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Assessing power quality in individual circuits of industrial electrical system

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ABSTRACT

This article evaluates energy quality in individual circuits within an industrial electrical system and its impact on common connection point parameters. The research is crucial due to rising challenges in power quality arising from increased nonlinear electrical loads in industrial processes. The study involves sequential steps, covering the industrial electrical system´s description, power quality parameters analysis, and issue identification. A comprehensive assessment was conducted on a 3,000 kVA, 13.8 kV/460 V point of common coupling (PCC) transformer, and 10 transformers (10 to 250 kVA) supplying individual circuits. Findings indicated load factors below 70% in all transformers and a power factor below 0.9 in eight. Issues like voltage variation, current imbalance, and harmonic distortion were identified in nine transformers supplying individual circuits, while the PCC exhibited no power quality problems. The research emphasizes the importance of including individual circuits in power quality assessments, as compliance with regulatory limits at the PCC may not guarantee the absence of power quality issues in individual circuits, affecting equipment lifespan and increasing energy losses.

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1. INTRODUCTION

Maintaining electrical power quality is crucial for equipment, preventing disruptions in voltage and current waveforms [1], [2]. Deviations in electromagnetic parameters can lead to faults or improper operation, causing energy and economic losses in both the power electrical system (SEP) and industrial electrical system (IES) [3], [4]. The industrial sector, a significant energy consumer, increasingly relies on electronic equipment, causing non-linear behavior and power quality issues within the IES [5]–[8]. Literature highlights studies characterizing power quality in the industrial sector, revealing prevalent issues such as voltage variations, unbalances, and distortions [9]–[14].

In study [9], harmonic disturbances in the cement industry are assessed through measurements of electromagnetic parameters, revealing voltage and current harmonics caused by non-linear loads. In study [10], it focuses on power quality in the granite slab manufacturing industry, comparing electromagnetic data with international standards and highlighting voltage harmonic issues due to non-linear loads. In study [11], MATLAB® simulation results on an IES in a steel plant show that nonlinear load characteristics generate harmonic currents and flickers. In study [12], it explores power quality in an oil processing plant, emphasizing voltage harmonics' impact on the supply network. The results demonstrate that the nonlinear loads within the IES contribute to power quality issues. In study [13], electromagnetic parameters in a non-ferrous metallurgical industry. Measurements are taken at the point of common coupling (PCC), determining that the non-linear power receivers within the company cause waveform distortions in current and voltage. In study [14], it analyzes harmonics in a hydroelectric plant, identifying major contributors without exceeding quality standards. Fifth and seventh-order harmonics are the major contributors to waveform disturbance in current and voltage. From those above, it is observed that these studies do not delve deeply into examining the effects of power quality parameters in individual circuits concerning the parameters at the PCC.

On the other hand, in the study [15], the authors surveyed the supply conditions of 916 motors in 12 industries in Paraná, Brazil. The survey results revealed that the motors operate at a load lower than the nominal, with slight undervoltage, voltage unbalance, and voltage harmonics. This highlights the importance of conducting power quality studies that consider the PCC parameters and individual circuits' parameters. In [16], a multi-vector approach identified harmonic distortion at specific load terminals and the PCC, assessing each loads impact on distribution line distortion. Faraby *et al.* [17] proposes a coordinated planning technique for radial distribution systems, achieving improved energy quality through simulations with particle swarm optimization. Results show that distributed generation, capacitors, and network reconfiguration effectively minimize energy quality issues. As detailed in [18], the authors initially conducted a study assessing steady-state power quality parameters in an IES. They compared measured and calculated variables with regulatory thresholds, revealing a need for further research into procedures that complement the purpose of power quality standards.

This study evaluates power quality issues in an IES of a metal mechanical company characterized by a high incidence of non-linear loads that impact the operation and lifespan of end-use equipment. Power quality parameters were analyzed both in individual circuits and at the PCC. Compared to existing scientific literature, the main contribution of this study lies in assessing the impact of electrical power quality parameters in individual circuits on the parameters of the PCC. Through this assessment, the aim is to highlight that even when electrical power quality parameters comply with regulations at the PCC in an IES, issues may arise in individual circuits, leading to energy losses and affecting the lifespan of industrial loads.

2. METHOD

This company operates continuously (24 hours a day, seven days a week) and is responsible for designing, manufacturing, and repairing structural components of mining equipment. The technological process in this company extensively utilizes non-linear electrical loads such as electric arc welding equipment, computer numerical control, cutting machines, light-emitting diode (LED) lighting, AC-DC inverters, and variable-speed compressors. The non-linearity of these loads causes power quality issues, leading to operational failures in the plant's equipment. For the assessment of electrical power quality parameters, a series of sequential steps based on the NTC 5001 [19], NTC 1340 [20], and IEEE 519 [21] standards were implemented. Figure 1 depicts a flowchart of the implemented steps.

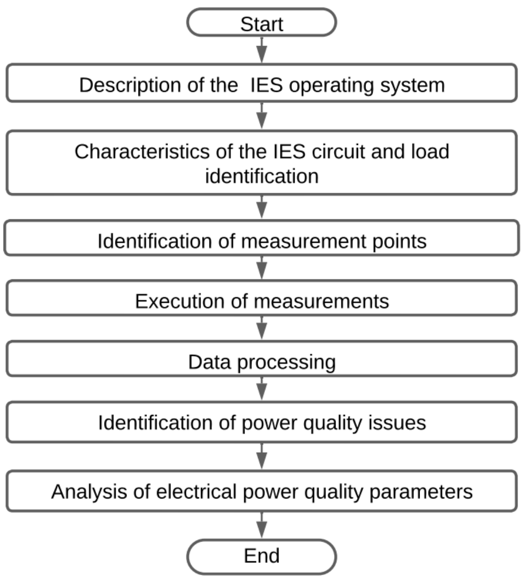

Figure 1. Flowchart of the implemented steps for the analysis of power quality in IES

Step 1: Description of the IES operating system

This step involves gathering initial information about issues affecting the electrical power quality in the IES. The process is carried out through interviews with administrative and operational staff in the industry, who provide information about equipment experiencing operational issues, their location within the IES, and the periods during which the problems occur. This case study conducted interviews with maintenance, operational staff, and department heads of the industry. From the interviews, the following issues were identified: Sudden trips in electrical protections, misconfiguration of cutting machines, and management of capacitor banks.

Step 2: Characteristics of the IES circuit and load identification

This step involves analyzing and verifying the single-line diagram through a plant walkthrough. Additionally, it consists in identifying non-linear electrical loads and their operational patterns. The electrical system is depicted in Figure 2, comprising a main transformer of 3,000 kVA with a transformation ratio of 13.8 kV/460 V and 10 secondary transformers of various capacities ranging from 10 to 250 kVA. These circuits power the administrative offices, welding and manufacturing workshops, painting workshops, kitchen, and all housing equipment with non-linear load characteristics.

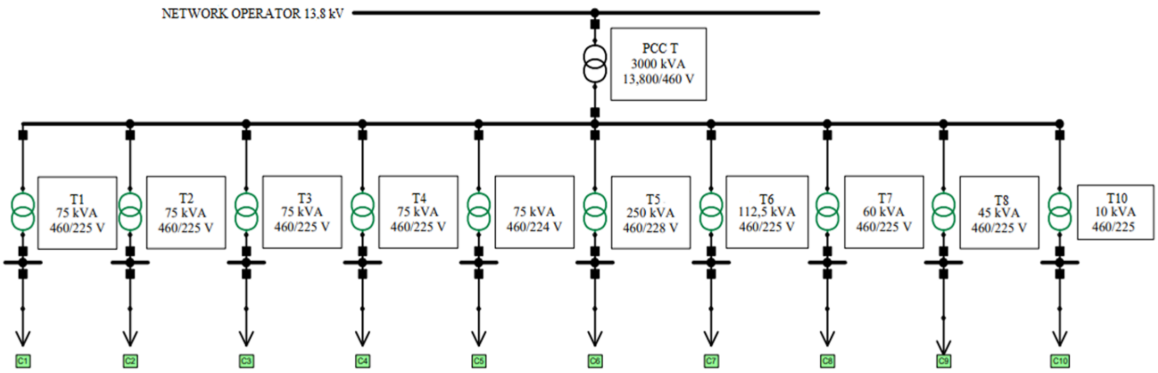

Figure 2. Single-line diagram

Step 3: Identification of measurement points

Points for measuring electromagnetic parameters related to electrical power quality are identified and defined. Data from the transformers (T) at the connection points are also collected. In this case study, measurements were taken at the PCC transformer and individual circuit transformers of the IES.

Step 4: Execution of measurements

Measurements are conducted following the guidelines set by standards, regulations, and norms [19]–[22]. The measurement equipment must comply with IEC 61000-4-30 [23] standards and be classified as Type A or B, depending on the scope of the study, and should have valid calibration. The measurement duration should encompass at least one complete power cycle [22], within minutes if the power is constant, a typical day, a week, or even more extended periods. However, according to the NTC 5001 [19] standard, the measurement period for different power quality parameters must be at least one uninterrupted week. In this case study, the measurement period lasted one week, and samples were taken every minute. Measurements were conducted simultaneously at selected points to assess the correlation between electromagnetic parameters. The measured variables were as follows: line voltage (V), line currents (I), active power (P), reactive power (Q), apparent power (S), power factor (PF), total harmonic distortion of voltage (THDv), total demand distortion (TDD), individual voltage harmonic distortion (IVD), and individual current harmonic distortion (IID).

Step 5: Data processing

This step involves organizing, validating, and conducting a statistical probability analysis to identify the percentage of data that exceeds the established limits [24]. Based on the measured variables, the parameters for load factor (L_f) in (1), voltage variation (V_v) in (2), voltage unbalance (PVU) in (3), and current unbalance (PIU) in (4) are calculated.

a. Load factor

$$L_f = 100\frac{S_t}{S_n} \quad (1)$$

where S_t is the total apparent power and S_n is the nominal apparent power.
b. Voltage variation

$$V_v = \frac{V_{avg}}{V_r} \tag{2}$$

where V_{avg} is the average line voltage and V_r is the rated voltage.
c. Voltage unbalance [19]

$$PVU = 100\,\frac{máx(|V_{ab}-V_{avg}|;|V_{bc}-V_{avg}|;|V_{ca}-V_{avg}|)}{V_{avg}} \tag{3}$$

where, V_{ab}, V_{bc}, V_{ca} are the line voltages and V_{avg} is the average line voltage.
d. Current unbalance [19]

$$PIU = 100\,\frac{máx(|I_a-I_{avg}|;|I_b-I_{avg}|;|I_c-I_{avg}|)}{I_{avg}} \tag{4}$$

where, I_a, I_b, I_c, are the line currents and I_{avg} is the average line current.
Step 6: Identification of power quality issues

Problem identification is conducted in a low-voltage IES using statistical methods. It is carried out by comparing processed data with the limits established in the standards NTC 5001 [19], NTC 1340 [20], and IEEE 519 [21]. Table 1 summarizes the recommended limits in the mentioned standards.
Step 7: Analysis of electrical power quality parameters

Table 1. Limits adopted by the standards

Electromagnetic parameter	Admissible limits	Standard
Voltage variation	5% overvoltage and 8% undervoltage.	NTC 1340-2013 [20].
Voltage unbalance	Maximum limit of 2%.	NTC 5001-2008 [19].
Current unbalance	Maximum limit of 20%.	NTC 5001-2008 [19].
Voltage harmonics	IVD < 5% and THDv < 8% in 95% of the recorded period.	IEEE Std 519 TM-2014 [21]
Current harmonics	For ISC/IL between 20<50, the ICD limits are 7.0 for (3≤h<11), 3.5 for (11≤h<17); 2.5 for (17≤h<23), 1.0 for (23≤h<35), and 0.5 for 35≤h<50 in 95% of the recorded period. The TDD < 8% in 95% of the recorded period.	IEEE Std 519 TM-2014 [21]

This involves analyzing the relationship between the parameters measured at the PCC and in the individual circuits. It includes conducting a correlation analysis among the variables, which further allows for establishing the influence of the power quality parameters of the individual circuits on the parameters at the PCC.

3. RESULTS AND DISCUSSION

This section presents the results obtained from the survey over a week, with samples taken every minute, regarding the power quality issues identified in the industry. These diagrams represent the distribution of the collected data, displaying quartiles along with their mean value and outliers. Notably, 75% of the recorded data will be depicted within the box in the diagram, allowing the identification of cases with more significant deviations. Figure 3 displays the box and whisker plot of the load factor at the PCC and in the individual circuits. Figure 4 displays the box and whisker plot of the power factor at the PCC and in the individual circuits. The upper and lower limits allowed according to the regulations [25] are also presented in the figure.

Figure 3 shows that 100% of the transformers are operating at low load. A more detailed analysis of the data reveals the following average loads: T1 is 34.4%, T2 is 40.6%, T3 is 12.1%, T4 is 4.41%, T5 is 13.8%, T6 is 40.9%, T7 is 20.7%, T8 is 2.57%, T9 is 1.01%, T10 is 35.2% and for the PCC T is 12%. Figure 4 shows that transformers T2, T3, T4, T5, T7, T8, T9, and T10 are experiencing low power factor issues as they lie outside the range recommended by resolution CREG 015-2018 [25]. Figure 5 displays the results of voltage variation at the PCC and in the individual circuits. The figure also presents the upper and lower limits allowed according to the regulation [20]. Figure 6 displays the results of voltage unbalance in both the PCC and individual circuits. It also illustrates the maximum allowed limit as per the regulation.

Figure 5 shows that transformers T3, T4, T5, T6, T8, and T10 exhibit voltage variation issues, with T4 and T8 displaying the highest percentage of data outside the limits set by the NTC 1340 [20]. A more detailed analysis reveals that the data rate outside the standard's limits for T3 is 3%, for T4 is 46%, for T5 is 2%, for T8 is 12%, and for T10 is 1%. In Figure 6, none of the transformers exceed the standard limit regarding voltage unbalance [19]. Figure 7 displays the results of the current unbalance in both the PCC and individual circuits. According to the NTC 5001 [19], the maximum allowable limit is also represented.

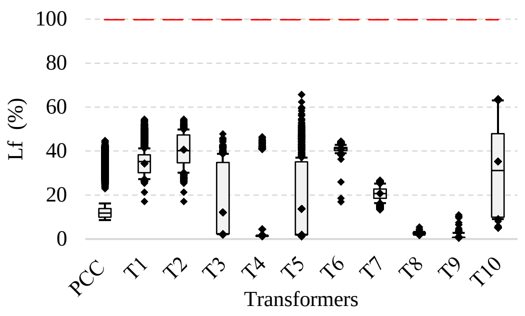

Figure 3. Load factor

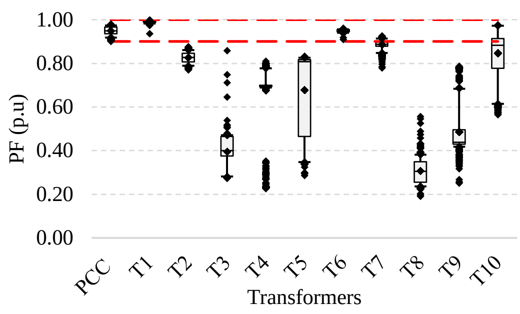

Figure 4. Power factor

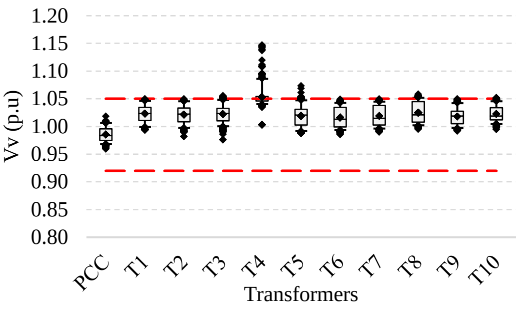

Figure 5. Voltage variation

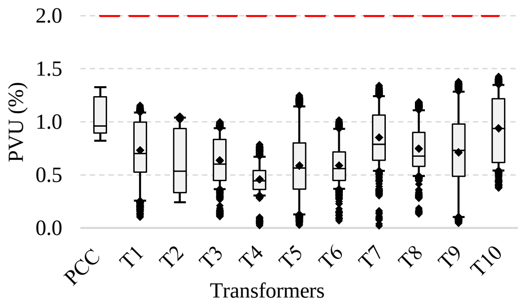

Figure 6. Voltage unbalance

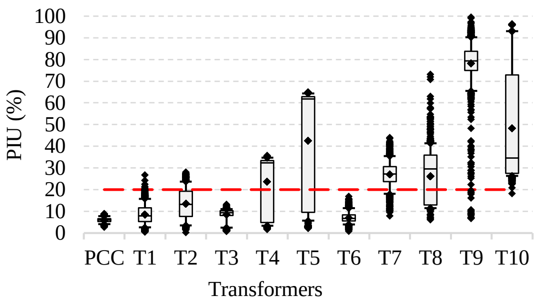

Figure 7. Current unbalance

In Figure 7, it can be observed that transformers T1, T2, T4, T5, T7, T8, T9, and T10 exhibit current unbalance beyond the limits established by the standard. A more detailed analysis of the data reveals that the percentage of data beyond the standard limits is as follows: in T1, 0.5%; in T2, 20.8%; in T4, 67.4%; in T5, 67.4%; in T7, 90.8%; in T8, 61.3%; in T9, 98.8%; and T10, 99.9%. Only T2, T4, T5, T7, T8, T9, and T10 exceed the established limits in more than 5% of the measurements [19].

Figure 8 displays the total harmonic distortion of voltage results in the PCC and individual circuits. It also depicts the maximum allowable limit according to the standard [21]. Figure 9 shows the total harmonic current distortion in the PCC and the individual circuits. It also represents the maximum limit allowed according to IEEE Std 519 [21].

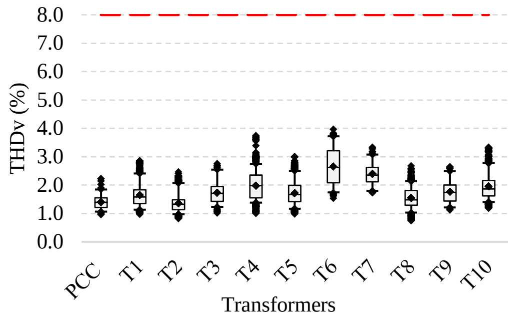

Figure 8. Total harmonic distortion of voltage

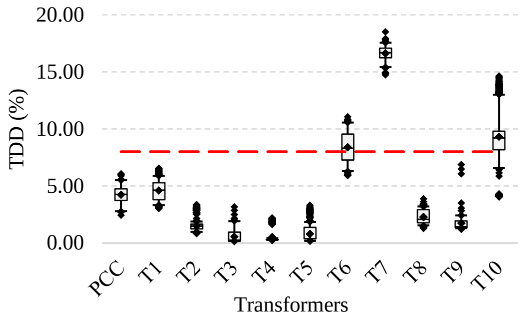

Figure 9. Total demand distortion

Figure 8 shows that none of the secondary transformers are above the limit established by the standard concerning the total harmonic distortion of voltage [21]. Likewise, it is noticeable that the THD is less than 5% in all transformers, ensuring that no individual voltage harmonic exceeds this limit. Figure 9 shows that the transformers T6, T7, and T10 show current distortion beyond the limit established by the standard [21]. A more detailed analysis reveals that the percentage of data outside the standard limits for T6 is 60%, for T7 is 100%, and for T10 is 79%. The results obtained from current distortion require presenting the results obtained from individual harmonic components to verify compliance with their limits.

Figure 10 presents the maximum-recorded value of the 3rd, 5th, 7th, and 9th order harmonics among all harmonics. Figure 11 displays all transformers' maximum registered values of the 11th and 13th-order harmonics. Figure 10 shows that transformers T1, T6, T7, and T10 exhibit individual harmonic distortion values of current above the limits [21]. In addition, transformers T2, T3, T4, T5, T8, T9, and the PCC T do not present harmonic issues. Figure 11 shows that transformers T7 and T10 exhibit maximum values of individual current harmonic distortion above the limits [21]. In addition, transformers T1, T2, T3, T4, T5, T6, T8, T9, and the PCC T do not present harmonic issues.

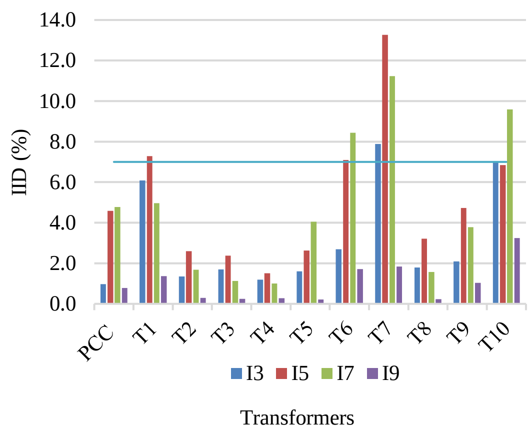

Figure 10. Individual harmonic distortion of current of 3rd, 5th, 7th and 9th order

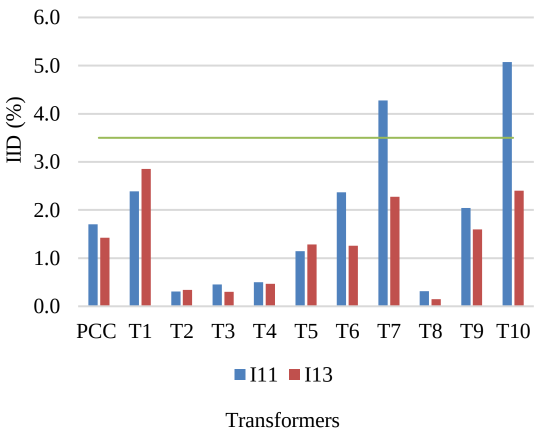

Figure 11. Individual harmonic distortion of current of 11th and 13th order

Figure 12 depicts a bar chart showing the percentage of data for the 3rd, 5th, 7th, and 11th-order harmonics from transformers T1, T6, T7, and T10, where measurements exceed the limits set by the regulation [21]. Figure 12 shows that in T1, 0.1% of data exceeds the maximum standard for the 5th-order harmonic, while in T6, it is 1.4%. For T10, 1.3% of data surpasses the maximum standard for the 3rd-order harmonic, but this occurs in less than 5% of the measured data. However, transformers T6, T7, and T10 exceed established limits in over 5% of measurements [21]. In T6, 25.2% of the data for the 7th-order harmonic exceeds the maximum. In T7, 32.6% for the 3rd-order, 100% for the 5th and 7th-order, and 40.4% for the 11th-order harmonic exceeds the maximum. In T10, 17.4% of the 7th-order and 14.1% of the 11th-order harmonic exceeds the permitted maximum.

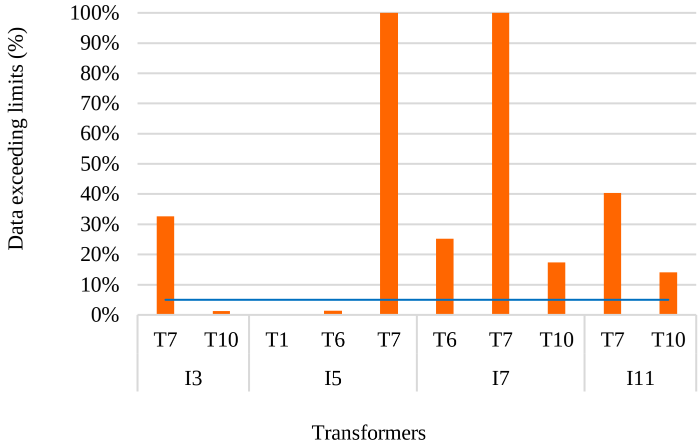

Figure 12. Percentage of data with individual harmonic distortion of current exceeding the limit established by the regulation

The results of the evaluation of energy quality allow for the following analysis: All transformers from individual circuits within the IES, including the PCC T, operate with an average load below 50%. Eight of the 10 transformers from individual circuits within the IES exhibit a low power factor. Five out of the 10 transformers from individual circuits within the IES do not meet the established limits for voltage variation. Seven of the 10 transformers from individual circuits within the IES do not comply with unbalanced limits. Three of the 10 transformers from individual circuits within the IES do not meet total harmonic distortion limits for current. Three of the 10 transformers from individual circuits within the IES do not meet individual harmonic distortion limits for current. The PCC does comply with all power quality parameters established by the standards.

4. CONCLUSION

This paper assesses the influence of electrical power quality parameters on individual circuits concerning the parameters at the PCC. The assessment was conducted in a case study of an IES with a high incidence of non-linear loads. The results reveal that nine out of 10 transformers in individual circuits exhibit issues related to electrical power quality. Eight transformers show a low power factor, all transformers operate at low load, five transformers experience voltage variation problems, seven transformers face current imbalance issues, three transformers exhibit total current harmonic problems, and three transformers display individual current harmonic distortion problems. However, the PCC does not manifest any electrical power quality issues.

The results indicate that electrical power quality parameters in an IES may comply with regulatory limits at the PCC; however, issues regarding electrical power quality might arise in individual circuits. This demonstrates that while standards establish assessment methodologies and permissible values for parameters related to electrical power quality at the PCC, it is necessary to include the analysis of individual circuits in power quality assessment procedures. Within these circuits, loads are connected that can reduce their lifespan and cause energy and economic losses in industries.

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