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Experimental Validation of Novel Stationary Frame Selective Harmonic Extraction Strategy

***Abstract**. This paper presents a novel stationary frame selective harmonic extraction strategy. Compared with the widely used methods based on the instantaneous power theory, it only needs one matrix transformation, which significantly reduces the computational burden. Time-domain simulation in the MATLAB/Simulink and experimental results based on the 32-bit fixed-point TMS320F2812 DSP platforms verify the effectiveness of the proposed method.*

***Streszczenie.** W artykule zaprezentowano uproszczoną metodę ekstrakcji harmonicznych. W porównaniu z ogólnie stosowaną metoda bazująca na teorii mocy chwilowej proponowana metoda wymaga tylko przekształcenia macierzy co znacznie redukuje obciążenie komputera. (**Eksperymentalna weryfikacja nowej metody selektywnej ekstrakcji harmonicznych**)*

Keywords: Selective harmonic extraction
Słowa kluczowe: selektywna ekstrakcja harmonicznych

Introduction

With the development of power electronics, the nonlinear loads are emerging in the utility. Consequently, the harmonic pollution is of great concern due to nonlinear loads. In general, the harmonic mitigation methods can be classified into two groups [1-5]. One is the passive filter. It has the advantages such as simplicity and easy implementation. However, its performance is limited to a few harmonics and resonance may be excited between the passive filter and grid impedance. On the other hand, the active filter is a good alternative to harmonic mitigation. The basic idea of active filter is to compensate the harmonic current in the utility by inject an equal but opposite current. Therefore, the harmonic current extraction is crucial for the successful use of active filter.

Harmonic extraction method can be categorized into two groups: full harmonic extraction and selective harmonic extraction. Due to delay and control bandwidth, selective harmonic extraction and control is preferred. In fact, the selective harmonic extraction is one of most important issues for active filter applications [6-10]. The solution based on the instantaneous power theory has been widely used in the past decades [11-12].However, its needs four matrix transformations and sine/cosine operations, which leads to complex procedures. A novel stationary frame selective harmonic extraction strategy is proposed to simplify the procedure and make it easy to implement.

Proposed strategy

In order to clarify the advantages of the proposed strategy, the conventional method is briefly discussed first. The schematic diagram of the conventional selective harmonic extraction algorithm is shown in Fig.1, from which it can be observed that it needs four matrix transformations and sine/cosine operations, which means complex calculations.

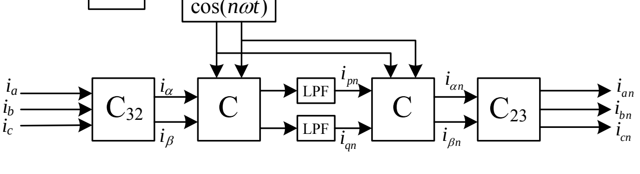


Fig.1 Conventional selective harmonic extraction

In this paper a stationary frame selective harmonic extraction algorithm derived from the Fig.1 is proposed to simplify the calculation. The time-domain expression of the selective harmonic extraction algorithm in Fig.1 can be expressed as follows:

$$\begin{bmatrix} i_{an}(t) \\ i_{bn}(t) \\ i_{cn}(t) \end{bmatrix} = C_{23} C \left\{ \left[h(t) \right] * \left\{ C C_{32} \begin{bmatrix} i_a(t) \\ i_b(t) \\ i_c(t) \end{bmatrix} \right\} \right\} \tag{1}$$

where * represents the convolution operation.

With Clarke transformation, equation (1) can be rewritten as:

$$\begin{aligned} i_{\alpha n}(t) = &\left[h(t) * \left(i_\alpha \cdot \sin(n\omega t) - i_\beta \cdot \cos(n\omega t) \right) \right] . \sin(n\omega t) \\ &+ \left[h(t) * \left(i_\alpha \cdot \cos(n\omega t) + i_\beta \cdot \sin(n\omega t) \right) \right] . \cos(n\omega t) \end{aligned} \tag{2}$$

$$\begin{aligned} i_{\beta n}(t) = &-\left[h(t) * \left(i_\alpha \cdot \sin(n\omega t) - i_\beta \cdot \cos(n\omega t) \right) \right] . \cos(n\omega t) \\ &+ \left[h(t) * \left(i_\alpha \cdot \cos(n\omega t) + i_\beta \cdot \sin(n\omega t) \right) \right] . \sin(n\omega t) \end{aligned} \tag{3}$$

With Laplace transformation, equation (2) and (3) can be rewritten as:

$$\begin{aligned} &L\left\{ \left[h(t) * \left(i_\alpha \cdot \sin(n\omega t) - i_\beta \cdot \cos(n\omega t) \right) \right] . \sin(n\omega t) \right\} = \\ &\frac{H(s+jn\omega)}{4} \cdot \left[-I_\alpha(s+2jn\omega) + I_\alpha(s) - jI_\beta(s+2jn\omega) - jI_\beta(s) \right] + \\ &\frac{H(s-jn\omega)}{4} \cdot \left[-I_\alpha(s-2jn\omega) + I_\alpha(s) + jI_\beta(s-2jn\omega) + jI_\beta(s) \right] \end{aligned} \tag{4}$$

$$\begin{aligned} &L\left\{ \left[h(t) * \left(i_\alpha \cdot \cos(n\omega t) + i_\beta \cdot \sin(n\omega t) \right) \right] . \cos(n\omega t) \right\} = \\ &\frac{H(s+jn\omega)}{4} \cdot \left[I_\alpha(s+2jn\omega) + I_\alpha(s) + jI_\beta(s+2jn\omega) - jI_\beta(s) \right] + \\ &\frac{H(s-jn\omega)}{4} \cdot \left[I_\alpha(s-2jn\omega) + I_\alpha(s) - jI_\beta(s-2jn\omega) + jI_\beta(s) \right] \end{aligned} \tag{5}$$

$$\begin{aligned} &L\left\{ \left[h(t) * \left(i_\alpha \cdot \sin(n\omega t) - i_\beta \cdot \cos(n\omega t) \right) \right] . \cos(n\omega t) \right\} = \\ &\frac{H(s+jn\omega)}{4} \cdot \left[jI_\alpha(s+2jn\omega) - jI_\alpha(s) - I_\beta(s+2jn\omega) - I_\beta(s) \right] + \\ &\frac{H(s-jn\omega)}{4} \cdot \left[-jI_\alpha(s-2jn\omega) + jI_\alpha(s) - I_\beta(s-2jn\omega) - I_\beta(s) \right] \end{aligned} \tag{6}$$

$$\begin{aligned} &L\left\{ \left[h(t) * \left(i_\alpha \cdot \cos(n\omega t) + i_\beta \cdot \sin(n\omega t) \right) \right] . \sin(n\omega t) \right\} = \\ &\frac{H(s+jn\omega)}{4} \cdot \left[jI_\alpha(s+2jn\omega) + jI_\alpha(s) - I_\beta(s+2jn\omega) + I_\beta(s) \right] - \\ &\frac{H(s-jn\omega)}{4} \cdot \left[jI_\alpha(s-2jn\omega) + jI_\alpha(s) + I_\beta(s-2jn\omega) - I_\beta(s) \right] \end{aligned} \tag{7}$$

Therefore, the stationary $\alpha\beta$ frame frequency-domain expression of (2) can be obtained as follows:

$$\begin{bmatrix} I_{\alpha n}(s) \\ I_{\beta n}(s) \end{bmatrix} = \frac{1}{2}\begin{bmatrix} H(s+jn\omega)+H(s-jn\omega) & -jH(s+jn\omega)+jH(s-jn\omega) \\ jH(s+jn\omega)-jH(s-jn\omega) & H(s+jn\omega)+H(s-jn\omega) \end{bmatrix}\begin{bmatrix} I_{\alpha}(s) \\ I_{\beta}(s) \end{bmatrix} \tag{8}$$

The first-order low pass filter (LPF) is

$$H(s)=\frac{\omega_c}{s+\omega_c} \tag{9}$$

Substitute (9) into (8), the stationary $\alpha\beta$ frame filter matrix can be obtained:

$$H_{\alpha\beta}(s)=\begin{bmatrix} \dfrac{\omega_c s+\omega_c{}^2}{s^2+2\omega_c s+\omega_c{}^2+(n\omega)^2} & \dfrac{-\omega_c n\omega}{s^2+2\omega_c s+\omega_c{}^2+(n\omega)^2} \\ \dfrac{\omega_c n\omega}{s^2+2\omega_c s+\omega_c{}^2+(n\omega)^2} & \dfrac{\omega_c s+\omega_c{}^2}{s^2+2\omega_c s+\omega_c{}^2+(n\omega)^2} \end{bmatrix} \tag{10}$$

For three-phase three-wire system, the stationary *abc* frame filter matrix can be obtained.

$$\begin{aligned}[H_{ab}(s)] &= \begin{bmatrix} 1 & 0 \\ -\dfrac{1}{2} & \dfrac{\sqrt{3}}{2} \end{bmatrix}[H_{\alpha\beta}(s)]\begin{bmatrix} 1 & 0 \\ \dfrac{1}{\sqrt{3}} & \dfrac{2}{\sqrt{3}} \end{bmatrix} \\ &= \begin{bmatrix} \dfrac{\omega_c s+\omega_c{}^2-\omega_c n\omega/\sqrt{3}}{s^2+2\omega_c s+\omega_c{}^2+(n\omega)^2} & \dfrac{-2\omega_c n\omega/\sqrt{3}}{s^2+2\omega_c s+\omega_c{}^2+(n\omega)^2} \\ \dfrac{2\omega_c n\omega/\sqrt{3}}{s^2+2\omega_c s+\omega_c{}^2+(n\omega)^2} & \dfrac{\omega_c s+\omega_c{}^2+\omega_c n\omega/\sqrt{3}}{s^2+2\omega_c s+\omega_c{}^2+(n\omega)^2} \end{bmatrix}\end{aligned} \tag{11}$$

Fig.2 shows the schematic diagram of the proposed harmonic extraction algorithm. In clear contrast with Fig.1, the proposed method only needs one matrix transformation, which significantly reduces the computational burden and makes it easy to implement. A notch filter is an option to enhance its performance, if necessary.

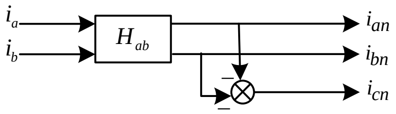


Fig.2 Proposed selective harmonic extraction

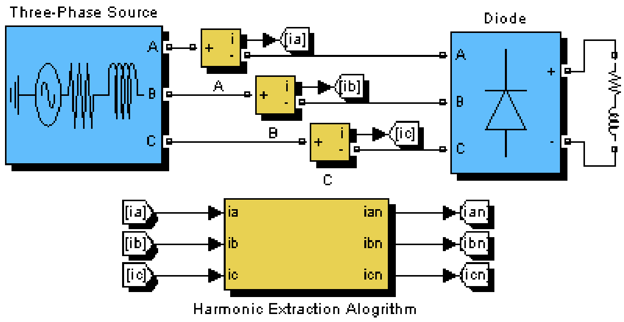
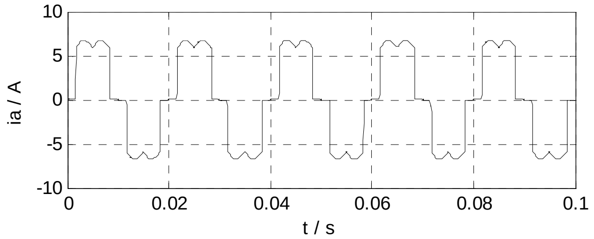


Fig.3 Simulation circuit configuration

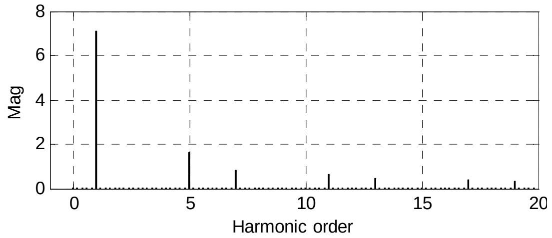
Simulation Results

The performance evaluation with the time-domain simulation of the proposed harmonic extraction method is carried out in the MATLAB/Simulink. The Simulation circuit configuration is shown in Fig.3. The simulation results are given in Fig.4.

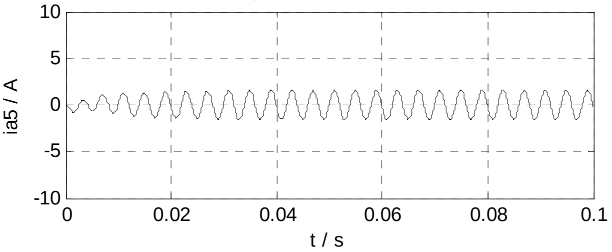
From Fig.4 (a) and Fig.4 (b), it can be observed that the load current consist of lots of harmonic components, mainly including 5th, 7th, 11th, 13th, etc. The amplitude of harmonic current tends to decrease as the harmonic frequency increases.



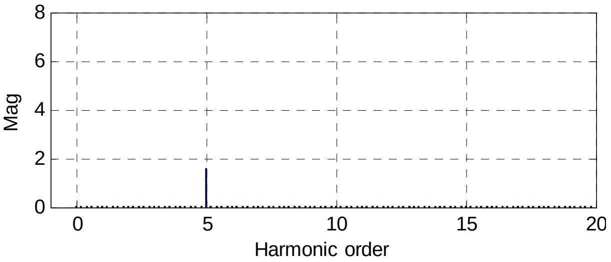
（a） nonlinear load current



（b） Spectrum of load current



（c） Extracted Harmonic current



（d） Spectrum of extracted Harmonic current

Fig.4 Simulation results

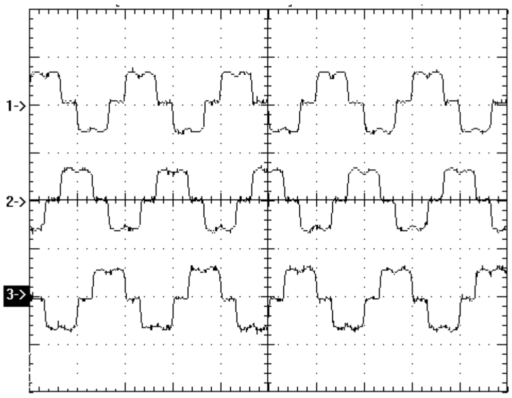
Fig. 4(c) and Fig.4 (d) shows the simulation results for 5th harmonic extraction. It is clear that the proposed method can achieve the accuracy extraction of the selective harmonic current.

Experimental Results

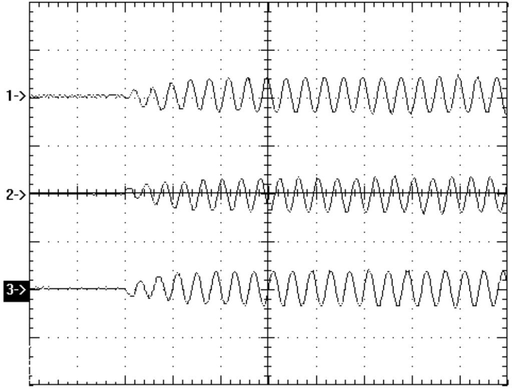
In order to verify the effectiveness of the proposed strategy, the experimental tests are carried out based on the TMS320F2812 DSP platform. Fig.3 shows the experimental results of load currents, which consist of the typically current harmonics, e.g., 5th, 7th, 11th, 13th, etc.

Fig.5 shows the selective harmonic extraction for 5th harmonic. It can be observed that the proposed method can achieve the accurate extraction of 5th harmonic.

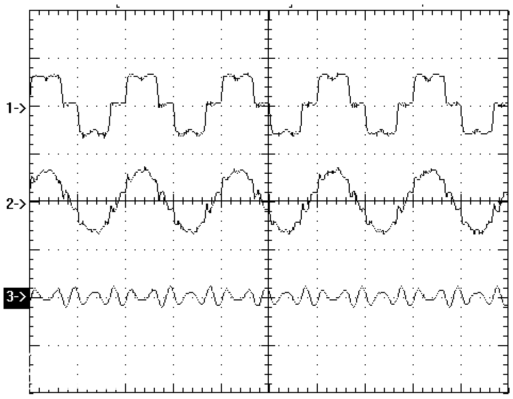
Also, it can be extended to other harmonic extraction, e.g. 5th and 7th. As shown in Fig.6, it can be observed that the filtered current, which is obtained by subtracting the load current with the extracted harmonic current, contain almost zero 5th and 7th harmonics. Therefore, the selective harmonic components can be precisely extracted with the proposed method. Compared with other existing selective harmonic extraction methods, the proposed method is very easy to implement, which is the main advantages, and a comprehensive comparison with other methods will be reported in a future paper. In summary, the proposed strategy is a good alternative for the selective harmonic extraction.



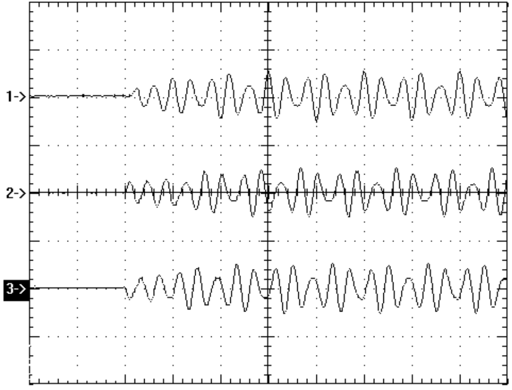
(Y-axis:5A/div, X-axis:10ms/div)
(a) load current



(Y-axis:2A/div, X-axis:10ms/div)
(b) Extracted Harmonic current
Fig.5 Experimental results of 5th harmonic extraction



(a) load current, filtered current, and extracted harmonic current
(Y-axis:5A/div, X-axis:10ms/div)



(Y-axis:2A/div, X-axis:10ms/div)
(b) Extracted Harmonic current
Fig.6 Experimental results of 5th and 7th harmonic extraction

Conclusion

This paper has presented a novel stationary frame selective harmonic extraction strategy. With the proposed method, four matrix transformations and sine/cosine operations of the conventional method can be simplified into one matrix transformation, which significantly reduces the computational burden. In good agreement with the theoretical analysis, experimental results have verified the effectiveness of the proposed strategy.

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