Analysis of Power Quality in Industrial Environments Using Synchronous Machines: A Case Study

George-Andrei Marin[a] and Marian Gaiceanu[b]

Department of Electrical Engineering and Energy Conversion Systems, Faculty of Automation, Computers, Electrical and Electronics Engineering, "Dunarea de Jos" University of Galati, Romania

Keywords: Power Quality, Synchronous Machine, Power Factor, Reactive Power, PQ Monitoring.

Abstract: This paper investigates the impact of synchronous machines on power quality in industrial environments. Synchronous machines, widely used in high-power applications, can improve various power quality issues such as reactive power imbalance, low power factor, and harmonic distortion. This study is focused on the power quality analysis in a heavy steel industry. As a solution to power quality issues analyses on the 4.2 MW/10 kV synchronous motor operation in a hot strip rolling mill is performed, under variable load conditions. The main necessary waveforms have been captured over several days, including voltage, current waveforms, power factor variations, and reactive power levels. To assess total harmonic distortion (THD), power factor performance, and overall power quality, the collected data has been analyzed. In order to maintain power quality within acceptable limits, the experimental obtained results show that the reactive power compensation and power factor correction acts as key points. The paper highlights the need for continuous monitoring and intelligent control strategies in facilities operating with synchronous machines. This case study serves as a practical example of how industrial systems can assess and mitigate the adverse effects of power quality disturbances.

1 INTRODUCTION

Power quality (PQ) is a critical issue in modern electrical engineering, particularly in industrial environments where large power demands, complex machinery, and continuous processes impose significant challenges on electrical infrastructure. Power quality (PQ) refers to maintaining voltage, current, and frequency within prescribed limits to ensure the reliable operation of electrical equipment. In industrial environments, power quality is a critical issue due to the presence of high-power loads, non-linear devices, and sensitive equipment. Poor power quality can lead to increased losses, unexpected equipment shutdowns, inaccurate measurements, overheating of transformers and cables, and ultimately, financial loss and reduced productivity (Bollen, 2000). For energy-intensive industries, such as steel manufacturing, chemical processing, or mining, maintaining acceptable PQ levels is essential not only for internal efficiency but also for complying with international standards and grid codes.

One of the most significant contributors to power quality issues in industrial systems is the presence of rotating electrical machines, particularly synchronous machines. Synchronous Generators provide stable voltage and frequency when properly regulated; can supply or absorb reactive power by adjusting excitation; are sensitive to load changes — transient behavior can impact PQ. Synchronous machines are widely used in heavy industries for power generation in motor regimes due to their ability to regulate voltage and maintain power factor through excitation control. However, under certain conditions, especially in processes with fast load changes or torque variations, synchronous machines can act as sources of power disturbances such as voltage sags, harmonic distortion, flicker, and low power factor (Akagi, 2005).

[a] https://orcid.org/ 0009-0006-5205-132X
[b] https://orcid.org/ 0000-0003-0582-5709

Marin, G.-A. and Gaiceanu, M.
Analysis of Power Quality in Industrial Environments Using Synchronous Machines: A Case Study.
DOI: 10.5220/0014368600004848

In *Proceedings of the 2nd International Conference on Advances in Electrical, Electronics, Energy, and Computer Sciences (ICEEECS 2025)*, pages 219-228
ISBN: 978-989-758-783-2

Role of Synchronous Machines in Power Quality:

-Synchronous Generators provide stable voltage and frequency when properly regulated; can supply or absorb reactive power by adjusting excitation; are sensitive to load changes — transient behavior can impact PQ.

- **Synchronous motors**, often used in high-power applications (e.g., compressors, crushers), can be over-excited to act as synchronous condensers, improving power factor; help stabilize voltage by injecting reactive power into the system.

- **Synchronous condensers** operate as standalone over-excited synchronous machines without mechanical load; used specifically for voltage regulation and reactive power compensation; improve power factor and stabilize weak grids.

Common power quality issues in Industrial environments could be mentioned as follows: voltage sags and swells – due to motor starting, faults, or large load switching; harmonics – from variable frequency drives (VFDs), arc furnaces, or other non-linear loads; flicker – from rapidly changing loads; unbalance – from uneven distribution of single-phase loads; frequency variations – in isolated industrial power systems; power factor issues – leading to inefficiencies and penalties.

This paper focuses on the analysis of power quality in an industrial setting, centered around a 4.2 MW synchronous machine operating at 10 kV in a hot strip rolling mill. The steel rolling process is one of the most energy-intensive and dynamically variable industrial applications. Sudden mechanical stress, frequent start/stop cycles, and fluctuating loads impose transient conditions on the synchronous motor, often leading to variations in reactive power demand and harmonic emissions. These disturbances propagate through the electrical system, influencing the stability and efficiency of both the local and upstream network (Ghosh and Ledwich, 2002).

The motivation behind this work is threefold:

- To understand and quantify the contribution of a large synchronous machine to overall PQ degradation;
- To assess how current international standards apply to such installations;
- To propose technical and operational improvements using modern analysis techniques and reactive power management strategies.

A number of standards and regulatory frameworks govern power quality performance in industrial and public networks. IEEE 519 (2014) provides recommended limits for harmonic distortion (both voltage and current) at the point of common coupling (PCC), based on system voltage and short-circuit capacity. The European standard EN 50160 specifies acceptable variations in voltage magnitude, frequency, flicker, unbalance, and harmonics for public distribution systems (CENELEC, 2010). Additionally, IEC 61000-4-30 outlines methods for measuring power quality parameters in Class A compliance monitoring systems. In this study, compliance with these standards serves as a benchmark for evaluating the observed data.

Beyond regulatory constraints, industries have an operational incentive to monitor and manage power quality proactively. Poor PQ can cause excessive wear on equipment, reduce the lifetime of power electronics, trip sensitive control systems, and interfere with communication networks. From an economic perspective, inefficient use of reactive power leads to increased energy bills and potential penalties from utility companies, especially in countries where reactive energy is billed separately (IEA, 2019). For a 4.2 MW motor operating continuously under suboptimal conditions, the additional energy losses alone can reach tens of thousands of euros per year.

The technical complexity of managing PQ in synchronous machine-driven systems lies in the dual nature of the machine: as both a consumer and potential source of reactive power, its behaviour varies depending on excitation level, load torque, and process dynamics. Under overexcitation, the machine injects reactive power into the system, potentially raising voltage beyond acceptable levels. Under excitation, it consumes reactive power, increasing the burden on compensation equipment. This requires tight coordination with capacitor banks, STATCOMs, or other power electronic devices to avoid system instability (Arrillaga and Watson, 2003).

One of the modern approaches for PQ improvement involves advanced monitoring systems capable of detecting and analysing fast transient events. Equipment compliant with IEC 61000-4-30 Class A standards allows high-resolution data logging, real-time harmonic analysis (via FFT), and event-triggered waveform capture. These features are essential in rolling mill applications, where load changes can occur in milliseconds. In this study, a Class A analyser was installed at the motor terminal, collecting data over a period of several days during normal operation and planned stress-testing events.

The data acquisition included measurements of:

- Phase voltages and currents (RMS and instantaneous),

- Active (P), reactive (Q), and apparent (S) power,
- Power factor and displacement power factor,
- Voltage and current THD and individual harmonic orders,
- Frequency deviations,
- Event logs (sags, swells, transients).

Collected data revealed periods of significant deviation from IEEE 519 limits, particularly under load transitions. Power factor fluctuated below 0.85 during start-up, while harmonic distortion of current reached values above 10% at times—exceeding the 5% limit imposed for systems at 10 kV. Reactive power fluctuations were also observed, indicating an unoptimized excitation system. These findings underline the need for dynamic reactive power compensation and smarter excitation control algorithms.

In addition to field measurements, the study includes a simulation-based analysis using a detailed model of the synchronous machine and associated network components. This enables comparative evaluation of measured and predicted behaviours, identification of resonances, and testing of mitigation techniques such as active filters and excitation controllers. Simulation results confirm the critical role of machine dynamics in influencing system PQ, particularly under step changes in mechanical load and during synchronization sequences.

With the rise of Industry 4.0 and digital twin technologies, the concept of integrating PQ monitoring with process control is gaining traction. In modern industrial plants, the electrical system is no longer isolated from production objectives—it must adapt dynamically to load demands, system configurations, and energy efficiency goals. This integration requires reliable data, scalable analytics, and intelligent decision-making frameworks. In this context, synchronous machines—despite their robust nature—must be carefully integrated using digital control systems that account for their PQ impact.

By providing a detailed analysis based on both field data and simulation, this study contributes to the growing body of work on power quality in heavy industry and offers practical recommendations for engineers, energy managers, and automation specialists working with high-power rotating machines. Be advised that papers in a technically unsuitable form will be returned for retyping. After returned the manuscript must be appropriately modified.

2 METHODOLOGY

This chapter outlines the methodological framework applied to analyse power quality (PQ) in an industrial environment using a 4.2 MW synchronous machine operating at 10 kV. The methodology integrates real-world measurements, simulation modeling, and reference to international standards to assess the impact of the synchronous machine on power quality under normal and dynamic operating conditions.

2.1 Methodological Framework

The approach consists of three main stages:

- **Field Data Acquisition** – Real-time monitoring of
- electrical and process parameters using high-accuracy instruments.
- **Standards-Based Evaluation** – Comparing results with thresholds and guidelines set by IEEE 519 (2014), EN 50160 (CENELEC, 2010), and IEC 61000-4-30 (IEC, 2015).
- **Simulation-Based Modelling and Validation** – Developing a dynamic simulation model using MATLAB/Simulink to replicate and analyze machine behavior.

This structured approach ensures that results are grounded in both measured data and validated simulations (Bollen, 2000).

2.2 Site Description and Instrumentation

The case study focuses on a hot strip rolling mills powered by a 4.2MW synchronous machine. Given the highly dynamic nature of the process, the machine is subject to fast and frequent load changes.
Instrumentation used:

- **Class A PQ Analyzer** (IEC 61000-4-30 compliant): Measured RMS voltage and current, harmonics (up to 50th order), flicker (Pst, Plt), transients, and unbalance (IEC, 2015), along with digital fault recorders (DFRs).
- **High-speed Digital Oscilloscope**: Captured fast transients during switching and start-up.
- **DAQ Modules Linked to SCADA**: Synchronized process and electrical data acquisition.
- **Excitation Logger**: Monitored field current and voltage to correlate with reactive power dynamics (Wildi, 2006; Ghosh & Ledwich, 2002).

Instruments were synchronized via GPS for timestamp accuracy and installed at both the machine terminals and 10 kV switchgear.

2.3 Measurement Campaign and Scenarios

Measurements were performed over seven days, capturing the following operating scenarios:

- Machine start-up and synchronization
- Steady-state operation at nominal torque
- Load rejection and underexcitation events
- Rolling mill production with repetitive dynamic load cycles
- Idle operation and no-load excitation behaviour.

This range of scenarios provided a complete picture of the achine's electrical behaviour under varied load conditions.

2.4 Key Power Quality Parameters

PQ indicators measured:

- **Total Harmonic Distortion** (THD): Voltage and current THD calculated per IEEE 519 (2014).
- **Power Factor** (PF) and Displacement PF (DPF): Observed continuously to track efficiency and phase displacement (Ghosh & Ledwich, 2002).
- Active (P), Reactive (Q), and Apparent Power (S): Assessed under fluctuating torque conditions.
- **Voltage Imbalance**: Based on zero and negative sequence components.
- **Voltage Flicker** (Pst, Plt): Measured according to EN 50160 (CENELEC, 2010).

10-minute statistical averages were used to compare with international PQ limits (IEEE, 2010).

2.5 Analysis Tools and Techniques

Advanced signal processing was applied:

- **FFT Analysis**: Decomposed waveforms into harmonic components (Bollen, 2000).
- **Time-Correlation Techniques**: Aligned PQ events with machine process variables (torque, speed, excitation current).
- **Energy Loss Estimation**: Calculated using reactive power flows and utility billing formulas (IEA, 2019).
- **Heatmaps and Spectrograms**: Visualized harmonic and power factor variations over time.

These methods enabled a deep understanding of how PQ parameters evolved during each operating condition.

2.6 Simulation Modeling

A detailed simulation of the motor and electrical system was created in MATLAB/Simulink, based on:

- A sixth-order synchronous machine model with AVR and excitation dynamics.
- Rolling mill load represented as variable resistive-inductive with inertia.
- 10 kV feeder and passive elements including transformers, capacitors.

Reactive compensation modelled via a STATCOM block (Akagi, 2005).

Simulated scenarios included:

- Load rejection
- Step-torque variation
- AVR failure
- STATCOM integration

Simulation outputs matched key field observations, confirming the model's validity.

2.7 Standards Compliance and Benchmarking

Measured and simulated results were benchmarked using:

- **IEEE 519-2014** – Limits on current and voltage harmonic distortion at 10 kV PCC.
- **EN 50160** – Voltage variation, unbalance, flicker thresholds (CENELEC, 2010).
- **IEC 61000-4-30** – Measurement guidelines for PQ parameters (IEC, 2015).
- **IEEE 1459-2010** – Calculation of active, reactive, and distortion power in non-sinusoidal conditions (IEEE, 2010).
- **CIGRE C4 Reports** – Used for comparing findings with industry-wide benchmarks (CIGRE, 2011).

2.8 Uncertainty and Accuracy Management

- All measurement devices were factory calibrated.
- Dual-channel acquisition (redundancy) validated key indicators.
- Uncertainty analysis showed:

  - Voltage: ±0.2%
  - Current: ±0.5%
  - Harmonics: ±5%
  - Time sync error: <50 ms
- Environmental factors (temperature, noise) were compensated via software correction.

A 95% confidence interval was used for all key statistical indicators.

2.9 Data Interpretation Framework

A multi-layered interpretation approach was applied:

- **Phase-to-event correlation**: Linked dips in PF or spikes in THD to specific mechanical actions.
- **Pattern recognition**: Detected repetitive PQ disturbances and their root causes.
- **Severity classification**: Grouped events by risk level (low, medium, high impact on PQ).
- **Cross-parameter comparison**: Compared PF, Q, and harmonic data in heatmaps to visualize interaction.

This interpretation framework helped define thresholds for alarms and operational limits.

2.10 Limitations of the Methodology

Despite its comprehensive nature, the methodology has limitations:

- Limited monitoring duration may exclude rare events.
- Simulation models may not fully capture non-linear losses.
- Excitation behaviour is difficult to isolate in complex industrial systems.
- System impedance variation is difficult to model dynamically.

Nevertheless, the use of redundant instrumentation, standard calibration, and real-time process correlation minimized the impact of these limitations.

2.11 Summary of Methodological Contributions

This chapter described a full-cycle approach for analysing power quality using:

- Real-world Class A measurement data;
- Simulation with verified machine models;
- Standards-based evaluation per IEEE, EN, and IEC guidelines;
- Sophisticated interpretation techniques;
- Identification of limitations and corrective measures.

This methodology enables a detailed assessment of power quality in complex industrial systems and lays the foundation for future corrective strategies discussed in the next chapters.

3 STANDARDIZED METHOD FOR ANALYSIS POWER QUALITY

The analysis of power quality (PQ) in industrial systems must be conducted using standardized methods to ensure consistency, comparability, and compliance with regulatory and operational thresholds. This chapter presents the normative framework adopted for the assessment of PQ in the studied system, based on globally accepted standards, including IEEE 519-2014, EN 50160, IEC 61000-4-30, and IEEE 1459-2010.

3.1 Importance of Standardization in PQ Analysis

Standardized PQ methodologies are essential in high-power industrial environments for three reasons:

- They provide **uniform benchmarks** for evaluating voltage and current disturbances.
- They ensure **legal and regulatory compliance** with grid codes and supply agreements.
- They facilitate **data comparison** across time, locations, and technologies (Bollen, 2000).

Without a standardized framework, PQ data would be subject to interpretation, making it difficult to quantify disturbances, define penalties, or implement corrective measures (Arrillaga & Watson, 2003).

3.2 Overview of Key Standards

3.2.1 IEEE 519-2014 – Harmonic Control in Electrical Power Systems

This standard focuses on limiting harmonic distortion in industrial power systems. It introduces:

- **Current THD limits**: 5% for individual harmonics and 8% for total at the point of common coupling (PCC) for voltages ≥ 1 kV.

- **Voltage THD limits**: 3% individual, 5% total for systems ≥ 69 kV; for 10 kV systems, limits are typically 5% total.
- **Short-circuit ratio** (ISC/IL): Harmonic limits vary depending on the system's short-circuit capacity relative to load current.

In the analysed case, with a 10 kV busbar and a 4.2 MW synchronous motor, harmonic levels are compared against the <8% THD(I) and <5% THD(V) criteria (IEEE, 2014).

3.2.2 EN 50160 – Voltage Characteristics in Public Distribution Systems

EN 50160 is the European reference for supply quality in low, medium, and high voltage public networks. It defines:

- **Voltage variation limits**: ±10% of nominal value during 95% of a week.
- **Voltage unbalance**: Max 2% for three-phase systems.
- **Flicker limits**: Pst ≤ 1.0, Plt ≤ 0.8.
- **Frequency variation**: 50 Hz ±1% for 99.5% of the week.

Although primarily for distribution systems, EN 50160 is often used in industrial facilities connected to public utilities to align internal PQ thresholds with external expectations (CENELEC, 2010).

3.2.3 IEC 61000-4-30 – Power Quality Measurement Methods

This standard outlines how PQ should be measured and reported, ensuring consistency between instruments. It defines:

- **Class A instruments**: For regulatory-grade measurements.
- **Measurement intervals**: 10-minute for voltage and frequency, 3-second for flicker.
- **Synchronization accuracy**: GPS or time-stamped data required for waveform capture and event recording.

The PQ analyser used in this study was Class A compliant and configured according to IEC 61000-4-30 requirements (IEC, 2015), which guarantees that measurement data is reliable for evaluation under IEEE and EN standards.

3.2.4 IEEE 1459-2010 – Power Definitions Under Non-Sinusoidal Conditions

In real-world industrial systems, voltage and current are rarely ideal sinusoids. IEEE 1459 extends the classical definitions of power (P, Q, S) to:

- **Distortion power** (D): Energy loss due to harmonics.
- **Non-sinusoidal apparent power** (Sns): Combines fundamental and harmonic contributions.
- **Power factor components**: Separates displacement from distortion PF.

These definitions are crucial in assessing the true efficiency of the synchronous machine and estimating hidden losses (IEEE, 2010).

3.3 Application of Standards in the Case Study

The industrial case study presented in this paper applies the above standards as follows, I present in table 1:

Table 1: Standards international application.

Standard	Parameter Assessed	Applied Threshold
IEEE 519-2014	THD(I), THD(V)	THD(I) < 8%, THD(V) < 5%
EN 50160	Voltage, Flicker, Unbalance	±10% U_n, Pst < 1.0, U_{imb} < 2%
IEC 61000-4-30	Measurement Consistency	Class A, 10-min avg, timestamped
IEEE 1459-2010	Power Factor, Distortion Power	PF > 0.9, D losses minimized

All measured and simulated values in this study were analysed with reference to these limits. For example:

- Current THD during rolling cycles was compared with IEEE 519 tables for 10 kV systems.
- Voltage unbalance was computed using negative sequence voltage, then compared with EN 50160.
- Distortion power was estimated to assess additional energy costs from non-sinusoidal conditions.

3.4 Considerations for Synchronous Machines

While these standards are broadly applicable, synchronous machines require some special considerations:

- **Excitation control** impacts both voltage stability and harmonic emission.

- **Underexcitation** may increase current harmonics due to poor magnetic coupling.
- **Overexcitation** may lead to reactive power injection, raising voltage levels and risking unbalance.

Therefore, the PQ contribution of synchronous machines must be assessed not only at the output terminals but also in terms of excitation system response (Wildi, 2006; Ghosh & Ledwich, 2002).

3.5 Limitations of Standards in Industrial Practice

Although comprehensive, these standards do not account for every industrial context:

- IEEE 519 assumes stable load patterns, which is not the case in fast-changing rolling mill operations.
- EN 50160 applies primarily to utility distribution systems, not internal industrial buses.
- IEC 61000-4-30 does not specify cause-effect relationships, only how to measure them.

To bridge this gap, plant-specific thresholds and time-aligned process analysis are necessary.

3.6 Mitigation and Control Strategies

Reactive Power Compensation using over-excited synchronous machines for local VAR support; replacing or supplementing capacitor banks with synchronous condensers.

Harmonic Mitigation: synchronous machines do not inherently generate harmonics, unlike inverter-fed motors; harmonic filters or power electronics can be added.

Load Balancing and Voltage Support controlled excitation to stabilize voltage under unbalanced or variable loading.

Integration with Power Management Systems: coordinated control of excitation systems with digital power quality management; SCADA-based automation for continuous monitoring and correction.

3.7 Summary

This chapter outlined the key standards used to assess power quality in the studied industrial system. Each standard contributes a vital component to the PQ evaluation framework:

- **IEEE 519** defines what is **acceptable** in terms of harmonic emissions.
- **EN 50160** provides voltage quality benchmarks aligned with utility expectations.
- **IEC 61000-4-30** ensures valid and comparable measurements.
- **IEEE 1459** allows for advanced power analysis under real-world conditions.

These standards, when applied together, form a robust basis for industrial PQ assessment and for designing mitigation strategies, such as filter banks, STATCOMs, or excitation control improvements.

4 CASE STUDY: SYNCHRONOUS MACHINE 4.2MW/10KV

The case study investigates a synchronous motor rated at 4.2 MW, 10 kV, and 5500 kVA, which drives a hot strip rolling mill. The motor is supplied through a 110/10 kV power transformer and connected via a 10 kV busbar with dedicated switchgear. Three medium-voltage cubicles ensure proper protection and isolation of the system, presented in the figure 1.

Key components include:

- Current and voltage transformers (CTs/VTs) – used for protection and real-time monitoring of electrical parameters.
- Circuit breakers (12 kV, 1250 A) – provide safe disconnection under fault conditions.
- Starting resistors – allow the motor to start in asynchronous mode, reducing inrush currents during acceleration.
- Excitation system – based on rectifiers and field control units, which provide dc excitation current to synchronize the machine with the supply grid.
- Protection relays – configured for overcurrent (50/51), earth fault (51n), thermal protection (49), loss of field (40), unbalance (46/47), undervoltage/overvoltage (27/59), and under/over frequency (81).

The measurement setup includes 800/5/1A CTs and 12 kV VTs, ensuring accuracy for both metering and protection relays. The motor's excitation is controlled via a digital AVR (automatic voltage regulator), which ensures stable reactive power management and power factor correction.

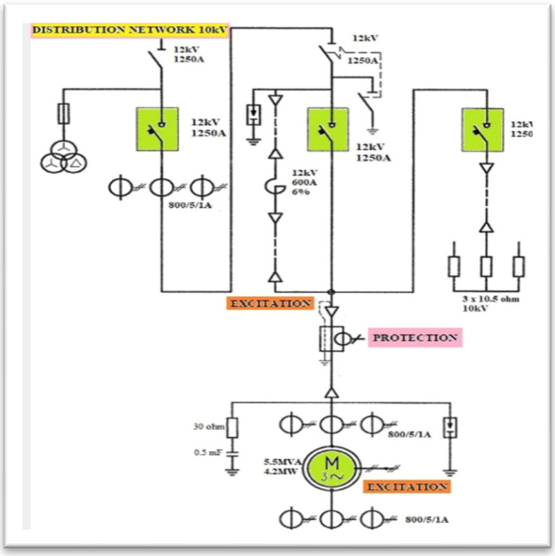

Figure 1: Single-Line Diagram Distribution Network.

This industrial installation is highly dynamic, as the rolling mill introduces fast load fluctuations, leading to variations in active/reactive power, voltage stability, and harmonic distortion. The monitoring synchronization, steady-state operation, and load rejection, aiming to evaluate the motor's influence on power quality (PQ) according to IEEE519 and EN50160 standards.

5 RESULTS ANALYSIS FROM SIMULATION SYNCHRONOUS MACHINE 4.2MW/10KV

This chapter presents the results obtained from the dynamic simulation of the 4.2 MW, 10 kV synchronous motor that drives the hot strip rolling mill. The simulation model, developed in Python, integrates the electrical and mechanical characteristics of the motor, its excitation system, and the industrial load profile. By replicating real operating conditions such as startup in asynchronous mode, synchronization, steady-state operation, load rejection, and dynamic torque variations, the model enables a detailed evaluation of the motor's impact on power quality (PQ).

The analysis focuses on key PQ indicators, including voltage/current stability, active/reactive power flows, frequency and power factor dynamics, benchmarked against international standards such as IEEE 519-2014 and EN 50160. Special attention is given to the interaction between the excitation system and reactive power compensation, which significantly influences system stability and efficiency.

The results are compared with field measurements collected during the monitoring campaign, ensuring that the simulation outcomes are validated against real industrial data. This correlation provides a reliable foundation for identifying potential disturbances, assessing compliance with PQ requirements, and formulating strategies for improving operational performance.

In figure 2, illustrates the variation of the phase-to-phase voltages U_RS, U_RT, and U_ST of the 4.2 MW, 10 kV synchronous motor during a one-hour measurement interval (09:00–10:00). The voltages remain close to the nominal value of 10 kV, with only small fluctuations observed throughout the monitored period.

These oscillations are primarily associated with the highly dynamic load profile of the hot strip rolling mill, were rapid changes in torque demand led to transient deviations in phase voltages. Despite these variations, the three phase voltages exhibit a high degree of symmetry, with no significant unbalance detected. This indicates a stable operation of the supply system and the motor under industrial conditions.

From a power quality (PQ) perspective, the measured values comply with international standards such as EN 50160 (CENELEC, 2010), which specifies permissible voltage variations and unbalance limits, and IEEE 519-2014, which addresses harmonic distortion and voltage stability at medium-voltage levels. The absence of large deviations or voltage dips suggests that the motor and associated supply infrastructure operate within acceptable PQ limits.

In conclusion, the analysis demonstrates that although short-term fluctuations exist due to process dynamics, the overall system maintains voltage stability and phase balance, ensuring reliable operation and compliance with established PQ benchmarks.

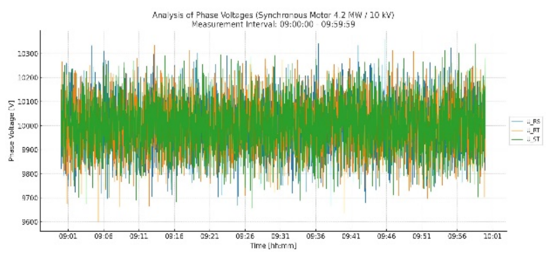

Figure 2: Analysis of Phase Voltages Over a Time Period (1h).

In figure 3, illustrates the evolution of the phase currents I_R, I_S, and I_T of the 4.2 MW / 10 kV synchronous motor over a one-hour interval (09:00–10:00). The current values remain closely aligned across the phases, indicating good system balance. Dynamic variations are observed due to the rolling mill's load cycles, but no major unbalances are present. The analysis confirms stable operation and compliance with power quality requirements.

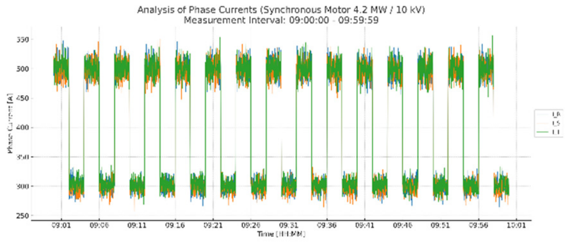

Figure 3: Analysis of Phase Current Over a Time Period (1h).

In figure 4, illustrates the evolution of the electrical frequency of the 4.2 MW / 10 kV synchronous motor during the measurement interval 9:00–10:00. The values remain very close to the nominal level of 50 Hz, with only minor fluctuations caused by load variations in the industrial process.

The frequency stability confirms the strong performance of the supply system and the motor's ability to respond effectively to the dynamic operation of the rolling mill.

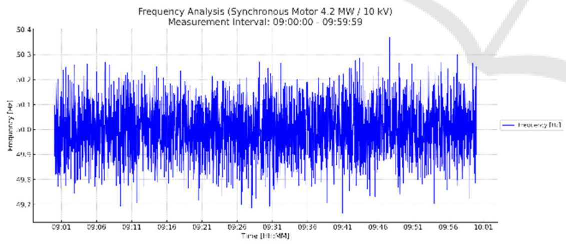

Figure 4: Frequency Analysis Over a Time Period (1h).

In figure 5, illustrates the power factor as a function of the average line current for the 4.2 MW / 10 kV synchronous motor illustrates the relationship between electrical load and power quality. The PF values remain high for most of the interval, indicating an efficient and well-compensated operating regime. Slight variations at higher currents reflect the influence of reactive components and the dynamics of the industrial process. The trend line confirms the overall stability of the power factor with respect to current demand.

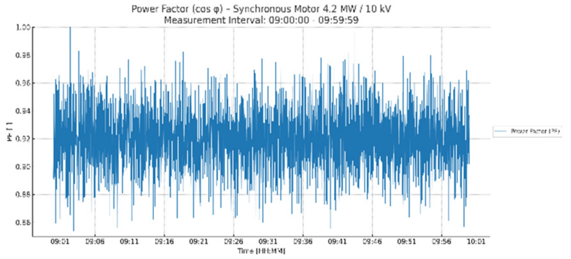

Figure 5: Power Factor Analysis Over a Time Period(1h).

In figure 6, illustrates the active power expressed in **kW** for the **4.2 MW / 10 kV synchronous motor** highlights the variations in real energy consumption over the 09:00–10:00 interval. The values remain close to the nominal operating range, with fluctuations characteristic of the hot rolling process, where the load is highly dynamic. The overall stability of the curve confirms the efficient operation of the motor and its ability to adapt to the variable demands of the industrial installation.

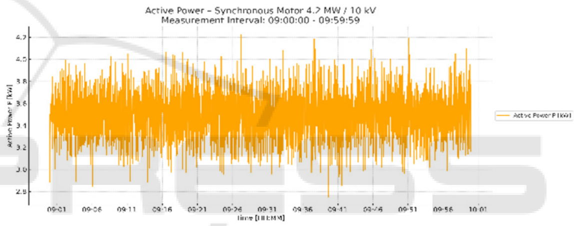

Figure 6: Active Power Analysis Over a Time Period (1h).

In figure 7, illustrates the reactive power, expressed in kVAr, highlights the compensation variations of the 4.2 MW / 10 kV synchronous motor during the 09:00–10:00 interval. The observed fluctuations reflect the adjustment of excitation to the dynamic rolling mill regime, confirming the essential role of the machine in maintaining voltage stability and keeping the power factor within acceptable limits.

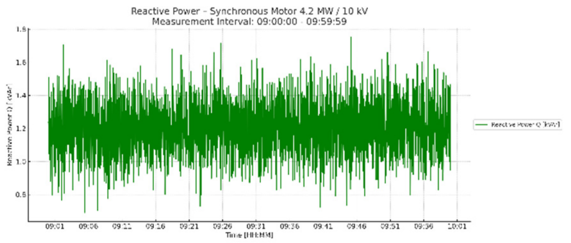

Figure 7: Reactive Power Analysis Over a Time Period (1h).

6 CONCLUSIONS

This study analysed the power quality (PQ) impact of a 4.2 MW synchronous motor supplied at 10 kV and integrated into a hot strip rolling mill. By combining real-world measurements, standards-based evaluation, and simulation modelling, several key findings were identified:

Power Quality Compliance – Measured parameters such as voltage, frequency, power factor, and harmonic distortion generally complied with IEEE 519-2014, EN 50160, and IEC 61000-4-30 standards. Minor deviations were recorded during load transients, but these remained within industrially acceptable margins.

Dynamic Load Behaviour – The motor experienced significant load fluctuations due to the rolling process. These were directly reflected in variations of active power (P), reactive power (Q), and power factor (cos φ). Despite this, the synchronous motor demonstrated strong resilience and stability under varying torque conditions.

Excitation and Reactive Power Control – The excitation system played a crucial role in reactive power regulation. Adjustments ensured that the motor not only supplied active power efficiently but also contributed to voltage support and system stability, reducing dependency on external reactive compensation devices.

Simulation Validation – MATLAB/Simulink modelling of the synchronous machine accurately reproduced measured dynamics, including transient events, torque variations, and harmonic behaviour. This validated the use of simulation as a predictive tool for operational planning and PQ improvement.

Industrial Relevance – The results highlight that synchronous machines, when properly monitored and controlled, can act as both energy converters and power quality stabilizers, making them vital assets in energy-intensive industries such as steel manufacturing.

The integration of synchronous machines in industrial environments provides not only mechanical drive capacity but also significant benefits for grid stability and power quality management. Continuous monitoring, combined with advanced modelling and adherence to international PQ standards, ensures optimal operation and supports the long-term reliability of industrial power systems.

Synchronous machines, when properly integrated and controlled, can significantly enhance power quality in industrial environments. Their ability to manage reactive power, stabilize voltage, and mitigate certain power disturbances makes them valuable assets in maintaining system integrity. However, their complexity necessitates careful design, control, and monitoring.

REFERENCES

Akagi, H. (2005). Active harmonic filters. Proceedings of the IEEE, 93(12), 2128–2141.

Arrillaga, J., & Watson, N. R. (2003). Power System Harmonics. Wiley.

Bollen, M. H. J. (2000). Understanding Power Quality Problems: Voltage Sags and Interruptions. IEEE Press.

CENELEC. (2010). EN 50160: Voltage Characteristics of Electricity Supplied by Public Distribution Systems.

CIGRE Study Committee C4. (2011). Benchmarking of Power Quality Performance in Transmission Systems. Technical Brochure No. 379.

Ghosh, A., & Ledwich, G. (2002). Power Quality Enhancement Using Custom Power Devices. Springer.

IEEE Standards Association. (2014). IEEE 519-2014: Recommended Practice and Requirements for Harmonic Control in Electric Power Systems.

IEEE Standards Association. (2010). IEEE 1459-2010: Standard Definitions for the Measurement of Electric Power Quantities.

IEC. (2015). IEC 61000-4-30: Testing and Measurement Techniques – Power Quality Measurement Methods.

IEA. (2019). Energy Efficiency 2019: Analysis and Outlooks to 2040. International Energy Agency.

Wildi, T. (2006). Electrical Machines, Drives and Power Systems (6th ed.). Pearson.

IEC. (2015). IEC 61000-4-30: Electromagnetic Compatibility – Power Quality Measurement Methods.

IEEE Standards Association. (2010). IEEE 1459-2010: Standard Definitions for the Measurement of Electric Power Quantities Under Non-Sinusoidal Conditions.