Investigation on the Work Efficiency of the LC Passive Harmonic Filter Chosen Topologies

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Abstract: The use of passive harmonic filters (PHFs) in an electrical system is in most cases for the fundamental harmonic reactive power compensation and harmonics mitigation. In comparison to other filters applied to improve the power quality, such as the shunt active power filter or hybrid active power filter, their main advantages are the low investment costs and easy applicability in low-, medium-, and high-voltage electrical systems. However, their installation demands a deep analysis of the electrical system as well as a thorough knowledge of the topology to be installed. Their work efficiency is influenced by the parameters of the electrical system (grid, load, and filter itself) which must be well-known before installation. The aim of this paper is to present an investigation on the work efficiency of the LC passive harmonic filter chosen topologies. The PHFs are investigated in the frequency domain through their impedance versus frequency characteristics as well as in the time domain through an electrical system. A comparative study between filters is also considered. The investigations on the case examples of PHFs are based on simulations and some laboratory studies are also presented.

Keywords: passive harmonic filters; voltage and current distortion; frequency characteristics; reactive power; harmonics mitigation; grid impedance

1. Introduction

In the recent years, the production of household appliances and industrial devices using power electronic components is in full growth. Due to the massive connection of such non-linear devices to the supply network (despite being in accordance with the standard), the supplied power quality is in a degradation mode.

The power quality refers mostly to the supply voltage quality (frequency, amplitude, waveform, phase shift between phase to phase, or phase to ground voltage, etc.) which should follow the recommendations fixed by standards (e.g., IEC, IEEE, EPRI, etc.) in accordance with the country or continent standards. The standard examples concerning the power quality characteristics, measurements and monitoring are for instance EN 50160 [1], IEC 61000-4-30 [2], and the IEEE standard 1159 [3], respectively.

The standard EN 50160 (for European countries) defines the voltage characteristics of the distribution systems (voltage dip and swell, harmonics, voltage interruption, transients, rapid voltage change, asymmetry, voltage fluctuation, etc.). The standard IEC 61000-4-30 focuses on the power quality measurement techniques. The IEEE standard 1159 is for monitoring the electric power quality [2,3].

At the point of common coupling in a building or in a town, if the supply voltage is of poor quality (harmonics, asymmetry, flickers, etc.), its improvement is therefore necessary to comply with the standards. There are different practical solutions used to mitigate the grid voltage and current disturbances, among which we mention the passive filter (e.g., PHFs), the active filter (e.g., shunt active power filters), and the hybrid filter (e.g., hybrid active power filters) [4].
In terms of power quality amelioration, the active solutions are more efficient than the passive ones, but their main drawbacks are the high cost, the complex control system, the difficulty for the large-scale (high-voltage) implementation, the fast control system response, and the low losses requirement, etc. [5–13].

In practice, the PHFs are commonly used to improve the displacement power factor (DPF) and reduce the voltage and current harmonics in the electrical system [14]. They present certain disadvantages, such as poor dynamic performance, sensibility to the change of their parameters, system parameters dependency (grid and load), resonance (series and parallel) problem, work efficiency influenced by the grid short-circuit power and harmonics, sensibility to the detuned phenomena due to the aging of their elements (mostly the capacitor), overload by harmonics other than the one on which they are tuned, etc. Compared to the shunt active power filters, they are low cost, simple in the structure, easy to maintain. They have highly efficient characteristics and can be used in high power applications (medium and high voltage), etc. [15–22].

The design procedure of PHFs is varied in the literature. On the one hand, there are traditional methods based on the computation of normal filter parameters, and on the other hand, there are optimization methods based on the defined optimization function and conditions. The most utilized optimization methods are: genetic algorithms [23–25], response surface methodology [26,27], swarm optimization [28], Particle Swarm Optimization (PSO) [29], bee colony optimization [30], Mixed Integer Distributed ant Colony Optimization (MIDACO) [31], probabilistic approach [32], Multi-island Particle Swarm optimization (MIPSO) [33], Ant Colony Optimization (ACO) [34], simulated annealing [35], optimal Multi-objective planning [36], Lagrange interpolation method [37], etc. These techniques can be accompanied by constraints (e.g., maximum voltage capacitor and reactive power etc.) [38–40].

There exist several topologies of PHF among which the single-tune filter, broad-band filters (first, second, and third order as well as C-type filter), the double tune filter, the group of single-tuned filters, the hybrid PHFs, etc. [41–45]. They differ in the number of components, the mitigation level of voltage and current harmonics at the point of common coupling (PCC), the immunity on detuning phenomena due to the change of their parameters, the power losses, the filtering band, the design method, etc. Each of the highlighted features has an influence on the filter design, work efficiency, and exploitation cost. Therefore, it is important to know the advantages and disadvantages of each topology when deciding which one to choose and also in optimal decision making in terms of technical and economical points of view. The case study examples of PHFs in a low voltage (LV) electrical system with adjustable speed drive as load are considered in this paper.

The literature on PHFs is very rich, but still, there are certain points or questions that need more clarification through detailed studies. For instance, which parameters or factors need to be included in the process of choosing the filter tuning frequency and damping resistance? Which filter generates more power losses? Which one is better on individual harmonic mitigation or mitigation of higher harmonics in wide band? Which one can easily cause the harmonic amplification? The above questions are investigated in this paper through a detailed study performed on the PHF chosen topologies such as the single-tuned filter and broad-band filters.

The choice of the PHF tuning frequency is controversial in the literature [46,47]. Because of factors, such as filter aging, manufacturer tolerance, atmospheric conditions, or fault, which may occur on the filter after its connection, it is advised not to tune the PHF on the exact frequency of the harmonic to be mitigated, but on the frequency a bit below that frequency [48]. The question which remains is: up to how many percentages below should be that tuning frequency? According to [49,50], the PHF tuning frequency should be chosen in the range between 3% and 15% below the frequency of the harmonic to be eliminated. But the investigation presented in this paper recommends choosing the PHF tuning frequency below the frequency of the harmonic to be eliminated by taking into account the electrical grid equivalent impedance of the harmonic to be eliminated.
The optimized selection of damping resistance value of PHFs, such as the second-order, third-order, and C-type filter is a very important process because the wrong selection of that resistance can lead to harmonics amplification or a reduction of the filter work efficiency. The selection process of damping resistance differs in the literature. In [51–54], it is computed through the filter quality factor. In [55–61], its computation is more complex taking into account various parameters, such as the grid short-circuit power and impedance, filter losses and efficiency, the damping of resonances, the harmonics amplification, etc. The case studies presenting the consequences of the wrong selection of PHFs damping resistance or tuning frequency are rare in the literature. This paper presents such cases.

The examples of a case study showing the dependency of the PHF work efficiency on the electrical grid parameters (short-circuit power and primary voltage spectrum) are difficult to be found in the literature, but in this paper, such of case is presented (laboratory investigation).

The purpose of this paper is to perform an investigation on the work efficiency of the chosen topologies of the LC passive harmonic filter (Figure 1), in the frequency and time domain. Each filter is individually analyzed focusing on the impedance versus frequency characteristics, influence of the detuning phenomenon, and damping resistance on the filtration efficiency, etc. The influence of the filter parameters changes on the grid voltage and current waveforms as well as spectrums is also presented. The investigated PHF structures are also compared. The studied case examples are based on simulations (MATLAB/SIMULINK [62]) as well as laboratory experiments.

![Figure 1. Simulated power system together with the passive harmonic filter (PHF) topologies.](image)

The novelties of this paper are the recommendations formulated after the simulation and laboratory investigations performed on the PHF chosen topologies.

2. Simulated Power System Description

The power system in which the PHF topologies are investigated in the time domain is a typical medium- to low-voltage distribution network (Figure 1). It consists of a three-phase electrical grid source with a transformer (T) and a line (l) feeding a three-phase controlled rectifier thyristor bridge with a DC drive at its DC side and an input line reactor (L) at its AC side. Between the line reactor (L) and the PCC, the filter topologies (from N° 1 to N° 5)
are connected and analyzed. The rest of the symbols used in this paper are explained in Figure 1.

The computed equivalent parameters of the simulated electrical grid observed from the PCC (Figure 1) when no load is connected are presented in Table 1. The formula of the load characteristic harmonics order is: $n = (6k \pm 1), k \in \mathbb{N}$.

| $S_{SC\_PCC}$ [MVA] | $I_{SC\_PCC}$ [A] | $L_S$ [$\mu$H] | $R_S$ [m$\Omega$] | $Z_S$ [$\Omega$] | $Z_{S(5)}$ [$\Omega$] |
|----------------------|-------------------|---------------|------------------|-----------------|-----------------|
| 0.33                 | 481.12            | 681.82        | 425.5            | 0.480           | 1.15            |

$S_{SC\_PCC}$—initial short-circuit power at the transmission line end (PCC), $I_{SC\_PCC}$—initial short-circuit current at the transmission line end (PCC), $Z_{S(5)}$—electrical grid 5th harmonic equivalent impedance at the PCC when no load is connected.

The line reactor ($L$) at the thyristor bridge input is used to mitigate the slope of current (see Figure 2) during the thyristor’s commutation, when the current is flowing from one phase to the next phase [64,65]. It protects the thyristor bridge electronics as well as the elements at the DC side against a short-circuit current [66]. Without $L$ at the thyristor bridge input, the PCC current presents very steep slope (Figure 2) but with $L$, the current slope is less steep and the PCC voltage commutation notches are less deep (Figure 2). The higher the thyristor input line reactor value, the better are the PCC current and voltage waveforms (see THD in Figure 2).

Simulation Assumptions

The filter topologies are tuned (apart from the topology $N^\circ 1$) to the frequency (242.5 Hz, 4.85th) a bit lower than the frequency of the harmonic to be eliminated (3% below 250 Hz, 5th). The analysis is focused on the mitigation of the 5th harmonic which is the lowest generated (by the load) characteristic current harmonic after the fundamental harmonic. For each topology, the capacitor’s resistance is neglected, the reactor’s resistance is computed basing on the quality factor ($q'$), the reactive power (fundamental harmonic) used for the system compensation is the same ($Q_f = -21725$ Var) for all considered topologies, the firing angle for the thyristor pulses generator is constant as well as the DC drive speed ($\omega = 1500$ rpm). The filter nominal voltage $U_f$ is set to 230 V. The data and characteristics of voltage and current at the AC side of thyristor bridge are considered at the steady state. Because of the symmetrical power system, only one phase is considered to present the results.

3. Simulation Results

The work efficiency of the filter topology is studied from the point of view of the detuning phenomena and choice of the damping resistance. To highlight these studies,
many characteristics are considered, such as the grid voltage, the current waveforms and spectrums (before and after the filter connection), the impedance versus frequency characteristics, and filter power losses.

Figure 3 presents the grid voltage waveforms and spectrums before and after the load connection. Figure 3b compared to Figure 3a shows that the grid voltage is distorted with commutation notches after the load connection.

![Figure 3. Grid voltage waveforms and spectrums: (a,c) when the load is not connected to the PCC and (b,d) when the load is connected to the PCC.](image)

3.1. Topology N° 1—Capacitore Bank

The capacitor banks are applied in the electrical network (medium voltage (MV) and high voltage (HV)) for purposes, such as displacement power factor (DPF) correction, voltage stabilization, network current balancing, etc. [67,68]. Even though they are used to improve the power quality, they are also the source of disturbances such as overvoltage (during the transient state when the capacitor bank is switched), which can damage the power system sensitive load connected, series and parallel resonance phenomena (with the grid inductance) which can amplify harmonics, etc. [69].

The designed capacitor bank to compensate the inductive reactive power generated by the adjustable speed drive is presented in Figure 4a and the parameters in Table 2. The impedance versus frequency characteristic is presented in Figure 4b.

![Figure 4. (a) First-order filter, (b) impedance versus frequency characteristic of the first-order filter.](image)

| Table 2. First-order filter parameters together with expressions used to compute these parameters. |
|---|
| $C_f = \frac{Q_l}{\omega \mu F}$ | $Z_l = R_f + \frac{U_f^2}{U_f}$ |
| $Q_l$ [Var] | $C_f$ [\mu F] | $Z_{f(0)}$ [\Omega] | $Z_{f(5)}$ [\Omega] | $Z_{f(7)}$ [\Omega] | $R_f$ [\Omega] |
| $-2172.5$ | $130.72$ | $24.35$ | $4.87$ | $3.48$ | $0.25$ |
The waveforms and spectrums of the grid voltage and current before and after the capacitor bank connection at the PCC are respectively shown in Figures 5 and 6. In Figure 6, it can be noticed that after the first-order filter connection (see Figure 6b,d), the amplitudes of the grid voltage and current of the 5th, 7th, 11th, and 13th harmonics have increased (e.g., the 11th harmonic has increased from 1.42 A to 7.20 A). This increase (harmonics amplification) is due to the fact that those harmonics have their frequency near the parallel resonance frequency which has occurred between the grid inductance and the capacitor bank. Observing the power system impedance versus frequency characteristic seen from the thyristor bridge input (Figure 7a, for \( Q_f = -2172.5 \ \text{Var} \)), the parallel resonance frequency is around 500 Hz. The 11th harmonic is the most amplified because its frequency is the nearest to the parallel resonance frequency. Although the capacitors bank has caused the amplification of certain harmonics, it has also reduced the amplitude of higher harmonics (from the 17th harmonic, comparing Figure 6 a–b) of the grid voltage and current. In this case example, it can be noticed that the THD has increased from 4.93% to 6.03% for the grid voltage and from 36% to 116.29% for the grid current (Figure 6).

The capacitor bank is bulked by harmonics and the dominant one after the fundamental is the 11th because of the resonance phenomenon (Figure 6e). Its connection without the detuning reactor in the power system with distorted voltage and current (Figure 3) is not recommendable.

The power system impedance versus frequency characteristics registered from the thyristors bridge input after increasing the capacitor bank reactive power from 2172.5 Var to 20 kVar is shown in Figure 7. With the increase of reactive power (capacitance as well), the series and parallel resonance are damped but the system is overcompensated. In Figure 7b it can be see that there is not series resonance as in Figure 7a because of the absence of the thyristor’s bridge input reactor.

In this case study, one can clearly see that the first-order filter has compensated the power system fundamental harmonic reactive power (the grid current fundamental harmonic amplitude is reduced from 15.86 A to 8.54 A—see Figure 6c,d) and reduced high harmonics in a wide range (from the 17th harmonic—see Figure 6a,b). However, its main disadvantages in the power system are the resonance phenomena and the harmonics amplification, mostly the harmonics near the parallel resonance frequency. To overcome these disadvantages, it is recommended to use a detuning-reactor to shift the parallel resonance to the save place, where there are no characteristic harmonics (e.g., below the 5th harmonic), hence the necessity of single-tune filter design.

![Figure 5. Supply network voltage and current waveforms: before (a,c) and after (b,d) the capacitor bank connection.](image-url)
Figure 6. Supply network voltage and current spectrums before (a,c) and (b,d) after the capacitor bank connection; (e) spectrum of capacitor bank current.

Figure 7. Impedance versus frequency characteristics of power system measured at the input of thyristor bridge: (a) with the input reactor $L$; (b) without the input reactor $L$ (just to show that the observed series resonance depends on the $L$ presence).
3.2. Topology No. 2—Single-Tuned Filter

Among PHFs, the single-tuned filter is the easiest to design because of its simplicity in structure [70, 71]. Like other PHFs, its design is based on the series resonance phenomenon (filter reactance of capacitor and reactor are equal for the resonance frequency) [72]. In practice, it is advised to tune the PHF to the frequency a bit lower than the frequency of the harmonic to be eliminated. The performed investigation in this case study shows that, one of the most important parameters that should be taken into account while choosing the PHF tuning frequency is the electrical grid equivalent impedance of the harmonic to be mitigated. The harmonic to be eliminated should be the first generated characteristic harmonic after the fundamental harmonic.

After the filter design and installation in the power system, what may happen if the choice of the tuning frequency is wrong or if the filter is detuned from its initial tuning frequency because of the aging of its elements, atmospheric conditions or faults that could occur on its elements while it is working. The considered case study also presents the examples of the influence of the detuning phenomenon of the single-tuned filter’s work efficiency.

Concerning the single-tuned filter under study, its capacitor and reactor resistance are neglected (Figure 8). On the one hand, the filter is tuned to the frequencies lower than the frequency of the 5th harmonic (Table 3, Figure 9a). On the other hand, it is tuned to the frequencies higher than the frequency of the 5th harmonic (Table 4, Figure 9b).

The frequency characteristics in Figure 9a show that the lower the filter tuning frequency (filter resonance frequency) from the 5th harmonic frequency, the higher is the filter 5th harmonic impedance (e.g., $n_{re} = 4.1$). The 5th harmonic is therefore worst mitigated at the grid side when the filter resonance frequency is chosen too far below the 5th harmonic frequency (see the spectrums in Figure 10b, d). For $n_{re} = 4.1$, comparing the 5th harmonic impedance of the filter ($Z_{f(5)} = 2.5 \, \Omega$—Table 3) to the one of the electrical grid ($Z_{S(5)} = 1.5 \, \Omega$—see Table 1), it can be noticed that the 5th harmonic impedance of the filter is the highest which explains the reduction of the single-tuned filter work efficiency. Therefore, the choice of the filter tuning frequency should be made taking also into account the grid impedance of the harmonic to be eliminated. Figure 9a also shows that when the filter resonance frequency is chosen below the frequency of the 5th harmonic, the 5th harmonic impedance of the filter is always on the inductive side of the characteristic and the parallel resonance occurring between the grid inductance and the filter capacitor is below the 5th harmonic frequency (Figure 12a).

The closer the filter resonance frequency to the harmonic frequency to be eliminated, the better is the filter work efficiency on the reduction of the harmonic to be eliminated, the less deep are the PCC voltage commutation notches (Figure 10a), and the lower are the grid current and voltage THD (Figure 10c and Table 5a). The impedance versus frequency characteristics of power system seen from the thyristors bridge input is presented in Figure 12a.

![Figure 8](image_url)

**Figure 8.** (a) Single-tuned filter, (b) expressions used to compute the single-tuned filter parameters. $\omega_{re}$—resonance frequency, $n_{re}$—harmonic order at the resonance.
Table 3. Single-tuned filter parameters. The filter is tuned to the frequencies lower or equal to the frequency of the harmonic to be eliminated (5th).

| \( f_{re} \) [Hz] | \( n_{re} \) | \( C_f \) [\( \mu F \)] | \( L_f \) [mH] | \( Z_{f(5)} \) [\( \Omega \)] | \( Z_{f(1)} \) [\( \Omega \)] | \( Q_f \) [Var] |
|------------------|----------|-----------------|-------------|-----------------|-----------------|-------|
| 205              | 4.1      | 122.95          | 4.9         | 2.52            | 24.35           | −2172.5 |
| 235              | 4.70     | 124.81          | 3.7         | 0.67            |                 |       |
| 245.5            | 4.85     | 125.17          | 3.4         | 0.32            |                 |       |
| 250              | 5        | 125.49          | 3.2         | 0.00            |                 |       |

Figure 9. Single-tuned filter impedance versus frequency characteristics: (a) when the filter is tuned to the frequencies lower or equal to the frequency of the 5th harmonic; (b) and when it is tuned to the frequencies higher or equal to the frequency of the 5th harmonic.

Table 4. Single-tuned filter parameters. The filter is tuned to the frequencies higher or equal to the frequency of the harmonic to be eliminated (5th).

| \( f_{re} \) [Hz] | \( n_{re} \) | \( C_f \) [\( \mu F \)] | \( L_f \) [mH] | \( Z_{f(5)} \) [\( \Omega \)] | \( Z_{f(1)} \) [\( \Omega \)] | \( Q_f \) [Var] |
|------------------|----------|-----------------|-------------|-----------------|-----------------|-------|
| 250              | 5        | 125.49          | 3.2         | 0               | 24.35           | −2172.5 |
| 285              | 5.70     | 126.70          | 2.5         | 1.16            |                 |       |
| 292.5            | 5.85     | 127             | 2.3         | 1.35            |                 |       |
| 305              | 6.1      | 127.21          | 2.1         | 1.64            |                 |       |

Figure 10. The single-tuned filter is tuned to the frequencies lower or equal to the frequency of the 5th harmonic: (a) grid voltage and (b) its spectrum; (c) grid current and (d) its spectrum before and after the filter connection.
Table 5. Influence of the single-tuned filter detuning phenomenon on the grid voltage and current THD.

| $n_{re}$ | THD$_{(U_a)}$ [%] | THD$_{(I_a)}$ [%] | $n_{re}$ | THD$_{(U_a)}$ [%] | THD$_{(I_a)}$ [%] |
|---------|-----------------|-----------------|---------|-----------------|-----------------|
| Without filter | 4.93 | 36 | Without filter | 4.93 | 36 |
| 4.1 | 4.24 | 49.7 | 5 | 3.79 | 18.74 |
| 4.70 | 3.94 | 31.54 | 5.70 | 6.49 | 172.17 |
| 4.85 | 3.84 | 22.35 | 5.85 | 6.42 | 169.08 |
| 5 | 3.79 | 18.74 | 6.1 | 5.77 | 146.29 |

Concerning the situation where the filter is tuned to the frequency higher than the 5th harmonic frequency, the filter impedance of the 5th harmonic has also increased (e.g., $n_{re} = 6.1$, Table 4), and is on the capacitive side of the characteristic (Figure 9b). The higher the filter resonance frequency from the frequency of the 5th harmonic, the more probable is the amplification of the 5th harmonic amplitude at the grid side (see the spectrums in Figure 11b,d). Figure 12b clearly shows how close the 5th harmonic is to the parallel resonance frequency (e.g., $n_{re} = 5.70$, $n_{re} = 5.85$, $n_{re} = 6.1$) which justifies it amplification at the grid side as it is presented in the spectrums of Figure 11b,d.

It has been experimentally demonstrated that, if the PHF is tuned to the frequency higher than the frequency of the lowest generated characteristic harmonic after the fundamental harmonic (e.g., 5th), the amplification of that characteristic harmonic can occur in the power system along with the grid voltage and current THD increase (Figure 11a,c, Table 5a, e.g., $n_{re} = 5.85$).

The grid impedance of the harmonic to be eliminated should be well-known and taken into account while chosen the PHFs tuning frequency.

The PHFs tuning frequency should be chosen below the frequency of the harmonic to be eliminated and the following condition should be taken into account: the filter equivalent impedance of the harmonic to be eliminated should always be smaller than the grid equivalent impedance of this harmonic, otherwise the filter efficiency will reduce and be less efficient in mitigating this harmonic from the grid side.

Figure 11. The single-tuned filter is tuned to the frequencies higher or equal to the frequency of the 5th harmonic: (a) grid voltage and (b) its spectrum; (c) grid current, and (d) its spectrum before and after the filter connection.
Figure 12. Impedance frequency characteristics of the power system seen from the rectifier input when the single filter is tuned to the frequencies lower than 250 Hz (a) and when it is tuned to the frequency higher than 250 Hz (b).

3.3. Topology $N^o$ 3—Second-Order Filter

In [63] the second-order filter work efficiency is tested on the suppression of high-order characteristic harmonics and harmonic resonance for a simulated electrical railway system (HV) with different type of locomotives. An example of second-order filter designed equations is presented in [73]. In this paper, the second-order filter work efficiency is investigated based on the choice of its damping resistance. The wrong choice of the damping resistance can lead to harmonic amplification in the electrical system. The second-order filter parameters are presented in Table 6 and the formula used to compute those parameters are shown in Figure 13.

Table 6. Parameters of 2nd order filter ($Q_f = -2172.5\text{Var}$).

| R [Ω] | $Z_{r(0)}$ [Ω] | $Z_{r(1)}$ [Ω] | $R_f$ [mΩ] | $C_f$ [µF] | $L_f$ [mH] | $n_{re}$ | $q'$ |
|-------|----------------|----------------|------------|------------|------------|---------|------|
| inf   | 0.32           | 24.35          |            |            |            |         |      |
| 60    | 0.61           | 24.35          |            |            |            |         |      |
| 18    | 1.55           | 24.36          | 74.9       | 125.17     | 3.4        | 4.85    | 14.25 |
| 8     | 2.89           | 24.38          |            |            |            |         |      |
| 3     | 4.46           | 24.52          |            |            |            |         |      |

The second-order filter frequency characteristics are presented in Figure 14. For high values of the damping resistance (e.g., $R = 60$ Ω—Figure 14b), the second-order filter has a characteristic similar to that of the single-tuned filter (Figure 14a, Figure 9a), presenting a small value of impedance for the resonance frequency ($n_{re} = 4.85$) and frequencies near that resonance frequency (e.g., the 5th harmonic frequency). For small values of this damping resistance (e.g., $R = 3$ Ω—Figure 14e), its frequency characteristic is similar to that of the first-order filter (see also Figure 4b), presenting a high value of impedance for the resonance frequency and frequencies in its vicinity (e.g., 250 Hz) and a small value of impedance for the high frequencies (e.g., 17th, 19th, 23rd, etc.).

The grid voltage and current waveforms and spectrums after the second-order filter connection in the power system with different damping resistance values are presented in
Figure 15. It can be observed that the depth of the grid voltage commutation notches is decreased with the damping resistance decrease (Figure 15a) as well as the grid voltage THD (Figure 16b). In the spectrum of Figure 16b,d, it can be noticed that there is a better reduction of grid voltage and current 5th harmonic amplitude when the damping resistance value is high (e.g., $R = 60 \, \Omega$) and a better mitigation of higher harmonics amplitude (e.g., 23rd, 25th, 29th, etc.—worst mitigation of the 5th harmonic) when the damping resistance is small (e.g., $R = 3 \, \Omega$). The grid current is more distorted when the damping resistance is chosen in the range of small values (Figure 16c).

![Second-order filter topology](image)

**Figure 13.** (a) Second-order filter, (b) expressions used to compute the second-order filter parameters. $R_{L_f}$—reactor resistance.

The second-order filter power losses are presented in Figure 16a. The decrease of the damping resistance value (e.g., $R = 8 \, \Omega$) has increased the filter power losses as well the grid side power losses ($P_S$).

The data presented in Table 6 show that when the damping resistance is decreasing, the 5th harmonic impedance of the filter ($Z_{f(5)}$) is increasing and can be higher than the 5th harmonic impedance of the grid ($Z_{S(5)}$—Table 1) which could decrease the second-order filter work efficiency on the 5th harmonic mitigation at the grid side. For instance, in the case of $R = 18 \, \Omega$, $8 \, \Omega$, and $3 \, \Omega$, the 5th harmonic impedance of the filter is higher than the 5th harmonic impedance of the grid and the 5th harmonic is worst reduced at the grid side (Figure 15b,d). The second-order filter work efficiency in terms of harmonic mitigation is presented in Figure 17. The power system impedance versus frequency characteristic observed from the thyristor bridge input terminals for different values of the filter damping resistance. Figure 18 shows that with the damping resistance decrease, the parallel and series resonances are damped.

Concerning the choice of the second-order filter damping resistance, this case study can allow to formulate the following recommendations: if the filter is designed to mitigate an individual harmonic (e.g., the 5th harmonic) in the power system, the damping resistance value should be chosen in such a way that the estimated grid equivalent impedance of that harmonic is higher than filter impedance of that harmonic. For the filter designed to mitigate the higher harmonic in a broad band (e.g., from the 17th harmonic), the damping resistance value should be chosen in such a way to avoid harmonic amplification in the electrical system.

### 3.4. Topology N° 4—Third-Order Filter

The examples of third-order filter design and application are presented in the literature [74–76]. However, it is difficult to find the literature in which the third-order filter work efficiency is investigated through the change of its parameters (e.g., damping resistance $R$).

The third-order filter lies in between the second-order filter and the C-type filter and the computation of its parameters in this paper is based on the series and parallel resonance phenomena (Figure 20). The filter series resonance frequency (242.5 Hz, $n_{rel} = 4.85$) is
chosen near the 5th harmonic frequency and the parallel resonance frequency is set at 300 Hz \((n_{re2} = 6)\). Below the series resonance frequency \((n_{re1} = 4.85)\), the filter is capacitive, between the series and parallel resonance frequency \((n_{re2} = 6)\), the filter is inductive and above the parallel resonance frequency, the filter is capacitive (Figure 20a). The parameters presented in Table 7 are computed using the expressions in Figure 19b. The damping resistance is added in series with the capacitor \(C_f\) (Figure 19a) and its influence on the third-order filter work efficiency is studied.

The third-order filter frequency characteristics are presented in Figure 20. As the damping resistance is increasing, the filter series and parallel resistance are damped (Figure 20a–c). However, for a high value of damping resistance (e.g., \(R = 8 \, \Omega\), Figure 20b), the filter parallel resonance is totally damped and only the series resonance remains (the frequency characteristic is similar to that of the single-tuned filter, Figure 20b).

The waveforms and spectrums of PCC voltage and current before and after the third-order filter connection (for different damping resistance values) are presented in Figures 21 and 22, respectively. After the filter connection, with the damping resistance increase from

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**Figure 14.** (a) Second-order filter impedance versus frequency characteristics for different damping resistance value: (b) \(R = 60 \, \Omega\), (c) \(R = 18 \, \Omega\), (d) \(R = 8 \, \Omega\), (e) \(R = 3 \, \Omega\).
0.08 Ω to 1.25 Ω, the filter work efficiency on the 5th harmonic grid voltage and current has decreased; the 7th, 11th, and 13th harmonics are amplified and the harmonics from the 19th are mitigated (see Figure 23, spectrums in Figures 21 and 22).

With the damping resistance increase from 0.08 Ω to the higher value (e.g., 8 Ω), the 5th harmonic grid voltage and current are amplified and the harmonics from 7th are better mitigated (see Figure 23, spectrums in Figures 21 and 22).

Figure 15. (a) Grid voltage and (b) its spectrum (p.u.); (c) grid current and (d) its spectrum (p.u.) before and after the filter connection.

Figure 16. (a) Active power at the PCC ($P_S$) and filter terminals ($P_f$), (b) grid voltage THD, (c) grid current THD.

Figure 17. Second-order filter work efficiency in terms of harmonic mitigation.
Figure 18. Power system impedance versus frequency characteristic observed from the thyristor bridge input terminals for different values of the filter damping resistance.

Table 7. Parameters of the 3rd order filter ($Q_f = -2172.5 \text{Var}$).

| $R$ [mΩ] | $Z_{f(0)}$ [Ω] | $Z_{f(1)}$ [mΩ] | $R_{lf}$ [mΩ] | $C_{f1}$ [µF] | $C_{f2}$ [µF] | $L_f$ [mH] | $n_{re1}$ | $n_{re2}$ |
|----------|----------------|----------------|--------------|--------------|--------------|----------|----------|----------|
| 80       | 1.07           | 24349.8        |              |              |              |          |          |          |
| 250      | 1.36           | 24349.8        | 4.3          | 128.74       | 242.70       | 1.2      | 4.85     | 6        |
| 750      | 2.28           | 24349.9        |              |              |              |          |          |          |
| 1250     | 2.70           | 24350.0        |              |              |              |          |          |          |
| 8000     | 3.11           | 24352.9        |              |              |              |          |          |          |

Figure 19. (a) Third-order filter, (b) expressions used to compute the third-order filter parameters.

$n_{re1}$—harmonic order at the series resonance, $n_{re2}$—harmonic order at the parallel resonance.

The power losses and THD in Figure 24 show that for an increasing filter damping resistance, the filter and grid power losses (Figure 24a) have increased as well as the grid current THD (Figure 24c). The grid voltage THD is reduced as well as the depth of the commutation notches (Figures 21 and 24b).
The power system impedance versus frequency characteristics seen from the thyristor bridge input (Figure 25) shows that the harmonics amplification observed in the grid voltage and current spectrums is due to the fact that those harmonics have their frequency near the parallel resonance frequency occurring between the filter and the electrical grid. For instance, with $R = 1.25 \, \Omega$, the harmonics from the 7th to the 17th have their frequency near the parallel resonance frequency (Figure 25).

The presented investigation has shown that regardless of the damping resistance value, the third-order filter will always cause the harmonics amplification in the electrical system with distorted voltage and current. To avoid an increase in the power loss in the electrical system, it is preferable not to use the damping resistance and to design such a filter with the smallest possible resistance of elements. Its design should take into account the electrical grid equivalent impedance of the harmonic to be eliminated which should be higher than the filter impedance of that harmonic.

**Figure 20.** Third-order filter impedance versus frequency characteristics for different damping resistance value: (a) $R = 0.08 \, \Omega$, (b) $R = 0.25 \, \Omega$, (c) $R = 1.25 \, \Omega$, (d) $R = 8 \, \Omega$.

**Figure 21.** Grid voltage waveforms and spectrums after the 3rd order filter connection with different value of damping resistance.
3.5. Topology N° 5—C-Type Filter

The C-type filter presented in Figure 26a is constituted of two capacitors (Cfa and Cfb), one reactor (Lf), and one damping resistance (R). Its specificity is that, the branch (in parallel with the damping resistance (R)) containing Lf and Cfb is tuned on the fundamental harmonic (series resonance) for the purpose of loss reduction [77–80]. The fundamental harmonic impedance of the (Lf, Cfb) branch is therefore limited to the reactor resistance RLf (if the damping resistance is smaller than RLf, the quantity of current flowing through R will be higher than the one flowing through the (Lf, Cfb) branch, see Figure 26a). A (big) part of the C-type filter fundamental harmonic power losses is related with the filter reactor resistance and damping resistance as well.
Figure 25. Power system impedance versus frequency characteristics observed at the thyristor bridge input for different values of the third-order filter damping resistance ($R$).

Figure 26. (a) C-type filter, (b) expressions used to compute its parameters.

The expressions used to compute the C-type filter parameters are presented in Figure 26b and the computed parameters are shown in Table 8. The damping resistance values are higher than the ($L_f$, $C_{fb}$) branch resistance $R_{lf}$. For an $R$ increase from 1.25 $\Omega$ to 8 $\Omega$, the electrical grid’s 5th harmonic impedance (Table 1) is smaller than the C-type filter’s 5th harmonic impedance (Table 8). This means that for those values of the damping resistance, the filter will be less efficient on the 5th harmonic mitigation (see spectrums in Figures 28 and 29).
Table 8. Parameters of C-type filter \((Q_f = -2172.5 \text{Var})\).

| \(R [\Omega]\) | \(Z_{f(1)} [\text{m} \Omega]\) | \(Z_{f(5)} [\text{m} \Omega]\) | \(R_{lf} [\text{m} \Omega]\) | \(C_{fa} [\mu \text{F}]\) | \(C_{fb} [\mu \text{F}]\) | \(L_f [\text{mH}]\) | \(n_{re}\) |
|---|---|---|---|---|---|---|---|
| 1.25 | 4.73 | 24.34 | 12.7 | 130.72 | 2900 | 3.4 | 4.85 |
| 5 | 3.51 | | | | | | |
| 8 | 2.67 | | | | | | |
| 25 | 1.04 | | | | | | |
| 2500 | 0.32 | | | | | | |

The C-type filter impedance versus frequency characteristics is considered in Figure 27. For high damping resistance values (e.g., \(R = 2.5 \Omega\)), the filter characteristic is close to that of the single-tuned filter (Figure 27c) and for the small values of the damping resistance (e.g., \(R = 1.25 \Omega\)), it is similar to that of the first-order filter (Figure 27b). In the zoom of Figure 27a,d, the fundamental harmonic series resonance can be seen.

The PCC voltage and current waveforms and spectrums before and after the C-type filter connection are shown in Figures 28 and 29, respectively. With the damping resistance value chosen in the range of small values (e.g., between 1.25 \(\Omega\) and 8 \(\Omega\)), the C-type filter is less efficient in terms of the 5th harmonic mitigation (amplification of the 5th, 7th, 11th, and 13th harmonics—Figure 32) at the grid side, but is more efficient in terms of higher harmonics (from the 17th) and grid voltage commutation dip mitigation (Figures 28 and 29).

With the C-type filter damping resistance value chosen in the range of high values (e.g., from 25 \(\Omega\)), the 5th harmonic is better mitigated at the grid side (because the 5th harmonic impedance of the filter is smaller than that of the electrical grid) and the higher harmonics are worst mitigated (from the 17th—Figure 32) in comparison to the case when the damping resistance values were chosen in the range of small values (see Figures 28 and 29).

Figure 27. Cont.
Figure 27. (a) C-type filter impedance versus frequency characteristics for different damping resistance value: (b) $R = 1.25 \, \Omega$, (c) $R = 8 \, \Omega$, (d) $R = 25 \, \Omega$, (e) $R = 2500 \, \Omega$.

The grid current fundamental harmonic amplitude (see spectrum of Figure 29) has decreased after the filter connection because of the load reactive current reduction at the PCC. For a high value of the damping resistance (e.g., $R = 2.5 \, k\Omega$), the C-type filter has generated less power losses (Figure 30a) and the grid current has a better shape (Figure 30c). The PCC voltage has a better shape when the damping resistance value is chosen in the range of small values (e.g., $1.25 \, \Omega$, $8 \, \Omega$, Figure 30b).

The power system impedance versus frequency characteristics seen from the thyristor input for different damping resistance is presented in Figure 31. The decrease of the filter damping resistance has damped the series resonance (caused between the filter elements) and parallel resonance (caused between the filter capacitors and the grid reactor) Figure 31a. The observed harmonics amplification in the spectrums of Figures 28 and 29 is due to their presence near the parallel resonance 9.85th (see Figure 31b). The work efficiency spectrum of the C-type filter on the harmonics mitigation in the power system is shown in Figure 32. The damping resistance has an important influence on the C-type filter work efficiency. Its optimized value should be chosen in such a way that the electrical grid equivalent impedance of the harmonic to be eliminated (e.g., 5th) remains higher than the filter equivalent impedance of that harmonic. In the case that the C-type filter is designed for higher harmonics mitigation in a broad band, the damping resistance optimized value should be chosen in a way to avoid the harmonics amplification in the electrical system (frequency characteristic not too close to the one of the first-order filter). The C-type filter behaves almost in the same way as the second-order filter in terms of damping resistance change.

3.6. Comparison Between the Investigated PHF Topologies

The broad-band filter (first-order, second-order, third-order, and C-type filter) and single-tuned filter have been previously studied and their characteristics have been presented. Now, a comparative study on the investigated PHF topologies (Figure 33) is presented.
Figure 28. Grid voltage waveforms and spectrums after the C-type filter connection with different value of damping resistance.

Figure 29. Grid current waveforms and spectrums after the C-type filter connection with different value of damping resistance.
Figure 30. Active power at the PCC ($P_S$) and filter terminals ($P_f$) (a), grid voltage THD (b), grid current THD (c) obtained before and after the C-type filter connection with different damping resistance value.

Figure 31. (a,b) Power system impedance versus frequency characteristics observed at the input of thyristor bridge for different values of the C-type filter resistance.

Figure 32. C-type filter work efficiency on the harmonic mitigation.
Figure 33. Compared topologies of PHF.

The filters are compared from the point of view of harmonics amplification and efficiency on the mitigation of the harmonic to be eliminated (e.g., 5th) and higher harmonics in a broad band. The comparison criteria are: the filter power losses \( \Delta P_f \), the PCC voltage and current of the 5th harmonic amplitude \( (U_{S(5)}, I_{S(5)}) \), the PCC voltage and current THD \( (\text{THD}_{US}, \text{THD}_{IS}) \), as well as the higher harmonics amplitudes (from the 7th harmonic).

The compared filters are assumed to have the same reactive power \( Q_f = -2172.5 \text{ Var} \), reactor quality factor \( q' = 85 \) and tuning frequency \( (n_{re} = 4.85) \) (see Table 9). The first-order filter resistance is neglected and the second-order, third-order, and C-type filter are assumed to have the same damping resistances (e.g., 0.08 \( \Omega \), 1.25 \( \Omega \), and 25 \( \Omega \), see Table 9).

Table 9. Comparison assumptions.

| Filter Type | Single-Tuned | Second-Order | Third-Order | C-Type |
|-------------|--------------|--------------|-------------|--------|
| 5th Order   | -            | 0.08         | 0.08        | 0.08   |
| 120th Order | -            | 1.25         | 1.25        | 1.25   |
| -            | -            | 8            | 8           | 8      |
| -            | -            | 25           | 25          | 25     |

The single-tuned filter and the first-order filter are compared to the second-order, third-order and C-type filter (when their damping resistance is increasing from 0.08 \( \Omega \) to 25 \( \Omega \)).

From the point of view of individual harmonic mitigation (e.g., 5th), the single-tuned filter is more recommendable than other topologies because it has the lowest amplitude of grid voltage and current 5th harmonic (Figure 34a,b).

All the broad-band filters present the problem of harmonics amplification. However, depending on choice of their damping resistance value, this problem can be mitigated. For small values of the damping resistance (e.g., 0.08 \( \Omega \), 1.25 \( \Omega \)), the third-order filter is more recommendable for the reduction of an individual harmonic than the second-order and C-type filter, and then comes the second-order filter (Figure 34a,b).

For high values of the damping resistance (e.g., 8 \( \Omega \), 25 \( \Omega \)), the C-type filter is more recommendable for the reduction of an individual harmonic (e.g., 5th) than the second-order and third-order filters. The second-order filter is more recommendable than the third-order filter (Figure 34a,b).

From the point of view of the 5th harmonic non-amplification (Figure 34a,b), the single-tuned filter is more recommendable than the other filters because its damping resistance value is small (e.g., 0.08 \( \Omega \), 1.25 \( \Omega \)), and the C-type filter is more recommendable than the other filters for high damping resistances (e.g., 8 \( \Omega \), 25 \( \Omega \)) (Figure 34c).
The single-tuned filter has the lowest PCC current THD among the broad-band filters (Figure 34d). For small values of R (e.g., 0.08 Ω, 1.25 Ω), the third-order filter is more recommendable than the second-order and C-type filters. For high values of R (e.g., 8 Ω, 25 Ω), it is better to apply the C-type filter than the second-order and third-order filters to improve the grid current THD. The first-order filter has the highest grid current and voltage THD.

The third-order filter generates less power losses than the single-tuned, second-order, and C-type filters (Figure 34e), then comes the single-tuned filter, and at the end the C-type filter. The second-order filter has generated more power losses than other filters.

Comparing the second-order filter to the C-type filter, it can be noticed (Figure 34a–d) that they have almost the same characteristics but from the power losses point of view, the C-type filter is more recommendable.

In Figure 35, the grid voltage and current spectrums are presented. From the point of view of higher harmonics mitigation in a broad band (e.g., from the 19th—see Figure 35a–d), the first-order filter is more recommendable. Observing Figure 35a–d, it can be noticed that the single-tuned filter presents no harmonic amplification.
Figure 35. Grid voltage and current spectrums before and after the filter connection. The filter damping resistance has the value of: (a) 0.08 Ω, (b) 1.5 Ω, (c) 8 Ω, (d) 25 Ω.
4. Investigation of the Single-Tuned Filter in the Laboratory

The laboratory set-up in which the single-tuned filter was investigated is presented in Figure 36a and its equivalent circuit in Figure 36b. The load is the adjustable speed drive. It is constituted of an electrical grid (see from the PCC), a load and a single-tuned filter were used for the fundamental harmonic reactive power compensation and the 5th harmonic mitigation. The smart meter PQ-BOX 200 was used for data recording. Because of the symmetrical electrical system, some data are considered only for one phase. The line reactor $L_{SS}$ near the PCC is not considered (Figure 36b) in the investigation.

The electrical grid is a typical medium- to low-voltage distribution network with a transformer of 1000 kVA (15.75 kV/0.4 kV). The computed equivalent parameters are presented in Figure 37. The 5th harmonic grid equivalent impedance ($Z_{S(5)}$) is around 49.5 mΩ. The PCC voltage before the load and filter connection is presented in Figure 38. It can be clearly seen that it contains harmonics and the 5th harmonic is dominating (Figure 38b).

The load is constituted of a three-phase thyristor bridge with a transformer at the AC side and a DC drive at the DC side (Figure 36b). The transformer has a power of 176 kVA and the DC drive has a power of 56 kW with nominal voltage of 220 V.

The single-tuned filter is constituted of reactor $L_f$ connected in series with the delta-connected capacitor $C_f\Delta$. Its parameters measured in the laboratory are shown in Table 10 (the tuning frequency is 245.5 Hz). Observing the data in Figure 37 and in Table 10, one can notice that the filter impedance of the 5th harmonic ($Z_{f(5)} = 748.5$ mΩ, Table 10) is higher (almost 15 times) than the electrical grid 5th harmonic equivalent impedance ($Z_{S(5)} = 49.5$ mΩ, Figure 37). Therefore, the filter will be less efficient on the 5th harmonic mitigation at the grid side. The measured impedance versus frequency characteristic of the filter is presented in Figure 39a.

The waveforms of the grid voltage and current as well as the filter and load input before and after the LC filter connection are presented in Figure 40a,b. The electrical system active and reactive powers are presented in Table 11.

Observing the grid voltage and current spectrums (Figures 41 and 42) before and after the filter connection, one can see that the 5th and 7th harmonic are amplified at the grid side after the filter connection (see also the true THD (TTHD) in Tables 12 and 13). The PCC voltage 5th and 7th harmonics are amplified from 6.33 V to 8.64 V and from 4.86 V to 10.93 V, respectively (Figure 41a,b, Table 13). The grid current 5th and 7th harmonics are amplified from 21.5 A to 42.37 A and from 8.46 A to 49.68 A, respectively (Figure 42a,b, Table 13).

The 5th harmonic amplitude at the grid side is supposed to be partially or even not mitigated by the filter because the 5th harmonic grid equivalent impedance is smaller than that of the filter. Additional investigations were performed because of the 5th and 7th harmonics amplification at the grid side.

Firstly, the impedance versus frequency characteristic of the electrical system seen from the transformer input is obtained through simulation (Figure 39b). It can be seen that the parallel resonance occurring between the filter capacitor and the electrical grid inductance is below the 5th and 7th harmonic frequencies. Therefore, the harmonics amplification is not due to the parallel resonance.

Secondly, the filter and load were disconnected from the PCC and a linear load was connected (see Figure 43). The current waveform flowing between the grid and the linear load (capacitor bank) is supposed not to contain harmonics, but it contains harmonics (Figure 44c,d). The electrical grid with a distorted primary voltage (see Figure 38b as well) behaves as a source of harmonics current which flows to the capacitor bank.
Figure 36. (a) Laboratory set-up, (b) equivalent circuit of the laboratory set-up.

Figure 37. Electrical network (grid) equivalent circuit with the parameters.
Figure 38. PCC voltage waveforms (a) together with the spectrum (b) when the filter and load are not connected.

Table 10. Measured parameters of the investigated single-tuned filter.

| $Z_f(5)$ [mΩ] | $Z_f(1)$ [mΩ] | $R_{L_f}$ [mΩ] | $C_f$ [µF] | $L_f$ [µF] | $Q_f$ [kvar] | $n_{re}$ | $q'$ |
|---------------|---------------|----------------|-------------|-------------|-------------|---------|------|
| 718.5         | 1839          | 1.68           | 600.84      | 232.49      | −27.87      | 4.91    | 43.47 |

Figure 39. (a) Frequency characteristic of the laboratory investigated single-tuned filter, (b) simulated impedance versus frequency characteristic seen from the transformer input.

Figure 40. Measured waveforms of: (a) the grid voltage and current waveforms, (b) transformer input and single-tuned filter terminals.
Table 11. Measured powers before and after the filter connection.

| Grid (PCC) | Transformer Input | Filter |
|------------|-------------------|--------|
| $P_s$ [kW] | $Q_s$ [kVar]      | $P_T$ [kW] | $Q_T$ [kVar] | $P_f$ [kW] | $Q_f$ [kVar] |
|------------|-------------------|----------|---------------|------------|-------------|
| Before the filter connection | 2.52 | 23.29 | 2.52 | 23.29 | - | - |
| After the filter connection | 2.30 | -3.56 | 2.46 | 24.44 | -0.15 | -28.00 |

Figure 41. Measured waveforms and spectrums of the PCC voltage before (a) and after (b) the filter connection.

Figure 42. Measured waveforms and spectrums of the grid current before (a) and after (b) the filter connection.
Table 12. Measured grid voltage and current parameters before the single-tuned filter connection.

| n   | \( U_S \) [V] | \( I_S \) [A] | \( I_F \) [A] | \( I_T \) [A] |
|-----|----------------|---------------|---------------|---------------|
|     | \( \text{Ampl} \) | \( \text{Ampl} \) | \( \text{Ampl} \) | \( \text{Ampl} \) |
| 1st | 223.49         | -90.72        | 104.84        | -174.54       |
| 3rd | 3.33           | 47.96         | 1.42          | -99.53        |
| 5th | 6.33           | 85.39         | 20.18         | -160.96       |
| 7th | 4.86           | -87.65        | 8.36          | 30.13         |
| 9th | 1.18           | -31.38        | 1.06          | 126.86        |
| 11th| 1.86           | -63.59        | 6.08          | 47.50         |
| 13th| 0.26           | -156.65       | 5.24          | -128.10       |
| TTHD [%] | 5.74          |               |              | 25.18         |

Table 13. Measured grid voltage and current parameters after the single-tuned filter connection.

| n   | \( U_S \) [V] | \( I_S \) [A] | \( I_F \) [A] | \( I_T \) [A] |
|-----|----------------|---------------|---------------|---------------|
|     | \( \text{Ampl} \) | \( \text{Ampl} \) | \( \text{Ampl} \) | \( \text{Ampl} \) |
| 1st | 227.38         | -89.29        | 18.68         | -32.12        |
| 3rd | 3.77           | 53.88         | 1.91          | -114.61       |
| 5th | 8.64           | 82.21         | 42.37         | -174.11       |
| 7th | 10.93          | -116.56       | 49.68         | -19.30        |
| 9th | 2.23           | 102.75        | 1.89          | -54.78        |
| 11th| 1.15           | 178.92        | 6.78          | -25.97        |
| 13th| 0.63           | 28.27         | 3.96          | -126.15       |
| TTHD [%] | 6.92          | 356.21        | 44.67         | 25.06         |

Figure 43. Laboratory equivalent circuit with the capacitors bank connected to the PCC.

Based on this second investigation, it can be concluded that the amplification of the 5th and 7th harmonics at the grid side is due to the fact that the additional 5th and 7th current harmonics are flowing from the electrical grid to the filter (which presents a lower impedance for them). Between the grid and the filter, there is superposition of harmonics (5th and 7th) flowing from the load side and from the grid side.

During the investigation on the single-tuned filter in the laboratory, two problems were noticed: the filter impedance of the harmonic to be eliminated (e.g., 5th) that was...
higher than the grid impedance of that harmonic and the harmonics amplification (e.g., 5th, 7th) at the grid side after the filter connection due to the initially distorted grid voltage. To solve the both problems, an additional line reactor can be used between the filter and the electrical grid (e.g., $L_{SS}$, see Figure 36). On the one hand, this additional line reactor will increase the grid equivalent impedance of the harmonic to be eliminated (increase of the filter work efficiency). On the other hand, it will mitigate the current harmonics amplitude flowing from the grid side (generated by the primary grid voltage). One of the inconvenient aspects of using this line reactor is the PCC voltage distortion which may increase (increase of the depth of the commutation notches).

Figure 44. (a) PCC voltage and (b) its spectrum, (c) grid current waveforms, and (d) its spectrum.

5. Conclusions

The knowledge of PHFs exists for many decades. It appears to be very rich as is indicated by the presented investigations. However, in the design process, often too little attention is paid to the change of their filtration properties due to the many factors highlighted in this paper. The performed investigations have showed that:

The PHFs (e.g., single-tuned and broad-band filters) should be tuned to the frequency a bit lower than the frequency of the harmonic to be eliminated because of the aging of their elements (LC), atmospheric conditions or fault which can cause the change of the filter’s initial tuning frequency. This tuning frequency should be chosen in consideration of the grid equivalent impedance of the harmonic to be eliminated which should be smaller than that of the filter. The harmonic to be eliminated should be a specific load characteristic harmonic (or electrical system characteristic harmonic) after the fundamental harmonic. In the case of more than one characteristic harmonic to be eliminated, the filter group can be used. A bad choice of the PHF resonance frequency can cause the amplification of harmonics at the electrical grid side and filter terminals.

The first-order filter designed for the fundamental harmonic reactive power compensation, in the electrical power system with distorted voltage and current, can be a source of harmonics amplification. In comparison to other filters, it is better in terms of higher harmonics mitigation in a wide band.

The second-order, third-order, and C-type filter work efficiency depends upon the choice of their damping resistance values. They can be the source of harmonics amplification if the damping resistance is not well chosen. Depending on their damping resistance
values, they are better for the reduction of harmonics in a wide band than the single-tuned filter (grid side).

The single-tuned filter compared to the broad-band filters (regardless of the damping resistance value) is better for the mitigation of an individual harmonic.

The second-order filter in comparison to the single-tuned filter and other broad-band filters (regardless of damping resistance values) generates more power losses.

The laboratory investigation has confirmed that before the PHFs are installed in the electrical system, information about the load or electrical system characteristic harmonics, PCC nominal and primary spectrum of the voltage, the filter properties and characteristics, the grid short-circuit power, and the equivalent impedance of the harmonic to be eliminated is needed.

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