NEWS REGARDING THE ELECTRICAL POWER QUALITY MONITORING IN THE ELECTRICAL TRANSMISSION GRID

NOUTĂȚI PRIVIND MONITORIZAREA CALITĂȚII ENERGIEI ELECTRICE ÎN REȚEAUA ELECTRICĂ DE TRANSPORT

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Abstract: *Electrical Power Quality Monitoring is essential for the reliable operation of the electrical transmission grid. This paper presents the modernization of the power quality monitoring system in Romania's transmission network, focusing on the transition to the new Power Quality Monitoring System implemented by Transelectrica in 2024 in collaboration with EnergoBit. This system expands the monitoring of power quality parameters throughout the entire transmission grid and introduces advanced ION9000 power quality analyzers to replace the outdated equipment. These next-generation analyzers offer superior measurement accuracy, the ability to capture ultra-short transient events, and full compliance with the latest power quality standards, enabling more comprehensive and precise monitoring. The paper also outlines the architecture of the new system, which uses a virtualized and redundant software platform for data acquisition and management, ensuring high availability and secure access to information. This modernization supports the reporting of performance indicators for the operation of the transmission grid and reporting to the Romanian Energy Regulatory Authority. Additionally, it reduces maintenance costs and increases system reliability.*

Keywords: Power quality, Remote monitoring, Power system measurements, Network security, Data analysis

Rezumat: *Monitorizarea calității energiei electrice este esențială pentru funcționarea fiabilă a rețelei electrice de transport. Lucrarea de față prezintă*

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modernizarea sistemului de monitorizare a calității energiei electrice din rețeaua de transport din România, concentrându-se pe tranziția la noul Power Quality Monitoring System implementat de Transelectrica în 2024, în colaborare cu EnergoBit. Acesta extinde supravegherea parametrilor de calitate pe întregul sistem de transport și introduce analizoare avansate de calitatea energiei electrice modelul ION9000 în locul echipamentelor vechi. Aceste analizoare de ultimă generație oferă o precizie superioară a măsurării, capacitatea de a înregistra evenimente tranzitorii de foarte scurtă durată și asigură conformitatea cu cele mai recente standarde de calitate a energiei, permițând o monitorizare mai cuprinzătoare și mai precisă. Lucrarea prezintă, de asemenea, arhitectura noului sistem, care utilizează o platformă software virtualizată și redundantă pentru achiziția și gestionarea datelor, garantând o disponibilitate ridicată și acces securizat la informații. Această modernizare contribuie la raportarea indicatorilor de performanță privind funcționarea rețelei electrice de transport și raportarea către Autoritatea Națională de Reglementare a Energiei. Totodată, reduce costurile de mentenanță și sporește fiabilitatea sistemului.

Cuvinte cheie: Calitatea energiei electrice, Monitorizare la distanță, Sistem de masurare, Securitatea rețelei, Analiza datelor

1. Introduction

Electrical power quality monitoring systems have a significant technical and economic importance for the proper operation of the national power system. CNTEE Transelectrica SA monitors power quality (PQ) parameters, complying with the requirements of the "Technical Code for the Electric Transmission Grid", "Performance Standard for Electric Transmission and System Services", and Technical Connection Notices, and periodically reports the compliance with allowable limits to the National Energy Regulatory Authority. Transelectrica reports the performance indicators of the operation of the Electrical Transmission Grid - RET to the Romanian Energy Regulatory Authority (ANRE). [1, 2, 3]

In recent years, rapid technological advancements have occurred in the Information Technology (IT) sector and the legislation related to measuring and monitoring electrical power quality, both in Romanian and at international level, has been updated since 2010, when the current system was acquired. Electrical PQ measurement is regulated by standard IEC 61000-4-30 "Testing and measurement techniques - Power quality measurement methods", and monitoring of PQ parameters is performed according to standard EN 50160, "Voltage characteristics supplied by public distribution networks". [4, 5]

Thus, Transelectrica initiated the replacement of the current electrical power quality monitoring system and existing power quality analyzers through a contract signed with SC EnergoBit SA in 2024, for the implementation of a new "Power Quality Monitoring System (PQMS)".

The new system aims to achieve the following objectives:

- To extend power quality monitoring across the entire transmission grid;
- To reduce the replacement or installation time for new analyzers compared to the scenario where these would be installed gradually, through refurbishment or modernization projects of the company's transformer substations;
- To reduce maintenance service costs related to the new system, estimated to be lower if a post-warranty maintenance contract is concluded with the contractor implementing the new system.

The implementation of the new system aims to achieve the following objectives:

- To expand the power quality monitoring across the entire National Transmission Grid (RET);
- To reduce of the time required to replace or install new analyzers;
- To decrease in the maintenance service costs associated with the legacy system;
- To upgrade to the latest versions of applicable power quality standards.

The new system will provide the following functionalities for the National Center for Electric Energy (CENEL) monitoring infrastructure (applications/modules/software functions):

- Import of data recorded by CENEL analyzers;
- Storage of recorded data;
- Reporting and aggregation of data;
- Publishing of data for system users;
- Secure access to data for both users and administrators;
- Protection and security of the recorded data. [6,7]

2. The architecture of the new PQMS

The new system will be developed to ensure redundancy principles, high availability, and operational safety for both the system and the communication network. The architectural solution requires a virtual model, creating virtual clusters, where services run automatically on the node with available resources, and replication can be ensured at the hypervisor or centralized storage system level.

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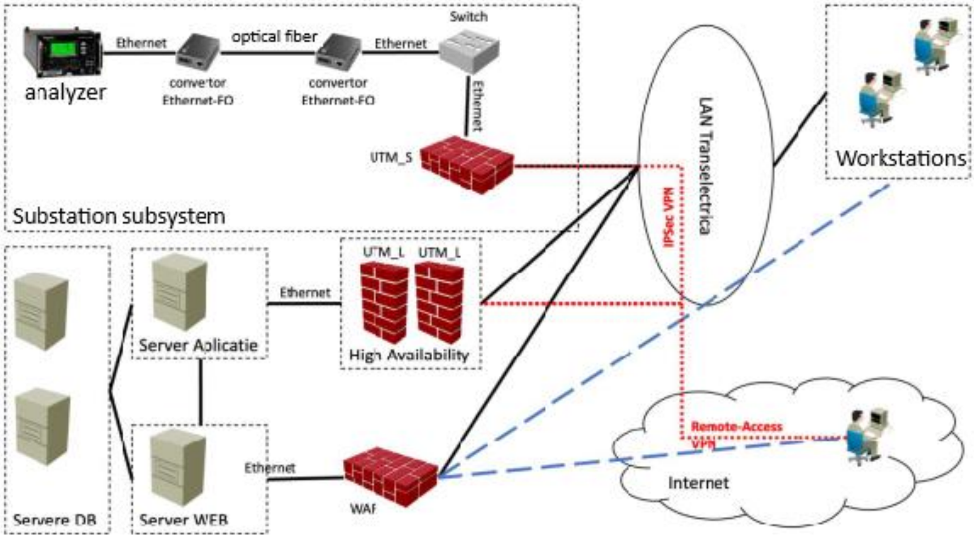

Fig. 1 Information security layers of the PQMS.

The IT platform is based on a hardware infrastructure integrated into two rack cabinets, with a rack-chassis configuration designed to ensure system redundancy and independent operation when required. The rack cabinet structure along with general specifications is presented in Figure 1.

For each component, minimum technical specifications have been calculated as follows:

– A minimum of 3 servers per rack is needed to ensure redundancy in the proposed cluster, providing continued functionality even if one server becomes non-operational. Using only two servers would risk encountering a split-brain scenario;

– The proposed number of cores is at least 40, calculated based on a current baseline of 12 cores/server (minimum), plus additional cores required by the new PQMS application (an additional 12 cores), along with reserve capacity for unforeseen situations;

– The system requires at least 768 GB of RAM, calculated based on a current baseline of 256GB/server, plus additional RAM required by the new PQMS application (128GB), along with reserve capacity for unforeseen situations;

– Storage capacity: Initial requirements specify 300 analyzers x 300GB per analyzer = 90TB. Thus, the storage was sized at 120TB usable space, including reserve space: (2.4 x 100 disks = 240TB raw in RAID10 → 120TB usable).

All application servers will run in a virtual environment. Database servers will also run on physical servers. The testing system consists of a single server acting as a hypervisor (virtualization host), connected to the rack cabinet 1 both for data (ToR switches) and management (management switch). This server will run virtual machines similar to those in the production cluster, allowing various operations to be tested before they are deployed for operator use. For the storage, the test system will use the server's internal disks, sufficient for testing operations.

The applications and provided services will be encapsulated in virtual machines of necessary sizes, and all three servers/cabinets will have identical roles, functioning as hypervisors capable of running the virtual machines containing these services. Required services (application, database, web) will run as virtual machines across the two clusters in the two racks.

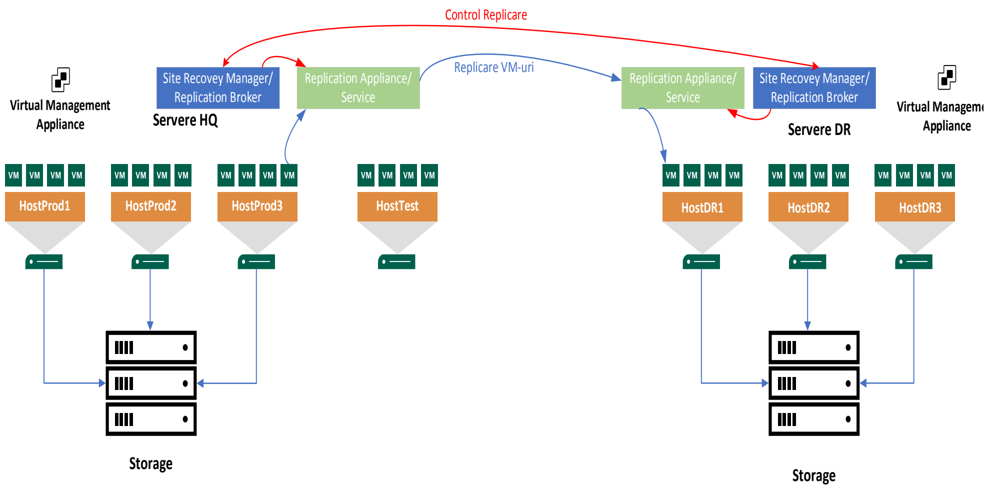

Fig. 2 Redundant virtualized PQMS infrastructure for production and disaster recovery sites

Energobit will implement a virtual infrastructure to support application servers, consisting of a cluster of three host servers with shared storage in each site.

Two identical sites will be implemented, designated for production and respectively disaster recovery (DR) roles, with synchronous or asynchronous replication of virtual machines application between them.

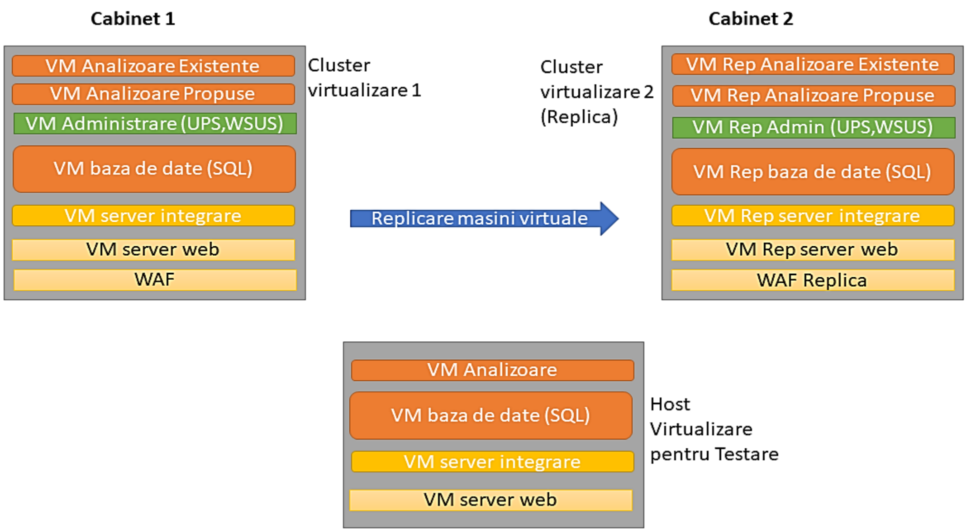

Fig. 3 Virtual machine diagram

There will be a minimum of 7 virtual machines on each cluster, as illustrated in Figure 3, structured as follows:

1. Virtual machine for existing analyzers;
2. Virtual machine for ION 9000 analyzers;
3. Virtual machine for infrastructure management (as UPS, WSUS);
4. Virtual machine for the database;
5. Virtual machine for integration server;
6. Virtual machine for web services;
7. Virtual machine for WAF. [8]

Figure 4 displays a detailed waveform report generated by Power Monitoring Expert (PME) 2024 for a 110 kV node, capturing both instantaneous and RMS voltage values across all three phases. The upper graph illustrates sinusoidal voltage waveforms (V1, V2, V3) with balanced amplitude near ±100,000 V and uniform frequency, demonstrating a 120° phase displacement indicative of stable nominal operation.

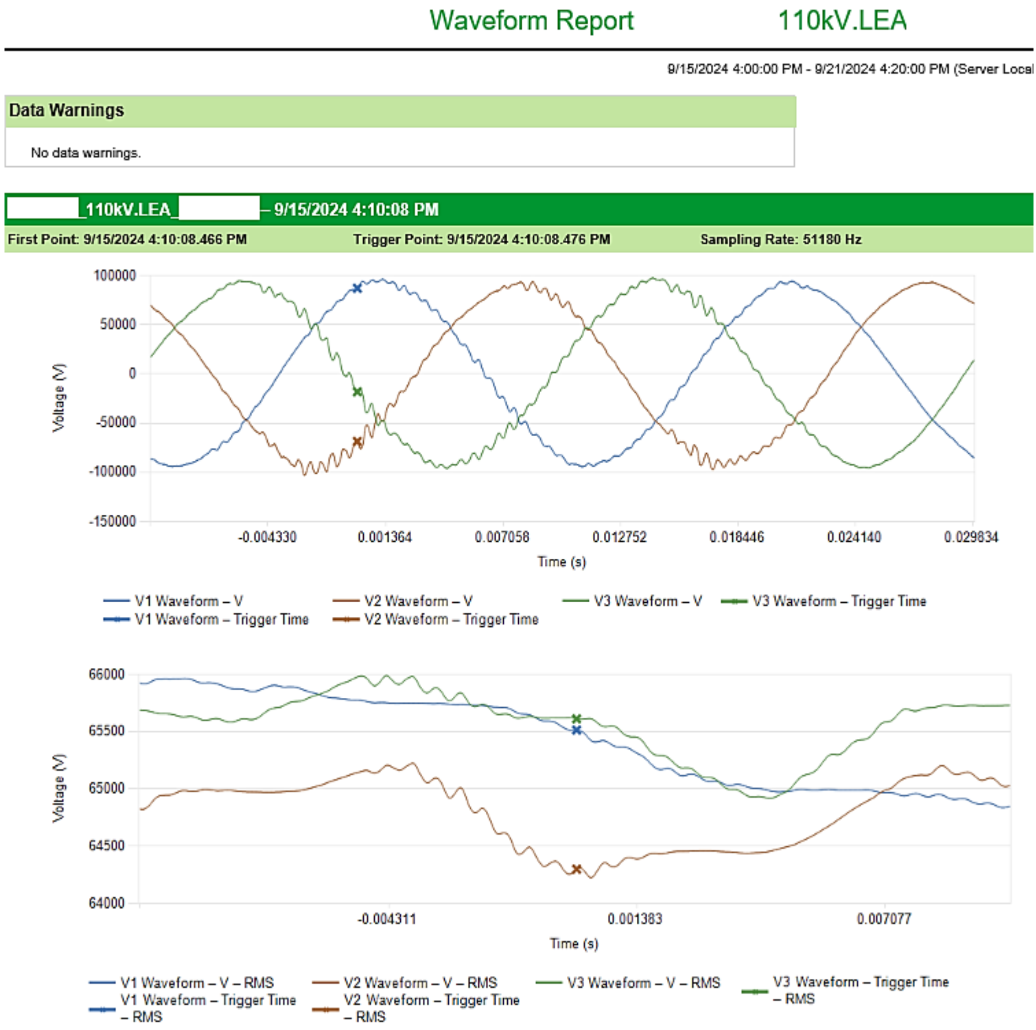

Fig. 4. Three-phase PQ assessment via PME 2024: waveforms and flicker.

The phase voltages are well-aligned, confirming appropriate synchronization and system symmetry. The sampling rate of 51180 Hz ensures high temporal resolution, enabling accurate detection of waveform anomalies. In the lower graph, RMS voltage values ranging between 64 kV and 66 kV are shown over a short observation window. A slight downward fluctuation is observed in phase V2, while phases V1 and V3 remain relatively steady. Trigger markers indicate the precise moment of waveform capture. These variations may reflect localized disturbances or dynamic load behavior. As no data warnings are flagged, the system is compliant with operational standards. Overall, both waveform integrity and RMS stability confirm normal power quality, characteristic of a well-regulated high-voltage transmission environment. [9]

3. The new PQ analyzer

As part of the PQMS upgrade, the newly deployed power quality analyzer across the grid is a next-generation device that replaces the earlier models. This advanced instrument now serves as the core field component at each monitoring point, offering high-precision measurements in accordance with Class 0.1S standards and incorporating a wide range of enhanced functionalities. Among its most notable capabilities are high-speed transient capture, which enables detection of events as short as 100 nanoseconds, and disturbance direction detection - features that were absent in previous generations. Fully compliant with the latest international Class A standards for power quality (IEC 62586 and IEC 61000-4-30), the device can automatically generate standardized compliance reports, thereby streamlining regulatory analysis. By integrating this state-of-the-art analyzer into the PQMS platform, Transelectrica significantly improves the accuracy, diagnostic depth, and overall reliability of power quality monitoring throughout the national transmission network. [10,11]

3.1 . Key Enhancements of the ION9000 Over the ION7650

The new generation of power quality analyzers introduces substantial improvements over its predecessor, offering advancements in accuracy, functionality, and compliance. Certified for Class 0.1S active energy measurement according to IEC 62053-22 and ANSI C12.20, it surpasses the older model’s Class 0.2S certification, while also ensuring Class 0.5S accuracy for reactive energy. This leap in precision positions the newer model as a reference standard in the industry.

One of the most significant additions is the High-Speed Transient Capture (HSTC) capability, available in the 9000T variant, which enables detection of disturbances down to 100 nanoseconds and up to 10 MHz, a considerable improvement compared to the previous device’s threshold of approximately 17 microseconds. This allows for the identification of extremely fast transients that were previously undetectable.

Moreover, the system now includes an innovative disturbance direction detection feature, capable of identifying whether an event - such as a sag, swell, or transient - originated upstream or downstream from the monitoring point. This functionality greatly simplifies troubleshooting efforts and was not present in the earlier series.

The device complies with the latest international standards, being classified as a Class A instrument under IEC 62586-1/-2 and IEC 61000-4-30 Ed.3, and can autonomously generate compliance reports. In contrast, the older analyzer only monitored relevant parameters, requiring external tools for full analysis.

From a cybersecurity standpoint, the new model incorporates state-of-the-art protections including HTTPS and SFTP encrypted communications, Syslog integration for event logging, as well as granular control over communication ports and protocols. These enhancements provide a robust defense compared to the limited password protection available in the earlier generation.

The underlying programmable ION™ architecture is preserved, but it now benefits from increased memory and processing resources. This enables advanced customization of control logic, data aggregation from downstream devices, complex calculations, and user-defined web interfaces. Such capabilities ensure long-term scalability and adaptability in dynamic energy environments.

An additional noteworthy improvement is the tamper-evident sealing system, featuring sealable terminal covers and a metrology lock to ensure measurement integrity and regulatory compliance. Installation flexibility has also been enhanced through a modular display system, offering either a 192 mm touchscreen or a 96 mm color display, both of which support panel, DIN-rail, or remote mounting via CAT5 cable up to 100 meters. These features collectively reinforce the device's status as a secure, adaptable, and future-ready solution for PQ monitoring. [12, 13]

Figure 5 illustrates the projected expansion of PQMS across Romania's eight regional transmission centers between 2024 and the system's planned commissioning date (PIF) in 2027. The bar chart distinguishes two data series: baseline installations completed in 2024 (light-blue bars) and the total number of PQMS units envisaged for full operational deployment in 2027 (dark-blue bars). All regions exhibit substantial growth, with Constanța, București, and Timișoara showing the most pronounced increases - rising from 36 to 53, 21 to 44, and 19 to 37 units, respectively. The aggregate column (TOTAL) highlights a network-wide escalation from 134 installed units in 2024 to 243 units forecast for 2027, representing an overall capacity increase of approximately 81 %. This upward trajectory underscores Transelectrica's strategic commitment to achieving comprehensive, nationwide coverage of PQ monitoring within the specified three-year timeframe and reflects the integration of ION9000 analyzers as the standard field instrument throughout the transmission grid.

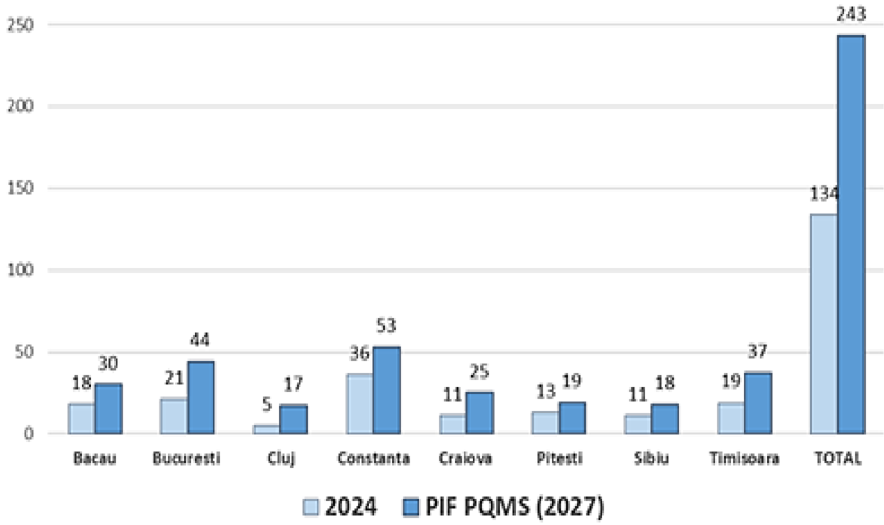

Fig. 5. Regional PQMS rollout and ION9000 implementation timeline.

3.2. Theory of operation

The following section presents the fundamental formulas implemented in the ION9000 power quality analyser, according with technical documentation detailing the capabilities and compliance features of the ION type power quality analyzer [14]:

A. True RMS Measurements

The following values are calculated by the Power Meter modules.

$$V_{\alpha}[V] = \sqrt{\frac{\sum_{k=1}^{N}(V_k^2)}{N}} \quad (1)$$

$$I_{\alpha}[A] = \sqrt{\frac{\sum_{k=1}^{N}(I_k^2)}{N}} \quad (2)$$

Table 1. **Explanation of the parameters used for true RMS measurements**

Term	Definition
V_α and I_α	Per-phase RMS quantities
V_k and I_k	Sampled voltage and current
N	Number of samples in the period of measurement

B. Total Harmonic Distortion (THD)

The following values are calculated in two places: the Harmonics Measurement module where Vn and In are based on FFT over 8 cycles, once per second, and the Harmonics Analyzer module where Vn and In are based on FFT over 1 cycle, every 2 seconds.

$$THD_{V\alpha}[\%] = \frac{\sqrt{\sum_{n=2}^{M}(V_n^2)}}{V_{!}} \times 100\% \tag{3}$$

$$THD_{I\alpha}[\%] = \frac{\sqrt{\sum_{n=2}^{M}(I_n^2)}}{I_{!}} \times 100\% \tag{4}$$

Table 2. **Explanation of the parameters used for total harmonic distortion**

Term	Definition
$THD_{V\alpha}$ *and* $THD_{I\alpha}$	Per-phase total harmonic distortion
V_n and I_n	Magnitudes of the n^{th} harmonic
V_1 and I_1	Magnitudes of the fundamental
M	Highest order harmonic calculated $(63^{rd})^*$

C. Unbalance

1. The following equation is used by the Power Meter module output.

$$V_{unbal}[\%] = \frac{largest\ deviation\ from\ V_{avg}}{V_{avg}} \times 100\% \tag{5}$$

$$I_{unbal}[\%] = \frac{largest\ deviation\ from\ I_{avg}}{I_{avg}} \times 100\% \tag{6}$$

2. The following equation is used by an Arithmetic module.

$$PQV_{unbal}[\%] = \frac{NPS}{PPS} \times 100\% \quad (7)$$

$$PQI_{unbal}[\%] = \frac{NPS}{PPS} \times 100\% \quad (8)$$

Table 3. **Explanation of the parameters used for unbalace**

Term	Definition
PPS	Positive Phase Sequence Magnitude for voltage or current
NPS	Negative Phase Sequence Magnitude for voltage or current
PQV_{unbal}	Negative Sequence Voltage Unbalance Factor
PQI_{unbal}	Negative Sequence Current Unbalance Factor

3. Symmetrical Components

$$PPS = \left|\frac{\bar{V}_{10} + (\bar{V}_2\angle + 120^{\circ}) + (\bar{V}_3\angle - 120^{\circ})}{3}\right| \quad (9)$$

$$NPS = \left|\frac{\bar{V}_{10} + (\bar{V}_2\angle - 120^{\circ}) + (\bar{V}_3\angle + 120^{\circ})}{3}\right| \quad (10)$$

$$ZPS = \left|\frac{\bar{V}_{10} + \bar{V}_{20} + \bar{V}_{30}}{3}\right| \quad (11)$$

Table 4. **Explanation of the parameters used for symmetrical components**

Term	Definition
PPS	Positive Phase Sequence Magnitude for voltage or current
NPS	Negative Phase Sequence Magnitude for voltage or current
ZPS	Zero Phase Sequence Magnitude for voltage or current
$\bar{\boldsymbol{V}}_1, \bar{\boldsymbol{V}}_2, \bar{\boldsymbol{V}}_3$	Vectors of the fundamental signal component
a	1∠120°
a^2	1∠240°

4. The Cyber Security requirements

To ensure the protection of PQMS against cyber threats, a comprehensive framework consisting of policies, concepts, technologies, and specialized equipment will be implemented. This cybersecurity strategy aims to minimize the risk of cyberattacks and reduce the vulnerability of the system, aligning fully with established international standards and organizational practices.

One of the primary focuses is to secure access during all bidirectional data transfers within the system. The publication of data on the internet or through web-based applications will be protected through secure communication channels and access controls. Communication between substations and the central control point will be encrypted and safeguarded using Virtual Private Network (VPN) technologies to ensure data confidentiality and integrity across distributed components.

To reinforce user identity verification, Multi-Factor Authentication (MFA) will be enforced throughout the platform. This mechanism will require users to authenticate using multiple factors, such as a combination of credentials and a security token. An intrusion detection strategy will also be implemented, with real-time alerts and notifications being sent to network administrators via alarms, SMS, or dashboard messages whenever suspicious activity or malware presence is detected.

The system will adhere strictly to the PQMS Security Concept, maintaining all required controls and applying specific security measures as defined. Access Control policies will be implemented in accordance with the guidelines of the Wholesale Energy Metering Operator (OMEPA), ensuring that access to sensitive areas of the system is restricted and clearly defined. In addition, continuous system monitoring will be conducted based on the formally agreed Monitoring Policy, helping to identify anomalies and performance issues as they arise.

Configuration Change Management procedures will be established to ensure that all modifications to the system are planned, authorized, and documented, minimizing the risk of unintended vulnerabilities. Malware protection mechanisms, including antivirus software with application whitelisting, will be deployed to prevent unauthorized or malicious software from executing on the system. These solutions will be configured in line with network requirements and kept updated with the latest security patches.

To ensure the resilience and availability of the PQMS platform, protection of data and infrastructure across the network will be prioritized.

Regular reviews of implemented security controls will be conducted to maintain their effectiveness over time. When threats are identified, they will be isolated swiftly to limit potential damage. Technical and procedural methods will be used to resolve vulnerabilities, followed by restoration and recovery operations designed to re-establish full system functionality. This will include the preparation of maintenance and recovery plans for all system components.

The integrity of data acquired, stored, validated, aggregated, and reported by the PQMS will be safeguarded rigorously throughout its lifecycle. Patching procedures will be applied regularly to address software or hardware-related issues and prevent exploitation of known vulnerabilities. Redundancy will be integrated into the system architecture so that no single point of failure whether caused by malfunction or maintenance can compromise the continuity of the entire IT infrastructure.

Operational continuity will also be ensured during maintenance, system updates, replacements, expansions, and commissioning. Contractors involved in such tasks will be provided with full technical documentation, including application source codes, and must obtain prior written authorization from OMEPA before commencing any scheduled work. This process guarantees that cybersecurity remains uncompromised even during structural or functional changes to the system.

To support the overall security posture, cybersecurity roles and responsibilities will be clearly defined for both system administrators and end users. Personnel will receive appropriate training tailored to their duties to ensure that all security procedures are followed correctly. Additionally, periodic cybersecurity audits will be conducted by certified professionals to validate compliance with internal and external security requirements.

The PQMS will maintain a secure operating environment by performing regular updates to vulnerable systems and applying configuration adjustments as needed. Antivirus solutions will be installed and maintained to reflect the specific needs of the PQMS network, with updates and patches applied systematically to keep the software effective against evolving threats.

The new PQMS system will implement its cybersecurity architecture through the deployment of four Unified Threat Management (UTM) devices installed in a redundant configuration at the central control point - two in each rack - and one UTM device installed at each of CNTEE Transelectrica's transformer substations. Communication will be conducted predominantly through fiber optic links, offering both speed and enhanced security.

Finally, to support the integrity and adaptability of this cybersecurity environment, firewall policies and configurations will be defined and periodically reviewed to ensure their continued relevance and alignment with the latest cyber risk landscape. These combined measures will ensure that the PQMS remains a robust and secure system, capable of withstanding the dynamic and evolving challenges of the modern cybersecurity environment. [6, 15]

5. Conclusions

The new PQMS introduces significant advancements across all architectural levels: measurement points equipped with state-of-the-art analyzers, robust LAN and WAN data communication infrastructure, a modernized central OMEPA node with updated hardware and software, and an enhanced user interface for data access and visualization. The entire monitoring ecosystem will be upgraded with next-generation devices, providing a comprehensive modernization of CNTEE Transelectrica's power quality infrastructure.

The IT platform will be fully redundant, encompassing data acquisition, processing, import/export, and publication subsystems, alongside resilient communication channels and operational spaces. The system architecture is designed for high availability, ensuring immediate failover in case of component malfunction and continuous operational integrity.

Moreover, the PQMS software will be tailored to meet the beneficiary's specific requirements, offering real-time monitoring, data acquisition, advanced analytics, and customizable reporting. Maintenance costs will be eliminated during the 3-year warranty period, followed by a 6-year service contract.

To ensure cybersecurity, a complete suite of policies, technologies, and equipment will be deployed, minimizing exposure to threats and ensuring compliance with modern information security standards.

Following the commissioning and operation of the new system, further work will be carried out to analyze the performance and results obtained in the field. A subsequent publication will present and interpret the collected data, offering insights into the effectiveness and reliability of the upgraded PQMS within the national transmission network.

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