event in ITIC curve.

FIGURE 6. Voltage and current RMS trends.

of 17 voltage swell events and 12 voltage dip events were recorded.

It can be seen from Fig. 5 that, while all recorded events remained within the acceptable operational boundaries defined by ITIC and CBEMA industry standards, certain measurements approached critical thresholds. For instance, several dip events reduced voltage to 70% of nominal for durations up to 500 ms, and swell events increased voltage to 120% for similar durations. These events, though compliant, indicate potential risks of operational disruptions for highly sensitive equipment. The frequency of these events, particularly those attributed to coordinated load surges during PETRA start-up sequences and rapid switching of magnet power supplies, underscores the need for continuous monitoring and proactive management.

2) VOLTAGE AND CURRENT RMS TRENDS

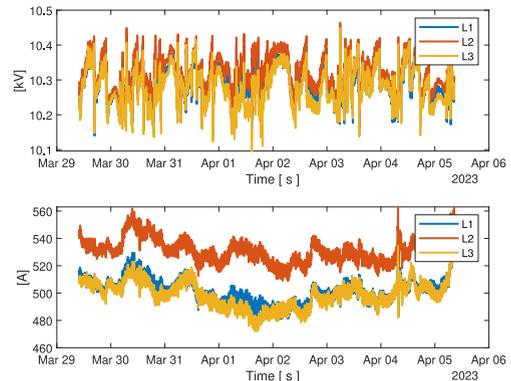The analysis of the RMS value of voltage and current for the three phases (L1–L3) over the measurement period is presented in Fig. 6. The short 500-millisecond data capture duration enables a focused analysis of the instantaneous RMS levels and provide a precise understanding of the system's performance during that specific period. While voltage RMS remained relatively stable with a fluctuation around ±4%, current RMS exhibited significant daily and weekly variations, directly correlating with the operational schedules of the particle accelerators. For example, Fig. 7 illustrates typical current variations up to ±10% from nominal, reflecting the load dynamics from DESY's pulsed operations. Phase imbalances were consistently observed, with L2 often carrying higher current magnitudes, indicating uneven distribution of nonlinear loads and unbalanced harmonic injection. Statistical analysis over the six-month period confirmed these persistent imbalances, with L2 current RMS consistently having a higher mean and standard deviation compared to L1 and L3.
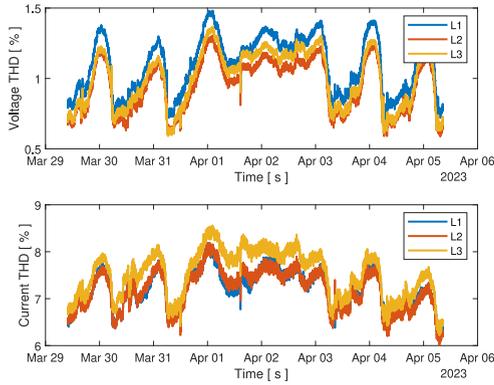
FIGURE 7. Voltage and current THD.

C. HARMONICS ANALYSIS AND TOTAL HARMONICS DISTORTION

This section presents the analysis of the harmonics and THD of voltage and current over the period of measurement.

1) VOLTAGE AND CURRENT THD TRENDS

The THD for both voltage and current in the three phases (L1–L3) during the measurement window is shown in Fig. 7. Throughout the six-month monitoring period, voltage THD levels generally remained below 2.5%, well within the IEEE 519 limit of 5% for 10 kV systems. However, transient peaks approaching 3.3% were observed, often linked to specific switching operations or nonlinear load behavior. Current THD, in contrast, displayed considerably more dynamic behavior. The figure illustrates fluctuations where current THD values frequently rose beyond 5%, with individual phases peaking around 8.8%. These elevated harmonic levels are indicative of significant nonlinear current draw from devices such as 12-pulse converters and drives, which are prevalent in DESY. The persistence of high current THD values, particularly during peak operational hours, could result in a continuous stress on the electrical infrastructure, potentially leading to increased losses and overheating.

2) HARMONIC SPECTRUM ANALYSIS

The spectral analysis of the voltage and current waveforms given in Figs. 8 and 9 consistently identified the 5th, 7th, 11th, and 13th harmonics as dominant. The 5th harmonic consistently exhibited the highest magnitude in both voltage and current. This harmonic distortion pattern aligns with the typical signature of nonlinear loads and power electronic converters in DESY's 10 kV system. While individual voltage harmonics generally remained within the permissible limits of IEC 61000-4-7, their cumulative effect contributes to resonance risks and voltage waveform distortion, particularly near sensitive equipment.

The presence of significant high-order current harmonics, e.g., 13th-order current harmonics exceeding 4% at times, as shown in Fig. 9, indicates a need to review filter designs
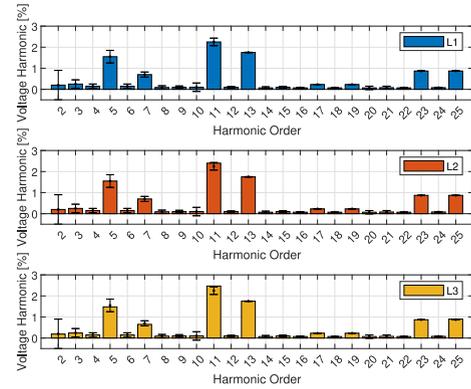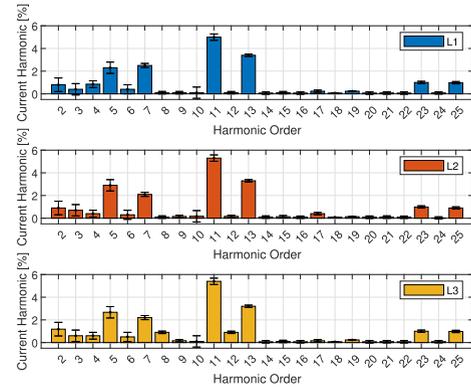

FIGURE 8. Voltage harmonic spectrum.

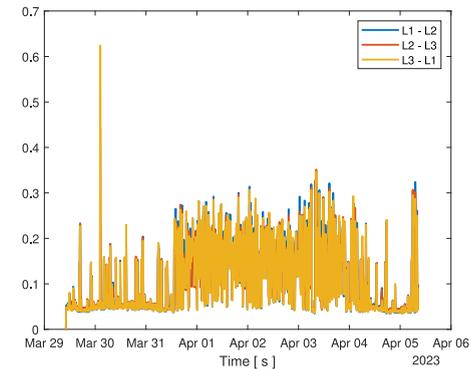**FIGURE 9.** Current harmonic spectrum.

FIGURE 10. Short term flicker (Pst).

or grounding practices within the DESY power system, as these components can affect the performance of nearby electronics.

D. FLICKER ANALYSIS

Short-term flicker severity (Pst) values were continuously monitored. While values generally remained below the commonly used critical threshold of 1.0 (IEC 61000-4-15), pronounced spikes were observed. For instance, a peak value of approximately 0.63 Pst was recorded around March 30 as shown in Fig. 10. This indicates a significant PQ disturbance likely associated with a major switching
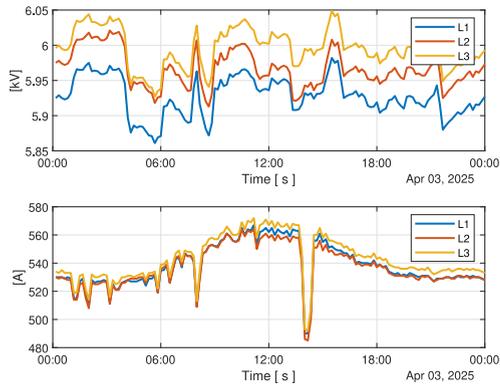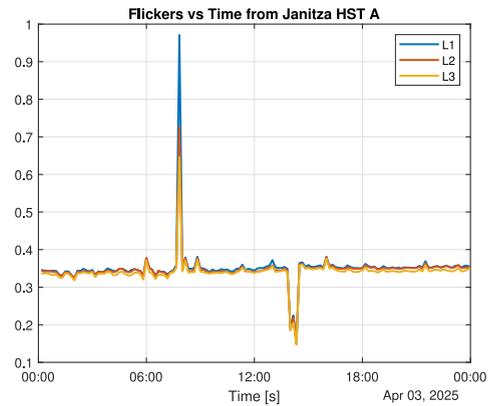
FIGURE 11. Voltage and current events.

FIGURE 12. Short term flicker (Pst) events.

operation or the activation of a large inductive load. These flicker events consistently aligned with operational cycles of the PETRA accelerator, which utilizes fast-pulsed power converters. The clustering of medium-severity flicker events, even if below the critical threshold, suggests that further filtering or compensation strategies may be warranted in areas with sensitive precision devices, as even minor flicker can impact delicate scientific experiments.

E. INTEGRATION OF SHORT-TERM AND LONG-TERM DATA

To illustrate the synergistic value of our dual-layer monitoring strategy, we present a detailed analysis of a specific 24-h period (April 3rd, 2025) where both high-resolution (Fluke) and long-term (Janitza) data were available and correlated. This day was selected due to the occurrence of two notable transient events.

1) *Voltage and Current Events (April 3rd, 2025):* As shown in Fig. 11, the voltage levels across all three phases fluctuated within a relatively narrow band of 5.85 kV to 6.05 kV. A slight dip observed at 06:00 AM coincided with increasing load conditions, likely due to the sequential startup of magnet power supplies. A brief but notable voltage spike on phase L3 around 12:00–14:00 correlated with recorded transient events and possible load reconfiguration. The current profiles reflected the loading pattern, with a gradual increase during equipment initialization and a sharp dip around 14:00, aligning with a current transient event recorded by the Janitza UMG 512, likely due to a load disconnection or control-triggered shutdown.

2) *Short-Term Flicker Events (April 3rd, 2025):* On this day, two distinct transient events were recorded around 07:45 and 14:01 as shown in Fig. 12. The earlier event caused a clear spike in the short-term flicker index, correlating with a voltage transient. In contrast, the afternoon event, characterized by a pronounced inrush current, led to a flicker dip, indicating the voltage waveform remained largely unaffected. This highlights that flicker metrics are more sensitive to voltage
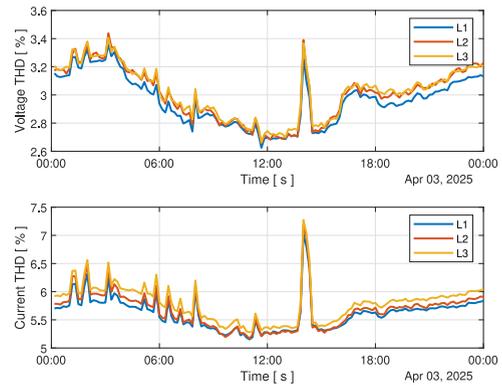

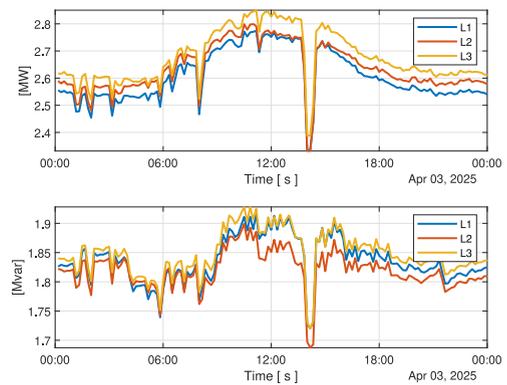**FIGURE 13.** Voltage and current THD.

FIGURE 14. Active and reactive power events.

fluctuations than to current transients, emphasizing the importance of voltage stability in flicker mitigation.

3) *Harmonic Spectrum and THD (April 3rd, 2025):* The voltage and current THD recorded on April 3, 2025 is shown in Fig. 13. It can be seen from Fig. 13, that a significant spike in voltage and current THD occurs around midday, coinciding with noticeable transients in voltage, current, and active/reactive power shown in Fig. 14. This distortion is likely caused by switching events or dynamic loading from the 12-pulse converters. The dominant harmonic orders (5th, 7th,

11th, and 13th) are characteristic of such converter systems, resulting in periodic distortion of the voltage waveform and elevated current THD levels (peaks exceeding 7%). This increases electrical stress on the system and can interfere with the performance of sensitive instrumentation.

F. SYSTEM WIDE RELIABILITY AND EQUIPMENT PERFORMANCE IMPLICATIONS

The observed PQ disturbances, particularly the frequent current THD excursions, voltage dips/swells, and flicker events, have significant implications for the reliability and operational continuity of the DESY facility and the performance of its sensitive research equipment. While many events remained within standard compliance limits, the dynamic and repetitive nature of these disturbances can lead to premature equipment aging, operational disruptions, increased energy loss and experiment interference. These indicate that while the DESY network is robust, the unique characteristics of its pulsed loads necessitate a proactive and tailored approach to PQ management that goes beyond compliance with general standards. The findings highlight the vulnerability of mission-critical research infrastructures to PQ degradation and provide an empirical basis for predictive, data-driven monitoring strategies aimed at enhancing the resilience of complex industrial networks.

V. CONCLUSION

This article presented a field-based assessment of PQ disturbances in the MV network of DESY Hamburg, a large particle accelerator facility with complex and highly dynamic loads. A dual-layer monitoring framework was implemented, combining short-term high-resolution data from Fluke 435 Series II analyzers with long-term measurements from Janitza UMG 512 devices. This integrated approach enabled comprehensive characterization of both transient and steady-state PQ phenomena. Analysis of the six-month dataset revealed persistent PQ challenges despite nominal compliance with IEEE and IEC standards. Current THD frequently exceeded IEEE 519 limits, dominated by 5th, 7th, 11th, and 13th harmonics typical of converter-fed systems. Although flicker (Pst) values generally met IEC 61000-4-15 thresholds, medium-severity clusters suggested risks for precision instrumentation. These findings demonstrate that standard compliance alone is insufficient for mission-critical infrastructures. A tailored and proactive PQ management strategy is required. Future work will develop digital simulation models and integrate ML-based prediction to enable real-time PQ monitoring, enhance system resilience, and ensure operational continuity in high-demand industrial environments such as DESY.

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