A Detailed Study of Active and Hybrid Power Filters

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***Abstract*—This paper provides a comparison between three different topologies, which can be used in current harmonic mitigation. The considered solutions are as follows: a pure active filter, a hybrid filter composed from a series connection of shunt passive and active filters and a newly proposed hybrid filter topology. In this paper the inverter power rating is seen as the main factor of interest, because it roughly determines the overall cost of the device. The comparison analyzes the advantages and drawbacks of the chosen topologies. The principles of operation as well as design considerations of the presented harmonic mitigation devices are presented. Simulations and experimental results confirm the theoretical analysis with a 3 kVA power rated laboratory setup.**

***Keywords*—active filters, hybrid filters, passive filters, power quality, power system harmonics.**

I. INTRODUCTION

Harmonic currents affect supply systems and may create serious problems like power losses, malfunction of equipment and resonances. Harmonic currents are caused mostly by the AC to DC conversion, widely used in both home and industry applications.

Traditionally passive filters dealt with the harmonics, because of their initial low cost and simplicity. However, passive filters have serious drawbacks, namely aging, large parameter tolerance and dependence of the filtering characteristic as a function of the of the grid impedance. These problems are the main driving forces for the development of the active power filters.

Active power filters mitigate harmonics with much better accuracy, but their cost is relatively higher than passive filters. This disadvantage excludes them from usage in cost-sensitive applications. To minimize this drawback, various types of hybrid topologies were presented and successfully implemented in recent years. These topologies mitigate the harmonic currents relatively well, while their cost is considerably reduced comparing to a pure active power filter solution.

This paper presents a comparison of a pure active and two hybrid topologies in respect to the harmonic mitigation performances (i.e. line current THD_i), rated power of the inverter and design issues. Both simulations and practical experiments on an existing laboratory setup rated 3 kVA sustains the comparison. The implementation of the control is almost the same in complexity for all the selected topologies and obtained harmonic mitigation performance is similar maintaining system current THD below 5 %. The paper concludes that the last topology presented in Fig. 2 is much more effective than the other solutions because of the lower size in passive components and the inverter, which makes it very attractive for high power industrial applications.

II. SELECTED TOPOLOGIES

A. *Active Power Filter (APF)*

The pure active power filter is taken here as a typical active solution for current harmonics mitigation. It consists of an PWM inverter connected in parallel between the system and nonlinear load.

Front inverter inductances are used to create compensating currents since in most cases Voltage Source Inverters (with a capacitor on its dc-side) are used. This is mainly because of their lower cost for low and average power [2], [6]. Such topology is well covered in literature and it is already used in practical applications. The advantage of this topology is well known theoretical analysis, which results in easy calculation of the parameters. This considerably minimizes the engineering effort, which has to be put on the design process.

The most important drawback of this topology is that it has to work against the full back voltage of the supply. Therefore, the inverter power rating is relatively high and the dc-voltage is around 700 V. This determines very high cost of the device because of the initial cost of high power semiconductors and considerable switching losses.

B. *Hybrid Power Filter I (HPF I)*

The first hybrid power filter topology which was taken into consideration during this comparison is shown in Fig. 1. It consists of a shunt passive filter in series with an active filter. This topology is described explicitly in [3].

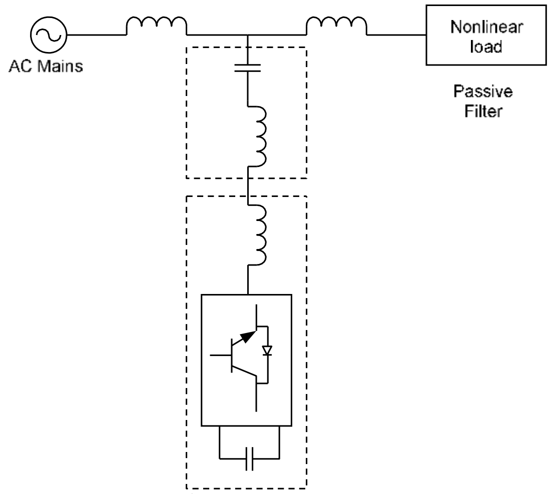

Fig.1 Hybrid Filter I – passive filter connected in series with an active filter altogether connected between the system and nonlinear load.

This topology has a major advantage in comparison to pure active solution because of the fundamental voltage drop on the passive filter capacitor, which allows the inverter to operate with a significantly lower DC voltage. This provides significant reduction in the inverter power rating compared to the pure active solution.

Nevertheless, there is still a large current flowing through the inverter due to the series connection with the passive filter. All reactive power drawn by the passive components circulates within the switching devices, which negatively affects inverter power rating. This can be regarded as the main drawback of this topology, which still increases its initial and maintenance costs. For that reason further research was performed in order to find a solution, which has as profitable relationship between the accuracy and cost, as possible.

C. Hybrid Power Filter II (HPF II)

In order to eliminate serious disadvantages of the previously described solutions, a third topology is

A. Active Power Filter

Active Power Filter model consists of supply system, nonlinear load, inverter, PWM pulse generator and control block. Usually a switching frequency filter is used to remove the high frequency components generated by the inverter. However, here it was not applied due to assumed low grid impedance, which resulted in questionable efficiency of any passive filtering. Switching frequency was set to 10 kHz.

The currents before and after the pure active filtering can be seen in Fig. 4. As it can be seen, the active power filter successfully mitigates the current harmonics. THD of the supply current is reduced from 25% to 3% meeting the IEEE-519 harmonic recommendations.

Current flowing between the system and the active filter can be seen in Fig. 5. Its RMS is equal to 3.93 A. U_{RMS} was equal to 515V. Inverter power can be calculated as shown in (1).

proposed in [4], as it is shown in Fig.2. In this case the

$$S = \sqrt{3} \cdot U_{RMS} \cdot I_{RMS} \quad (1)$$

active filter is connected between the passive elements.

The parallel connection of the passive and active filter reduces the current flowing through the inverter (from 6.5A to 2.8A). Simultaneously, fundamental voltage drop on the passive filter's capacitors still results in a considerable dc-voltage reduction (from 700 V to 200 V). These two factors determined the lowest inverter power rating from the devices presented in this comparison.

Moreover, high frequency components created by the inverter are not blocked by the passive components due to low impedance of the capacitors. This problem oc curs in the previously presented topology where low impedance was provided only for frequencies close to the passive filter's resonance frequency, resulting in reduced capability to compensate high order harmonics. In addition, presented solution allows the passive filter to mitigate harmonics and compensate reactive power, while the active filter is not operating (during its failure or maintenance brake) due to the parallel connection.

III. SIMULATIONS

Simulations were performed in order to confirm theoretical considerations. As the nonlinear load a simple where:

U_{RMS} - voltage measured between two phases on AC side of the inverter [V]

I_{RMS} - current in one phase on AC side of the inverter [A]

These values result in apparent power of the inverter equal to **3.5 kVA**, hence its power rating is 35% of the nonlinear load. Size of the inverter strongly depends on the load THD_i. For that reason, active power filters are designed for particular nonlinear load, with previously determined level of the current distortion. Otherwise large safety margin should be considered during the inverter design process. This would have a significant impact on the cost of the entire device.

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B. Hybrid Power Filter I

This device, which consists of both passive and active filters, is more complicated than previous topology. However, as it was previously proved in literature [3], it is advantageous because of the power reduction of the PWM inverter.

The passive filter is designed in such way, that it

6-pulse diode rectifier with 10kVA load having a displacement power factor equal to 0.95 is considered. The load current and its FFT analysis are given in Fig.3.

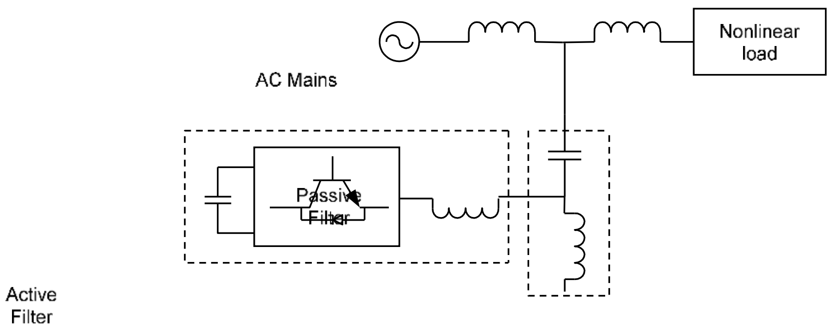


Fig.2. Hybrid Filter II – active filter connected between the elements of the passive filter altogether connected between the system and nonlinear load.provides low impedance for a frequency close to the 5th harmonic, namely 235 Hz and compensates fundamental reactive power.

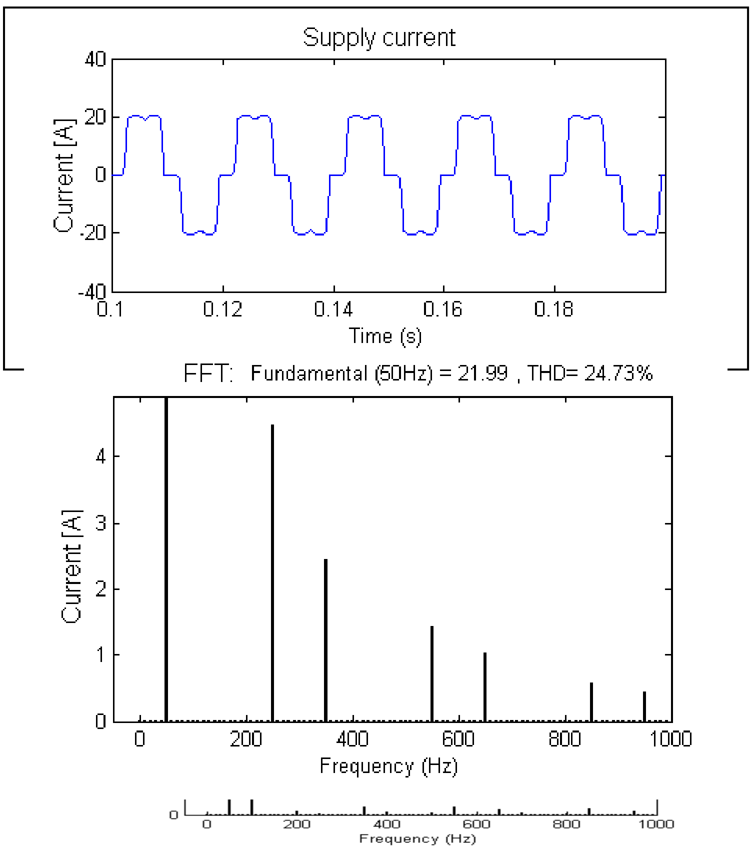


Fig. 4. Current after filtering by the pure Active Power Filter measured at the system side.

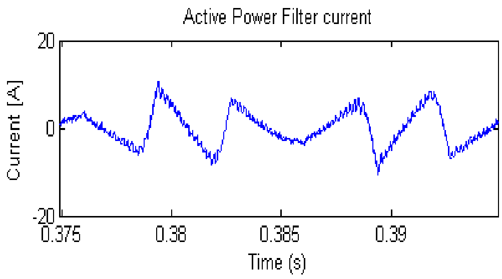


Fig.5. Active power filter current during steady state operation.

The main reasons for the mistuning of the passive filter can be listed as follows:

- protection from the existing voltage distortion,
- filter detuning because of the capacitors aging,
- tolerances of the passive elements parameters,
- temperature influence.

More detailed information about the passive filters can be found in [1].

The dc-voltage (due to the fundamental voltage drop on capacitors) is reduced to 200V. The system current after connecting the proposed hybrid filter is shown in Fig. 6.

Current harmonics are reduced from 25% to 3.7%, which can be regarded as a satisfactory result. However, as it was mentioned before, this topology has a serious drawback of big current flowing through the inverter. Its RMS current is 6.5 A. This current is shown in Fig.8. U_{RMS} was equal to 119V in this case. Using equation (1) the power of the inverter can be calculated as **1.35 kVA**.

C. Hybrid Power Filter II

Similarly to the previous harmonic mitigation solution, the passive filter is tuned to 235 Hz. The active part of the hybrid filter is connected in parallel between the passive elements without any matching transformer.

The steady state operation of this hybrid filter can be observed in Fig.8. Supply current THD is sufficiently reduced (from 25% to 3.4%). True RMS of the inverter current is 2.8 A and U_{RMS} is equal to 120V. According to (1) the inverter power is equal to **0.59 kVA**, which is considerably lower comparing with the two other topologies. Inverter current course is shown in Fig.9.

D. Comparison of Simulation Results

A summary of the simulation results is presented in Table 1

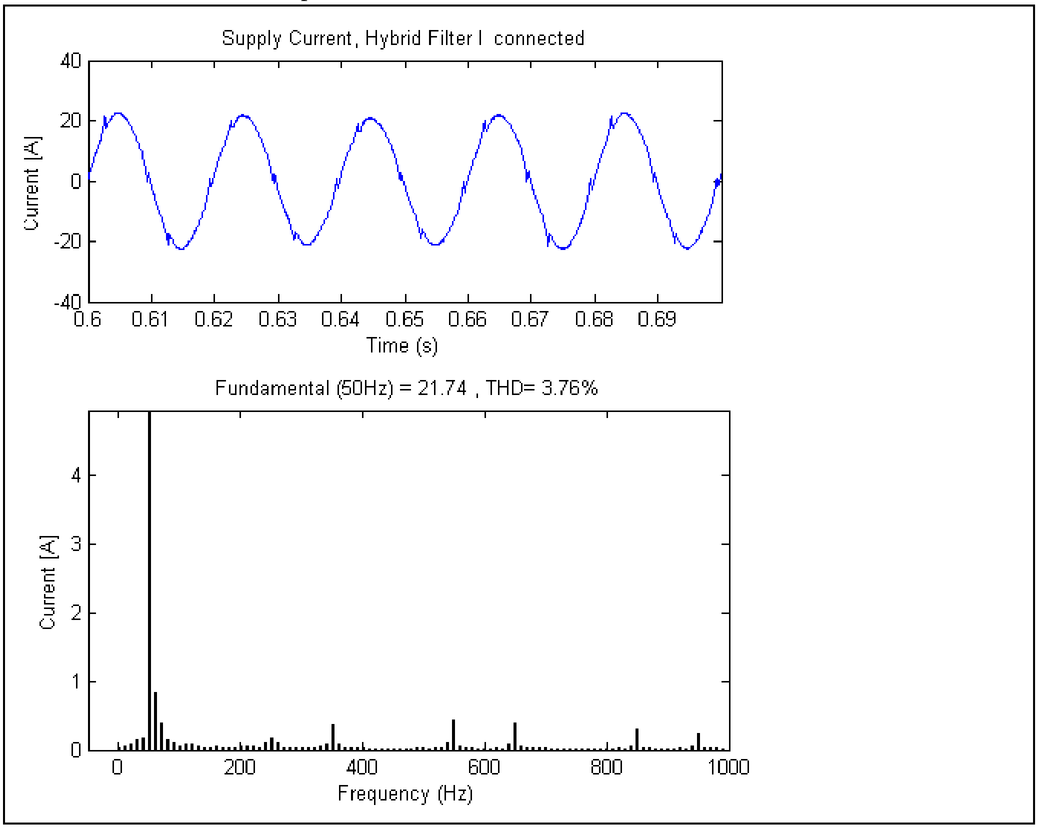


Fig. 6. Current after filtering by the Hybrid Power Filter I measured at the system side.

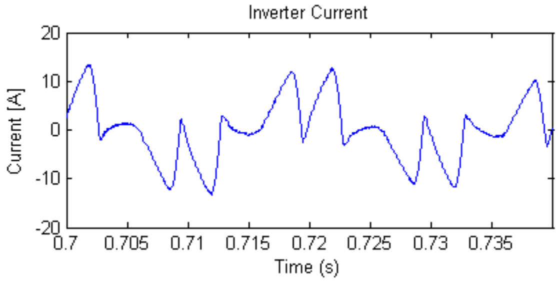


Fig.7. Inverter current in Hybrid Power Filter I during steady state operation.

Since inverter power is the main factor in this comparison, the following quantities were taken into account: harmonic mitigation efficiency considered by measuring the current THD_i after connection of harmonic compensation device, the voltage value on the capacitor at the dc-side of the inverter, the RMS current flowing through the inverter in steady state operation of the device. These quantities allow determining the inverter power.

The results obtained in simulations show that the pure active filter provides the best harmonic mitigation efficiency. It decreased the THD_i of the system current from near 25% to 3%, which is considerably low regarding no switching frequency filter installed, and thus the ripple also contributes to the harmonic distortion.

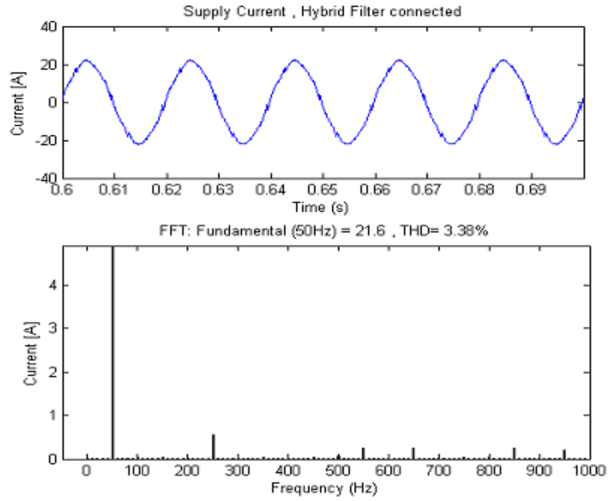


Fig. 8. Current after filtering by the Hybrid Power Filter II measured at the system side.

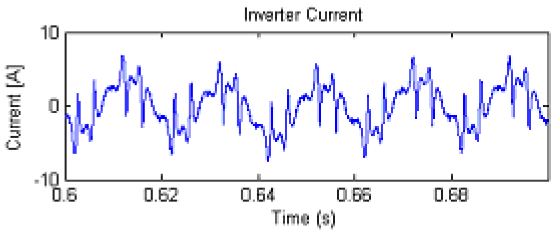


Fig. 9. Inverter current in Hybrid Power Filter II during its steady state operation.

Nevertheless, the hybrid filters' ability to compensate current distortion is only slightly worse and should be sufficient for most applications. It is measured that all the presented topologies provide satisfactory current harmonic compensation.

The dc-voltage value of both hybrid filters is 3.5 times lower then the dc-voltage of an active power filter. This is because, in order to create any current flowing through the line inductor, the dc-voltage needs to be higher than the maximum voltage on the ac-side of the inverter [8]. In both hybrid topologies the line capacitors provide large fundamental voltage drop, thus the dc-voltage should be higher than the maximum voltage value on the inductors, which is considerably low due to its impedance characteristic.

The inverter currents vary considerably between the presented topologies. The largest current flows through the HPF I, which is the result of series connection of the active and passive filters. The passive filter provides reactive power compensation, which determines large reactive currents. Some fundamental component is also necessary to feed the dc-capacitor, in order to maintain the inverter in operation, and thus a real current is used by the APF. Due to the parallel connection between the active and passive device, the smallest current is flowing through the HPF II. It consists of harmonic compensating current and also a fundamental component for the dc-capacitor. However it is reduced by the harmonic component (5^{th} harmonic), which flows through the passive filter.

The overall inverter power, which roughly determines the cost of the harmonic mitigation device, is an important factor in cost-sensitive applications. Low inverter power rating rapidly improves the profitability of the investment in harmonic compensation. In presented comparison the pure active power filter requires the largest inverter, which apparent power is 46% of the load apparent power.

Application of HPF I reduces the inverter power rating considerably (to 13.5%). However, it is still regarded as an expensive solution in high power applications. The third presented topology (HPF II) provides the most significant inverter power reduction. It reaches only 5.9% of the load apparent power.

IV. PRACTICAL IMPLEMENTATION Control part was implemented in Matlab/Simulink software with Real-Time Workshop developed for dSpace hardware. A dedicated monitoring software ControlDesk

Table 1. Comparison of different design parameters between the selected topologies.

	Active Power Filter	**Hybrid Power Filter I**	**Hybrid Power Filter II**
Line-side current distortion THD_i	3%	3.7%	3.4%
Dc-voltage value	700V	200V	200V
Inverter Voltage (RMS)	515V	119V	120V
Inverter current	3.9A	6.5A	2.8A
Overall inverter size	3.5 kVA	1.35kVA	0.59 kVA
Inverter power rating	35%	13.5%	5.9%

allows to view all relevant signals and change all coefficients in real time.

The control algorithm of the APF can be seen in Fig.10. It is developed in dq-synchronous reference frame using PI controllers [7]. The harmonic component is extracted from the load current by the high pass filtering in dq-reference frame. The PI controller creates the reference voltage, which is transformed back to the abc and rescaled (division by half of the dc voltage). An outer control loop is used to maintain the desired dc-voltage value. The Phase Locked Loop (PLL) synchronizes all transformation blocks with the system frequency [5].

Regarding two hybrid devices, the control algorithm and dc-voltage value are exactly the same for both. Their control method depends on dq-synchronous frame and its controllers operate in a close loop. In this case system current is measured and its distortion is maintained possibly close to zero by the “P” controller in a main control circuit [4]. Additional loop connected to the q-axis charges the dc-capacitor to the desired value and maintains it constant [3].

In figures 11 and 12 measured waveforms on existing devices on a laboratory stand are shown. The apparent power of the nonlinear load is 3 kVA. As can be seen in the pictures, both topologies provide a good harmonic compensation. They successfully maintain the THD_i of the system current below the 5% meeting IEEE harmonic recommendation.

The APF voltage RMS was 510 V and inverter current was measured as 1.07 A. This resulted in apparent power of the active filter equal to **0.95 kVA**. Power rating of the inverter is 32 % of the nonlinear load. In case of HPF II it was possible to apply dc-voltage value equal to 50 V and mitigation efficiency was still satisfactory. Measured current flowing through the inverter was 2A and inverter voltage RMS was equal to 30V. Such values determined inverter apparent power, which was only **0.1kVA** (3.3% of the nonlinear load).

Fig.10. Block diagram of the control algorithm of an active power filter showing the main control circuit and dc-voltage control loop

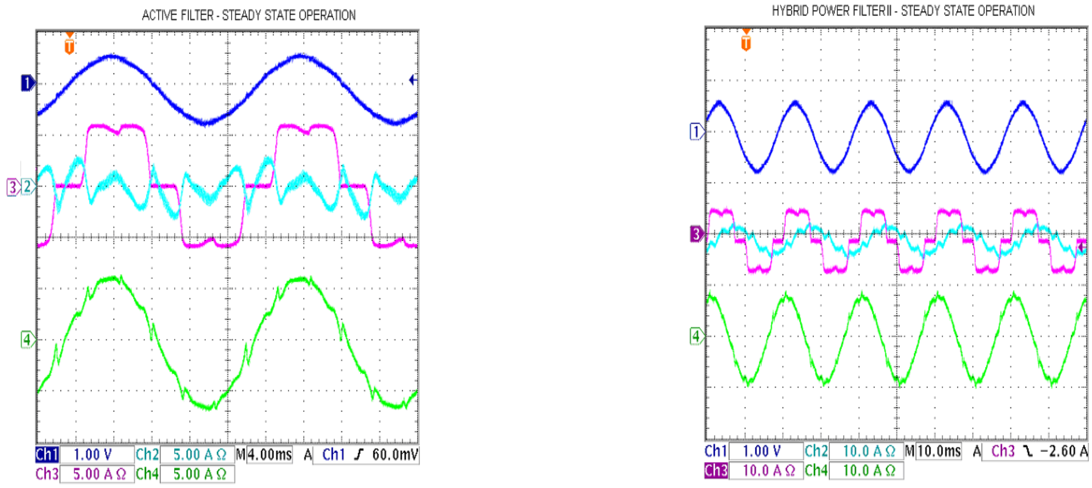
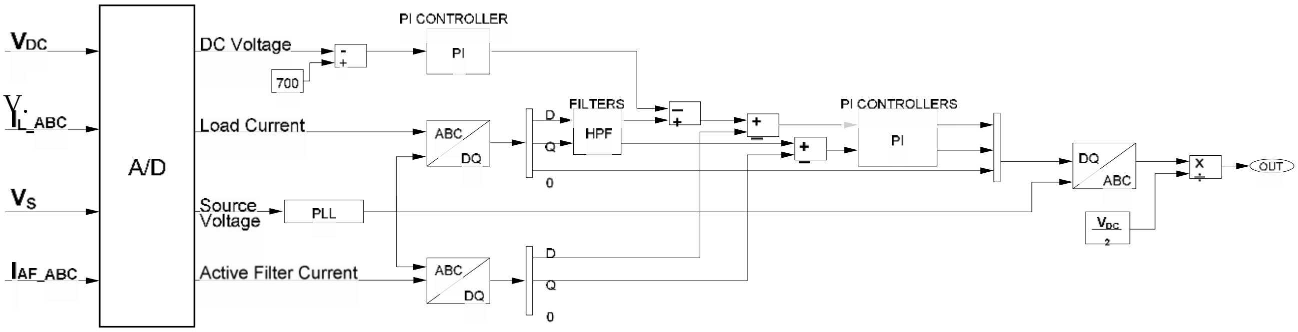


Fig. 11. Measured waveforms for the APF operating in steady-state conditions on the laboratory setup: (1) system voltage, (2) inverter current, (3) load current, (4) system current.



CONCLUSIONS

In this paper a comparison between an active power filter and two hybrid power filters was presented. The main goal was to find a solution, which has as profitable relationship between the accuracy and cost, as possible. Current distortion was mitigated sufficiently by the all proposed devices. However, as it was proved in this paper, there is a great difference in inverter sizes between these topologies. According to above presented simulations and practical experiments, active device connected between the elements of the shunt passive filter (HPF II) is the most advantageous topology.

It ensures proper harmonic mitigation with minimal initial costs, which frequently is crucial factor in cost- sensitive applications. In addition, in high power applications, this hybrid power filter topology can be used as an upgrade to the existing passive filter improving its performance and cancelling its serious drawbacks. More simulation and implementation results can be found in [9].

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