ASSESSMENT OF THE POWER QUALITY IN THE CIRCUIT OF A STORAGE SYSTEM. EXPERIMENTAL STUDY

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The study includes an experimental analysis of the power quality in an industrial installation in which a solar source supplies the user and determines, during hours of excess energy, the charging of a battery and during peak hours it contributes to reducing the energy taken from the public electrical grid. The analysis carried out in the paper was based on data obtained through determinations within a real scheme and had as its objective the investigation of the voltage profile, harmonic distortion, reactive power exchange, current unbalance, flicker severity, power factor, and bidirectional energy flow while confirming compliance with internationally recognized power-quality standards [1]. The data necessary for the study were obtained both through readings of equipment from the intelligent measurement and monitoring infrastructure within the enterprise and from records of the mobile equipment used. The analyzed network includes a solar source of about 500 kW made with photovoltaic panels, a storage installation with about 615 kWh, the 20/0.4 kV power supply system from the public network and the power supply circuits of the receivers in the enterprise. The monitoring system within the electrical installation allows the acquisition of essential electrical parameters for operating control and for detecting abnormal conditions. The experimental results indicate that investigated electrical installation architecture can improve energy efficiency and reduce dependence on the utility grid, without compromising electrical power quality. The analysis demonstrates the benefits of integrating renewable energy with smart power flow monitoring. Overall, the study provides practical recommendations for improving the efficiency, grid compatibility, and sustainable operation of modern smart industrial microgrids.

Keywords: Active user with photoelectric source and battery, power quality, harmonic distortion, Smart Grid, industrial microgrids.

1. Introduction

The electrical performance of the industrial distribution system, integrating a hybrid photovoltaic installation consisting of both ground-mounted and rooftop arrays, together with a battery energy storage system (BESS), can be accurately characterized using three-phase power-flow models. Such an approach enables the

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evaluation of power converter efficiency, voltage and current unbalance, harmonic distortion, renewable energy utilization, and the intelligent control of the energy storage system to optimize power exchange with the utility grid and enhance overall operational reliability [1,3].

Solar photovoltaic energy powers rechargeable batteries, decreasing electricity grid usage during charging operations.

Experimental Analysis of the Operating Characteristics of the Electrical Installation provides objective validation of system behaviour under real operating conditions. Continuous power – quality monitoring performed in accordance with international standards has a crucial role in identifying harmonic emissions, voltage disturbances and efficiency losses [2].

Since the photovoltaic generation system, the industrial loads, the distribution transformer supplying power from the utility grid, and the battery energy storage system (BESS) are all connected to the same low-voltage busbar, the measured voltage characteristics reflect the combined influence of all these components within the electrical network.

The power electronic converters interfacing the photovoltaic system and the battery energy storage system (BESS) may introduce significant power quality disturbances into the industrial electrical network. Consequently, a detailed assessment of the relevant power quality indices is required, together with the implementation of appropriate mitigation measures to ensure compliance with the limits specified by the applicable standards [4].

Interface converters with the storage system use different topologies whose selection depends on power capacity, efficiency targets and power – quality requirements. Conventional six – pulse converters remain the most common solution due to their robust and economical design, while the six-pulse rectifier with PWM control results in significantly lower harmonic distortion, better current quality in the input circuit, improved power factor, and enhanced energy efficiency [4]. These advanced converter technologies are especially suitable for interfacing with storage batteries in a company equipped with solar power sources, where high energy quality and its bidirectional management are essential. Their electrical behaviour can be accurately assessed using mathematical models describing three – phase power flow, harmonic distortion and converter performance, under both grid – connected and renewable energy operating conditions [5].

Although the installation is an industrial facility, standard grid compliance requirements remain applicable. At the request of the regional system operator, the excess generated power can be supplied to the downstream distribution network beyond the point of common coupling (PCC); otherwise, energy export to the national power system would not be permitted. As illustrated in Fig. 1, the measurements were performed at three locations identified by the M1, M2 and M3 point.

The electrical current absorbed by the battery interface converter is regulated using a vector current control strategy, which provides fast dynamic response and accurate tracking of the reference current during both charging and discharging modes. This control strategy minimizes harmonic distortion, improves the input power factor, enables bidirectional power transfer between the AC and DC sides, and provides accurate regulation of the battery charging current. By adjusting the converter switching pattern, the input current is shaped to closely follow the sinusoidal waveform of the grid voltage, thereby enhancing both conversion efficiency and power quality [10]. As a result, the battery receives a stable DC supply, while the AC network experiences an approximately resistive load with minimal reactive power demand. The conversion process transforms sinusoidal AC energy into regulated DC power suitable for battery charging [2,3].

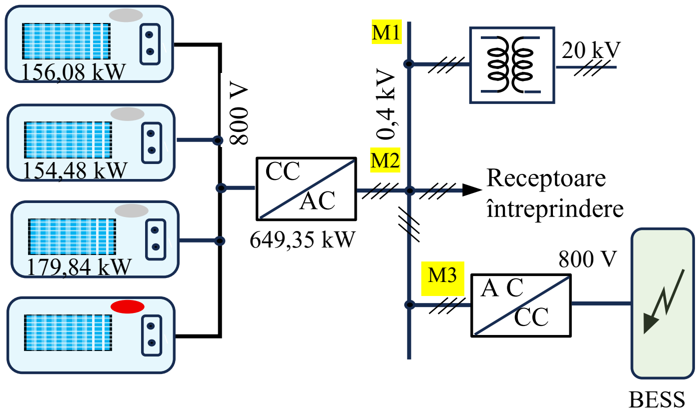


Fig. 1 Single-line diagram of the analyzed electrical network.

2. Succinct mathematical model of an industrial system that includes photovoltaic panels and an energy storage system

This mathematical model combines conventional three – phase power equations with renewable energy balance and power quality indicators. The proposed global Power Quality Index (PQI) offers an integrated criteria for assessing industrial battery charging stations by simultaneously accounting for converter efficiency, harmonic distortion, voltage/current unbalance and power factor [4]. The model being suitable for Smart Grid monitoring, SCADA – based supervision and experimental validation [5,6]. Power quality measurements were performed at three monitoring locations, denoted as M1, M2, and M3. Monitoring point M1 was installed on the 0,4 kV side of the 20/0,4 kV distribution transformer, providing a reference for the power quality conditions at the low-voltage busbar. Monitoring point M2 was located at the AC output terminals of the photovoltaic inverter system to assess the electrical quantities associated with the integrated PV generation. Monitoring point M3 was installed at the low-voltage AC connection of the Battery Energy Storage System (BESS), allowing the evaluation of the electrical parameters at the bidirectional interface between the storage system and the distribution network during both charging and discharging operation [4,6].

$$PQI = w_1 \cdot PF + w_2 \cdot \eta - w_3 \cdot THD - w_4 \cdot k_U - w_5 \cdot k_I; \quad (1)$$

where:

- Power factor PF (point M2)

$$PF = P / S; \quad (2)$$

- Active power exchanged with the AC network:

$$P = \sqrt{3} \cdot U_L \cdot I_L \cdot PF; \quad (3)$$

- U_L - line-to-line RMS voltage;
- I_L - line RMS current (in the 0.4 kV AC circuit – LV).
- Charging efficiency η:

$$\eta = (P_{DC} / P_{AC}) \times 100; \quad (4)$$

- P_{DC} - useful DC charging power delivered to the battery;
- P_{AC} - AC electrical power absorbed from the utility grid;
- THD_U - total harmonic distortion of the supply voltage

$$THD_U = \frac{\sqrt{\sum H_h^2}}{H_1} \cdot 100; \quad (5)$$

- H_1 - RMS value of the fundamental voltage;
- H_h - RMS value of the *h*-th harmonic component;
- k_U - Voltage unbalance factor:

$$k_U = \frac{U_2}{U_1} \cdot 100, \quad (6)$$

- U_1 - positive-sequence voltage component,
- U_2 - negative-sequence voltage component,

$$k_I = \frac{I_2}{I_1} \cdot 100, \quad (7)$$

- I_1 - positive-sequence current component,
- I_2 - negative-sequence current component.
- w_1, w_2, w_3, w_4, w_5– weighting coefficients assigned to the power factor, charging efficiency, harmonic distortion, voltage unbalance, and current unbalance, respectively.

Knowing the global quality factor is essential for characterizing the operational performance of a company that includes a photovoltaic source and a battery storage system, because it allows for the quantitative assessment of energy quality, energy conversion efficiency, harmonic emissions, grid interaction, and overall system reliability under real operating conditions [7].

3. Case Study: Experimental Power – Quality Monitoring of a Photovoltaic – Assisted Industrial Battery Charging Station

The experimental research confirms that the integration of photovoltaic system paired with industrial battery charging systems improves overall energy efficiency while maintaining voltage quality, harmonic distortion and power factor within the limits set by international standards, The results shown in Figures 2...14 confirm that the monitored electrical quantities remained within the specified operating limits [3,4,7]. As an example, the voltage profile presented in Figure 2 demonstrates that the values recorded at measurement point M2 were consistently maintained within the allowable tolerance band of *Un* ± 10%. The implementation of Smart Grid technologies, SCADA included, AMI and predictive monitoring platforms, enables continuous supervision of electrical performance, optimizes renewable energy utilization, and optimizes the reliability and sustainability of modern industrial charging infrastructure [8].

Power quality monitoring represent the cornerstone of Photovoltaic-integrated battery charging architecture (charging infrastructure), providing the real time electrical information required to optimize converter operation, detect harmonic disturbances, maintain voltage stability, support predictive maintenance and ensure compliance with international power quality standards, while enabling intelligent energy management strategies as illustrated by the results obtained at measurement point M3 [2,4,6].

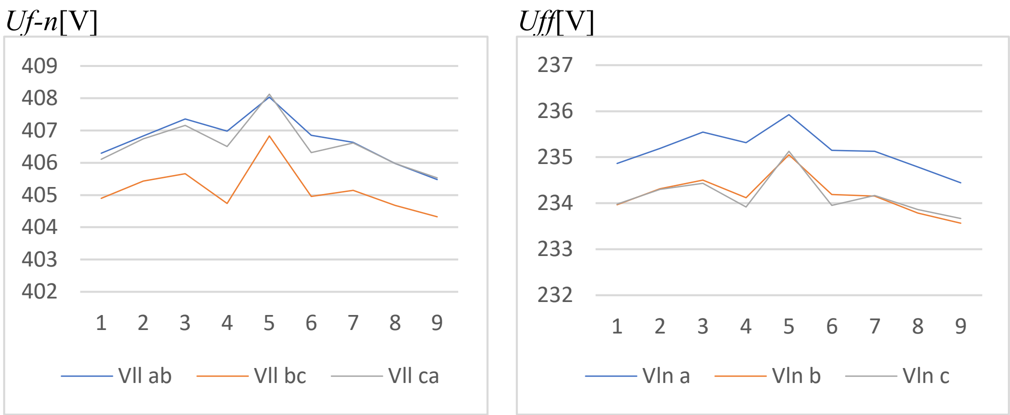
As industrial charging stations turn more toward AI driven, digitally interconnected Smart Grid architectures incorporating BESS, Digital Twin technologies and bidirectional energy exchange, comprehensive monitoring of voyage, current, harmonic distortion, power factor, frequency and transitional events will become indispensable for improving operational reliability, maximizing renewable energy utilization, strengthening cybersecurity aware control and achieving sustainability.

To validate the proposed engineering recommendations, a comprehensive power quality monitoring campaign was carried out on an industrial battery charging station supplied by both the utility grid and a photovoltaic generation system. The research focused on the continuous acquisition of the principal electrical quantities required to assess user performance, energy efficiency and compliance with power quality standards (at monitoring point M2). Monitoring proved critical for identifying the operating characteristics of the charging infrastructure, detecting harmonic phenomena, verifying voltage stability and providing the data necessary for predictive maintenance and intelligent energy management [4].

The recorded measurements included voltage and current waveforms, active reactive and apparent power, power factor, harmonic distortion, frequency and energy flow between the photovoltaic panels, the battery charger and the electrical network. The corresponding results are presented in the following figures.

For all plots presented in Figs. 2–14, the horizontal axis (x-axis) denotes the monitoring time, represented by consecutive 10-minute intervals considered representative of the system operating conditions. These intervals include both the most commonly observed operating states and those associated with significant deviations of the monitored variables. The vertical axis (y-axis) illustrates the corresponding values of the electrical quantities, each figure highlighting the evolution of a particular monitored parameter.

Fig. 2 presents the time domain variation of the three – phase voltages, phases A, B, and C. Indicating that voltage levels remain within nominal limits during operation, demonstrating the stability of the supply network despite the nonlinear load introduced by the battery charger [6].



Time [consecutive 10-minute intervals] *Time* [consecutive 10-minute intervals]

a. Phase-to-Neutral Voltage (V) b. Line Voltages (V)

Fig. 2. Measured phase voltages during the charging process.

Obs. The horizontal axis (x-axis) corresponds to time, represented by nine consecutive 10-minute intervals (90 minutes in total). The selected interval was extracted from a representative day and reflects operating conditions that occurred most frequently throughout the monitoring period [1,4].

Fig. 3 shows the evolution of the charging currents for each phase. Reflecting the dynamic behavior of the battery charging cycle, including initial inrush currents and subsequent stabilization, revealing potential asymmetries or imbalances among phases.

At first glance, the waveform profiles presented in Figs. 2–14 may appear unconventional when compared with the idealized sinusoidal behavior commonly assumed in theoretical analyses. However, the observed variations are relatively small and reflect the inherent differences between real operating conditions and the simplified assumptions adopted by conventional steady-state symmetrical sinusoidal models. Since the investigated distribution network operates under practical conditions, being continuously influenced by nonlinear loads, power electronic converters, photovoltaic generation, and load fluctuations, slight waveform distortions and parameter variations are expected. Consequently, the recorded measurements accurately describe the behavior of an actual electrical network rather than that of an idealized or laboratory test system. The objective of this study is therefore to capture and present the phenomenology of a real semi-industrial distribution network based on extensive field measurements performed at several monitoring locations. Despite these minor local variations, the voltage waveforms remain highly correlated throughout the network. Owing to the relatively low impedance of the low-voltage bus supplying the monitored installation, nearly identical voltage profiles were recorded at monitoring points M1, M2, and M3 during the same observation period [7].

Fig. 4 depicts the active power flow among system components. It highlights the contribution of the photovoltaic system in reducing grid dependency, especially during peak solar generation periods and illustrates bidirectional energy exchange with the grid.

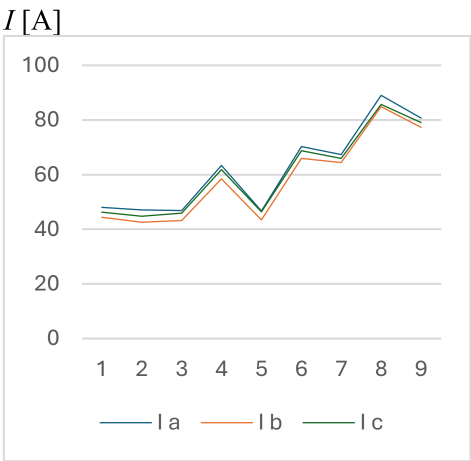


Fig. 3.Measured charging electric currents

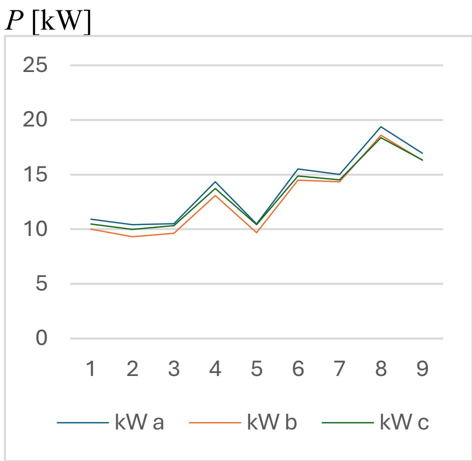


Fig. 4. Active power exchanged between the photovoltaic system, battery charger, and utility grid

The recorded power quality disturbances originate from the dynamic variation of voltage and current phasors, as well as their phase displacement, caused by the intermittent nature of photovoltaic generation. Rapid cloud movements, alternating shaded and illuminated operating conditions, and abrupt weather changes produce unequal inverter outputs and continuously varying electrical operating conditions as indicated by the monitoring results obtained at point M2.

Fig. 5 illustrates the reactive power dynamics during the charging process. The variation indicates the influence of the power electronic interfaces and control strategies on reactive power consumption or injection, impacting overall power quality. Fig. 5 shows that, during the passage of a cloud over the photovoltaic array, the output power of the PV inverters decreases progressively rather than instantaneously, following the reduction in solar irradiance. As the available photovoltaic power becomes insufficient, the Battery Energy Storage System (BESS) changes its operating mode from charging to discharging, supplying power to the loads connected to the low-voltage network. During this transition, the interaction between the grid-connected converters of the PV system and the BESS may temporarily produce a pronounced capacitive operating condition, accompanied by rapid variations in the power factor and reactive power exchange. In practical industrial installations, such transient phenomena may impose significant electrical stress on sensitive low-voltage power electronic equipment, including variable-speed drives, static converters, and soft starters used for electric motor control. If these conditions are sufficiently severe or occur repeatedly, they may accelerate the degradation of electronic components and, in extreme cases, contribute to premature failure of converter control boards or other sensitive electronic circuits (fault reports, overvoltage measurements, post-fault analyses etc.).

Fig. 6 shows the apparent power demand as a combined effect of both active and reactive power components, this figure providing insight into the total load imposed on the electrical infrastructure [6].

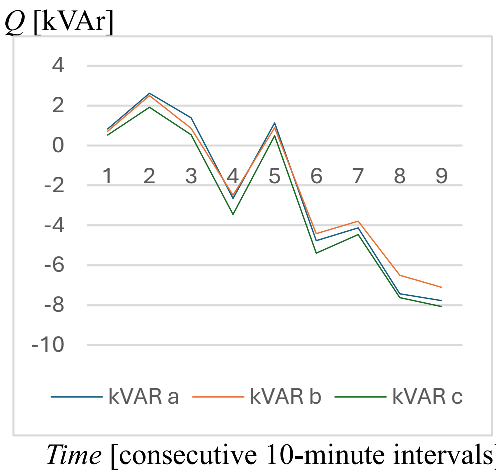


Fig. 5. Reactive power variation during battery charging

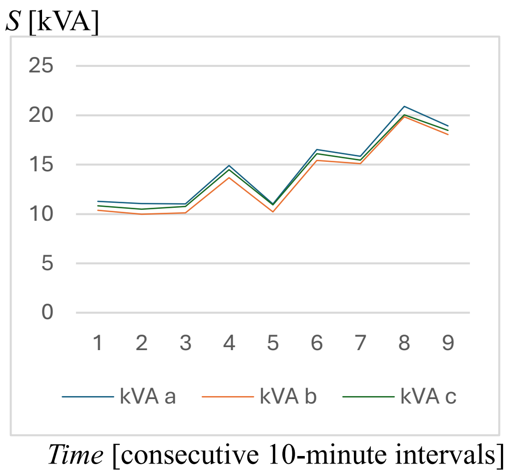


Fig. 6. Apparent power profiles recorded during operation

Fig.7 consolidates the system power characteristics by simultaneously presenting the active, reactive, and apparent power measured at Point M2. The recorded power profiles clearly illustrate the transition of the Battery Energy Storage System (BESS) from charging mode, where it operates as a load by absorbing electrical power, to discharging mode, where it supplies electrical energy to the low-voltage network. This operating mode change occurs during the passage of clouds over the photovoltaic installation, which temporarily reduces solar irradiance and significantly decreases the power generated by the PV array due to panel shading. Under these conditions, the BESS automatically switches to discharge operation to compensate for the reduction in photovoltaic generation and support the power balance of the electrical system. This integrated view facilitates comparative analysis and highlights correlations between these power components.

Fig. 8 shows the evolution of the power factor throughout the charging process, when variations in power factors reflect changes in load characteristics and the effectiveness of power factor correction mechanisms in point M1 [4,9]. It should be noted that the power factor (PF) is presented in this study according to the representation adopted by the power quality monitoring instrument. Therefore, it is expressed as a percentage rather than as a dimensionless quantity. In this representation, 100% corresponds to a unity power factor (PF = 1.0), while lower percentage values indicate increasing deviations from the ideal operating condition [9]. Consequently, all references to power factor throughout this paper follow the percentage-based convention provided by the monitoring equipment, ensuring consistency between the graphical results and their interpretation. Although phase power factors remain nearly constant below unity, the overall unity factor results from rapid inductive-capacitive transitions, while PWM converter control intentionally introduces short delays to protect static switching devices and continuously regulate reactive power.

To provide a sound interpretation of the results presented in Fig. 8, particularly the variations of the power factor, it is first necessary to examine the simultaneous evolution of the active (P), reactive (Q), and apparent (S) power over the selected monitoring interval. This analysis establishes the physical basis for the observed power factor behavior and supports the comments presented in the subsequent discussion. Since the measurements were performed on a fully operational semi-industrial electrical installation comprising photovoltaic generation, a Battery Energy Storage System (BESS), industrial loads, and a common low-voltage busbar, the recorded power profiles reflect the actual dynamic interactions among these interconnected components. Consequently, the following discussion is based on measured operating conditions in a real electrical network, where transient events and the coordinated response of power-electronic converters may produce behaviors that differ from those predicted by simplified steady-state theoretical models.

As discussed in the analysis of Fig. 7, under normal operating conditions the Battery Energy Storage System (BESS) is configured to operate at a (unity power factor PF = 1). This control strategy is intentionally implemented to minimize unnecessary reactive power exchange with the network and to avoid undesirable inductive or capacitive operating conditions. Consequently, during steady-state operation the BESS primarily exchanges active power with the grid.

However, transient environmental events, such as the passage of a dense cloud over the photovoltaic array, can cause a rapid reduction in solar irradiance. In such situations, one or more photovoltaic inverters may temporarily cease operation or disconnect from the grid, as illustrated by the inverter shown in Fig. 1 (red status indicator). As a result, the BESS rapidly changes its operating mode from charging (power absorption) to discharging (power injection) in order to compensate for the sudden loss of photovoltaic generation and maintain the power balance of the low-voltage network.

During this transition, the power electronic converters of the BESS require a short dynamic adjustment period. Consequently, the measured power factor may temporarily deviate from its nominal unity value, exhibiting rapid excursions toward very low values as the converter passes through short-lived inductive and capacitive operating states. Depending on the converter control settings and response time, these transient conditions typically last only a few minutes before the control system restores the programmed operating point.

Such mode transitions produce highly dynamic and, at first sight, unusual power-quality waveforms. Although these characteristics may appear difficult to reconcile with the simplified theoretical models commonly developed for balanced sinusoidal systems, they accurately reflect the behavior of a real semi-industrial electrical network containing multiple grid-connected photovoltaic inverters, a battery energy storage system, and supervisory control functions. Therefore, the observed fluctuations should be interpreted as the natural response of coordinated power-electronic converters operating under rapidly changing generation conditions rather than as abnormal system behavior.

Fig. 9 presents the voltage total harmonic distortion levels (THD_U). The results indicate the impact of nonlinear loads and inverter-based generation on voltage waveform quality and compliance with power quality standards.

It should be noted that Figs. 9, 11, and 14 do not characterize the Battery Energy Storage System (BESS) itself. Instead, they represent the electrical quantities measured at the low-voltage busbar, where the photovoltaic system, the BESS, the utility grid, and the industrial loads are interconnected. Consequently, the recorded voltage characteristics reflect the combined influence of all these interconnected components rather than the operation of the BESS alone.

Fig. 10 illustrates the current harmonic distortion, typically more pronounced due to power electronic converters. Elevated THD_I values suggest the presence of switching effects and require assessment against harmonic limits [1,2].

Fig. 11 depicts the system Voltage Unbalance Profile. Confirming that curve deviations remain minimal, indicating stable grid operation and proper synchronization of the photovoltaic inverter [1,4].

Fig. 12 provides a cumulative representation of Negative-Sequence Electric Current Magnitude, highlighting the contribution of renewable energy to the charging process and quantifies grid energy savings.

Fig. 13 shows finickier severity indices for each phase. Presenting values assess voltage fluctuations effects on visual perception and confirm whether the system remains within acceptable flicker limits [10]. High-frequency switching in power electronic converters produce harmonics, while harmonic limits restrict distortion to preserve grid stability and power quality [11].

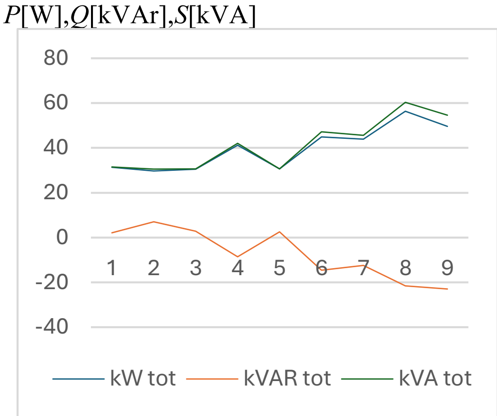
Fig. 14 details the harmonic spectrum of voltage and current signals, the analysis identifies dominant harmonic orders generated by the system and confirms that similar patterns are observed across all phases [11]. According to some researchers, disturbances attributed to the BESS charging system should be distinguished from those originating in the public utility grid. However, the influence of upstream network disturbances is substantially attenuated by the medium-voltage/low-voltage transformer, whose star–delta winding configuration effectively minimizes their propagation into the analyzed industrial installation.

The absence of a pronounced peak around midday is expected, since this study does not focus on the daily photovoltaic generation profile [12]. Instead, the analysis investigates the electrical behavior during rapid transitions between clear-sky and cloudy conditions over very short time intervals, where the most significant disturbances in power flow and power quality are likely to occur.

Meaningful converter optimization requires defined objectives, identified converters, standardized evaluation criteria, and demonstrated performance improvements through validated analyses.

Transitions between inductive and capacitive operation result from converter control strategies, reactive power regulation, and changing photovoltaic generation conditions.

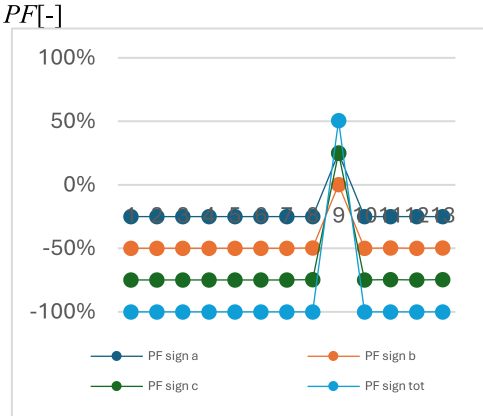
P[W],*Q*[kVAr],*S*[kVA]



Time [consecutive 10-minute intervals]

Fig. 7. Total Active, Reactive and Apparent power profiles (the simultaneous evolution of the three powers over the same time interval)

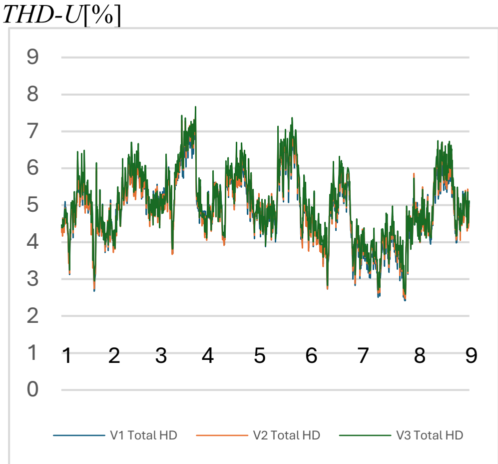
PF[-]



Time [consecutive 10-minute intervals]

Fig. 8. Power factor evolution during the battery charging process (100% is equivalent to a power factor of 1.0).

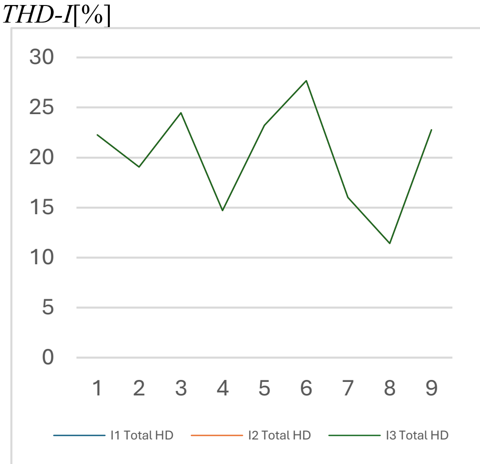
THD-U[%]



Time [consecutive 10-minute intervals]

Fig. 9. Voltage total harmonic distortion (THD_U)

THD-I[%]



Time [consecutive 10-minute intervals]

Fig. 10. Electric Current total harmonic distortion (THD_I)

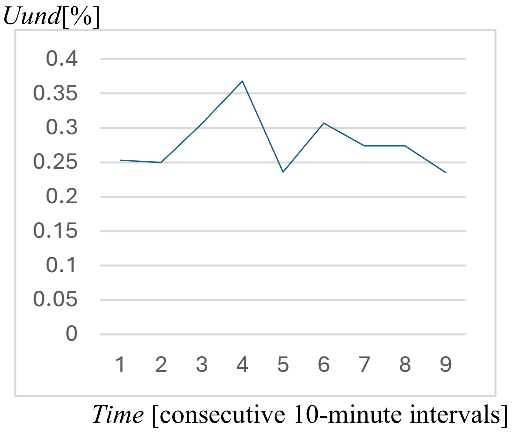


Fig. 11. Voltage Unbalance Profile

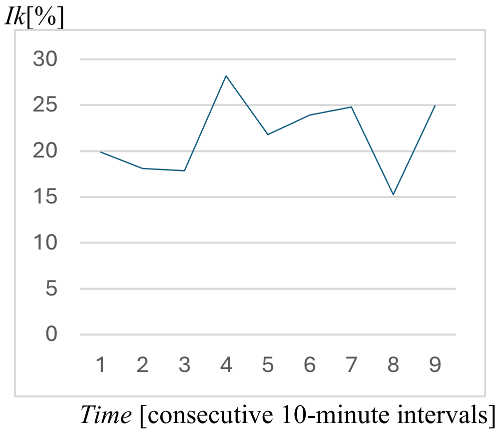


Fig. 12. Negative-Sequence Electric Current Magnitude

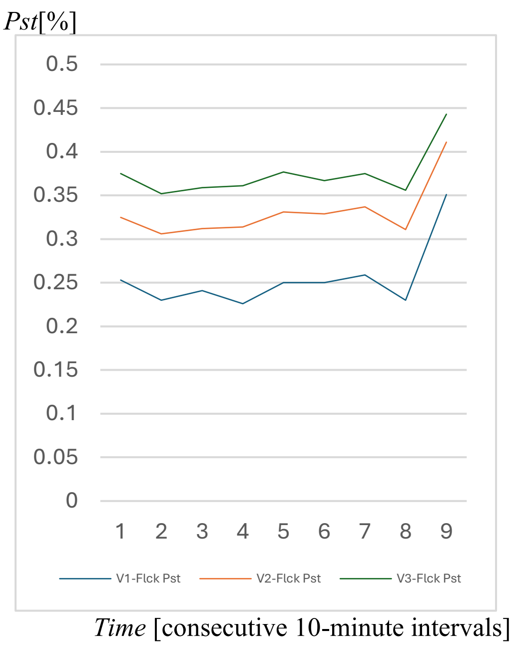


Fig. 13. Short-Term Flicker Severity (Pst) and Long-Term Flicker Severity (Plt) for Phases A, B, and C

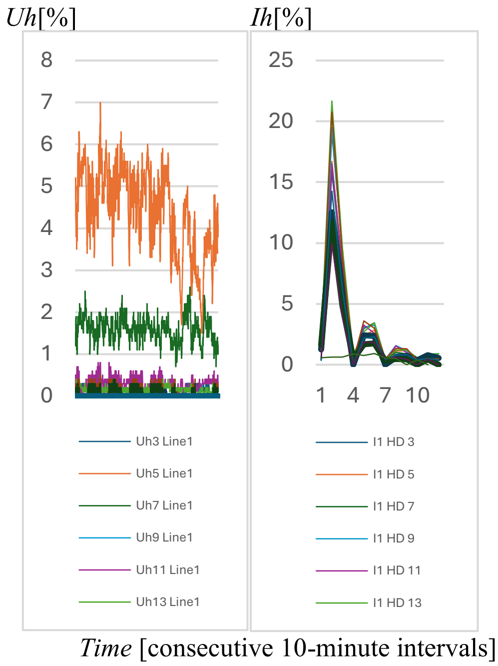


Fig. 14. Voltage and Current Harmonic Components During the Monitoring Period (Similar variations are observed for phases A, B, and C)

The findings demonstrate that continuous power quality monitoring provides the real time information required to optimize converter operation, identify harmonic disturbances, verify compliance with international standards and improves the overall efficiency and reliability of industrial charging systems [9]. Furthermore, the monitored database establishes the foundation for advanced Smart

Grid functionalities, including predictive maintenance, Digital Twin implementation, Battery Energy Storage System (BESS) coordination, artificial intelligence – based energy management and future bidirectional energy exchange. Thereby, supporting the development of secure, resilient and carbon – neutral industrial energy infrastructures.

The experimental research confirms that integrating photovoltaic paired with industrial battery charging systems, supported by continuous power – quality monitoring and Smart Grid technologies, enables highly efficient, reliable and standards – compliant operation [9]. Meanwhile establishing a scalable framework for the future deployment of AI – driven energy management, Battery Energy Storage Systems (BESS), Digital Twins and sustainable smart industrial microgrids.

From Figs. 6 and 7, it can be observed that as the BESS load and consequently the power transmitted by the BESS increases, the system gradually shifts from an inductive operating mode (ergo correctly compensated) to a capacitive one, thereby creating specific operational issues that must be addressed subsequently.

Furthermore, the implementation of Smart Grid technologies, SCADA included, AMI and predictive monitoring platforms, enables continuous supervision of electrical performance, optimizes renewable energy utilization, and optimize the reliability and sustainability of modern industrial charging infrastructure7], being indispensable for the proper operation and effective management of power flows within the analyzed industrial electrical system.

4. Conclusions

Overall, the experimental research confirms that the coordinated integration of photovoltaic package, Battery Energy Storage Systems (BESS), intelligent energy management and continuous power – quality monitoring provides a robust engineering framework or future Smart Grid and Smart City infrastructures, where complex industrial facilities operate as intelligent micro-cities with integrated energy management. Thus, ensuring higher energy efficiency, enhanced operational reliability, improved renewable energy utilization and greater resilience of sustainable urban electrical networks.

The integration of Battery Energy Storage Systems (BESS) into intelligent urban energy infrastructures significantly improves renewable energy utilization, grid flexibility and power quality, thereby supporting the development of greener and low-carbon Smart Cities.

The integration of Battery Energy Storage Systems (BESS) with advanced Energy Management Systems, artificial intelligence, and continuous power quality monitoring improves energy dispatch, reduces peak demand, and enhances grid reliability. Continuous monitoring is essential for maintaining grid-code compliance and stable photovoltaic operation, while short-term power quality disturbances mainly result from rapid variations in solar irradiance caused by cloud movement, changing weather conditions, and sudden transitions between shaded and full-sun operation.

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