Evaluation of Harmonic Detection Methods for Active Power Filter Applications

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Abstract – **In the attempt to minimize the harmonic disturbances created by the non-linear loads the choice of the active power filters comes out to improve the filtering efficiency and to solve many issues existing with classical passive filters. One of the key points for a proper implementation of an active filter is to use a good method for current/voltage reference generation. There exist many implementations supported by different theories (either in time- or frequency-domain), which continuously debate their performances proposing ever better solutions. This paper gives a survey of the common used theories. Then, the work here proposes a simulation setup that decouples the harmonic reference generator from the active filter model and its controller. In this way the selected methods can be equally analyzed and compared with respect to their performance, which helps anticipating possible implementation issues. The conclusions are collected and a comparison is given at the end, which is useful in deciding the future hardware setup implementation. The comparison shows that the choice of numerical filtering is a key factor for obtaining good accuracies and dynamics for an active filter.**

*Keywords – **power system harmonic; harmonic distortion; active filters; harmonics analysis; Discrete Fourier Transform; digital signal processing, signal detection.***

I. Introduction

It is a fact that the continuous proliferation of the electronic equipments either for home appliances or for industrial use has the drawback of increasing the non-sinusoidal currents into the power network. Different mitigation solutions are currently proposed and used involving either passive techniques, active techniques or perhaps more elaborated combinations such as wave-shaping or hybrid filters. In the last decades the use of active techniques has become more interesting due to the technological progress in switching devices, DSP's, numerical methods and control algorithms. As a result, if initially the active filters were tested mainly in laboratory conditions now tend to be implemented more and more in real-life applications. Therefore, there is an increased interest to develop and use the best detection method of the distorted currents/voltages that have to be compensated.

There are numerous published methods that describe different topologies and different algorithms used for active filtering. In many of them it usually prevails the description of a single method but there are publications which explain and compare couples of such methods describing their advantages and disadvantages by giving as final indices the dynamics, the THD reduction, the inverter efficiency or the cost of the entire active filter [1]–[7]. Usually the comparisons are made between different active filters, each considered as a whole unit, (sometimes treated as a black-box), in which only the harmonic detection method used is stressed out and the rest is left behind [1], [3], [5]. There is no doubt that the active filter includes beside the harmonic detection method (alias the current/voltage reference generators) also other parts such as the A/D devices, the current and the dc-voltage controllers, the PWM inverter and the protection elements. Fig. 1 shows a typical diagram of a shunt active power filters for adjustable speed drive application.

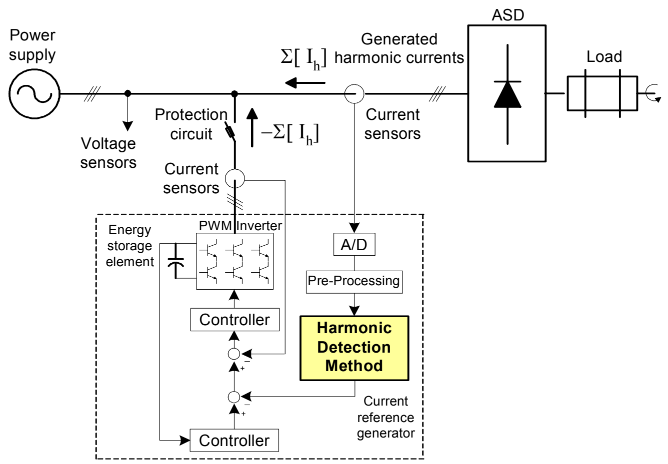

Fig. 1. One-line diagram of a shunt active filter in a feed-forward configuration with an adjustable speed drive as load. The diagram shows the place of the harmonic detection block inside the active filter.

If some of the elements enumerated above are the same for different active filter topologies, however, this will not be the case for the controller block of which performance and tuning precision might give different responses for the entire active filter. Consequently, the comparison done between different active filters that use respectively different harmonic detection methods is not a direct effect of only the performance of the detection block, but also of the quality of the controller. Therefore, this work analyzes the harmonic detection methods decoupled from the entire active filter in order to see its contribution.

At first, the work investigates the theoretical background of the common used harmonic detection methods. Therefore the paper gives a concise description of each. The actual study contributes to the existing comparisons [1]-[7] by adding a new trend for the harmonic detection with resonant controllers [34]-[39].

Then, as an investigation this paper extends the existing comparisons found in [2] with a proposed simulation study. The study isolates the harmonic detection method from the active filter and replaces the input signal from the sensors with a known signal, artificially constructed. Thus, the output signal that should be predictable now is recorded and compared between each analyzed harmonic detection method.

The paper presents the most relevant results of the simulations. Different issues observed in the study are listed and also the limitations of this approach are described. The results indicate that the choice of numerical filters is a key factor for obtaining good accuracies and dynamics. Finally the released conclusions are compared in respect to different criteria, which gives an overview and helps deciding on the final experimental setup for an active filter.

II. Harmonic Detection Methods

One of the most discussed software part (in the case of an DSP implementation) of an active filter is the harmonic detection method. In brief, it represents the part that has the capability of determining specific signal attributes (for instance the frequency, the amplitude, the phase, the time of occurrence, the duration, energy, etc.) from an input signal (that can be voltage, current or both) by using a special mathematical algorithm.

Then, with the achieved information, the controller (current controller in Fig. 1) is imposed to compensate for the existing distortion. It can be easily seen that if there are some errors when estimating one of the above attributes, the overall performance of the active filter could be seriously degraded in such a way that even sophisticated control algorithms cannot recover the original information.

Therefore, different algorithms emerged for the harmonic detection, which led to a large scientific debate on which part the focus should be put on, the detection accuracy, the speed, the filter stability, easy and inexpensive implementation, etc.

The classification of these methods can be done relative to the domain where the mathematical model is developed [7]. Thus, two major directions are described here, the time-domain and the frequency-domain methods. Such classification is given Table I. The description of the methods will be provided in the following.

TABLE I: Classification of the most used harmonic detections in APF.

Domain	Harmonic Detection Method
Frequency-domain	– Discrete Fourier Transform (DFT) – Fast Fourier Transform (FFT) – Recursive Discrete Fourier Transform (RDFT)
Time-domain	– Synchronous fundamental "dq-frame" – Synchronous individual harmonic "dq-frame" – Instantaneous power "pq-theory" and variants – Generalized integrators and variants

A. Frequency-domain Methods

The frequency-domain methods are mainly identified with Fourier analysis, rearranged in such a manner that this provides the result as fast as possible with a reduced number of calculations, to allow a real-time implementation in DSP's.

A.1. Discrete Fourier Transform (DFT) is a mathematical transformation for discrete signals which gives both the amplitude and phase information of the desired harmonic by calculating (1).

$$\overline{X}_h = \sum_{n=0}^{N-1} x(n)\cdot\cos\left(\frac{2\pi\cdot h\cdot n}{N}\right) - j\cdot\sum_{n=0}^{N-1} x(n)\cdot\sin\left(\frac{2\pi\cdot h\cdot n}{N}\right)$$
$$\overline{X}_h = X_{hr} + j\cdot X_{hi} \qquad (1)$$
$$\left|\overline{X}_h\right| = \sqrt{X^2_{hr} + X^2_{hi}}\,; \qquad \varphi_h = \arctan\left(\frac{X_{hi}}{X_{hr}}\right)$$

where: N is the number of samples per fundamental period; $x(n)$ is the input signal (voltage or current) at point n; X_h is the complex Fourier vector of the h^{th} harmonic of the input signal; X_{hr} is the real part of X_h; X_{hi} is the imaginary part of X_h. $|X_h|$ is the amplitude of the vector; φ_h is the phase of the vector.

Once the harmonics are detected and isolated with (1) it is just a matter of reconstruction back in time-domain to create the compensation signal for the controller [8], [9].

A.2. Fast Fourier Transform (FFT) follows the same mathematical representation as in (1) but in a different form [14] to reduce the number of calculations and hence the required DSP time. The algorithms use an operation called decimation (which can be in time- or frequency-domain) that relies on the recursive decomposition of an N point transform into 2 point transforms of $N/2$ (Fig. 2). This process can be applied to any N-sampled signal if N is a regular power of 2, so the decomposition can be applied repeatedly until the trivial "1-point" transform is reached and calculated. Thus, the total number of calculations are reduced from N^2 to $N\cdot\log_2(N)$.

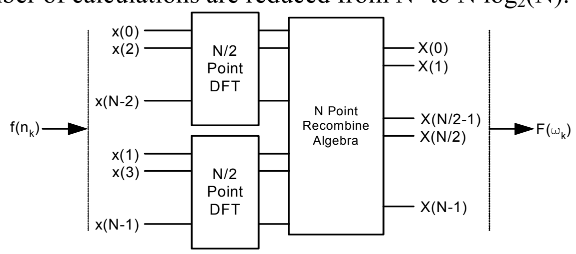

Fig. 2. Exemplification of the decimation in time algorithm for the Fast Fourier Transform (FFT).

A.3. Recursive Discrete Fourier Transform (RDFT) uses the same principle of the DFT (1) but calculated on a sliding window [13], [16]. Such sliding window is moving at every sampling time with a number of samples (usually just one for simplicity). Thus, the DFT analysis can actually be performed on the new set of samples (the new window).

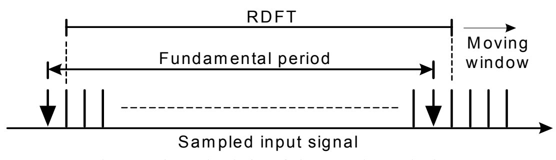

Fig. 3. The principle of the moving window DFT.

The only differences between the old and the new window are the first and the last samples, but all the other samples are the same. Since the result of the DFT was calculated before for the old window, a recursive expression as in (2) is found to avoid the same calculation for the new window. It is also demonstrated that (2) can be rearranged as a transfer function (3) in the form of a finite impulse response FIR filter [10], [11]. It can be proved that the transfer function (Bode plot in Fig. 4) has the attenuation equal to zero (dB) at the detected frequency, for this selected case of h=5 (the 5th harmonic). Such FIR representation, or maybe more advanced forms [10] is very convenient to isolate a specific harmonic from the input signal.

$$\overline{X}_h = \frac{1}{N}\sum_{i=0}^{N-1} x(i)\cdot W^{-hi}; \qquad W = \exp\left(j\frac{2\pi}{N}\right) \tag{2}$$
$$X_h(k) = \frac{1}{N}\big(x(k) - x(k-N)\big) + W^h \cdot X_h(k-1)$$

$$H_h(z) = \frac{X_h(z)}{x_h(z)} = \frac{1}{N}\cdot\frac{1-z^{-N}}{1-W^h z^{-1}} \tag{3}$$

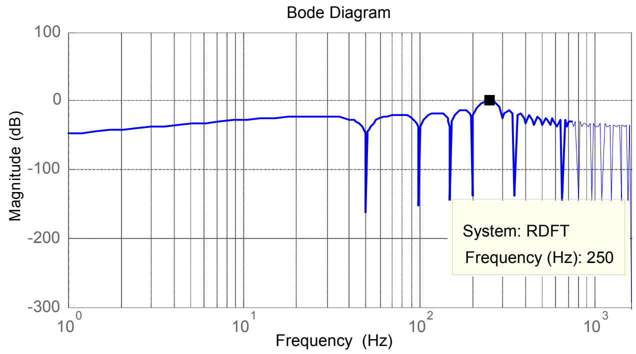

Fig. 4. Bode plot of Recursive Discrete Fourier transform as in (3) with *h*=5 and *N*=64.

The common drawbacks of the Fourier theories and its variants may be listed as: a proper usage of the Shannon theorem, a proper design of the anti-aliasing filter, a careful synchronization between the sampling and fundamental frequencies, a careful application of the windowing function, a proper usage of the zero-padding if the inter-harmonics are required, large memory requirements to store the samples of the last fundamental period, large computation power required for the DSP, the impossibility of having precise results in transient conditions [3].

B. Time-domain Methods

The time-domain methods are mainly used to gain more speed or fewer calculations compared to the frequency-domain methods.

B.1. Synchronous fundamental dq-frame is derived from the space vector transformation of the input signals, which initially are achieved in the abc-coordinates (stationary reference frame) from the sensors and then transformed into the dq-coordinates (rotating reference frame with fundamental frequency) by means of the Park transformation (4). The dq-frame rotates with the fundamental angular frequency that makes in this frame the fundamental currents to appear as dc-components and the harmonics as ac-signals.

$$\begin{pmatrix} i_d \\ i_q \end{pmatrix} = \frac{2}{3}\cdot\begin{pmatrix} \cos\theta & \cos(\theta-\frac{2\pi}{3}) & \cos(\theta+\frac{2\pi}{3}) \\ -\sin\theta & -\sin(\theta-\frac{2\pi}{3}) & -\sin(\theta+\frac{2\pi}{3}) \end{pmatrix}\cdot\begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} \tag{4}$$

where: i_d, i_q and i_a, i_b, i_c are the currents in the dq-frame respective in abc-frame; and θ is the reference angle.

Thus, the detection of the harmonics becomes a matter of removing the dc-signal with a High-Pass Filter (HPF in Fig. 5 with a cutting frequency between 25 Hz - 120 Hz) [17], [18], [21], [22].

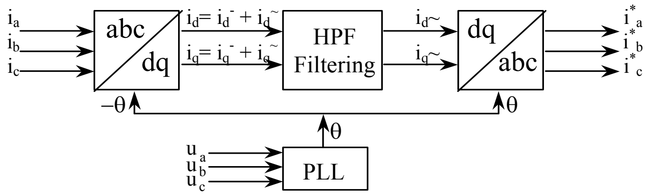

Fig. 5. Principle algorithm of the synchronous fundamental dq-frame.

B.2. Synchronous harmonic dq-frame is similar in principle as the fundamental dq-frame method. The exception is that the harmonic d-q frame rotates now with a frequency equal to the selected harmonic. Thus, in the harmonic dq-frame, only the respective harmonic will be a dc-signal and all other frequencies including the fundamental will be ac-components. The detection of the respective harmonic resumes in removing the ac-signals with low-pass filters (LPF in Fig. 6) [20], [23], [24].

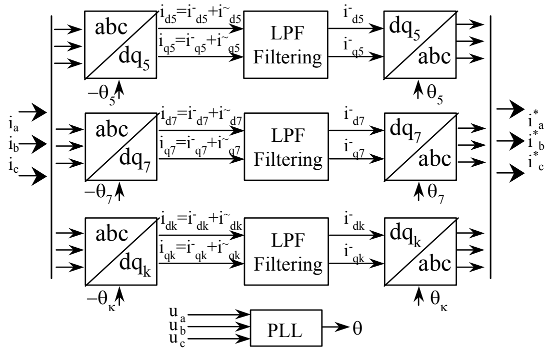

Fig. 6. Diagram of the multiple synchronous harmonic d-q transformations.

One drawback is the necessity of the angular position possibly from an PLL, that requires a careful implementation if the voltages are not balanced and sinusoidal. Another issue is the numerical implementation of the filters (HPF respective LPF) that have influence in the APF dynamic and accuracy. Due to the non-ideal filtering rejection and the phase shifting introduced by the numerical filters, the reference signal will not be exactly in the opposite phase nor with the same shape as the acquired disturbance. This limitation adds to the existing delays from the A/D and PWM blocks requiring separate compensation algorithms. This can turn to be difficult in practice especially for the harmonic dq-frame where these compensations and the respective controllers must be tuned individually [23]. Another issue is encountered for unbalanced load currents, therefore, the system must include all positive, zero and negative components, which again amplifies the

number of calculations and makes a more difficult tuning of each controller.
However, the dq-theory is extensively used in active filters because of well-covered literatures and individual control of hamronics.

B.3. Instantaneous power theory (and variants) determines the harmonic distortion from the instantaneous power calculation in a three-phase system, which is the multiplication of the instantaneous values of the currents and voltages [29]. The calculations may be done in αβ-coordinates as in (5).

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \cdot \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (5)$$

The values of the instantaneous power p and q, which are the real respective imaginary powers, contain dc- and ac-components [25], [28] depending on the existing active, reactive and distorted powers in the system. The dc-components of p and q represent the active and reactive powers and must be removed with high-pass filters (HPF in Fig. 7 with a cutting frequency between 5 Hz - 35 Hz) to retain only the ac-signals. The ac-components calculated back to the abc-frame represent the harmonic distortion, which is given as the reference for the current controller. Again the presence of the numerical filters have influence in the dynamic and the accuracy for the entire APF.

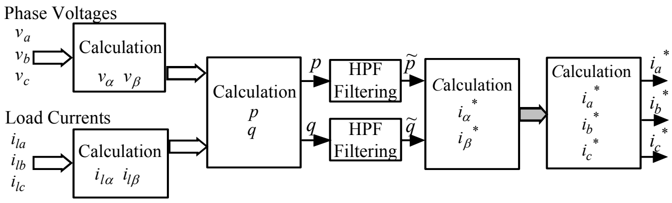

Fig. 7. Principle diagram of the instantaneous power theory.

The calculation in (5) is affected if the system has zero-sequence component due to an existing unbalance. Therefore, also a p_0 (also referred sometime as "0" power) component must be added to provide a complete analysis [28]. Other techniques based on the same principle improve different other feature, as like the cancellation of the neutral currents [30], the minimization of the energy storage element [32], the pre-processing of the input voltages to keep only the positive sequence [28].

B.4. Generalized integrator (and variants) comes out from the limitation that a PI controller in dq-frame which does not have a good tracking capability for non-continuous signals (i.e. harmonics) and therefore creates steady-states errors. Thus for non-continuous signals a better approach is by using generalized integrators. A generalized integrator derives the integration in time-domain as a second order transfer function in *Laplace*-domain (Fig. 8), which will give an infinite gain at the selected resonant frequency. Thus both the filtering and the controllers can be implemented in the stationary-frame instead of the rotating-frame. Such approach leads to a number of different implementations since one can decide either for individual harmonic compensation (notch filter) [36] or for a broadband approach (band-pass, high-pass or low-pass filters) [33], [35], [39].

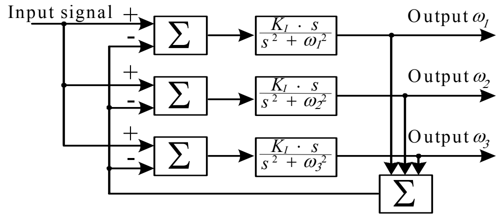

Fig. 8. Diagram of the generalized integrators approach.

The transfer function of the system in Fig. 8 is given in Fig. 9 for different values of the integration constant K_i (here chosen the same for all integrators). As it can be seen one issue is the determination of optimum integration constant K_i, since a smaller value gives a good selectivity but determines a slow dynamic response. Furthermore, the controller must be tuned depending on the existing plant (not present in Fig. 8 and Fig. 9), which makes the method dependent on the transfer function of the existing process.

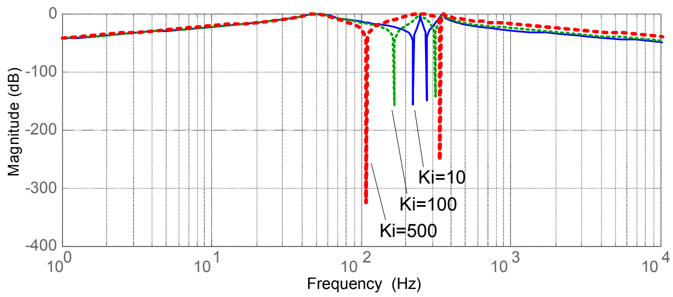

Fig. 9. Bode characteristic of the system in Fig. 8 for different values of the K_i constant. The integrators are tuned for the 5th, 7th and 11th harmonics of a 50 Hz fundamental frequency.

Other attempts for harmonic detection methods are enumerated in the literature like sinusoidal subtraction, notch filtering, Fryze-Bucholz-Depenbrock, Kalman filters [40], [41], [42], but because of different issues with non-ideal conditions met in a real implementation, these methods are not largely used in active power filters.

III. Comparison of Harmonic Detection Methods

A comparison is done next by simulations to reveal the performance for some of the presented methods in respect to the settling time and the accuracy of the results. An input signal (the load current for a shunt APF) is artificially constructed from the 50 Hz fundamental component and the sum of several harmonics. The 5th harmonic has an amplitude of about 30 % from the fundamental and is injected alone for a specific time interval. Fig. 10 shows how the test input signal is created for a single phase. The parameters used to obtain the resultant signal in Fig. 10 are given in more details in Table II. It can be noticed that the resultant signal has a similar shape as the line currents obtained from a three-phase diode rectifier.

Table II. The characteristics of the input signal.

Indices	Amplitude	Phase	Starting time [s]
Fundamental	30	0, 120, 240	0
5th harmonic	10	5x(0, 120, 240)	0.05
Higher harmonics (7th, 11th, 13th, 17th)	1.5 each	h x (0, 120, 240)	0.15 all at the same time

As the 5th harmonic is separated from the other higher harmonics between the time-interval of 0.05 s – 0.15 s, the output obtained from each detection method should be predictable now and easy to be studied during this interval. Therefore, the goal is to record the output of the harmonic detection method in respect to the settling time and the accuracy in detecting the 5th harmonic (as illustrated in Fig. 11).

In order to have the same base of comparison for all methods, the output results will be displayed in the same abc-frame as the original input signal. Thus, for example for the dq-frame the d and q components are transformed back into the abc-frame.

In the case of a real active filter implementation the output of each method represents the reference imposed to the inner loop controller (i.e. current for a shunt APF). This controller, which has a certain response time, will introduce even more delays in the loop due to the limited tracking capability, but this limitation does not appear here. The algebraic reconstruction into the abc-frame emulates an ideal inner loop controller.

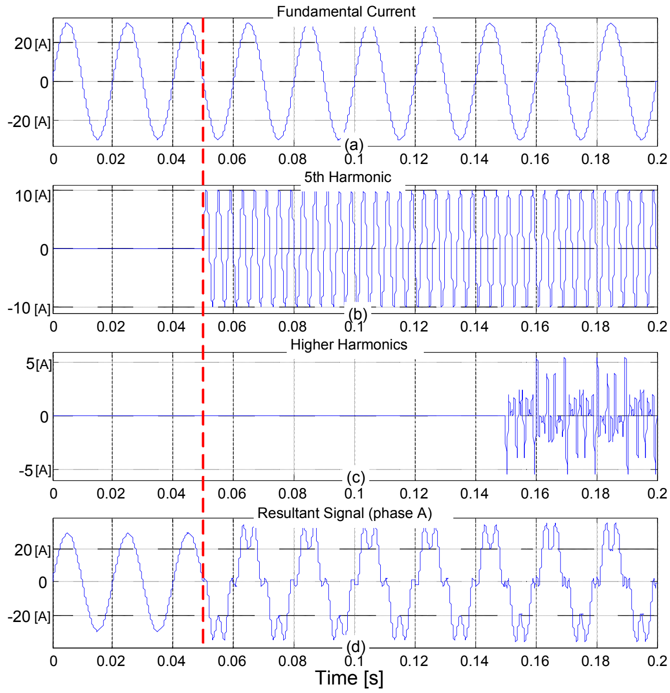

Fig. 10. Obtaining the input test signal for testing the harmonic detection techniques. a) fundamental current, b) 5th harmonic current, c) higher harmonics currents, d) resultant test signal.

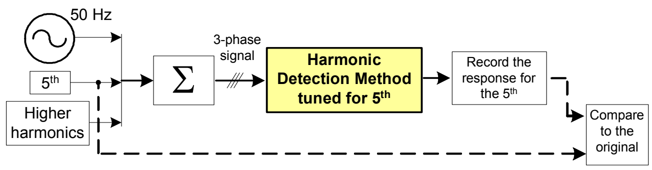

Fig. 11. Simulation setup realized to study the performance of different harmonic detection methods isolated from the model of the active filter.

Table III. Settings used for configuring the harmonic detection method.

Harmonic detection method	Characteristics
DFT for the 5th harmonic	256 samples / fundamental
RDFT	256 samples / fundamental
Fundamental dq-frame	HPF 120Hz, 2nd order Butterworth
5th harmonic dq-frame	LPF 20Hz, 2nd order Butterworth
Instantaneous pq theory	HPF 10Hz, 3st order Butterworth
5th generalized integrator	T_i=300

The methods considered for this comparison are listed in Table III where also some of their characteristics are provided from different references in §II.

Fig. 12 illustrates the results of the simulation as time waveforms obtained from each method. The settling time, the overshoot and the phase error are measured for each detection method as given in the Table IV.

In the case of the DFT methods, the settling time is limited to at least the windowing time (1 fundamental period in this case), and the requirement is that the harmonic should be constant during the windowing interval. For the RDFT method the response is better but still limited to the duration of the window as any FIR filter response.

The fundamental dq-frame has a faster response and a good overshoot but suffers from a large phase error due to the phase shift created by the HPF. Therefore, the compensation currents are not in phase with the disturbance, which is an impediment for an exact harmonic cancellation.

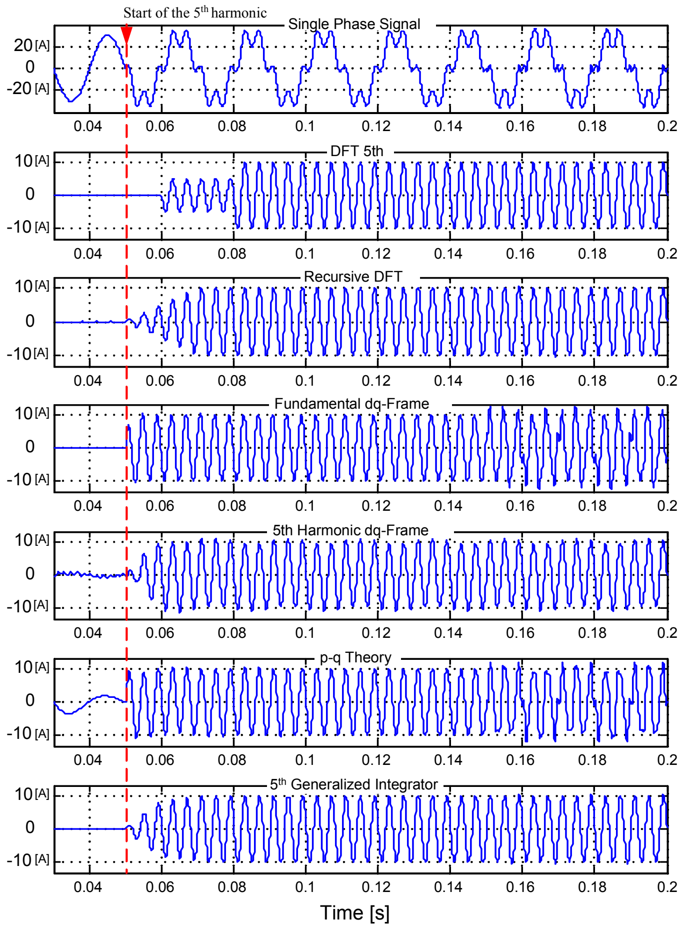

Fig. 12. The dynamic responses obtained for the analyzed methods according to Fig. 11.

Table IV. Results obtained from the harmonic detection methods (Fig. 12).

Harmonic detection method	Settling time [ms]	Phase error [deg]	Overshoot or ripple [%]
DFT 5th	30 ms	0°	0%
Recursive DFT	20 ms	0°	0%
Fundamental dq-Frame	10 ms	33.4°	1% overshoot
5th Harmonic dq-Frame	20 ms	0°	10% ripple
p-q Theory	10 ms	3.2°	30% overshoot
5th Generalized Integrator	30 ms	0°	0%

As a compromise the HPF may be implemented with a low pass filter (LPF) as in 1-LPF, where in this case the dc-signals coming from the LPF have no phase shift, therefore, the harmonic distortion keeps the same phase after the dc-signal subtraction.

The harmonic dq-frame does not have the issue with the phase shift because the 5th harmonic becomes dc-component filtered by a LPF, but here due to a low cutting frequency, the response time being degraded. Another issue is with the large existing ripple because the fundamental frequency (bigger in amplitude) appears in the harmonic dq-frame as an ac-signal, which must be removed by the LPF, and therefore, a good selectivity or a low cutting frequency must be selected in order to reduce it. However, increasing the filter order or decreasing the cutting frequency will degrade the response time.

For the pq-theory the output has a characteristic given by the HPF used. In this case the overshoot suffers, while the response time is relatively fast. The phase error of the HPF may be improved also by selecting a (1-LPF) implementation instead.

In the case of the generalized integrator the main limitation is given by the settling time, which depends of the integration constant T_i used. Such large response time (comparable the DFT case) is not suitable for applications where the harmonics frequently vary within a few fundamental cycles.

Regarding the presence of the higher harmonics it was observed that they are well rejected by harmonic dq-frame, while the DFT and RDFT are disturbed at least 1 fundamental cycle. The generalized integrator method is however, affected by these higher harmonics since there was no other controller tuned to remove these harmonic components.

The influence of the filters may be seen in Fig. 13, where three of the presented methods are practically tested with a dSpace system (TMS320F240) for an active filter implementation. The load currents from a three-phase diode rectifier are processed by the respective harmonic detection methods and the signal obtained (i.e. current reference) is summed with the distorted current. The summation done here excludes the contribution of the current controller and the PWM inverter that will actually decrease the tracking speed even more by introducing more delays. The results are presented in Fig. 13 where both the THD_i and the level of the 5th harmonic are calculated for each result.

Based on the conclusions obtained from the above simulations the practical results in Fig. 13 have now an easier interpretation. For instance even if both methods, fundamental dq-frame and instantaneous pq-theory are implemented with HPF techniques, the second method gives a better result, explicable by the smaller phase-shift, as measured in Table IV.

Table V presents other conclusions, which are important for a practical implementation of the active filter (where a "+" sign indicates an advantage or an increase in performance). For example, the pq-theory has good dynamics but needs sinusoidal input voltages, while the dq-techniques depend on the angular speed. The generalized integrator method requires individual tuning for each frequency but does not need the voltage information and also does not have the filtering issues.

Regarding which of these techniques is better for a given case, some assumptions may be made as like the existence of a fast DSP that will alleviate the numerical issues. Also the acquisition of both voltages and currents might be beneficial for the APF circuit protections or other enhanced features provided by the APF. Therefore, the design should mainly consider the characteristics of the distorted currents for instance, the dominant harmonic currents, their levels, the variation in time, and the existence of certain unbalance in the system.

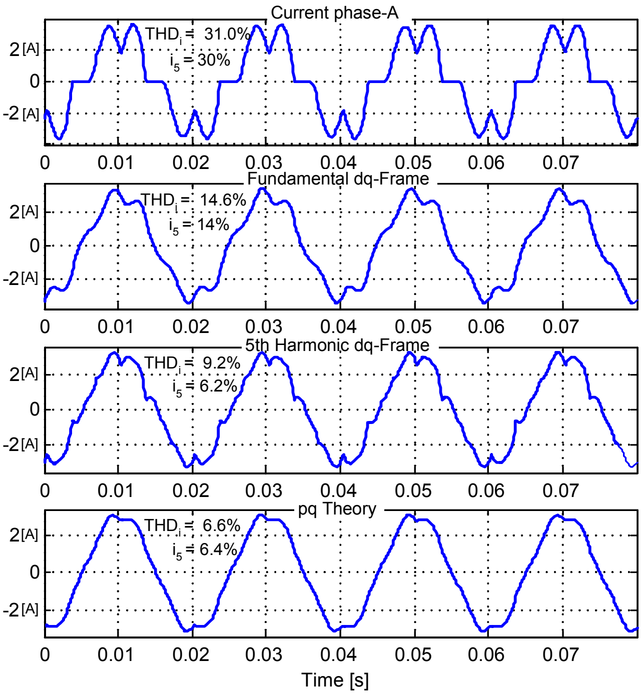

Fig. 13. Practical validation of the fundamental dq-frame, harmonic dq-frame and instantaneous pq-theory. The choice of the filter implementation is responsible for a good current reference framework.

Table V. Evaluation of the studied harmonic detection method.

	FFT	**DFT**	**RDFT**	**Fund. dq-frame**	**Harm. dq-frame**	**pq Theory**	**Generalz. integr.**
No of sensors (3-phase application)	3 x *I*	3 x *I*	3 x *I*	3 x *I*, 2 x *V*	3 x *I*, 2 x *V*	3 x *I*, 3 x *V*	3 x *I*
No of numerical filters	/	/	/	2 x HPF	2 x LPF	2 x HPF	N x controllers
Requires additional tasks	Windowing	Windowing	/	PLL	PLL	Voltage Preproc.	/
No of calc. (excluding filters)	– –	– –	+	+	– –	+	–
Numerical implementation issues	Number of calculations	Number of calculations	Instability for low precision	Filtering	Filtering, Tuning control	Filtering	Tuning control
Related implementations	Decimations 4^k, 16^k	/	Rotating frame	Different filtering approaches	Different filtering approaches	Filters type; other theories pqr, pq0	Different filtering approaches
Single-phase/Three-phase applications	1-ph / 3-ph	1-ph / 3-ph	1-ph / 3-ph	Inherently 3-ph	Inherently 3-ph	Inherently 3-ph	1-ph / 3-ph
Requires voltage usage	No	No	No	Yes	Yes	Yes	No
Performance when unbalanced voltages	++	++	++	+	+	–	++
Performance when unbalanced currents	++	++	++	+	++	++	+
Selective harmonic compensation	No	Yes	Yes	No	Yes	No	Yes
Transient response time	–	–	+	++	+	++	+
Steady state accuracy	+	+	+	–	+	+	–

IV. Conclusion

The paper gives an evaluation of the common used methods for harmonic detection in active power filter applications. The description of the related theories is provided here together with a number of references and some of the issues are pointed out. Then the paper proposes a simulation setup to study the performance of the detection methods independent from the active filter. The simulations show that the choice of numerical filtering is a key factor for obtaining good accuracy and dynamics.

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