Two harmonic detection methods used in industrial shunt active filters

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Selective harmonic compensation is suitable for cases where balanced network conditions exist and the rating power of the active filter is to be maintained. The overall harmonic compensation is suitable for more general purpose provided the rated power is available. Both simulations and measurement are provided to backup the comparisons and discussions.

This paper describes two harmonic detection methods used in industrial shunt Active Filters. The methods are overall harmonic compensation and selective harmonic compensation. Both methods are described and analyzed in the paper together with several practical design steps for Adjustable Speed Drives applications. The methods are compared in the case of voltage unbalance and pre-distortion, common cases in industrial applications. The paper concludes with guidelines of using each method in different cases.

There is a remarkable progress in Active Filter (AF) applications during last decades, encouraged mainly by the increased performance of the power switches. Furthermore, the evolution of Digital Signal Processors and new control theories enable superior harmonic compensation characteristics and stable operation of AF's compared to classical passive filters.

One large application field of AF's is compensation of line-side harmonic currents generated by frequency converters. Although other methods exist in literature to minimize such harmonic currents [1], the use of AF is more appealing because of control ability and possibility of tuning in the desired performance [2].

Provided that the front-end converter of an Adjustable Speed Drive is a diode bridge rectifier the line-side currents in ideal grid conditions contains characteristic harmonics of orders $+6h+1$, where h is a positive integer number [3]. In the case of unbalanced or pre-distorted grid voltages the frequency converter generates non-characteristic harmonic currents (of inverse rotating sequence and also even orders).

The AF can be configured to achieve specific goals such as compliance with harmonic standards, stable operation on the grid, maintain safe operation within the designed power rating, etc. In severe cases of voltage unbalanced and pre-distortion such goals can be too complex and may not necessarily converge all together. It is therefore a question of how to set the AF harmonic compensation to obtain the best overall performance.

There are two modes of harmonic compensation modes in an AF in terms of compensated bandwidth: the overall and the selective harmonic compensation, each of these modes giving different performances depending on the existing conditions and limitations. A third compensation mode, i.e. Direct Harmonic Control [4] is reported in literature but is not going to be extensively described in this paper.

The purpose of this paper is to describe and compare both the Overall Harmonic Compensation and Selective Harmonic Compensation. This is done by presenting several practical situations and the potential performance and limitation when using each of the mentioned method. Simulations are used to support many of the conclusions reached in the paper. An industrial AF laboratory setup supports the comparisons from a practical perspective. The paper concludes with several guidelines and recommendations.

Shunt active filter

The connection of the shunt Active Filter and a simplified control diagram is given in Fig. 1. The block diagram of the proposed control (Fig. 1) is a typical implementation of an AF having current controllers in the inner loop and the voltage controller in the outer loop [5]. The control value of the current control loop is the load current (see the load current sensors IL in Fig. 1). The selection of the switching sequence for every switching operation through the use of the sliding mode control is discussed in detail in [6]-[8].

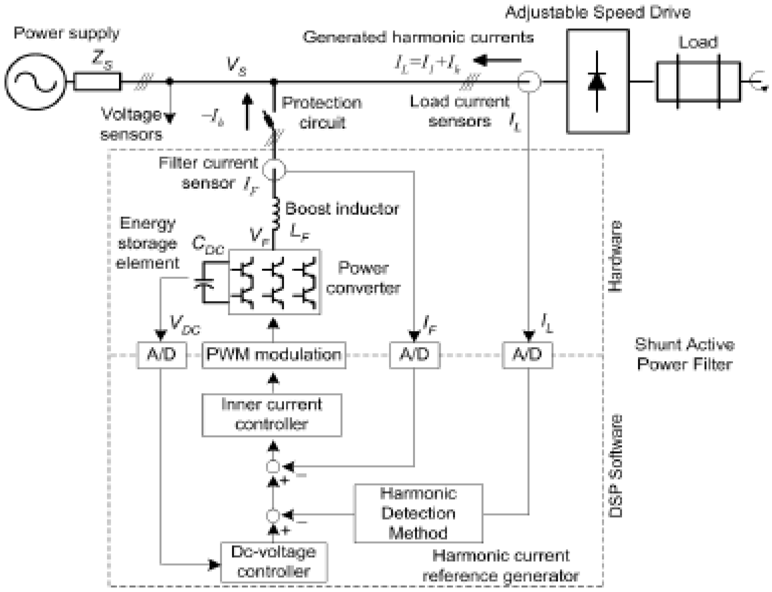


Fig. 1. One-line diagram of a shunt active filter in a feed-forward configuration with an adjustable speed drive as load.

The dc-voltage control loop is a classical PI controller. Its output is the current reference in d-axis, which determines real power to be drawn from the grid for keeping the dc-voltage at the imposed voltage. The compensation of the reactive power is possible, by providing the imposed current reference in the q-axis current controller, though it is not used in this work.

The harmonics are detected by measuring the load currents (line-side current *IL* from frequency converter in Fig. 1) and supplying this information in the control. This control part is described in more details in the following section.

Harmonic detection methods

The harmonic detection method is the part of the AF's control that has the capability of determining specific attributes of the harmonics (frequency, amplitude, phase, time etc.) from an input signal (the load current in Fig. 1) by using dedicated filtering algorithms. The achieved information is imposed as reference current to the inner controller to compensate the existing harmonic current distortion [10]-[13].

Depending on the design of AF's harmonic control there are several possibilities to compensate harmonic currents in terms of bandwidth, as described in the followings.

Overall Harmonic Compensation

The overall harmonic compensation (hereafter referred to as OHC) aims to provide as harmonic reference current the entire harmonic spectrum present in the load current except the fundamental frequency, which is to be supplied by power network. The OHC relies on overall harmonic detection method as illustrated in Fig. 2.

Therefore, the main function of the harmonic detection block is to filter out the fundamental frequency. This can be achieved in different manners:

- in stationary abc-frame, by using Notch Filters (although this may be prone to phase delays if not carefully implemented, causing improper harmonic compensation) or Fourier based filters tuned to remove the fundamental component [14].
- in synchronous fundamental dq-frame by High-Pass Filter that eliminates the dc-component alias the fundamental frequency [15].
- by using the instantaneous power theory [16], which again resumes to removal of the fundamental component (dc-component) by High-Pass Filter.

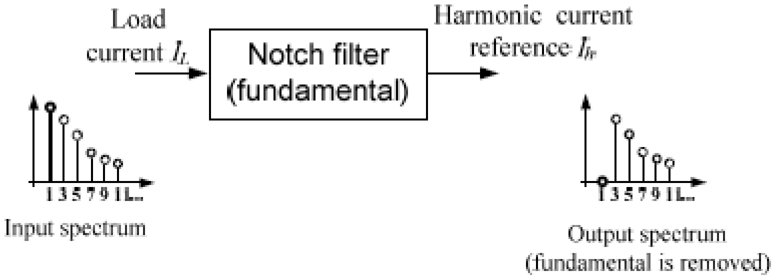


Fig. 2. Simplified illustration of generation of the harmonic current reference by using the overall harmonic detection method.

The OHC is applicable for loads with wider or unknown harmonic spectrum or for AF designed to cope with not well specified operating conditions, where harmonics of unpredicted orders may appear.

Selective Harmonic Compensation

The selective harmonic compensation (hereafter referred to as SHC) aims to provide in the harmonic reference current only several selected harmonic orders. The bandwidth of the compensated harmonic current is therefore limited to the selected harmonic orders. This selectivity can be implicitly provided through the selected algorithm (i.e. only several harmonic orders are compensated by design) or by user's choice (the user enables or disables what harmonic orders are to be compensated). Similar as the OHC method this can be done in both, stationary abc-frame or synchronous dq-frame:

- in stationary abc-frame, by using Band-Pass filters or Fourier based filters tuned to output the selected harmonic orders.
- in synchronous fundamental dq-frames by using again Band-Pass filters to isolate specific harmonic orders, alias the selected harmonics but shifted to different frequencies into the dq-frame [17].
- in synchronous harmonic dq-frames by using Low Pass filter to detect the dc-component, alias the selected frequency [18].

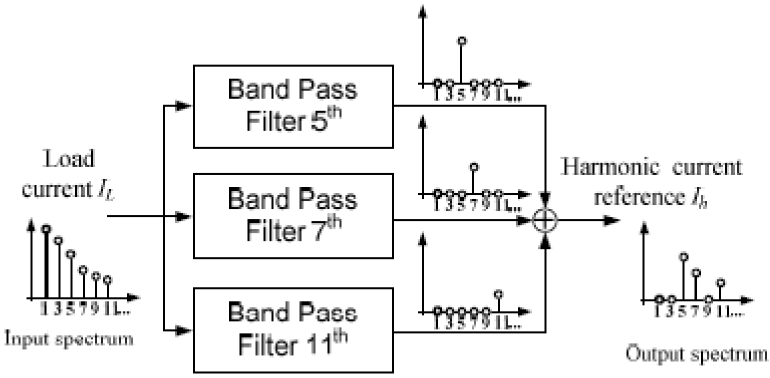


Fig. 3. Example of generation of the harmonic current reference by using the Selective Harmonic Compensation method.

Fig. 3 gives an example of SHC that uses three Band Pass filters to output only the 5th, 7th and 11th harmonic currents.

The rest of the harmonics are not included in the reference current therefore, they are not compensated.

Another approach that provides the same functionality as the SHC is to have selective current controller in the control.

The use array of resonant current controllers for selective harmonic regulation was reported in [19], [20], [21]. Therefore, since the desired selectivity lies in the current controller there is no particular need to introduce additional filters in the harmonic reference generation [22].

The OHC is applicable for loads with known harmonic spectrum (i.e. known non-linear loads) designed to work in specified operating conditions, where harmonics of known orders appear. Applications with frequency converters comply with these conditions, because of the known orders in the harmonic spectrum of line-side currents.

Direct Harmonic Control (DHC)

The principle of the operation is based on combining the both OHC and SHC methods. The power rating of the active filter can be reduced by the corresponding choice of harmonic reference signals. This is briefly described in [4], [9]. The same principle can be used for the phase correction of individual harmonics to compensate active filter hardware delays.

Discussion

Several practical aspects are discussed in this section in order to reveal more insights of each of the described harmonic detection methods.

DSP Calculation Time

The DSP calculation burden is much lower in OHC compared to SHC. This is because the OHC requires only one filter (i.e. to remove the fundamental component from the load current). For a typical spectrum of up to 25 order in Adjustable Speed Drives applications, where the characteristic harmonic orders follow the rule of $+6h+1$ assuming balanced voltage systems, the number of filters required for SHC is 8.

Therefore, the calculation burden is at least 8 times higher then the OHC. In the case of unbalanced systems as discussed later here, the calculation burden is at least doubled, since both direct and inverse rotating systems must be considered for a complete harmonic cancelation.

Compensation of Delays

One common requirement in AF’s is the high speed of feeding back the harmonic compensation currents into the grid in order to effectively cancel the load harmonic distortion.

Any delays present in the control loop (i.e. from anti-aliasing filtering, discrete DSP execution, uncompensated LCL frequency characteristics, etc.) make the compensation of harmonic currents a challenging task. Assuming a practical example of an AF running at 100 µs sampling time on a 60 Hz power system, one single sample delay means 10° phase shift for the 5th harmonic respective 55° phase shift for the 25th harmonic. Although the delay at the 5th harmonic is relatively small, because this harmonic is one of the dominant harmonics in the spectrum, the delays still cause a noticeable effect if not compensated.

Therefore, the compensation of delays is a must in AF applications. Several delay compensation methods described in literature in [23], proved that it is more difficult to assure a proper compensation of delays for OHC. Because the OHC provides wide bandwidth reference current, the delay compensation has to be able to do the same. For the SHC method, the delay compensation is easier and has better control, as this can be done individually for each harmonic order.

Voltage Unbalance

As just mentioned the frequency converter applications issue characteristic harmonic currents of $+6h+1$ (ex. -5, +7, -11, +13, etc.) assuming balanced grid voltages. In the case of unbalanced grid voltages non-characteristic harmonic current are issues as well by the frequency converters. Therefore, depending on the selected harmonic control the AF may be able (or allowed) to compensate them or not. The OHC by default accommodates an easy and inexpensive implementation of overall harmonic compensation as all harmonics are included in the harmonic reference current. For the SHC separate filter banks have to be included in the control, which increases the complexity and the DSP calculation burden. On the other hand SHC has more freedom in configuring the AF to compensate only the desired harmonics, and thus may assure lower overloading of the power unit and higher stability.

Voltage Pre distortion

Voltage harmonic pre-distortion determines as well generation of the non-characteristic harmonic currents in Frequency converters. Therefore, the same conclusions apply as for the previous discussion of voltage unbalance.

Power Rating of Active Filter

As the OHC compensates the entire spectrum including characteristic and non-characteristic harmonic orders, the AF’s power unit is loaded at a higher degree compared to the SHC method, for unbalanced and pre-distorted grid voltages.

Assuming a frequency converter that generates harmonics currents in the amount of 30 % THDi for ideal grid voltages, the AF rating is selected about 30 % of the frequency converter rated power. In the case of unbalance grid the THDi may increase up to 50% — 70% depending on the unbalance degree. Therefore, an AF operating with OHC has to be able to provide the same output power, meaning two times more output power than it was initially designed for. If an AF fitted with OHC reaches the maximum power limitation then the resultant becomes distorted in its entire spectrum, all harmonic orders being affected. An AF fitted with SHC can be set to target only several harmonic orders such that the inverter is not overloaded, thus still being able to compensate the selected harmonics to the standard levels. The other non-characteristic harmonics may be left uncompensated but the AF's output power rating remains within the rated value.

Network Resonances

The network impedance is not purely inductive, due to presence of capacitive loads, capacitive power compensators, and different power electronics containing input capacitors for filtering purposes or simply due to the parasitic capacitance of cables. This changes the impedance frequency characteristic such that several resonance points appear. The presence of harmonic currents of the same order as the resonance frequency is dangerous because it determines high harmonic voltages in the system.

If properly installed in the network, an AF fitted with OHC can damp the resonance at the expense of an increased power rating. It is more difficult for SHC to provide the same functionality because the resonance frequency rarely lies at exact characteristic harmonic frequencies.

Harmonic Mitigation Performance

It is estimated that in an ideal system both harmonic compensation methods are able to provide the same stationary harmonic compensation performance. However, as discussed in the previous sections, the performance of the AF is sensitive to the amount of uncompensated delays and non-ideal conditions.

Assuming a properly rated AF in respect to the compensated frequency converter load and a realistic physical industrial hardware setup, it is estimated than the SHC has more chances to provide a better stationary mitigation performance then the OHC. This is because of the ability to control individual harmonic currents with better precision.

In respect to dynamic compensation of harmonic currents OHC seems to provide a faster response, because the injected harmonics need no filtering except the removal of fundamental component. Therefore, the harmonics are present at the output in a shorter time, which means faster dynamic harmonic compensation performance.

Simulation results

In order to validate the discussions in §III the models of frequency converter and AF are simulated in Matlab/Simulink emulating as close as possible the discrete behaviour of the DSP and the analogue hardware components of a real setup (see Fig. 4 and
Table I).

Fig. 5 presents the line-side current of the frequency converter. Both time domain waveform and harmonic spectrum are given, identifying the characteristic harmonic orders of $+6h+1$. The simulation assumes ideal grid voltages (balanced grid and no voltage pre-distortion).

The AF control (Fig. 4) has the ability to select either OHC or SHC methods. The OHC method is implemented in the fundamental dq-frame, with a High-Pass filter (implemented in the form of 1-LPF to avoid more delays in the loop from the HPF) that removes the fundamental component (see Fig. 5a).

Any other existing delays are compensated with a derivative term.

The SHC is implemented in multiple individual harmonic dq-frame rotating at the following orders: -5th, +7th, -11th, +13th, -17th, +19th, -23rd and +25th. The Low Pass Filtering (LPF in Fig. 5b) in individual harmonic rotating frame is equivalent with Band Pass filters in stationary frame, and give the needed selectivity. The delay compensation in SHC is realized by individual correction in each harmonic rotating frame of the harmonic reference angles in the *dqk-abc* transformation (identified by θ^{c}_{k}, where *k is* harmonic order).

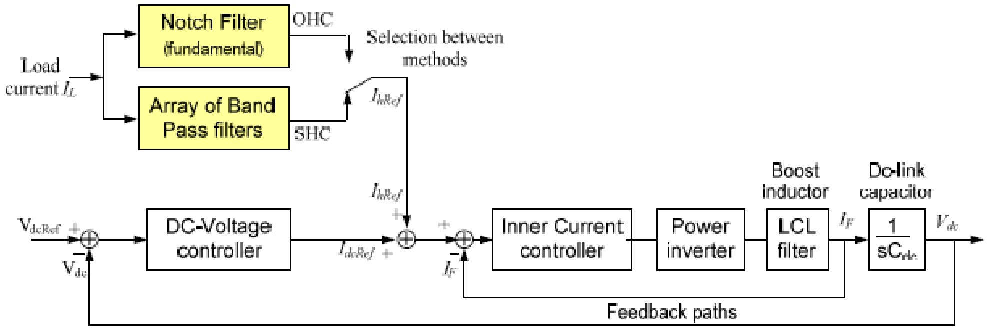


Fig. 4. Control diagram of the simulated Active Filter. Both harmonic detection methods are included.

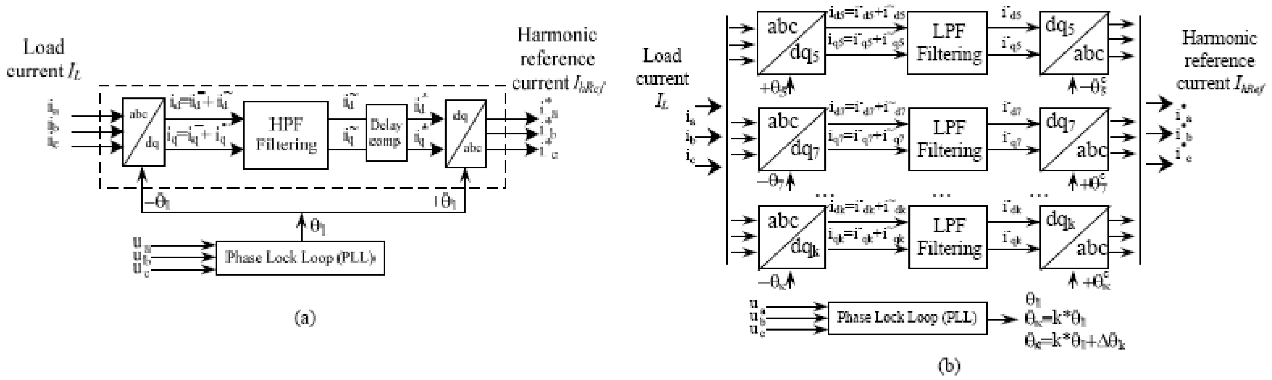
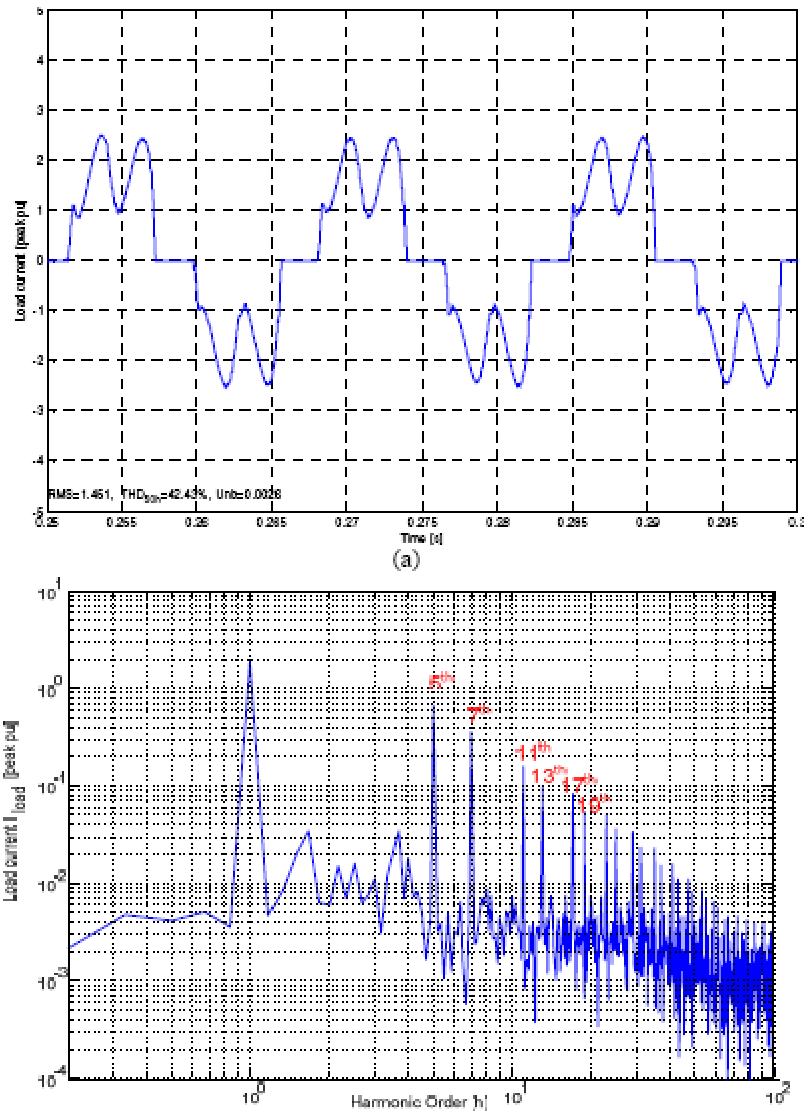


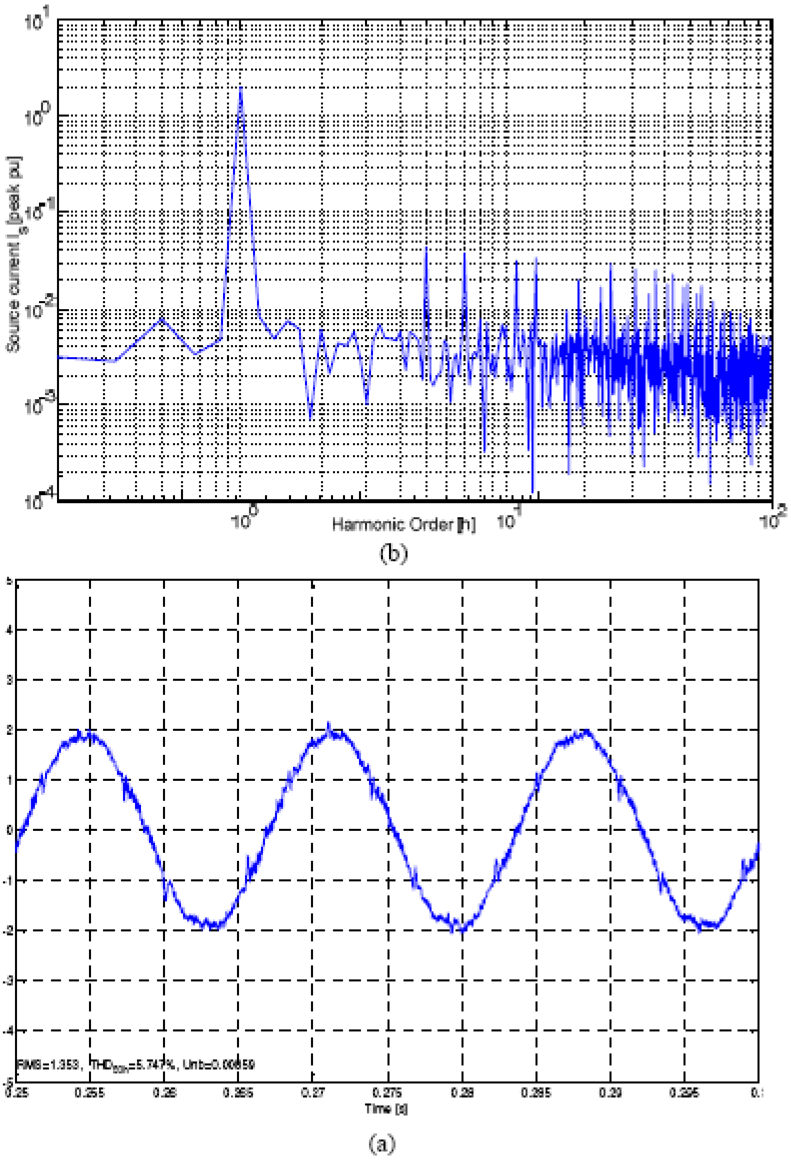
Fig. 5. Detail implementation of a) overall harmonic detection, b) selective harmonic detection.



(a)

(b)

Fig. 6. Simulated line-side current [per unit] from frequency converter. a) time domain waveform, b) harmonic spectrum



(b)

(a)

Fig. 7. Simulated grid current after harmonic compensation with AF set in Overall Harmonic Compensation. a) time domain waveform, b) harmonic spectrum.

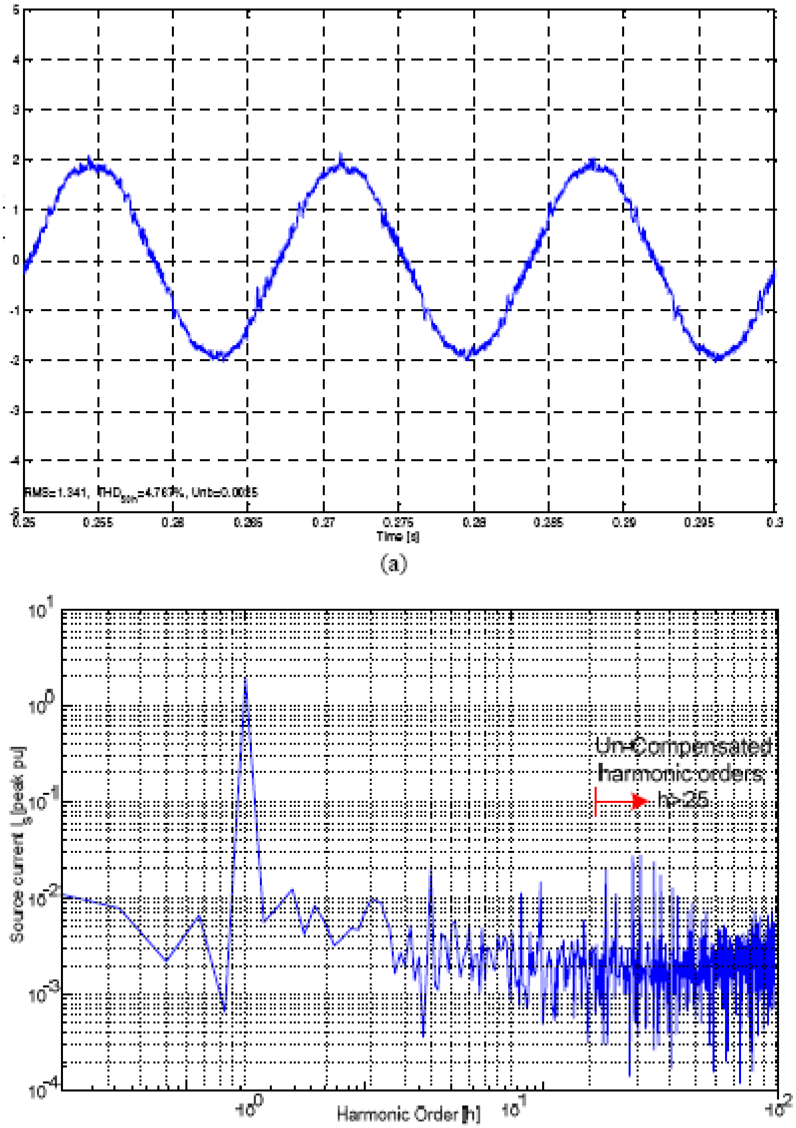


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Fig. 8. Simulated grid current with AF set in Selective Harmonic Compensation up to 25 order.
a) time domain waveform, b) harmonic spectrum.

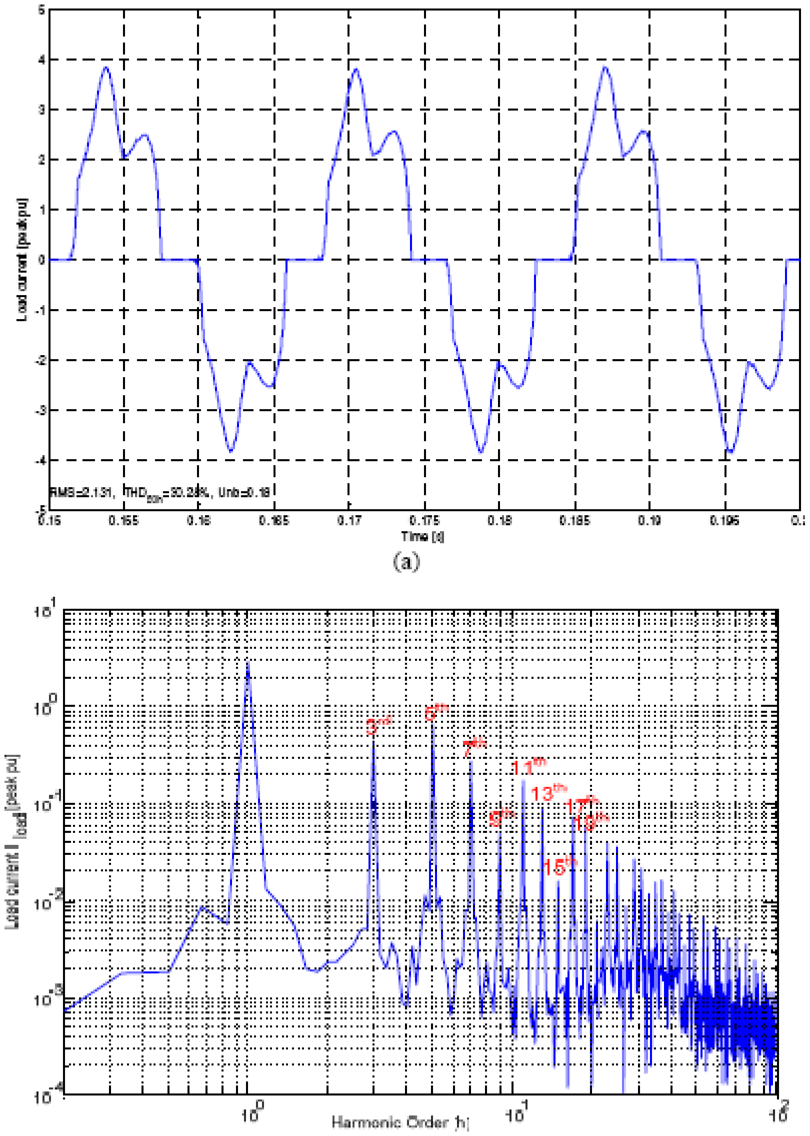

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Fig. 9. Simulated line-side current [per unit] from frequency converter. The grid has 1 % unbalanced voltage. a) time domain waveform, b) harmonic spectrum.

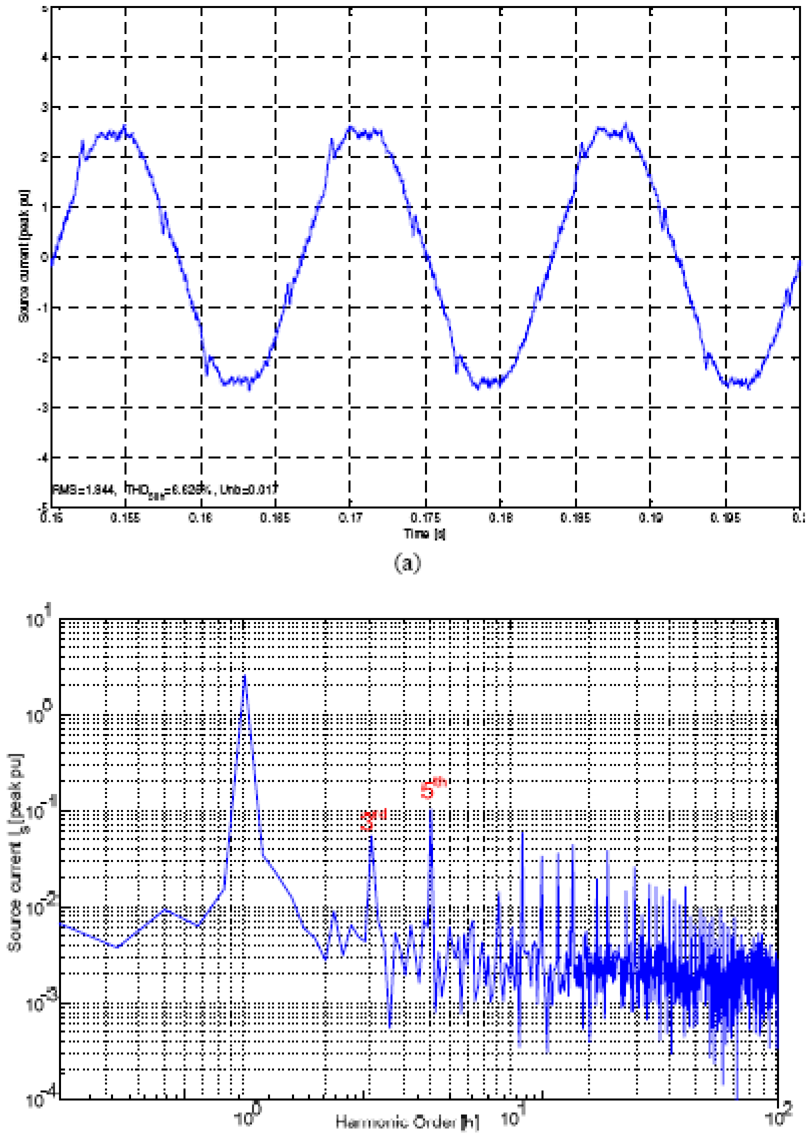

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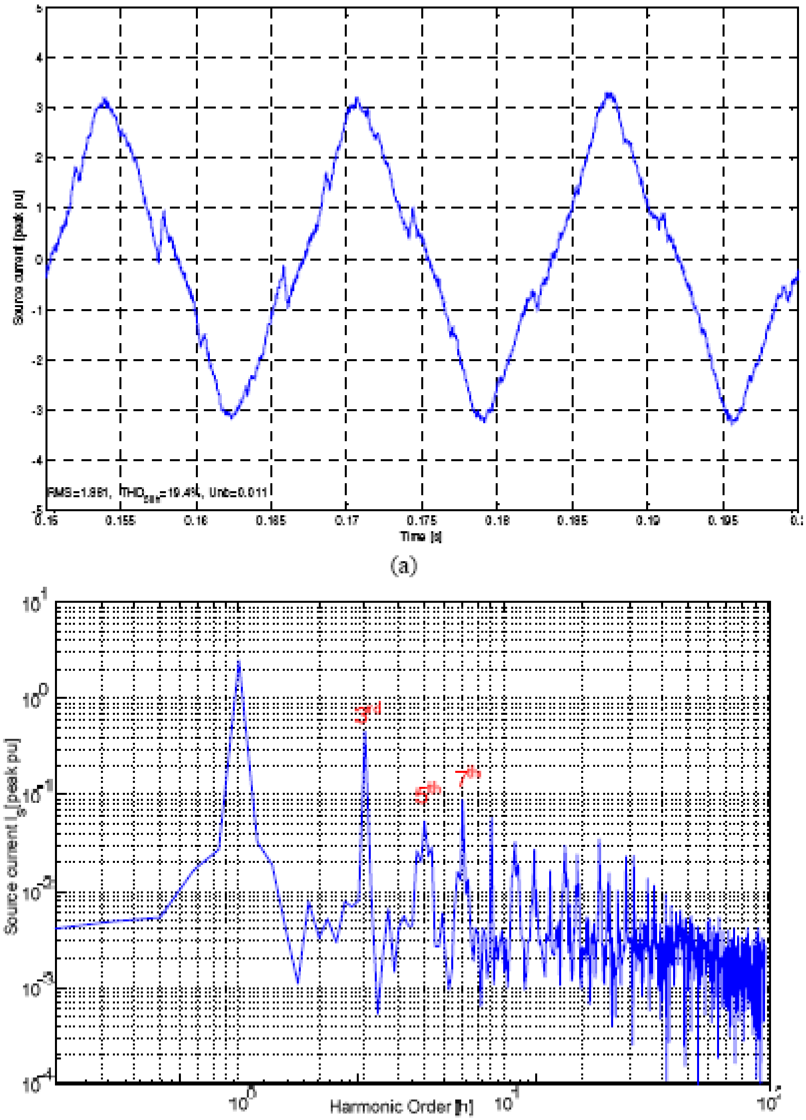
Fig. 10. Simulated grid current with AF in Overall Harmonic Compensation for 1 % unbalanced voltage. a) time domain waveform, b) harmonic spectrum.



(a)

(b)

Fig. 11. Simulated grid current with AF in Selective Harmonic Compensation (25 order) for 1 % unbalanced voltage. a) time domain waveform, b) harmonic spectrum.

TABLE I. Conditions of AF simulations and experimental tests.

Rated current of AF inverter (peak)	1 pu = 170 Apk (i.e. 120 A RMS)
Source voltage (peak value)	1 pu = 328 Vpk (i.e. 230 V RMS)
Rated power of nonlinear drive	2.5 times higher than AF
Sampling frequency of OHC or SHC	75 us
Switching frequency of AF	variable switching [4]

Fig. 6 and Fig. 7 present the grid current before and respective after the harmonic compensation with AF, when the OHC is used. Fig. 8 presents the simulations results of SHC method (only the first 25 characteristic harmonic orders). Higher orders are not compensated due to the high calculation burden. The uncompensated harmonics higher than 25th can be clearly seen in Fig. 8b.

The THDi is lower with the SHC because of better delay compensation, due to individual adjustment for each harmonic order. The SHC provides 4.8% THDi compare to the value of 5.7% with the OHC method.

A case of grid voltage unbalance (1 % negative sequence unbalance) is also simulated for comparison. The frequency converter's lineside current (one single phase is given in Fig. 9) measures 18 % unbalanced current. A high 3rd harmonic is seen in the spectrum. The SHC provides a THDi of 18 %, because of the uncompensated 3rd order harmonics. As expected the OHC is able to compensate the 3rd harmonic reaching a source current THDi of 6.6 %. On the other hand the AF inverter current is 0.69 pu RMS in SHC mode compared to 0.82 pu RMS in OHC (again due to the 3rd order harmonic currents).

Experimental results

The above discussed harmonic detection methods are tested on a laboratory setup. The same conditions mentioned in Table I applies for the laboratory stand. The frequency converter (nonlinear load) is a 3-phase typical industrial equipment loaded with an induction motor. An active filter is connected in parallel to the frequency converter for compensation of the line side harmonic currents.

Fig. 12 shows the measured grid current after harmonic compensation with AF in OHC operation mode (THDi of 8 %) versus SHC (THDi of 4 %). It proves that the compensation of the delays (identified as the cause of higher THDi) is more challenging in the OHD case, the same as occurred in simulations.

Conclusion

This paper describes two harmonic detection methods used in industrial shunt Active Filters. The paper focus on presenting practical issues met in both methods. It is concluded that the Selective Harmonic Compensation is suitable for cases where balanced network conditions exist and the rating power of the AF is to be maintain. The Overall

Harmonic Compensation is suitable for more general purpose Active Filter provided the rating power is available. Both simulations and measurement are provided to backup the comparisons and discussions.

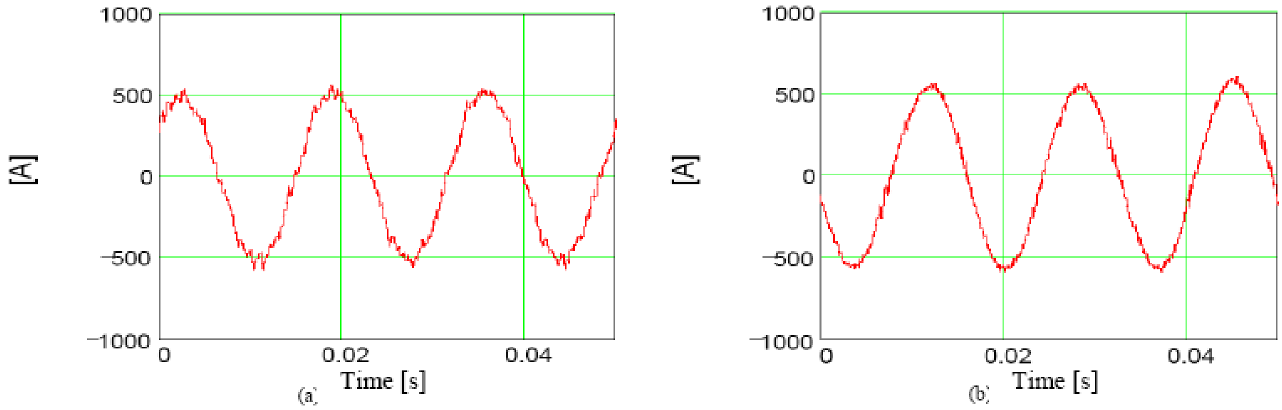


Fig. 12. Measured grid current with AF in: a) Overall Harmonic Compensation mode, b) Selective Harmonic Compensation mode.

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