Harmonic Detection Algorithm based on DQ Axis with Fourier Analysis for Hybrid Power Filters

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Abstract: - The paper presents the DQ axis with Fourier analysis (DQF) algorithm to identify harmonic quantities for hybrid power filters. This algorithm is a combination of the advantages of DQ axis method and sliding window Fourier analysis (SWFA). This paper also presents the harmonic elimination by using the DQF algorithm for both three-phase balanced and unbalanced systems. The results show that the unbalanced system becomes a balanced condition with successfully reducing the quantity of system harmonic components after completely harmonic elimination by using the proposed algorithm. The results confirm that the DQF algorithm is flexible and suitable in terms of design for hybrid power filters.

Key-Words: - harmonic elimination, harmonic detection, hybrid power filter, DQ axis with Fourier

1 Introduction

Presently, nonlinear loads are widely used in industries in which these loads mainly generate the harmonics into the power system. These harmonics cause a lot of disadvantages into the power system [1,2,3,4]. This paper represents the new algorithm of harmonic detection operated with hybrid power filters for three-phase power systems called the DQF algorithm. This algorithm is a combination of the advantages of the DQ axis method [5] and the sliding window Fourier analysis (SWFA) [6]. The DQF algorithm has been reported since 2007 [7] in which it is operated with only the active power filter to eliminate all harmonic components in the system. This paper extends the work in [7] to apply the DQF harmonic detection with hybrid power filters for eliminating some harmonic components depending on the engineering design and the rest harmonics can be cancelled by using passive power filters. This is because the co-operation of both power filters (hybrid power filters) is to reduce the rated of active power filter as to achieve the lower cost.

The hybrid power filter in this paper is the combination between active and passive power filters

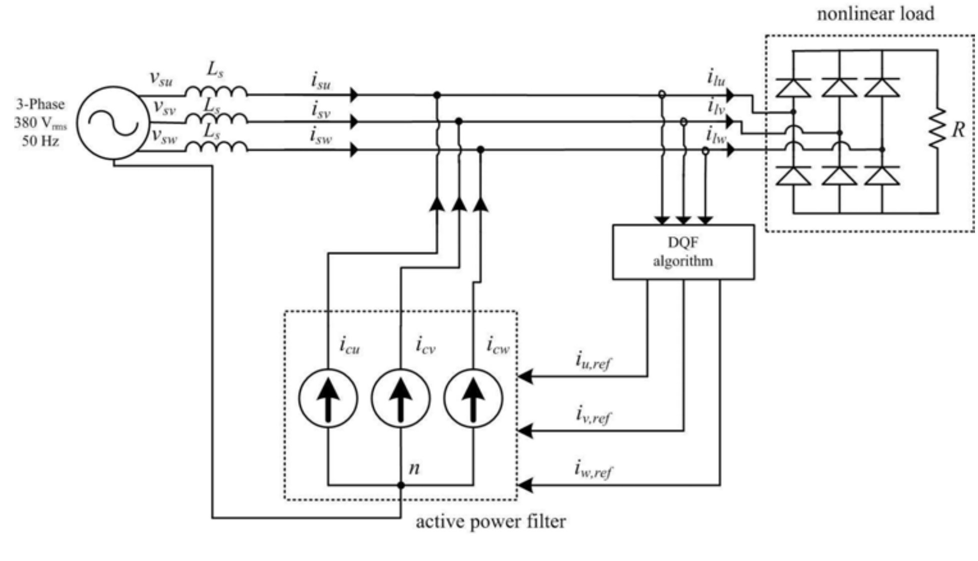

Fig.1 The system with a resistive load connected to a three-phase diode rectifier representing a nonlinear load

in which the DQF harmonic detection is operated with active power filters to eliminate some harmonic components and passive power filter is for the rest harmonic components. Therefore, there are five cases for studies in this paper. The first is to eliminate only the fifth harmonic of the system, while the second case is the fifth and seventh harmonic elimination. The third case is for all harmonic eliminations excepting the fifth and seventh harmonic components and the fourth case is to cancel all system harmonic components. All four cases are for balanced three-phase power systems.

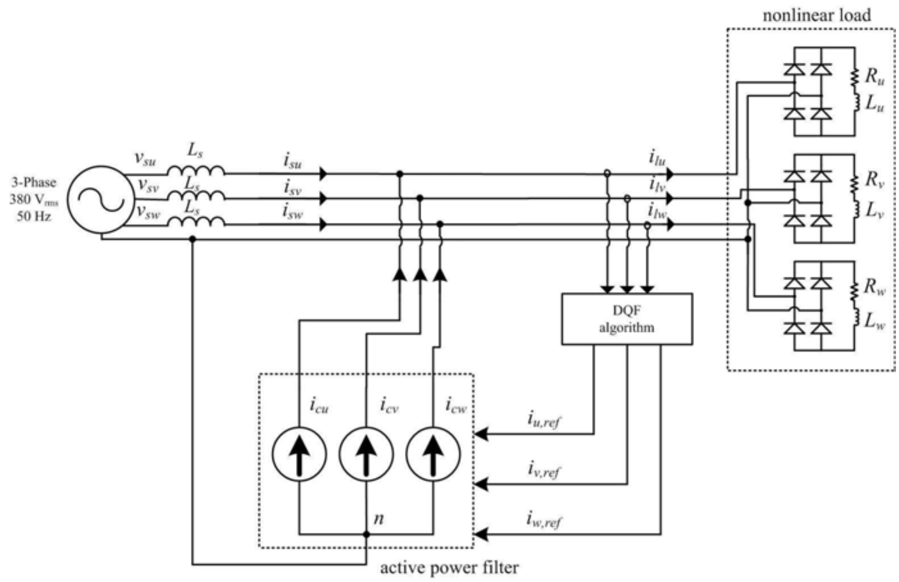

Fig.2 The system with RL loads connected to three single-phase diode rectifiers representing a nonlinear load

The last case is to eliminate all harmonic components for unbalanced system to show how the power system becomes a balanced condition after completely harmonic elimination.

The performance indices of the proposed harmonic detection are %THD and %unbalance of the compensated power system. The two nonlinear loads in this paper are the three-phase diode rectifier with a resistive load and three single-phase diode rectifiers with RL loads as depicted in Fig.1 and 2, respectively. An ideal current source is used to represent the active power filter. The DQF harmonic detection provides the good results in terms of the harmonic elimination with high accuracy and this algorithm also makes the unbalanced system becoming to a balanced condition after completely harmonic elimination.

2 Harmonic Detection via the DQF Algorithm

The DQF harmonic detection in this paper is the calculation to define the three phase reference currents ($i_{u,ref}$, $i_{v,ref}$, $i_{w,ref}$) for the active power filter to eliminate system harmonic components. There are four cases for the balanced power system corresponding to Fig.1:

Case I: 5th harmonic elimination

The diagram to represent the DQF harmonic detection to eliminate the 5th harmonic component of the system in Fig. 1 (Case I) is shown in Fig. 3. In Fig.3, three phase harmonic currents are transformed to the space vector currents on the αβo frame by using (1).

$$\begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i_{Lu} \\ i_{Lv} \\ i_{Lw} \end{bmatrix} \tag{1}$$

Then only the currents on α and β axes are transformed to the synchronously rotating dq frame ($i_{dn\omega}$, $i_{qn\omega}$) by using (2).

$$\begin{bmatrix} i_{dn\omega} \\ i_{qn\omega} \end{bmatrix} = \begin{bmatrix} \cos(n\omega t) & \sin(n\omega t) \\ -\sin(n\omega t) & \cos(n\omega t) \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{2}$$

where ω is the fundamental frequency of the system and n is the eliminated harmonic components of order n, in this case n is set to 5. Consequently, using (3) and (4) is to determine the dc component of $i_{d5\omega}$ and $i_{q5\omega}$ called i_{d5} and i_{q5}, respectively.

$$i_{dn}(kT) = \frac{A_{0dn}}{2} \tag{3}$$

$$i_{qn}(kT) = \frac{A_{0qn}}{2} \tag{4}$$

where A_{0dn} and A_{0qn} in (3) and (4) can be calculated by using (5) and (6), respectively.

Case II: 5th and 7th harmonic elimination

The diagram for the DQF harmonic detection to eliminate the 5th and 7th harmonic components of the system in Fig. 1 (Case II) is shown in Fig. 4.

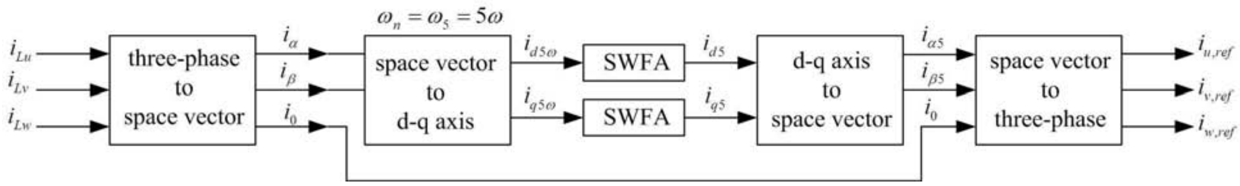

Fig. 3 DQF algorithm for 5th harmonic elimination

$$A_{0dn} = \frac{2}{N}\sum_{k=N_0}^{N_0+N-1} i_{dn\omega}(kT) \tag{5}$$

$$A_{0qn} = \frac{2}{N}\sum_{k=N_0}^{N_0+N-1} i_{qn\omega}(kT) \tag{6}$$

where T is the sampling interval, N_0 is the starting point for computing, N is the total number of sampled points in one cycle, and k is the time index. A_{0dn} and A_{0qn} for the first period can be calculated as given in (5) and (6) so as to achieve the initial value for the DQF algorithm. For the next period, these values can be calculated by using (7) in which this approach called SWFA [2].

$$\begin{bmatrix} A_{0dn}{}^{(new)} \\ A_{0qn}{}^{(new)} \end{bmatrix} = \begin{bmatrix} A_{0dn}{}^{(old)} \\ A_{0qn}{}^{(old)} \end{bmatrix} - \frac{2}{N}\begin{bmatrix} i_{dn\omega}[(N_0-1)T] \\ i_{qn\omega}[(N_0-1)T] \end{bmatrix} + \frac{2}{N}\begin{bmatrix} i_{dn\omega}[(N_0+N)T] \\ i_{qn\omega}[(N_0+N)T] \end{bmatrix} \tag{7}$$

When i_{dn} and i_{qn} are achieved via the SWFA approach in (7), the values of $i_{\alpha n}$ and $i_{\beta n}$ can be calculated by using (8) and the reference three-phase currents for the active power filter are defined in (9). These reference currents are used for the active power filter to generate the compensating currents into the system for the harmonic elimination.

$$\begin{bmatrix} i_{\alpha n} \\ i_{\beta n} \end{bmatrix} = \begin{bmatrix} \cos(n\omega t) & -\sin(n\omega t) \\ \sin(n\omega t) & \cos(n\omega t) \end{bmatrix} \begin{bmatrix} i_{dn} \\ i_{qn} \end{bmatrix} \tag{8}$$

$$\begin{bmatrix} i_{u,ref} \\ i_{v,ref} \\ i_{w,ref} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 & \frac{1}{\sqrt{2}} \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} & \frac{1}{\sqrt{2}} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i_{\alpha n} \\ i_{\beta n} \\ i_0 \end{bmatrix} \tag{9}$$

It can be seen from Fig. 4 that $i_{\alpha 5}$, $i_{\beta 5}$, $i_{\alpha 7}$, and $i_{\beta 7}$ can be calculated from (1)-(8) by setting n equal to 5 and 7, respectively. Consequently, $i_{\alpha F}$ is the current from the combination of eliminated harmonic currents on the α axis, while $i_{\beta F}$ is the total injected harmonic currents on the β axis. Then, the three-phase reference currents for the active power filter can be calculated from $i_{\alpha F}$, $i_{\beta F}$, and i_o by using (10).

$$\begin{bmatrix} i_{u,ref} \\ i_{v,ref} \\ i_{w,ref} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 & \frac{1}{\sqrt{2}} \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} & \frac{1}{\sqrt{2}} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i_{\alpha F} \\ i_{\beta F} \\ i_0 \end{bmatrix} \tag{10}$$

Case III: All harmonic components elimination excepting 5th and 7th

The diagram for the DQF harmonic detection to eliminate all harmonic components excepting the 5th and 7th of the system in Fig. 1 (Case III) is shown in Fig. 5. In Fig.5, i_{d1} and i_{q1} are the fundamental currents of the system on the dq frame and these currents can be used to calculate all harmonic currents on the dq frame, i_{dh} and i_{qh}, as given in (11) and (12), respectively. These currents on the αβ frame can be calculated from i_{dh} and i_{qh}. However, this case is to eliminate all harmonics excepting the 5th and 7th. Therefore, $i_{\alpha F}$ and $i_{\beta F}$ can be calculated by (13) and (14), respectively. The three phase reference currents for the active power filter can be calculated from $i_{\alpha F}$, $i_{\beta F}$, and i_o by using (10) the same as Case II.

$$i_{dh} = i_{d1\omega} - i_{d1} \tag{11}$$

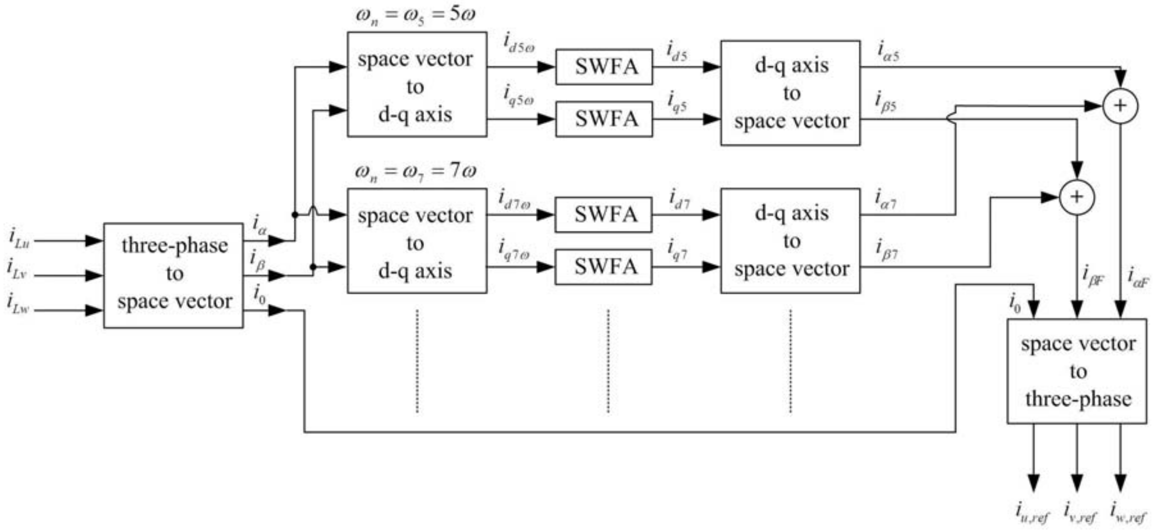

Fig. 4 DQF algorithm for 5th and 7th harmonic elimination

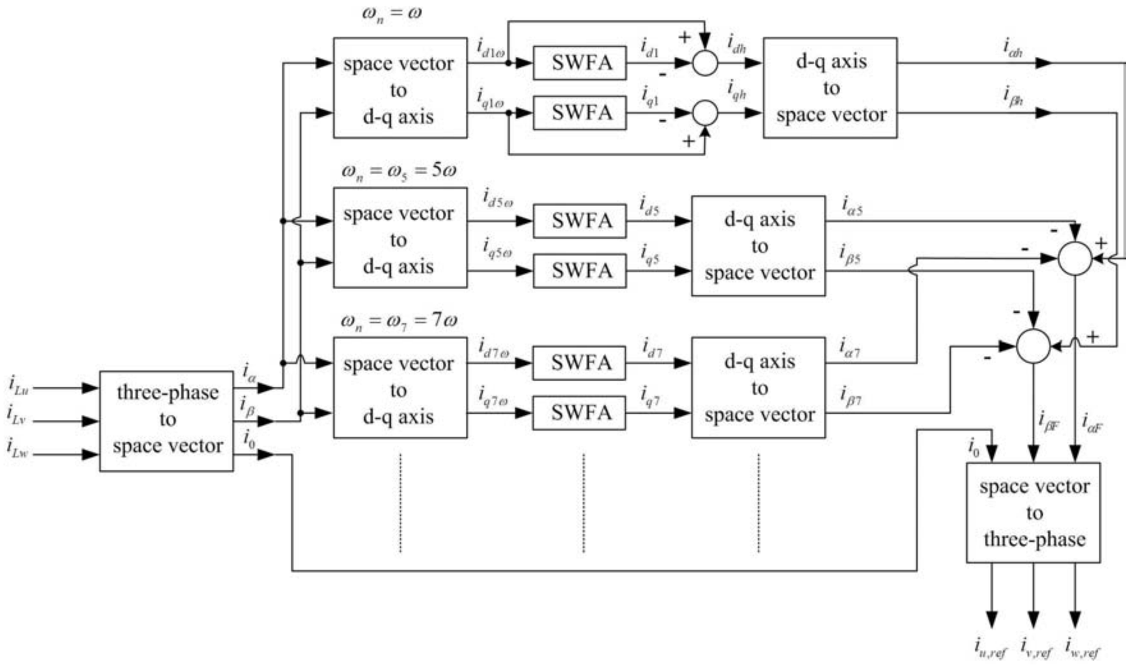

Fig. 5 DQF algorithm for all harmonic elimination excepting 5th and 7th

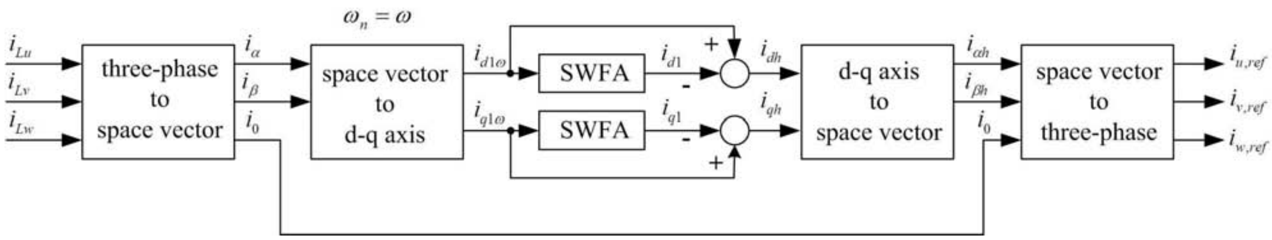

Fig. 6 DQF algorithm for all harmonic elimination

$$i_{qh} = i_{q1\omega} - i_{q1} \tag{12}$$

$$i_{\alpha F} = i_{\alpha h} - i_{\alpha 5} - i_{\alpha 7} \tag{13}$$

$$i_{\beta F} = i_{\beta h} - i_{\beta 5} - i_{\beta 7} \tag{14}$$

Case IV: All harmonic components elimination

The diagram for the DQF harmonic detection to eliminate all harmonic components of the system in Fig. 1 (Case IV) is shown in Fig. 6. From Fig. 6, the three phase reference currents for the active power filter can be calculated from $i_{\alpha F}$, $i_{\beta F}$, and i_o by

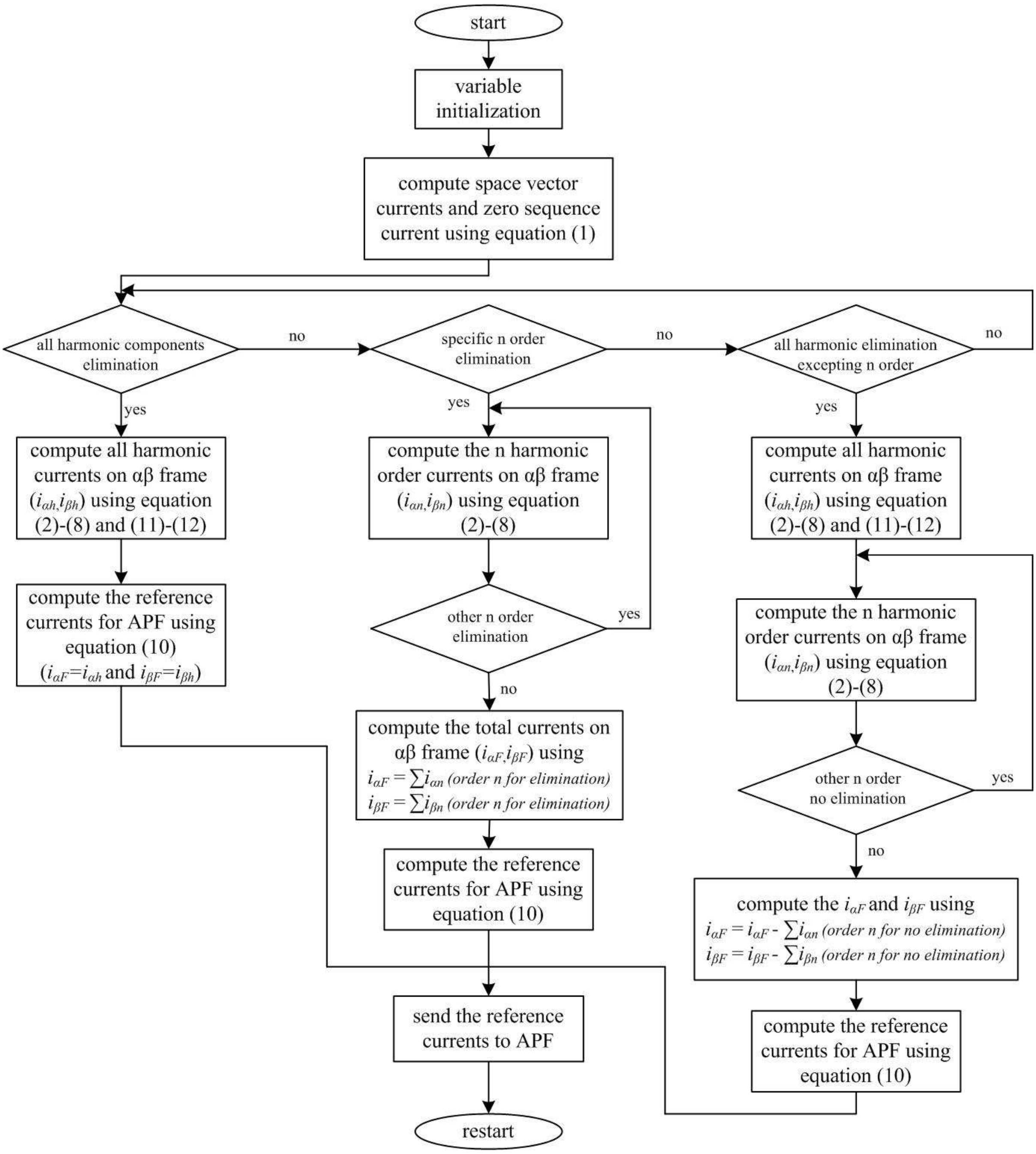

Fig. 7 The block diagram for generalized DQF harmonic detection

using (10) the same as Case II and III in which $i_{\alpha F}$ and $i_{\beta F}$ are equal to $i_{\alpha h}$ and $i_{\beta h}$, respectively. The $i_{\alpha h}$ and $i_{\beta h}$ are all harmonic currents of the system on the αβ frame.

The summary of generalized harmonic detection using the DQF approach in this paper is shown in Fig. 7. It can be seen from Fig. 7 that the proposed method can be applied to eliminate all harmonic, specific n harmonic orders or all harmonic excepting n harmonic order depending on the designers for general cases. For the rest harmonic, the passive power filter can be used to reduce the cost of power filter.

3 The Simulation Results

There are five cases for the simulation results in which cases I-IV are for the three-phase balanced system as shown in Fig.1 with $L_s = 1\,\mu H$ and $R = 500\,\Omega$. The case V is for the unbalanced system as shown in Fig. 2 with $L_s = 1\,\mu H$, $L_u = L_v = L_w = 1\,H$, $R_u = 20\,\Omega$, $R_v = 50\,\Omega$ and $R_w = 70\,\Omega$.

Case I: 5th harmonic elimination results

The simulation results for eliminating the 5th harmonic components of the system in Fig.1 by using the DQF harmonic detection operated with an ideal active power filter are shown in Fig. 8.

It can be seen from Fig. 8 that the line currents (i_{su}, i_{sv}, i_{sw}) are equal to the load currents (i_{Lu}, i_{Lv}, i_{Lw}) during the first period (t=0-0.02 second). This is because the active power filter is not operated during the first period. Therefore, $\%THD_{i,u}$ at phase u is equal to 22.54% as shown in Table 1. However, after t=0.02 second the active power filter injects the compensating currents to the system to eliminate the 5th harmonic (case I) in which the reference currents can be calculated from the DQF algorithm as explained in Section 2. As a result, the 5th harmonic in Table 1 is remarkable reduced from 22.58% to 0.06%, while other orders are the same as the one before compensation. For this approach, the passive power filter can be used to eliminate other harmonic components depending on the engineering design so as to achieve the lower cost of active power filters. Because of eliminating the 5th harmonic, $\%THD_{i,u}$ can be reduced from 22.54% to 8.44%. Hence, the line currents after compensation are nearly sinusoidal waveform.

Case II: 5th and 7th harmonic elimination results

The results for case II are shown in Fig. 9. It can be seen that the line currents (i_{su}, i_{sv}, i_{sw}) after compensated are very close to the sinusoidal waveform compared with the results in case I. This is because the 7th harmonic component is eliminated for this case in which the 7th harmonic is reduced from 7.43% to 0.03% to achieve the smaller $\%THD_{i,u}$ (4.89%).

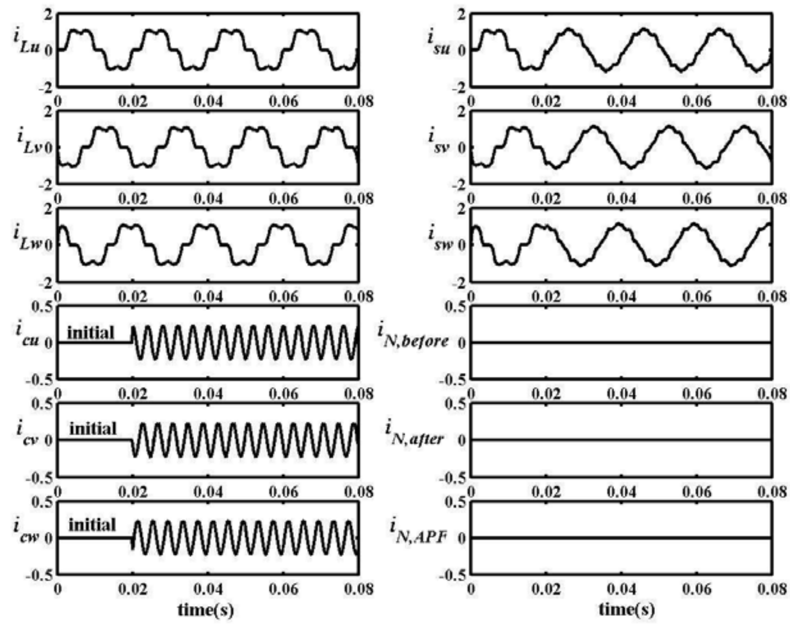

Fig.8 5th harmonic elimination for the power system in Fig.1

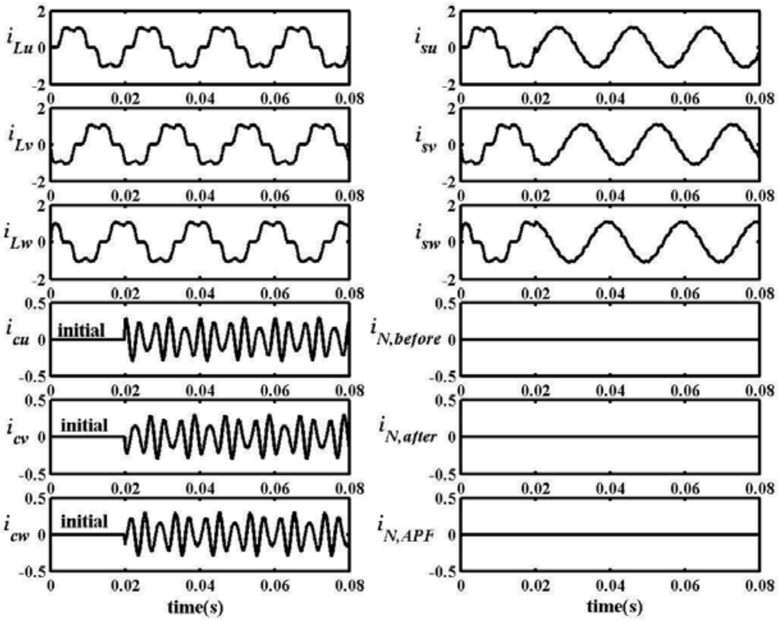

Fig.9 5th and 7th harmonic elimination for the power system in Fig.1

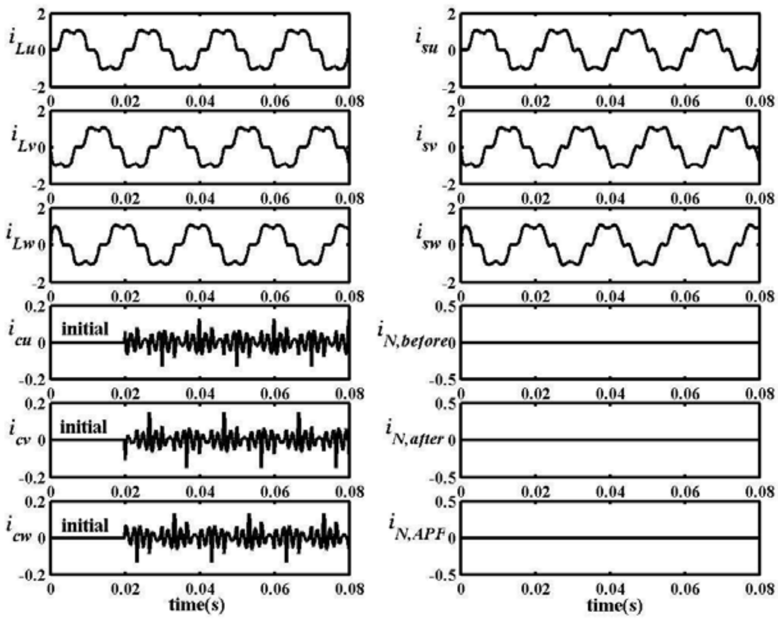

Fig.10 All harmonic components elimination excepting 5th and 7th

Table 1. Harmonic Elimination Results for Balanced System

case	order 5 (%)	order 7 (%)	order 11 (%)	order 13 (%)	order 17 (%)	order 19 (%)	$\%THD_{i,u}$
before compensated	22.58	7.43	4.47	2.25	1.53	0.67	22.54
I	0.06	7.43	4.47	2.25	1.53	0.67	8.44
II	0.06	0.03	4.47	2.25	1.53	0.67	4.89
III	22.58	7.43	0.001	0.002	0.0005	0.0007	22.02
IV	0.0004	0.0007	0.0003	0.0004	0.0001	0.0002	0.002

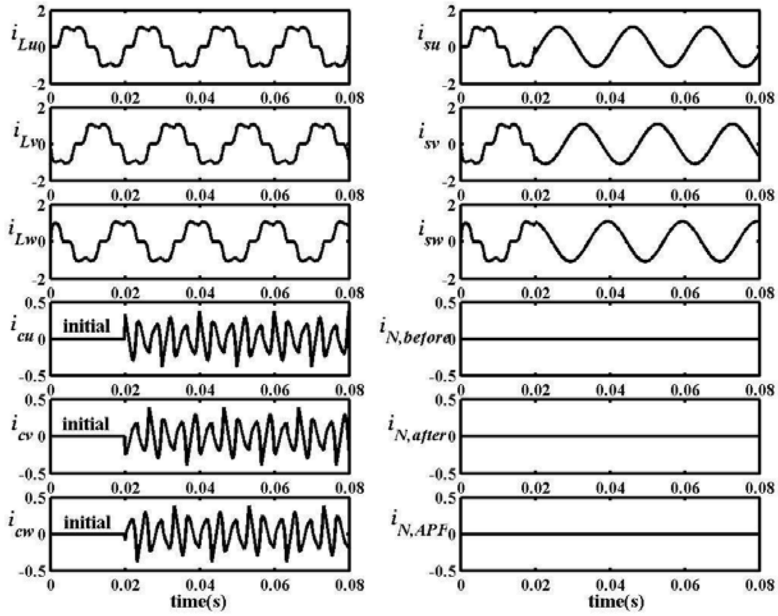

Fig.11 All harmonic components elimination results

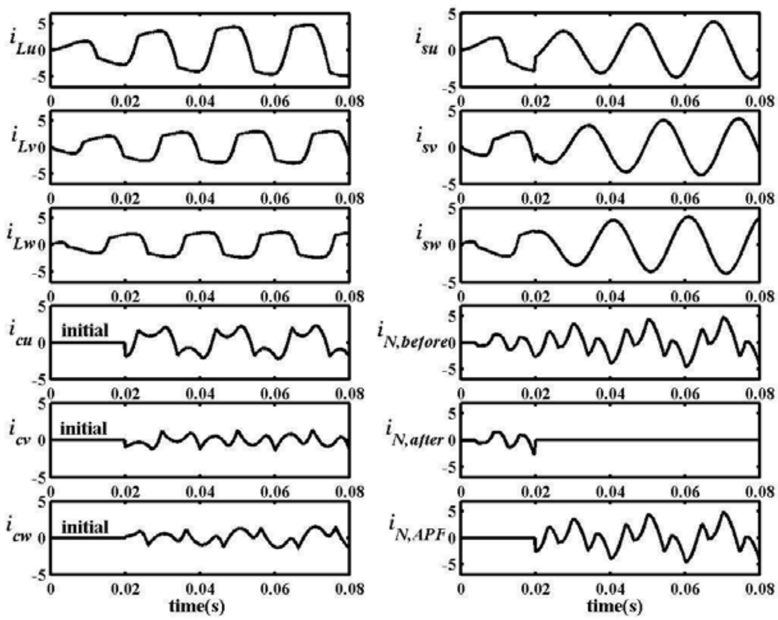

Fig.12 All harmonic components elimination results for unbalanced system

Table 2. Harmonic Elimination Results for Unbalanced System

$\%THD_{i,u}$	$\%THD_{i,v}$	$\%THD_{i,w}$	$\%THD_{i,av}$	$i_{u,rms}$	$i_{v,rms}$	$i_{w,rms}$	%unbalance
before compensated							
17.11	22.79	24.24	21.38	4.21	2.58	2.05	42.71
after compensated (case V)							
0.12	0.08	0.07	0.09	2.85	2.85	2.85	0

Case III: All harmonic components elimination excepting 5th and 7th results

The results for case III are shown in Fig. 10. It can be seen that the line currents is not nearly sinusoidal because the 5^{th} and 7^{th} harmonic components are not eliminated for this case in which the nonlinear load in Fig.1 mainly generates the 5^{th} and 7^{th} harmonic components. Therefore, the $\%THD_{i,u}$ is reduced from 22.54% to 22.02%. According to the results for this case, it shows that the DQF harmonic detection is flexible to operate with active power filters.

Case IV: All harmonic components elimination results

The results for case IV are depicted in Fig. 11. The $\%THD_{i,u}$ is very small compared with the previous cases because all harmonic components are eliminated. However, this condition causes higher rating of active power filters and consequently higher cost. Therefore, the hybrid power filter is more powerful in which it is the combination between active and passive power filters. The proposed harmonic detection as presented in this paper can provide the three-phase reference currents for the active power filter to eliminate some harmonic components and the rest harmonics can be cancelled by using passive power filters.

Case V: All harmonics elimination for unbalanced power systems

According to the results from cases I-IV, the neutral current ($i_{N,before}$) is equal to 0 because the system before compensation is balanced. However, after compensation, the neutral current ($i_{N,after}$) is still equal to 0. For this case, the DQF harmonic detection operated with the active power filter to eliminate all harmonic components for the unbalanced system as shown in Fig.2 is depicted in Fig. 12.

$$\%\,\text{unbalance} = \frac{|\text{maximum current deviation from average rms current}|}{\text{average rms current}} \times 100\% \quad (15)$$

$$\%THD_{i,av} = \frac{1}{3}\sum_{k=u,v,w} \%THD_{i,k} \quad (16)$$

As can be seen from Fig. 12, the power system is unbalanced because the magnitude of each phase is not the same. The %unbalance as shown in Table 2 is 42.71% calculated from (15). Due to unbalanced situation, the neutral current is not zero and it may cause the damage in the neutral line. Moreover, before compensation, $\%THD_{i,av}$ is equal to 21.38% as addressed in Table 2 calculated from (16). After compensation, this value is extremely reduced to 0.09% by using the proposed harmonic detection with the ideal active power filter. In addition, it is interesting that the unbalanced system can become a balanced condition after all harmonics eliminated completely in which %unbalance is equal to 0 as shown in Table 2. Hence, the neutral line current is 0 because the zero sequence current is used for the DQF harmonic detection as explained in section 2 to achieve the reference currents for the active power filter to generate the injected currents into the system.

From the literature survey, there are many researches for the harmonic detection methods using artificial intelligent (AI) approaches such as genetic algorithm (GA) [8], adaptive linear neural network (ADALINE) [9], and fuzzy logic [10]. Therefore, for the future work, AI techniques will be applied with DQF algorithm to obtain the better harmonic detection methods compared with the reported method in this paper.

4 Conclusion

This paper presents the DQF harmonic detection operated with the active power filter and passive power filters called the hybrid power filter. The proposed harmonic detection can be successfully used to calculate the harmonic reference currents for eliminating some or all harmonic components. After compensation completely, the harmonic quantities can be reduced and the system is balanced even through the system before compensation is unbalanced. Therefore, the proposed harmonic detection is very flexible and suitable in terms of design for hybrid power filters.

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