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NEW ACHIEVEMENTS IN IMPROVING PQ IN PCCS WITH HIGH DISTORTION AND UNBALANCE BY IMPLEMENTING APFS. PART 1: EXPERIMENTAL INVESTIGATION AND PQ ANALYSIS

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Abstract: The paper presents the results of the analysis of the power quality in the point of common coupling of an internal network of an industrial enterprise, following the recording of the energy parameters in the critical load interval. The equivalent load in the point of common coupling (PCC) consists mainly of nonlinear single–phase loads, which makes the phase powers to be strongly unbalanced. The recordings made and their processing highlighted the poor power quality and the need to identify an appropriate solution to improve the power quality. It was proposed to use a four–wire shunt active power filter (SAPF) with split filtering capacitor.
Keywords: three–phase four–wire active power filter, power quality, nonlinear load, harmonic distortion

1. INTRODUCTION

The problems caused by the poor quality of electricity in the distribution networks are multiple and have been the subject of many scientific papers. [2,13,16,20,22] In Mertens at al. [13], a broad view of the situation of the electrical distribution system with respect to short–duration voltage variation, harmonic and voltage imbalance phenomena is provided. In internal distribution networks, which are usually three–phase four–wire networks, consumers have a great diversity, the required powers vary frequently and within wide limits, and current harmonics and unbalanced charging of phases determine the most important harmful effects. [8,17,21]

The existence of many single–phase nonlinear loads (such as personal computers, printers and air conditioning) has generated very important power quality problems in three–phase four–wire low voltage systems. [1,6,7,18,19] Although attempts are being made to balance the single–phase loads, the incomplete balancing leads to the existence of a current through the neutral wire [19]. On the other hand, significant third–order harmonics result in the neutral wire charging even 70% more than the line wires [1]. Several case studies are presented in [7] to illustrate some characteristics of the power quality specific to the common computer systems.

A comprehensive analysis of the total harmonic distortion factor (THD) associated to some laptops provided by different companies is shown in [6] and illustrates values over 70%.

As many nonlinear loads exist and the associated powers are not constant usually, the current harmonics pollution and the unbalanced operation are among the most common problems. In order to solve the power quality (PQ) problems, there are many solutions illustrated in the literature, such as the simple passive filtering, the use of dedicated transformers or the powerful shunt active power filters (SAPFs). [4–6,8,10,12,14,15,18,19]

The common solution of active power filtering adopted in the low voltage systems is based on the use of voltage source inverters. In the distribution networks within enterprises, three–phase four–wire SAPFs are required. Although there is a four–leg topology of SAPF in the literature, the three–leg SAPF with split capacitor is preferable, as it uses fewer switching legs, with implications in cost and complexity. In the four–leg main circuit structure, eight IGBTs and four coupling reactors are required. The three–leg SAPF structure with split capacitor presented in [14] is used to compensate the harmonics, reactive power and zero–sequence current.

In this paper, the case study of power quality improvement in a department of a large Romanian enterprise are presented. The recorded energy parameters in the point of common coupling (PCC) with the distorting loads for several hours show that the following three objectives must be met: the currents harmonic distortion mitigation and compensation of both reactive power and current unbalance. The remaining of the paper is organized as follows. Section 2 presents the power quality indicators of the nonlinear load taken into consideration as a case study. The substantiation of the solution for the power quality improvement is then presented in the next section. Finally, some concluding remark are drawn. The part II of the paper presents the conceived shunt active power filtering system, the structure of the control part and the control algorithm implementation on a dSPACE DS1103 PPC controller board. The experimental results illustrate the active filtering performance and validate the proposed solution to meet the three identified compensation objectives (current THD, reactive power and current unbalance).

2. POWER QUALITY INDICATORS OF THE NONLINEAR LOAD

The nonlinear load taken into consideration in order to improve the power quality consists of a group of single–phase consumers in a department of a Romanian enterprise. The recording of the energy parameters in PCC with the nonlinear load was made on December 8, 2020 starting at 11:02 a.m. by a dedicated power quality analyzer (Fluke 435). The acquisition sample time was 5 seconds. In addition, a Fluke 41B power quality analyzer and the waveforms of currents recorded the power quality indicators over one period and voltages were oscillographed (Figure 1).

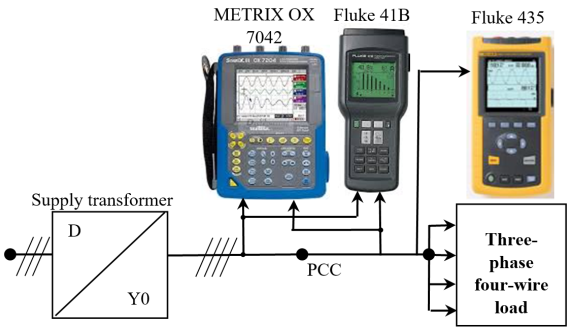

Figure 1. The block diagram of the experimental platform

The analyzed power quality indicators were: phase current distortion factors calculated with the first 50 harmonics (Figure 2); the rms values of the phase currents (Figure 3); phase power factors (Figure 4); unbalance of phase active powers (Figure 5); phase reactive powers (Figure 6). The analysis refers to the evolution of these indicators according to the recording number (n). Thus, the corresponding time can be obtained based on the expression:

$$t = 11h:02m + 5s \cdot (n - 1). \tag{1}$$

As it can be seen in Figure 2, the current distortion factors differ greatly from one phase to another and have rapid variations. In the first phase, the highest values (over 50%) were recorded and are maintained for more than half of the recording interval, and the maximum value recorded is 55%. In the second phase, values around 30% were recorded for about half the time, but there are also time intervals when the recorded values are over 50%. The maximum value recorded is about 54%. On the third phase, slightly variable values around (13–14) % were recorded most of the time, but there are two intervals in which values of over 30% were recorded. This last aspect seems to be periodic.

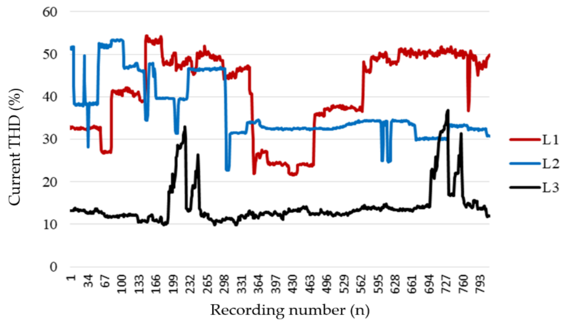

Figure 2. Harmonic distortion factor of the phase currents during recordings

The rms values of the phase currents (Figure 3) show the strong unbalance of the currents on the three phases and their frequent and fast variations. The lowest values were recorded on the first phase, varying between 7A and 15A. The highest values (between 10A and about 25 A) were recorded on the second phase. On the third phase, the current is (14–15) A for the longest time and has two decreases to (10–12) A. The neutral wire current, which is important (between 7A and 13A) and frequently variable, shows the existence of a severely unbalanced regime.

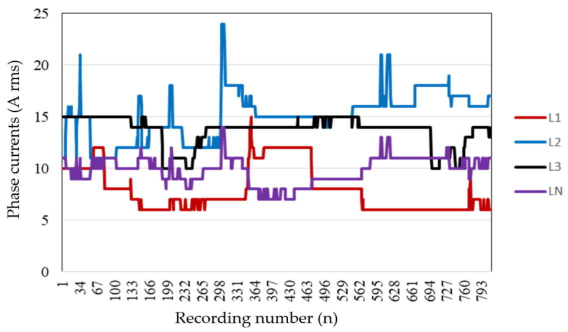

Figure 3. RMS values of the phase currents during recordings

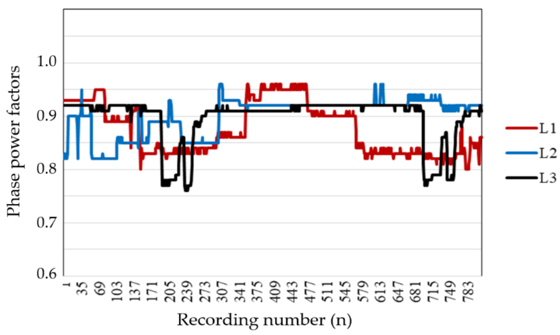

Figure 4. Phase power factors during recordings

The evolution of the phase power factors (Figure 4) is as follows: on the first phase, between 0.83 and 0.97, with frequent and fast variations; on the second phase, between 0.82 and 0.97; on the third phase, between 0.76 and 0.92. An even more eloquent indicator of the phase load unbalance is the deviations of the active powers on each phase from the average per phase of the total active power (Figure 5). It is found that: the biggest unbalance is registered on the first and second phases (–60% on the first phase and over + 70% on the second phase). On the third phase, the unbalance changes between –20% and + 40%.

The strong unbalance of the load is also shown by the evolution of the reactive powers on phases (Figure 6). The following is observed: on phase A, the reactive power requirement is reduced (average value is about 225 VAR) and there are two peaks of about 500 VAR for short periods of time; on phase B, the reactive power is mainly between 650 VAR and 800 VAR, but it has four rapid increases (1000–1200) VAR; on phase C, the reactive power is significant (about 1200 VAR) and less variable than on the other phases.

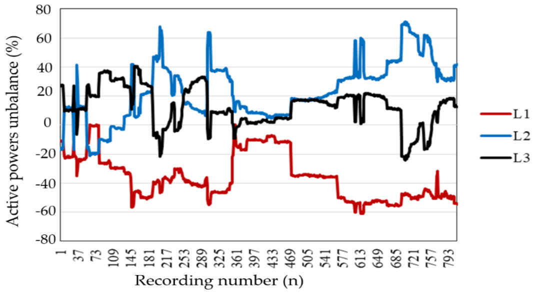

Figure 5. Active powers unbalance during recordings

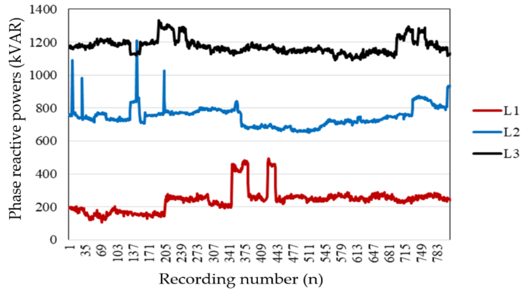

Figure 6. Phase reactive powers during recordings

Following the analysis, several conclusions are highlighted regarding phase unbalance in the considered PCC.

1. There is a strong unbalance of the distortion power highlighted by the different degree of current distortion in phases (Figure 2).
2. There is a strong unbalance of active power highlighted by its degree of unbalance in phases (Figure 5).
3. There is a strong unbalance of reactive power highlighted by its different values in phases (Figure 6).
4. There is a strong global unbalance of currents, highlighted by their different rms values in phases (Figure 3).

3. SUBSTANTIATION OF THE SOLUTION FOR PQ IMPROVEMENT

For the improvement of the identified PQ problems in the case study considered, the adopted solution consists in connecting a three–phase three–leg four–wire shunt active power filter.

In the operation of SAPF, the powers specific to the unbalanced and nonsinusoidal regime intervene, as follows:

≡ Active power per phase (P_{Li}) and total active power (P_L) calculated as the sum of active powers per phases (P_{LA}, P_{LB}, P_{LC}).

$$P_L = P_{LA} + P_{LA} + P_{LC}; \tag{2}$$

≡ Total reactive power (Q_L), as the sum of reactive powers in phases (Q_{LA}, Q_{LB}, Q_{LC}),

$$Q_L = Q_{LA} + Q_{LA} + Q_{LC}; \tag{3}$$

≡ The total apparent power at the load terminals (S_L) calculated by the expression proposed by Buchholz for unbalanced and non–sinusoidal regime [3], [11],

$$S_L = \sqrt{(U_A^2 + U_B^2 + U_C^2) \cdot (I_A^2 + I_B^2 + I_C^2)}, \tag{4}$$

where U_A, U_B, U_C and I_A, I_B, I_C are the phase voltages and currents (rms values);

In order to establish the SAPF power to achieve the total compensation, the apparent power to be compensated was calculated, taking into account the following requirements:

≡ The SAPF system must compensate the distortion power (D),

$$D = \sqrt{S_L^2 - (P_L^2 + Q_L^2)}, \tag{5}$$

≡ The SAPF system must compensate the reactive power (Q_L);

≡ The SAPF system must compensate the active power unbalance (P_{LU}), calculated as:

$$P_{LU} = \sum_{i=A}^{C} \left| P_{Li} - \frac{P_L}{3} \right|, \tag{6}$$

Thus, the apparent power to be compensated (S_C) is:

$$S_C = \sqrt{D^2 + Q_L^2 + P_{LU}^2} = \sqrt{S_L^2 - P_L^2 + P_{LU}^2}. \tag{7}$$

The graphic representation of S_C during the recordings (Figure 7) highlights the following aspects:

≡ The values evolve between 3.5 kVA and 7.2 kVA with an average value of about 5 kVA;

≡ The maximum value of 7.2 kVA corresponds to the 304 record, and values over 7 kVA are maintained for 30 seconds.

As a result, the use of a three–phase three–leg four–wire SAPF with rated power S_{FN} = 8 kVA was proposed.

The recorded phase voltages and load phase currents in the most unfavorable situation are illustrated in Figure 8 and Figure 9 respectively.

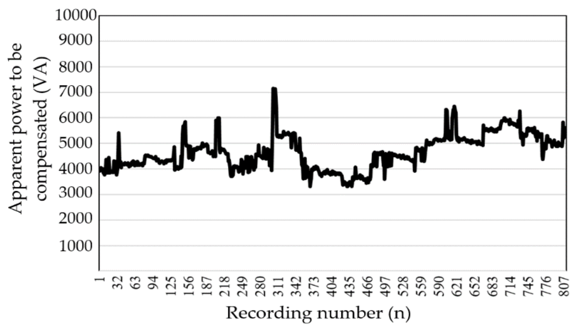

Figure 7. Apparent power to be compensated

The harmonic spectra of the load currents (Figure 10) show that the most important harmonics are of the 5th order on phase A and 3rd order on phases B and C.

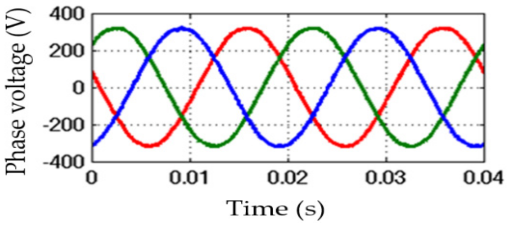

Figure 8. Waveforms of phase voltages: v_A – in red; v_B – in green; v_C – in blue.

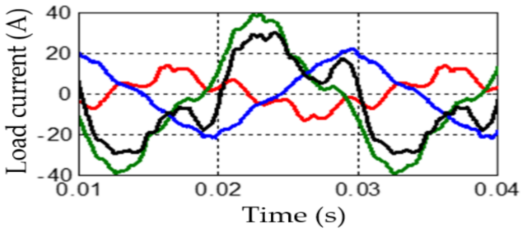

Figure 9. Waveforms of load phase currents: i_{LA} – in red; i_{LB} – in green; i_{LC} – in blue; i_{LN} – in black.

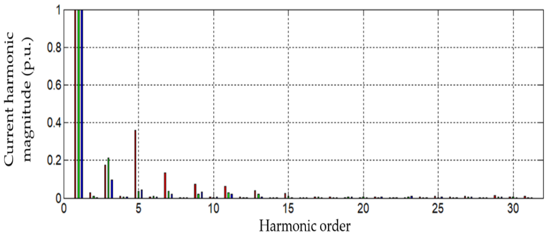

Figure 10. Harmonic spectra of load phase currents (for i_{LA} - in red; for i_{LB} - in green; for i_{LC} - in blue).

4. CONCLUSIONS

The investigations conducted in this paper on the power quality indicators in a compartment of a large Romanian enterprise illustrated the necessity of compensation the current harmonic distortion, the reactive power and load unbalance.

The recorded energy quantities revealed high values of load current THD (maximum 55%). The highest value of the load unbalance index was about 70 %. The lowest power factor on a phase was 0.76.

The most unfavorable situation from the point of view of the apparent power to be compensated was identified. It corresponds to highest compensating power of 7.2 kVA. Therefore, the installation of a three–phase three–leg four–wire SAPF with rated apparent power of 8 kVA was proposed.

The design of the SAPF, the proposed control algorithm and its implementation on an experimental setup, together with the performance of the active filtering system are presented in the part II of the paper.

Note: This paper was presented at XXth National Conference on Electric Drives – CNAE 2021/2022, organized by the Romanian Electric Drive Association and the Faculty of Electrotechnics and Electroenergetics –University Politechnica Timisoara, in Timisoara (ROMANIA), between May 12–14, 2022 (initially scheduled for October 14–16, 2021)

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