Improving Power Quality and Efficiency in Electrical Plants using a Three-Phase Series Hybrid Passive Filter

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***Abstract* — The presence of harmonics introduces disturbances and losses in electrical systems that cause malfunctions and inefficiencies. In this paper, a passive three phase series hybrid power filter (PSHPF) is designed and applied in a commercial facility for reducing harmonics and distorced power generated by unbalanced linear/nonlinear loads, in this way the energy efficiency and the quality of power are improved. The filter is connected in series and can be switched on or off without interrupting the load operation. The filter inductance is suitably modified through some mutual inductances which are connected and disconnected using simple contactors. In this manner, additional losses related to the use of power electronic switches are not introduced. The proposed filter can reduce the typical critical parameter of power quality and can improve the overall efficiency of the system connected, from the power line to load. The simulation results show that proposed filter is capable of compensating harmonics and reactive power under unbalanced nonlinear load and/or non-ideal mains voltages.**

Keywords— passive filter, harmonics reduction, energy efficiency, power quality, harmonic power.

I. INTRODUCTION

As known, the harmonics play an important role in the operation of electrical systems. The sources of harmonics in power systems are typically related to non linear and switched loads, as electric arc furnaces, static VAR compensators, inverters, DC converters, switch-mode power supplies, and AC or DC motor drives. There are two main effects that can be associated to the presence of harmonics: the system losses increase and the introduced disturbances make the system less reliable. In particular, the effect of triplex harmonics come with overheating in wires, overheating in transformer units. In recent years, more attention has been given to harmonic problems and solutions [1]–[12]. To reduce the harmonics in power system, shunt or parallel filters are used, both active and passive. Recently, active hybrid power filters are introduced to overcome the main problems of previous ones [6], [8], [10], [13]. Active filters are becoming a viable alternative to the traditional passive filters to reduce harmonics in power systems. Some topologies have been proposed in the literature [5], [6]. However, these filters become costly at increased power levels. In any case, these filters require energy in order to function, by increasing the system losses. Because of the consideration of hardware cost, passive filters were used to reduce the problems of harmonics in electrical systems conventionally. In Fig.1 the typical topologies of passive compensator are shown. However, they still has several problems. The most serious problem is that the series-parallel resonance may occur between the system impedance and passive filters. This series-parallel resonance will result in the amplification of harmonic voltage, and it may damage the passive filters and neighboring power equipment. Shunt hybrid power filters are used to compensate current harmonics, but in most cases, they also have additional functions, such as compensation for reactive power, current unbalance and neutral current. When varying single-phase loads are connected to the three-phase utility distribution system, loading conditions resulting in continuously changing and unbalanced. The reasons given above, and the growing interest in low-cost passive filters has led researchers to investigate hybrid passive filters [14]–[20]. If the requested reduction of the harmonic content required by the system is not high, then it is possible to use series passive filters able to meet the requirements. By combining series and parallel passive filters is possible to obtain better performance reducing problems. The high power capacity application of the hybrid power filter becomes more practical than that of the active power filter [21]. Additionally, the resonance problem of passive power filters is solved due to the combination of series and parallel variable connections. The methods that are applied to the hybrid power filter designs to compensate for reactive and

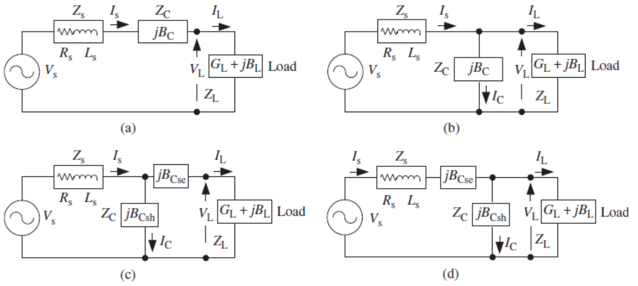


Fig. 1. Passive harmonic compensators: (a) series, (b) shunt, (c) short-shunt hybrid, and (d) long-shunt hybrid.

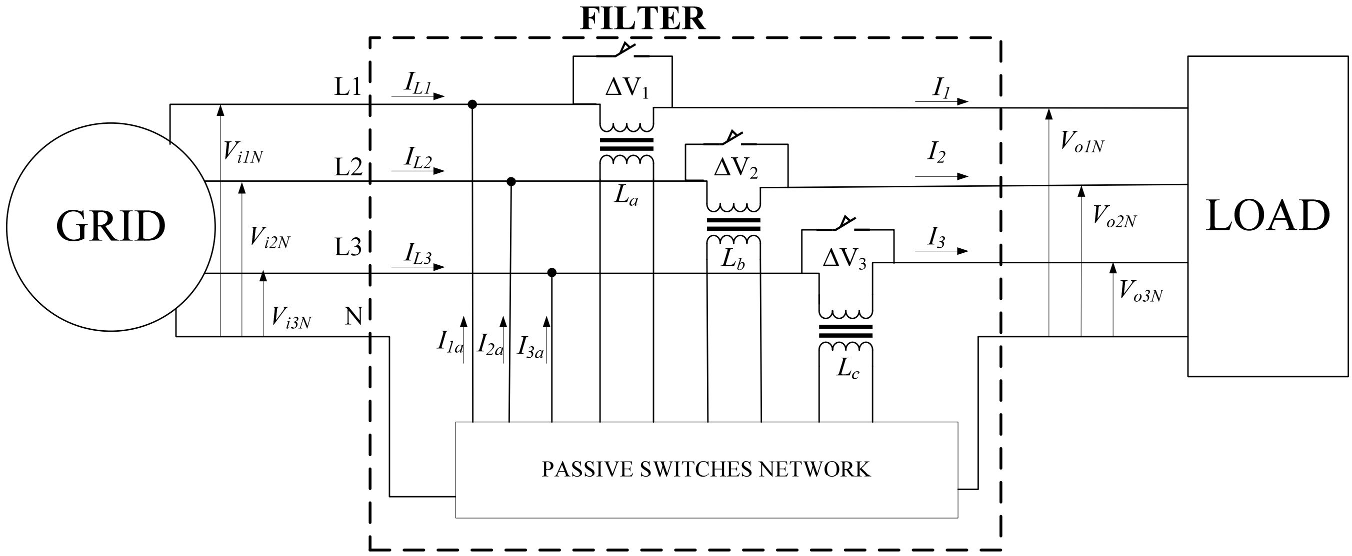


Fig. 2 The proposed series-hybrid passive filter

harmonic current in a three phase system, suppose a major assumption of balanced three phase system to meet all requirements of derivations. However, under practical conditions, the three-phase power system cannot be continuously balanced due to unbalanced loadings in radial distribution feeders [22].

In this paper, a passive three phase series hybrid power filter (PSHPF) is designed and applied in a commercial facility for reducing harmonics and reactive power generated by unbalanced linear/nonlinear loads. The filter inductance is suitably modified through some mutual inductances which are connected and disconnected using simple contactors. In this manner, additional losses related to the use of power electronic switches are not introduced. This filter uses a control algorithm based on the comparison between the supply voltages and their desired values. This method is simple to implement, easy to adjust, not costly, adaptable to load currents, etc.. As a result of the installation of this filter, it's possible to achieve more efficiency of the system, both in terms of reducing losses and in term of noise and failure reduction caused by the presence of harmonics. The proposed filter can reduce the typical critical parameter of power quality and can improve the overall efficiency of the system connected, from the power line to load. Computer simulations results using Symscape Power System of Matlab concluded that the proposed filter may become a feasible and viable approach to implement for unbalanced ac source and/or load and/or distorted ac source. The simulation results show the performance of the proposed filter and its capability to compensate for harmonics and reactive power even under unbalanced nonlinear load, and/or non-ideal mains voltages and can reduce the resonance problem of existing power factor correction capacitors. Finally, the performances of the proposed filter are verified in a commercial building.

II. SERIES-HYBRID PASSIVE FILTER

Considering the known several conventional techniques [12], [22], [23], a new configuration has been developed. Figure 2 shows the proposed filter. On each of the phases is inserted a series inductor mutually coupled with a second inductor whose value is determined by appropriate switching of the contactor block. The currents that are circulated on the secondary windings, are re-entered in the power circuit, upstream of the main inductances. Since the primary inductance is connected in series, the main purpose of the filter is to keep the potential drop ΔV within the limits imposed by regulations and by the project, so as to ensure the proper functioning of the connected equipment. In this sense, the control system reads the value of the voltage input and changes accordingly, the value of the inductances mutually coupled. Another significant advantage of this configuration is the possibility to size the primary inductance based on the rated current of the system, while secondary inductances let you do the filtering operations, regardless of the load current value. The switches in parallel to the primary inductors allow plugging in the filter at any time without interrupting the operation of the load.

The passive switches are controlled by a system capable of measuring the voltages V_{iXN}. In this way the value of the secondary inductances L_a, L_b and L_c, are modified so as to produce a current I_{Xa} can compensate for the voltage drop ΔV_x. In any case:

$$\begin{cases} I_1 = I_{L1} + I_{1a} \\ I_2 = I_{L2} + I_{1b} \\ I_3 = I_{L3} + I_{1c} \end{cases} \tag{1}$$

and

$$\begin{cases} V_{o1N} = V_{i1N} + \Delta V_1 \\ V_{o2N} = V_{i2N} + \Delta V_2 \\ V_{o3N} = V_{i3N} + \Delta V_3 \end{cases} \tag{2}$$

It is noteworthy that the power filter system above series-hybrid can be easily switched on and off without affecting the operation of the load and without involving the system protections. Also, while the series inductances work as a filter on the line current, the derived inductances allow to maintain the proper output voltage level.

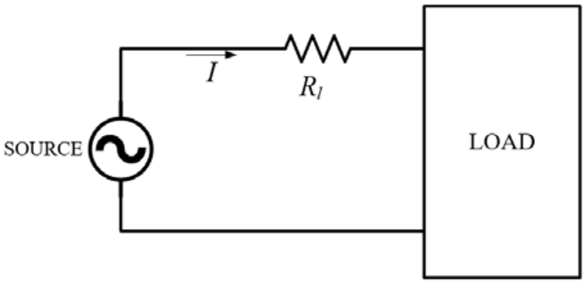


Fig.3. Example to demonstrate the effect of the harmonics.

III. EXPERIMENTAL RESULTS

To understand the effectiveness of the filter consider the following example, shown in Fig. 3. If we assume that the line resistance is equal to 10 mΩ and that the load is absorbing a current of 100 A, then the losses on the line are equal to:

$$P_{loss,1} = R_l \cdot I^2 = 0.01 \cdot 100^2 = 100 \text{ W} \tag{3}$$

Now, if the current containing additional third, fifth, and seventh harmonics whose amplitudes are inversely proportional to their harmonic order, the RMS becomes:

$$I = 100 \cdot \sqrt{1^2 + \left(\frac{1}{3}\right)^2 + \left(\frac{1}{5}\right)^2 + \left(\frac{1}{7}\right)^2} = 108.24 \text{ A} \tag{4}$$

and the losses increase up to:

$$P_{loss,2} = R_l \cdot I^2 = 0.01 \cdot 108.24^2 = 117.15 \text{ W} \tag{5}$$

Then, the additional losses due to harmonics are equal to:

$$\Delta P = P_{loss,2} - P_{loss,1} = 117.15 - 100 = 17.15 \text{ W} \tag{6}$$

or

$$\Delta P_{add}\,\% = \frac{\Delta P_{add}}{P_{loss,1}} = 17.15\% \tag{7}$$

Thus, the presence of the third, fifth and seventh harmonic of the current has increased the losses on the line of 17.15%. In this case, the THD = 41.41% and PF = 92.39%.

If we consider the same case, but without the seventh harmonic, by performing similar calculations we obtain:

$$\Delta P_{add}\,\% = \frac{\Delta P_{add}}{P_{loss,1}} = 15.11\% \tag{8}$$

where THD = 38.87% and PF = 93.21. Then, it's enough a minimal change in THD (-2.54%) and PF (+0.82%) to obtain a reduction of additional losses on the line (-2.04%). In general, it can be proved that the difference of losses on the line, that is obtained by modifying current THD, is equal to:

$$\Delta P_{add}\,\% = \frac{\Delta P_{add}}{P_{loss,1}} = \left(1 - \frac{PF_{before}^2}{PF_{after}^2}\right) \tag{9}$$

To verifiy this results, a simulation by Simulink and SimPowerSystem was performed. The system simulated is shown in Fig. 4, where a three-phase rectifier and three single-phase are used to obtain the requested harmonics.

TABLE I. EXPERIMENTAL RESULTS

Losses reduction		
Parameter	***Bypass***	***Saving***
Active Power	34.4	34.1
Apparent Power	41.55	40.29
THD$_I$	0.5728	0.5635
Power Factor	0.8278	0.8463
$\Delta P_{add}\,\%$	4.32%	

Finally, to evaluate the effectiveness of the filter, an experiment was carried out in the laboratory in which the filter has been tested on a group of LED lamps fed with elettronic power supplies. During the experiment, the filter was inserted

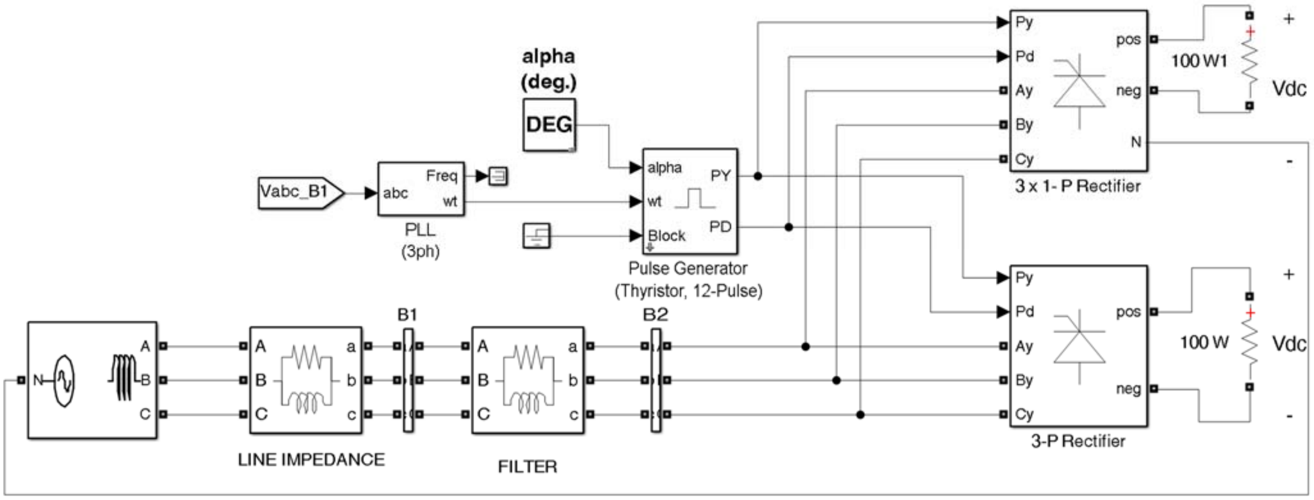
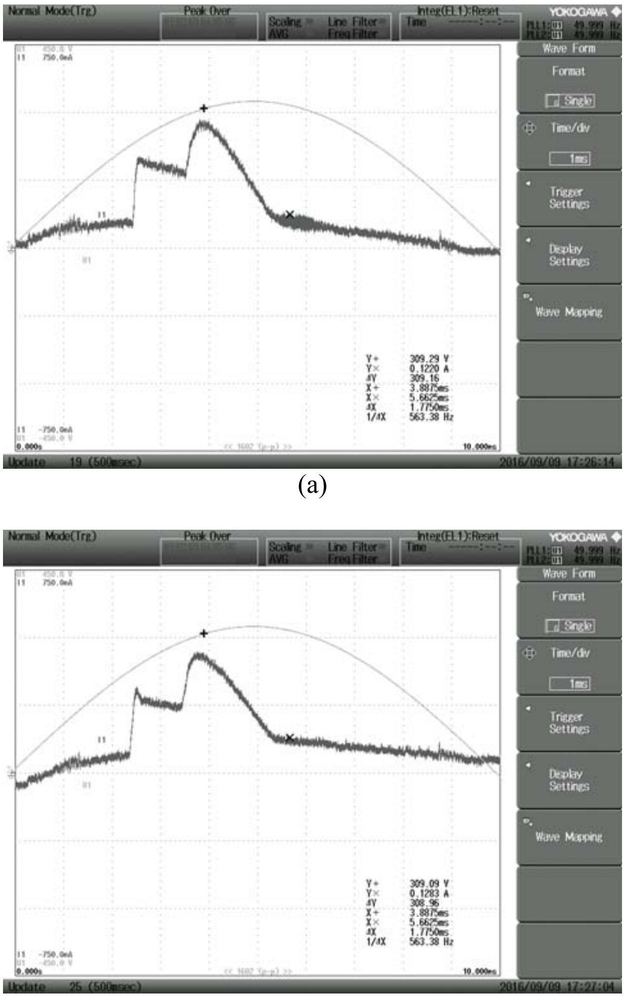


Fig.4. The Simulink model used to verify the filter effects.

Fig.5. Experimental setup.



(a)

(b)

Fig.6. The filter input waveform in (a) saving mode and (b) bypass mode.

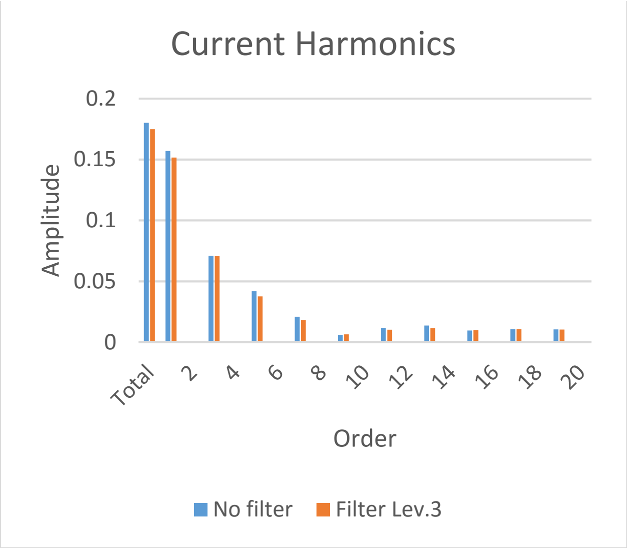


Fig.7. Harmonics measured.

(saving mode) and removed (bypass mode), always making sure the power supplied to the lamps keeps constant. In Fig.6, the input waveforms are shown both when the filter is in bypass mode and when it is in saving mode. It is possible to note how the voltage remains unchanged, while the current is changed. In particular, the peak value is reduced. These changes can be evaluated by the measurements of the parameters related to harmonics. In Table I the results of the simulation are summarized.

IV. CONCLUSION

In this paper, a passive three phase series hybrid power filter (PSHPF) is designed and applied in a commercial facility for reducing harmonics and reactive power generated by unbalanced linear/nonlinear loads. The filter is connected in series and can be switched on or off without interrupting the load operation. The filter inductance is suitably modified through some mutual inductances which are connected and disconnected using simple contactors, removing additional losses due to power electronic switches. The effectiveness of the filter was first simulated by Simulink and then tested by experimental measurements in the laboratory. The results obtained are in line with expected target for this kind of filters.

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