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A New Harmonic Detection Method with Reduced Dynamic Response Time for Hybrid Active Power Filter

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Abstract

This paper proposes a new harmonic detection method with reduced dynamic response time for Hybrid Active Power Filter. First, the i_p-i_q harmonic detection method has been analyzed to see its disadvantages as well as highlight the problem to be solved in this paper. Accordingly, the only disadvantage of the i_p-i_q method is in the low-pass filter. The low- pass filter has the disadvantage of a large dynamic response time. To overcome this drawback, the paper presents a new solution for improving the low-pass filter that is to use a low-pass filter with a large cut-off frequency in parallel to a mean value module. To demonstrate the effectiveness of the proposed method, the simulation results performed on a Hybrid Active Power Filter model have demonstrated that: the proposed method is more effective than the i_p-i_q method in improving dynamic response and minimum of current total harmonic distortion in steady-state.

Keywords: Hybrid active power filter, i_p-i_q harmonic detection method, low pass filter, mean value module, dynamic response.

I. INTRODUCTION

The instantaneous active and reactive power theory, or the so-called “p-q Theory” was introduced by Akagi, Kanazawa, and Nabae in 1983 [1]. Since then, there have been many applications of the "p-q Theory" in different fields such as electric machine, harmonic filter, new energy, et al [2-3]. In which the i_p-i_q harmonic detection method is a development of the "p-q Theory" and it is used for systems with distorted or unbalanced sources. The i_p-i_q harmonic detection method is the most commonly used method. From a signal with any waveform, the i_p-i_q method will find the fundamental component and harmonic component that constitutes the waveform. However, the i_p-i_q method has the disadvantage of slow response time because it uses the low-pass filter (LPF) [4-6] or high-pass filter (HPF) [7-9]. The LPF and HPF have slow response and only a slight variation of frequency will also result in a significant phase shifting.

To improve the disadvantage of the i_p-i_q harmonic detection method, a few papers have proposed by using the neural network [10-11]. With the use of neural networks to determine harmonic currents, it has the advantage of giving accurate results in steady-state if the training algorithm is used well. However, there are shortcomings that the mathematical model is too complex, the ability to respond too slowly. Therefore, it is less used. Another method is FBD (Fryze-Buchholz-Dpenbrock) method [12-14], which is based on the sliding-window iterative algorithm. This method has the advantage of not using phase-locked loop block and skip low-pass filter. Even so, it has the disadvantages of complex and slow response. The harmonic detection method uses the Fuzzy Least Mean Squares algorithm has been introduced [15-16] and has also improved accuracy in steady-state. However, this method has a response in transient period is slow, large overshoot when the load changes rapidly. Another method used to determine harmonic currents is the method using fast Fourier transform [17]. The disadvantage of Fast Fourier Transform method is that it is not flexible to load changes because the sampling frequency has been fixed.

In short, the above listed methods have disadvantages of large dynamic response time. In this paper, a new method for determining harmonic currents has been proposed. This method is improved from the i_p-i_q method. The purpose of this improvement is to reduce the overshoot, transient time. From the mathematical analysis of the i_p-i_q method, we find that its disadvantage is that it depends on the LPF. From there, a parallel connection of a LPF with a large cut-off frequency and a mean value module will significantly reduce the dynamic response time of the method while retaining the accuracy in the steady state. To demonstrate the effectiveness of the proposed method, simulation results are performed on an HAPF system [18-20]. These simulation results have demonstrated the effectiveness of the proposed method in minimizing current total harmonic distortion (THD), while the dynamic response time is greatly reduced.

The structure of the paper is divided into five parts: Part I is an overview of the problem to be studied, the harmonic detection method and its disadvantage is analyzed in Part II, harmonic detection method with reduced dynamic response time for the Hybrid Active Power Filter is proposed in section III, The simulation results and discussion are presented in section IV and part V are the conclusions of the paper.

II. HARMONIC DETECTION METHOD AND ITS DISADVANTAGE

Let's consider the i_p-i_q harmonic detection method [1-3] shown in Fig. 1. The use of the Phase-Lock Loop (PLL) is to generate reference sine waves (*sin (ωt)* and *–cos (ωt)*) with the same amplitude and synchronization as the source voltage.

According to Fig. 1, we have:

$$\begin{bmatrix} i_p \\ i_q \end{bmatrix} = [C][C_{32}]\begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \tag{1}$$

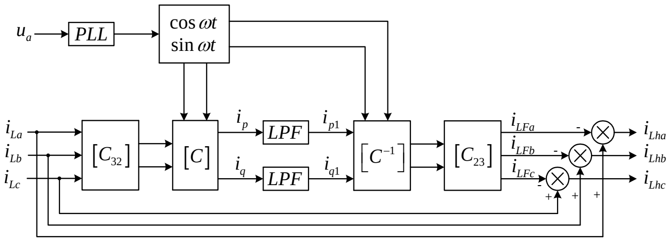

Fig. 1. i_p-i_q harmonic detection method

Where:

$$[C_{32}]=\sqrt{\frac{2}{3}}\begin{bmatrix}1 & -\frac{1}{2} & -\frac{1}{2}\\ 0 & \sqrt{\frac{3}{2}} & -\sqrt{\frac{3}{2}}\end{bmatrix};$$

$$[C]=\begin{bmatrix}\sin\omega_1 t & -\cos\omega_1 t\\ -\cos\omega_1 t & -\sin\omega_1 t\end{bmatrix}$$

Use a low-pass filter to filter the direct current component of i_p and i_q, we get i_{p1} and i_{q1}.

$$\begin{bmatrix}i_{LFa}\\ i_{LFb}\\ i_{LFc}\end{bmatrix}=[C_{23}][C^{-1}]\begin{bmatrix}i_{p1}\\ i_{q1}\end{bmatrix} \quad (2)$$

Where

$$[C_{23}]=\sqrt{\frac{2}{3}}\begin{bmatrix}1 & 0\\ -\frac{1}{2} & \sqrt{\frac{3}{2}}\\ -\frac{1}{2} & -\sqrt{\frac{3}{2}}\end{bmatrix}$$

$[C^{-1}]$ is the inverse matrix of matrix $[C]$

From here, the harmonic current components are defined as:

$$\begin{bmatrix}i_{Lha}\\ i_{Lhb}\\ i_{Lhc}\end{bmatrix}=\begin{bmatrix}i_{La}\\ i_{Lb}\\ i_{Lc}\end{bmatrix}-\begin{bmatrix}i_{LFa}\\ i_{LFb}\\ i_{LFc}\end{bmatrix} \quad (3)$$

From the above analysis, we can see that: in the i_p-i_q harmonic detection method only LPF block is the main influence on its accuracy. Because, the conversion matrices [C_{32}], [C_{23}], [C] and [C^{-1}] are pure mathematical conversions, so there are no errors and delays in computation. The LPF passes through frequencies that are smaller than the cut-off frequency and blocks frequencies greater than the cut-off frequency. However, due to the filtering characteristics of LPF, it must have a large transient time to achieve the value in steady-state. When the higher the cut-off frequency, the smaller the transient time, but the overshoot is large and the value in steady-state is not smooth. Conversely, when the cut-off frequency is small, the transient time will be very large, but the value in steady-state very smooth. Fig. 2 is the waveform of i_p and Fig. 3 is the waveform of i_{p1} (after passing LPF). From Fig. 3 we can see that the transient time to achieve the steady-state is 0.06s.

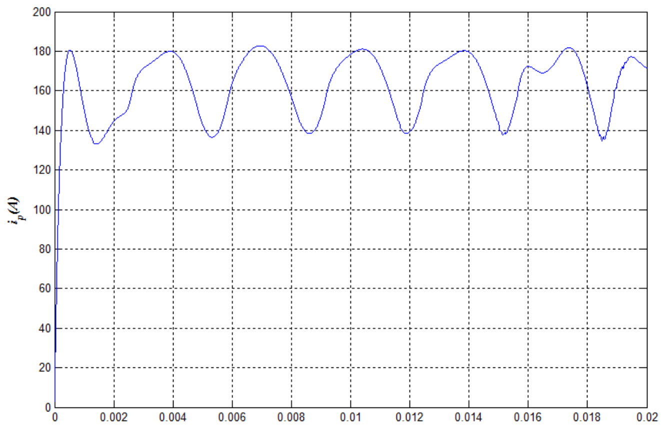

Fig. 2. The waveform of i_p

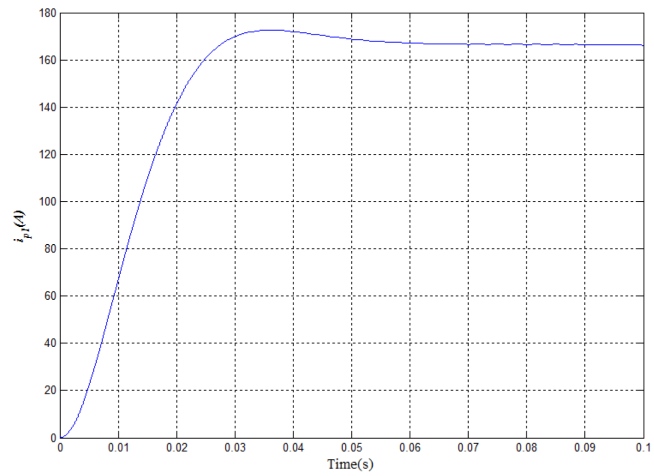

Fig. 3. The waveform of i_{p1}

III. HARMONIC DETECTION METHOD WITH REDUCED DYNAMIC RESPONSE TIME FOR HYBRID ACTIVE POWER FILTER

To reduce the dynamic response time of LPF also means to reduce the dynamic response time of the i_p-i_q harmonic detection method, this paper provides a method to improve the disadvantage of LPF as follows:

Assume three-phase source voltage and three-phase load current of the form:

$$\begin{cases} i_{La}=\sum_{n=1}^{\infty}\sqrt{2}I_n\sin(n\omega t+\varphi_n)\\ i_{Lb}=\sum_{n=1}^{\infty}\sqrt{2}I_n\sin\left[n\left(\omega t-\frac{2\pi}{3}\right)+\varphi_n\right]\\ i_{Lc}=\sum_{n=1}^{\infty}\sqrt{2}I_n\sin\left[n\left(\omega t+\frac{2\pi}{3}\right)+\varphi_n\right]\end{cases} \quad (4)$$

$$\begin{cases} u_a = \sqrt{2}U_n \sin(\omega t) \\ u_b = \sqrt{2}U_n \sin\left(\omega t - \dfrac{2\pi}{3}\right) \\ u_c = \sqrt{2}U_n \sin\left(\omega t + \dfrac{2\pi}{3}\right) \end{cases} \tag{5}$$

Where ω is the angular frequency of the source

I_n, U_n and φ_n are RMS and original phase angle, $n = 3k \pm 1, k \geq 0$

We have:

$$\left[C_{32}\right]\begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} = \sqrt{3}\begin{bmatrix} \sum_{n=1}^{\infty} I_n \sin(n\omega t + \varphi_n) \\ \sum_{n=1}^{\infty} I_n \cos(n\omega t + \varphi_n) \end{bmatrix} \tag{6}$$

According to (1), we have:

$$\begin{bmatrix} i_p \\ i_q \end{bmatrix} = \left[C\right]\left[C_{32}\right]\begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} = 3U_n\begin{bmatrix} \sum_{n=1}^{\infty} I_n \cos\left[(1-n)\omega t - \varphi_n\right] \\ \sum_{n=1}^{\infty} I_n \sin\left[(1-n)\omega t - \varphi_n\right] \end{bmatrix} \tag{7}$$

The Eq. (7) through the PLL block will separate the direct current component

$$\begin{bmatrix} i_{p1} \\ i_{q1} \end{bmatrix} = \begin{bmatrix} 3U_1 I_1 \cos(-\varphi_1) \\ 3U_1 I_1 \sin(-\varphi_1) \end{bmatrix} \tag{8}$$

On the other hand, from (7) when $n = 1$, we have the direct current as in (8) and the alternating current (AC) as follows:

$$\begin{bmatrix} i_{pAC} \\ i_{qAC} \end{bmatrix} = \begin{bmatrix} \sum_{n=2}^{\infty} 3U_n I_n \cos\left[(1-n)\omega t - \varphi_n\right] \\ \sum_{n=2}^{\infty} 3U_n I_n \sin\left[(1-n)\omega t - \varphi_n\right] \end{bmatrix} \tag{9}$$

From (9) we find that when n is larger, its mean value will be zero. In other words, the average value of i_p and i_q will be i_{p1} and i_{q1}. Thus, in the steady-state we can completely replace LPF by a formula to calculate the average value, or the so-called "mean value module" as shown in Fig. 4.

To reduce the dynamic response time, the T period of the integral formula should not take the full time simulation but must ignore the initial period. According to Fig. 2, the T period can be taken from 0.004s to the end of the simulation time. In the period from 0s to 0.004s switch K in position 1, the circuit that works with a LPF has a large cut-off frequency to reduce the transient time. At time t = 0.004s switch K changes from position 1 to position 2, the circuit works with the mean value module.

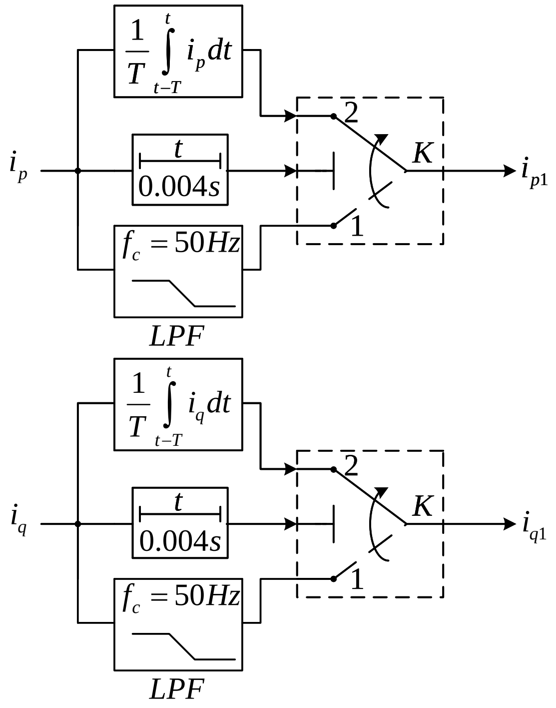

Fig. 4. LPF improvement model

IV. SIMULATION RESULTS AND DISCUSSION

To demonstrate the effectiveness in reducing the dynamic response time and the applicability of the proposed method, the simulation results were performed on an HAPF model 220V-50Hz as shown in Fig. 5. The closed loop control principle of the HAPF system can be summarized as follows: from the load current i_L through the harmonic detection method to separate the harmonic component of i_L, called i_{Lh}, this is considered as the reference signal. This reference signal will be compared with the actual signal from HAPF is i_F. The error of these two signals will go through the controller to generate switching pulses for the inverter and generate i_F. As a result, the supply current i_s becomes the ideal *Sin* wave. Thus, the harmonic detection method is one of the most important steps in the control of HAPF system.

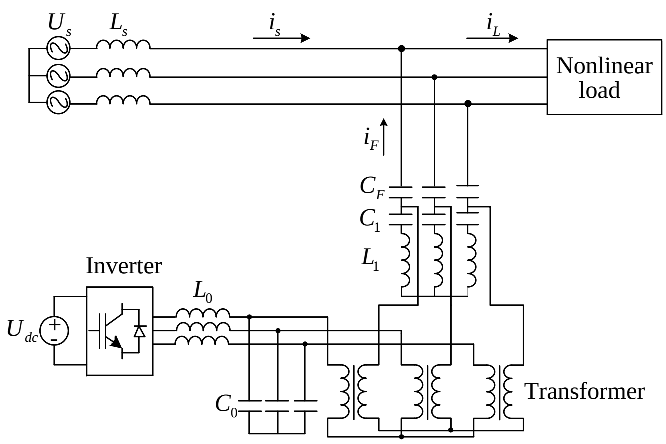

Fig. 5. Structure of a HAPF

The control block diagram for HAPF as shown in Fig. 6.

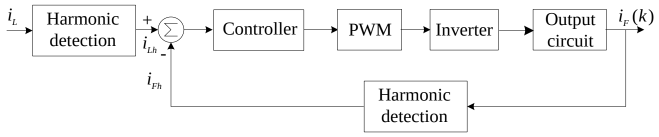

Fig. 6. Control block diagram for HAPF

The parameters of the HAPF are given as in Table 1.

Table 1. HAPF parameters

L_0 (mH)	C_0 (μF)	L_1 (mH)	C_1 (μF)	C_F (μF)	U_{dc} (V)	L_s (mH)
1.0	60	29.77	349.2	100	535	0.2

When using the i_p-i_q harmonic detection with the cut-off frequency of LPF is 50Hz, the simulation results are shown in Fig. 7. From Fig. 7 we find that: transient time when using i_p-i_q method is 0.02s, leading to the transient time of the supply current i_s is 0.05s, and this time is quite large. The THD of the fundamental current i_{LF} in steady-state is 0.15% and it is shown in Fig. 8. The THD of the supply current i_s in steady-state is 2.25% and it is shown in Fig. 9.

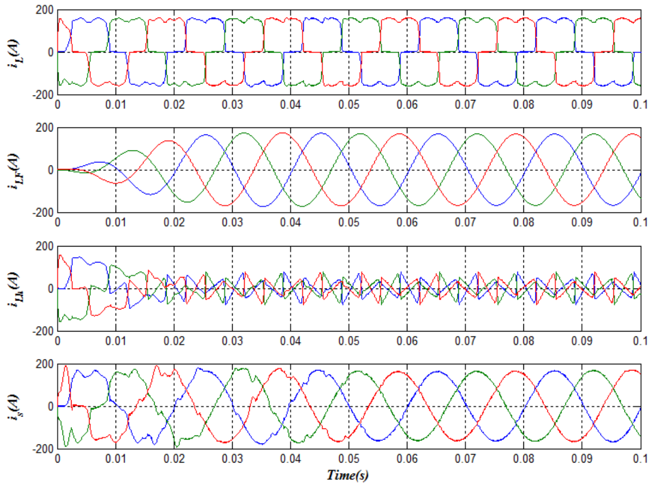

Fig. 7. Simulation results with the i_p-i_q harmonic detection method

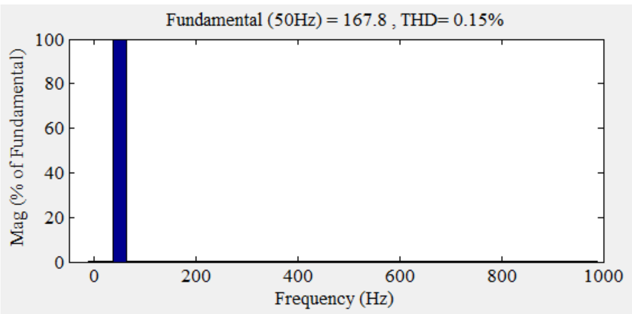

Fig. 8. THD of the fundamental current i_{LF} in steady-state with i_p-i_q method

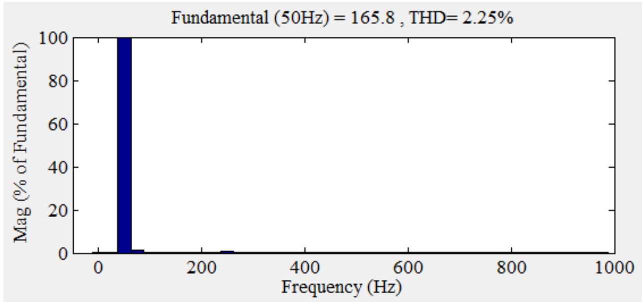

Fig. 9. THD of the supply current in steady-state with i_p-i_q method

When the proposed method is used, in which LPF with a cut-off frequency of 50Hz working for a period from 0s to 0.004s. At time t=0.004s switch *K* passes through the mean value module. The simulation results with the proposed method are shown in Fig. 10.

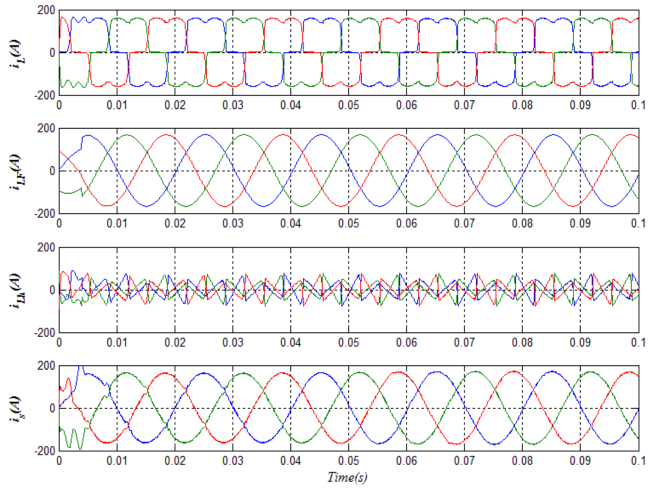

Fig. 10. Simulation results with the proposed method

From Fig. 10, we can see that the dynamic response time of the method is only 0.004s then it is steady state, whereby the dynamic response time of the supply current is only 0.01s. The THD of the fundamental current at steady-state is 0.16% and it is shown in Fig. 11 (equivalent to the THD of the fundamental current in i_p-i_q method). The THD of the supply current i_s is 1.72% and it is shown in Fig. 12.

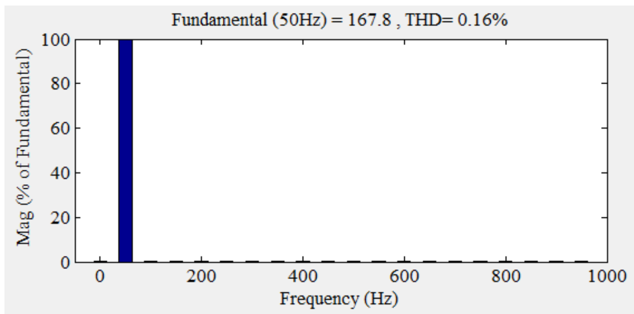

Fig. 11. THD of the fundamental current in steady-state with proposed method

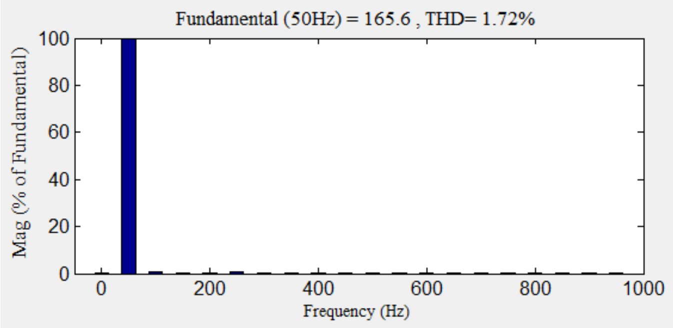

Fig. 12. THD of the supply current in steady-state with proposed method

V. CONCLUSION

The paper has provided a new harmonic current detection method for HAPF. This method separates the fundamental current component and the harmonic current component of any waveform with a very short dynamic response time. Compared with the i_p-i_q harmonic detection method, simulation results have demonstrated the effectiveness of the proposed method in reducing dynamic response time and minimizing current total harmonic distortion. Furthermore, the proposed method can be applied to all types of Hybrid Active Power Filter. This study contributes to the stability of the Hybrid Active Power Filter system and further improve power quality in the system power.

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