The power factor and the upper harmonics

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Abstract. Upper harmonics that occur in electrical installations due to the use of semiconductor components increases the angle of phase difference between the voltage and the current of a phase. Following this, the power factor decreases, which necessitate, then, installations to compensate for it – to reduce or cancel the upper harmonics. In this work we present a case study on how upper harmonics influence the power factor. This work has been supported by Project CNFIS-FDI-2018-0282.

1. Introduction
In single-phased circuits with a sinusoidal voltage and current variations, the power factor is defined as the cosine of the angle of phase difference between these two entities [1]. For installations that operate under alternating, non-sinusoidal current, we define the following power types:
- Active power, P:
  \[ P = \sum_{\nu=1}^{n} U_{\nu} \cdot I_{\nu} \cdot \cos \varphi_{\nu} \quad [W] \]  
  where \( U_{\nu} \) and \( I_{\nu} \) are the real values of the phase voltage and the phase current, corresponding to the \( \nu \) level harmonics, while \( \varphi_{\nu} \) is the phase displacement between the current \( I_{\nu} \) and the phase voltage \( U_{\nu} \). This power is translated to mechanical work or other active type of energy.
- Reactive power, Q:
  \[ Q = \sum_{\nu=1}^{n} U_{\nu} \cdot I_{\nu} \cdot \sin \varphi_{\nu} \quad [Var] \]  
  which is the average oscillatory power value that is exchanged between the consumer and the source as the energy of the windings’ electromagnetic field or as the energy of the capacitors’ electric field.
- Distorting power, D:
  \[ D = \sum_{\nu,\lambda=1}^{n} U_{\nu}^2 \cdot I_{\lambda}^2 - 2 \cdot U_{\nu} \cdot U_{\lambda} \cdot I_{\nu} \cdot I_{\lambda} \left( \cos \varphi_{\nu} - \cos \varphi_{\lambda} \right) \quad [Var] \]
where $\nu$ and $\gamma$ are the harmonic degrees for two different harmonics.

- Aparent output, $S$:

$$ S = P^2 + Q^2 + D^2 \quad [VA] \quad (4) $$

For circuits where upper harmonics occur, the power factor, $\lambda$, is defined as the ratio between the active and aparent output [2], [3]:

$$ \lambda = \frac{P}{S} \quad (5) $$

Equations (1), (2) and (3), (4) are represented by the power triangle and the parallelepiped, respectively (Figure 1).

The distorting power, $D$, in Figure 1 leads to a large phase displacement between the terminal voltage and the current, which causes a small power factor (below the neutral one of 0.9) [4]. The power factor is characterising the electricity consumer. A small power factor value leads to needless load of the synchronous generators as well as of the electric transportation and distribution lines, with negative impacts on the energy bill which contains the used reactive energy. For this reason an adjustment of the user’s power factor is necessary.

The use of capacitator batteries to adjust the power factor is significantly expensive, and does not reduce nor eliminate the upper harmonics. At the same time, using such batteries, resonance phenomena may happen [5]. Therefore, to reduce the upper harmonics and the reactive and distorting powers it is indicated that resonance circuits L-C are used, circuits which reduce the phase shift between the phase voltage and phase current, for each phase, and increases the power factor above the neutral value [6-8].

The installations to adjust power factors use reactive coils to protect the capacitator against harmonic distortions in the network introduced by equipment with integrated high power electronics.

To correct the wave form and to adjust the power factor, industrial appliances use automated electronic controllers which exactly establish the necessary capacity depending on the values of the active, reactive, and distorting power [9-12].
2. Case study

The installation we use to testify for the statements in the previous section use the UniTrain test bench and an experimenting module to raise the power factor by reducing the harmonics content.

The experimenting module is connected to the “Experimenter” adaptor in the UniTrain bench. This adaptor has two d.c. power sources (5 V and 15 V) as well as a three-phase voltage source [13].

The experimenting module (Figure 2) to compensate the power factor consists of: two 330 Ω/8 W loading resistances, a power correction circuit, and a circuit with a simple rectifier. The power correction circuit is done at 15 V. Similar systems that have a correcting controller and which measures the voltage and current values are used also for real-time power factor adjustments [14].

![Figure 2. Experimenting module](image)

Our analysis is done for a circuit with a simple rectifier, then for the circuits that commands the harmonic dampening and the power factor adjustment. Figures 3 and 4 show the schematics of the two analysed cases. The rectifier is a.c. powered at terminals V1-V2. The arrows indicate where the voltage and current measurements are done.
Figure 3. Simple rectifier circuit schema

Figure 4. Harmonics dampening circuit schema

Figure 4 also shows a power factor correction circuit (PFC) whose role is to reduce or cancel the upper voltage and current harmonics, reducing the distorting power and increasing the power factor.

3. Experimental findings
We experimented with the two circuits shown in Figures 3 and 4. Realizing the schema in Figure 3 allows us to determine the a.c. power voltage variation and the corresponding voltage harmonics variation, in the absence of load (no-load run), see Figures 5 and 6. We note that in the absence of a load, there are no harmonics of the power voltage.
When we connect a load resistance, the power voltage wave shape is distorted (Figure 7) and low amplitude harmonics of level 3, 5, and 7 occur in both load voltage and load current (Figures 8 and 9, respectively). The c.c. voltage provided by the rectifier is almost constant around 22.9 V (Figure 7).
The a.c. variation diverges quite a lot compared to the sinusoid variation, causing even order harmonics (levels 2, 4, and 10) and odd level harmonics (levels 3, 5, 7, 9, 1, 13, 17, and 19). We note that the amplitude of the level 3 harmonic is almost equal to the amplitude of the fundamental harmonics, contributing considerably to the distorted power. Note, also, that the level 5 harmonics has an amplitude of approximately 64% of the fundamental harmonics. Thus, the power factor will be quite reduced (Figure 8).
On Figure 10 we read the active, reactive and distorted power values as: $P = 1.4 \, \text{W}$, $Q = 0.5 \, \text{VAr}$, $D = 1.9 \, \text{VAd}$. We can compute the apparent output $S = 2.41 \, \text{VA}$. The power factor computed with relation (5) is, then:

$$\lambda = \frac{1.4}{2.41} = 0.58$$

(6)

For this power factor value, the reactive energy cost is comparable with the cost of the active energy. In this case we must correct for the Power factor.

Using now the wiring in Figure 4, to dampen the harmonics and adjust the power factor, we observe that for a no-load circuit operation the waveform of the power voltage is sinusoidal.
(Figure 11) and has no harmonics (Figure 12). The output voltage is lower by 1 V, being almost linear. The current absorbed from the source, during no-load operation, has a lower value, but higher than during the non-PFC operation. Figure 13 shows: a continuous component of approximately 0.025 A, even components harmonics (levels 2 and 4) with dampened amplitudes, and odd harmonics (levels 3, 5, 7, 9, 11, 13). We note that the amplitude of the level 3 components is of approximately 0.03 A, that is almost 3 times higher than the amplitude of the fundamental.

Figure 11. Voltage and current variations during no-load operation, with PFC

Figure 12. Power voltage harmonics for no-load operation, with PFC
Connecting a load we note a very slight alteration of the a.c. power voltage wave form (Figure 14), the occurrence of a level 3 voltage harmonics (Figure 15) whose amplitude is approximately 0.0185 of the amplitude of the fundamental harmonic, while we can neglect the level 5 and 7 harmonics.

The absorbed current measured at the power source has a variation shape much more closer to a sinusoidal shape, being in the same phase with the power voltage. The level 3 harmonics have a approximately 13% amplitude of the fundamental harmonic amplitude (Figure 16). We note the presence of level 7 and 9 harmonics, with an amplitude of approximately 4.6% of the fundamental harmonic amplitude. Among the even order harmonics we note the presence of the level 4 harmonic whose amplitude is of about 5.6% of the fundamental harmonic amplitude.
Reducing the power current harmonic amplitudes reduces the distorting power and increases the power factor (Figure 17). We note that the active, reactive and distorting power values are: $P = 2.7$ W, $Q = 0.2$ VAr, and $D = 0.7$ VAr. The apparent output is $S = 2.796$ VA, and the computed power factor is:

$$\lambda = \frac{2.7}{2.796} = 0.966$$  \hspace{1cm} (7)

For this power factor value, the reactive energy cost is comparable to the cost of the active energy. In this case a correction of the power factor is needed.
Figure 17. Active, reactive, and distorted power as well as the apparent output for load operation, with PFC

4. Conclusions
Analysing the two circuits using the same load resistance has shown that for the wiring using an PFC the active power sent to the load has an almost double value compared to the non-PFC wiring.

The reactive power in the PFC wiring is reduced to 40% of the reactive power, corresponding to the first case we analysed, while the distorted power is reduced to 36.8%.

Using the PFC, the power factor grows from 0.58 to 0.966, with the latter value considerably higher than the neutral factor.

The two analysed wirings show the necessity of using controllers to compensate the power factor. Thus, when the electric circuits are non-linear, to compensate the power factor the capacitor plays the most important role, intercalating lower or higher capacitor values must be commanded electronically.

References
[1] So E 2002 IEEE trial-use standard 1459-2000, definitions for the measurement of electric power quantities under sinusoidal, nonsinusoidal, balanced, or unbalanced conditions, 2002 IEEE Power Engineering Society Winter Meeting, Conference Proceedings, New York, USA, Jan. 27-31
[2] Piroi I Electric Energy Uses, Editura Eftimie Murgu Reșița, 2009 (in Romanian)
[3] Rusinaru D, Lecture Notes in Electrical, Networks http://retele.elth.ucv.ro/Rusinaru%20Denisa/Retele%20electrice%20I/c11_re.pdf, (Accessed: 27.02.2020).
[4] ***Ordinul 76/2019, Ordin pentru modificarea și completarea Metodologiei privind stabilirea obligațiilor de plată a energiei electrice reactive și a prețului reglementat pentru energia electrică reactivă, aprobate prin Ordinul președintelui Autorității Naționale de Reglementare în Domeniul Energiei nr. 33/2014
[5] Petrean L E, Horgos M, Pavel N and Petrean L 2008 The effect of power quality disturbances on the electromagnetic compatibility, Revue Roumaine des Sciences Techniques-Serie Electrotechnique et Energetique 53 (2) 147-154
[6] ***Mijloace și metode de ameliorare a factorului de putere, http://www.euedia.tuiasi.ro/uee/uee_files/L6_factor%20putere-2col.pdf, (Accessed: 27.02.2020).
[7] ***Imbunătăţirea factorului de putere, http://retele.elth.ucv.ro/Rusinaru%20Denisa/Retele%20electric%20I/c11_re.pdf (Accessed: 27.02.2020).

[8] Kim J Chang, Kim D and Kwak S S 2019 Direct Power-Based Three-Phase Matrix Rectifier Control with Input Power Factor Adjustment, *Electronics* 8(12) 1427

[9] ***Instalatia automata pentru imbunatatirea factorului de putere – stand experimental, Networks http://retele.elth.ucv.ro/Mircea%20Paul%20Mihai/PTDEE/Laborator_007.pdf (Accessed: 27.02.2020).

[10] Kim M 2020 Feed-forward control scheme to improve light-load power factor for single-stage flyback PFC converters, *Electronics letters* 56(1)

[11] Tashakor N and Khooban M H 2020 An Interleaved Bi-Directional AC-DC Converter With Reduced Switches and Reactive Power Control, *IEEE Transactions on Circuits and Systems II-Express Briefs* 67(1) 132-136

[12] Garces-Gomez, Y A, Hoyos F E and Candelo-Becerra J E 2019 Classic Discrete Control Technique and 3D-SVPWM Applied to a Dual Unified Power Quality Conditioner, *Applied Sciences-Basel* 9(23) 5087

[13] ***Lucass-Nuelle, Networks http://www.lucas-nuelle.us/2769/pid/9084/apg/4778/Course-Power-electronics-4:-Active-power-factor-correction-PFC-.htm (Accessed: 27.02.2020).

[14] Fahim S R, Avro S S, Sarker S K and Das S K 2019 A novel fractional order power factor measurement, *SN Applied Sciences* 1(12) 1611