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Harmonic detection an AC excited generation system based on in-phase correlation filtering*

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Abstract: The paper reports results of investigation on the harmonic detection technique of a complicated power supply system such as an AC excited generation system, which has a variable fundamental frequency and low order harmonics with rich sub-harmonics whose frequencies are lower than the fundamental one. The in-phase correlation filtering technique, based on the frequency shifting principle, is proposed in this paper. Theoretical analysis and experimental results validate the effectiveness of this technique for the harmonic detections of AC excited generation systems.

Key words: in-phase correlation filtering, harmonic detection, AC excited generation system
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INTRODUCTION

In an AC excited generation system, the rotor windings of the asynchronous generator are supplied by three-phase AC excitation current generated by a cycloconverter. This technique ensures variable speed, constant frequency power generation, and enables independent control of the output active and reactive power from the generator. However, the voltage generated by the cycloconverter for excitation contains lots of harmonics which lead to high harmonic distortion in the output voltage of the generator. Consequently, the quality of the output power deteriorates. Therefore, a technique for eliminating the output harmonics is the key to commercialization of this novel power generation scheme.

The output power harmonics of an AC excited generator possess characteristics differing from those produced by normal power electronic equipment.

1. If the harmonic distortion of the output voltage is higher than that of the output current, the voltage reference needed for harmonic detection is difficult to obtain.

2. When the generation system is operated at variable speed, constant output frequency mode, the frequency of the excitation current varies and is quite low, normally (1-10) Hz.

3. The harmonic components to be filtered out are complicated and contain both "load harmonics" originated due to the load nonlinearity of the cycloconverter and the "source harmonics" produced in the power generation by the non-sinusoidal excitation current.

For example, in an AC excited generation system fed by a 6-pulse 36-thyristor cycloconverter operating without circulating current, triggered by the cosine-intersection method, the output voltage from the cycloconverter contains harmonics at the frequencies of $f_k = |6 \cdot q \cdot f_1 \pm (2 \cdot n+1) f_0|$, where $q = 1, 2, \cdots +\infty$ and $n = 0, 1, \cdots, +\infty$, with wide harmonic bandwidth and variable frequency. The central harmonic frequencies of the resultant output of the cycloconverter excited generation system become very complicated and can be given by $(6k \pm 1) f_1 + 6(k-1) s f_1$ which are functions of the stator output fundamental frequency f_1 and the slip frequency sf_1 (Wu et al., 1998, 1999.).

Proper harmonic filtering requires precise measurement of the harmonics. Among different harmonic detection methods (Akagi et al.,

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1984; Wang et al., 1997; Luo et al., 1993), that based on the instantaneous reactive power theory has been widely used due to its high accuracy and rapid dynamic response. However, this method is only suitable for detecting the current harmonics on which the power system has voltage references (Akagi et al., 1984). As previously described, in an AC excited generation system, both output voltage and current are non-sinusoidal and there is no clear voltage reference available for harmonic analysis and detection. It is extremely difficult to design a band filter to filter the voltage waveform because of the large variation of the fundamental frequency and the wide bandwidth of the harmonic components. This paper proposes an in-phase correlation filtering technique based on the phase shifting principles suitable for detecting the power harmonics generated by the AC excited generation system. The principle of this technique and its application for harmonic detection of an AC excited generation system will be discussed and the effectiveness of this technique will be validated by experimental results.

PRINCIPLE OF THE IN-PHASE CORRELATION FILTERING TECHNIQUE

According to the digital signal processing theory (Oppenheim et al., 1989), a three-phase time-varying arbitrary real signal $[f_1(t), f_2(t), f_3(t)]^T$ can be expressed as a series of periodic components with different frequencies. The three-phase signal with frequency of ω, a variable, can be decomposed as positive sequence components

$$\left[A_+\cos(\omega t+\xi_+), A_+\cos\left(\omega t-\frac{2}{3}\pi+\xi_+\right), A_+\cos\left(\omega t+\frac{2}{3}\pi+\xi_+\right)\right]^T,$$

negative sequence components

$$\left[A_-\cos(\omega t+\xi_-), A_-\cos\left(\omega t+\frac{2}{3}\pi-\xi_-\right), A_-\cos\left(\omega t-\frac{2}{3}\pi-\xi_-\right)\right]^T,$$

and zero sequence component

$$f_0(t)=[f_1(t), f_2(t), f_3(t)]/3.$$

Since the detection of $f_0(t)$ is relatively simple, no further discussion on it is necessary.

For simplicity, the three-phase time-varying arbitrary real signal $[f_1(t), f_2(t), f_3(t)]^T$ can be expressed by an instantaneous complex function $\boldsymbol{f}(t)$, as expressed below.

$$\boldsymbol{f}(t)=\frac{2}{3}[1, a, a^2]\cdot[f_1(t), f_2(t), f_3(t)]^T=\frac{2}{3}[f_1(t), af_2(t), a^2f_3(t)] \quad (1)$$

where $a=e^{j2\pi/3}$, $j=\sqrt{-1}$. It should be pointed out that instead of being a phasor, $\boldsymbol{f}(t)$ is an instantaneous complex function, which is the expression of a three-phase instantaneous signal in the time-domain. Therefore, the positive, negative and zero sequence components with frequency of ω become

$$\boldsymbol{f}_{\omega_+}(t)=\frac{2}{3}[1, a, a^2]\cdot\left[A_+\cos(\omega t+\xi_+), A_+\cos\left(\omega t-\frac{2}{3}\pi+\xi_+\right), A_+\cos\left(\omega t+\frac{2}{3}\pi+\xi_+\right)\right]^T=A_+e^{j(\omega t+\xi_+)} \quad (2)$$

$$\boldsymbol{f}_{\omega_-}(t)=\frac{2}{3}[1, a, a^2]\cdot\left[A_-\cos(\omega t-\xi_-), A_-\cos\left(\omega t+\frac{2}{3}\pi-\xi_-\right), A_-\cos\left(\omega t-\frac{2}{3}\pi-\xi_-\right)\right]^T=A_-e^{j(-\omega t+\xi_-)} \quad (3)$$

$$f_0(t)=\frac{2}{3}(A_1+aA_2+a^2A_3)=A_0e^{j\xi_0} \quad (4)$$

where A_+, A_-, A_0, and ξ_+, ξ_-, ξ_0, are the amplitudes and initial phase angles of the positive, negative and zero sequence components, respectively, and A_1, A_2, A_3, the amplitudes of phase functions $f_1(t), f_2(t), f_3(t)$, respectively.

Assuming the Laplace transform and Fourier transform of the complex signal $\boldsymbol{f}(t)$ are $\boldsymbol{F}(s)=\boldsymbol{L}[\boldsymbol{f}(t)]$ and $\boldsymbol{F}(\omega)=\boldsymbol{F}[\boldsymbol{f}(t)]$ respectively, then the centre of coordinates on the frequency axis of the frequency spectrum $\boldsymbol{F}(\omega)$ represents the DC component, while the left and right axis represent the negative and positive sequence components, respectively. Since $|\boldsymbol{F}(\omega)|=A_+$

and $|F(-\omega)| = A_-$, it can be seen that the frequency spectrum of $f(t)$ is not symmetric with respect to $\omega = 0$. Therefore, the negative sequence components whose frequencies are identical to the positive sequence components should also be treated as harmonics and need to be detected and decomposed. Since

$$F[f(t)\cdot e^{-j\omega_0 t}] = F(\omega + \omega_0) \tag{5}$$

it is clear that the frequency spectrum of the complex signal $f(t)e^{-j\omega_0 t}$ can be obtained by left shifting that of $f(t)$ along the frequency axis by ω_0, i.e., the component of $f(t)e^{-j\omega_0 t}$ with frequency of ω has the same amplitude and phase angle as that of $f(t)$ with frequency of $(\omega + \omega_0)$, and especially, the DC component of $f(t)e^{-j\omega_0 t}$ corresponds to the components of $f(t)$ with frequency of ω_0. This principle is called frequency shifting. Using this technique, a band-pass or band-elimination filtering $B_{\omega_0}(\omega)$ of signal $f(t)$ with central frequency of ω_0 can be implemented in a few steps. Firstly the narrow band filtering $B_0(\omega)$ of signal $f(t)e^{-j\omega_0 t} = u(t)$ at a central frequency of zero is performed to obtain the complex signal $v(t)$ at $\omega = 0$. Then $v(t)$ is multiplied by $e^{j\omega_0 t}$ to recover the original spectrum, and finally to get the output of $f_{out}(t) = v(t)e^{j\omega_0 t}$. This process is the fundamental of in-phase correlation filtering.

HARMONIC DETECTION USING IN-PHASE CORRELATION FILTERING

Let us define a complex signal as

$$u(t) = f(t)\cdot e^{-j\omega_0 t} = \frac{2}{3}[1, a, a^2]\cdot[f_1(t), f_2(t), f_3(t)]^T e^{-j\omega_0 t} = \frac{2}{3}\left[f_1(t)e^{-j\omega_0 t} + f_2(t)e^{-j\left(\omega_0 t - \frac{2}{3}\pi\right)} + f_3(t)e^{-j\left(\omega_0 t + \frac{2}{3}\pi\right)}\right] = u_x(t) + j\cdot u_y(t) \tag{6}$$

whose real and imaginary components can be expressed by

$$\begin{bmatrix} u_x(t) \\ u_y(t) \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos(\omega_0 t) & \cos\left(\omega_0 t - \frac{2}{3}\pi\right) & \cos\left(\omega_0 t + \frac{2}{3}\pi\right) \\ -\sin(\omega_0 t) & -\sin\left(\omega_0 t - \frac{2}{3}\pi\right) & -\sin\left(\omega_0 t + \frac{2}{3}\pi\right) \end{bmatrix}\cdot \begin{bmatrix} f_1(t) \\ f_2(t) \\ f_3(t) \end{bmatrix} = \frac{2}{3}M_{uv}^{+}(\omega_0)\begin{bmatrix} f_1(t) \\ f_2(t) \\ f_3(t) \end{bmatrix} \tag{7}$$

where $M_{uv}^{+}(\omega_0)$ is the frequency spectrum shifting matrix of the positive sequence, whose elements can be determined accordingly. The resultant filtered complex signal $v(t)$ is then defined as

$$v(t) = v_x(t) + uv_y(t) \tag{8}$$

Since there are

$$\left.\begin{aligned} e^{j\omega_0 t} &= \frac{2}{3}[1, a, a^2]\cdot \left[\cos(\omega_0 t), \cos\left(\omega_0 t - \frac{2}{3}\pi\right), \cos\left(\omega_0 t + \frac{2}{3}\pi\right)\right]^T\cdot \\ e^{j\left(\omega_0 t + \frac{\pi}{2}\right)} &= \frac{2}{3}[1, a, a^2]\cdot \left[-\sin(\omega_0 t), -\sin\left(\omega_0 t - \frac{2}{3}\pi\right), -\sin\left(\omega_0 t + \frac{2}{3}\pi\right)\right]^T \end{aligned}\right\} \tag{9}$$

the output complex signal after spectrum recovering $f_{out}(t)$ can be computed by

$$f_{out}(t) = v(t)e^{j\omega_0 t} = v_x(t)e^{j\omega_0 t} + v_y(t)e^{j\left(\omega_0 t + \frac{\pi}{2}\right)} = \frac{2}{3}[1, a, a^2]\cdot \begin{bmatrix} v_x(t)\cos(\omega_0 t) - v_y(t)\sin(\omega_0 t) \\ v_x(t)\cos\left(\omega_0 t - \frac{2}{3}\pi\right) - v_y(t)\sin\left(\omega_0 t - \frac{2}{3}\pi\right) \\ v_x(t)\cos\left(\omega_0 t + \frac{2}{3}\pi\right) - v_y(t)\sin\left(\omega_0 t + \frac{2}{3}\pi\right) \end{bmatrix} = \frac{2}{3}[1, a, a^2]\cdot \begin{bmatrix} f_{out1}(t) \\ f_{out2}(t) \\ f_{out3}(t) \end{bmatrix} \tag{10}$$

Therefore, the output three-phase signals can be derived

$$\begin{bmatrix} f_{out1}(t) \\ f_{out2}(t) \\ f_{out3}(t) \end{bmatrix} = \begin{bmatrix} \cos(\omega_0 t) & -\sin(\omega_0 t) \\ \cos\left(\omega_0 t - \frac{2}{3}\pi\right) & -\sin\left(\omega_0 t - \frac{2}{3}\pi\right) \\ \cos\left(\omega_0 t + \frac{2}{3}\pi\right) & -\sin\left(\omega_0 t + \frac{2}{3}\pi\right) \end{bmatrix}\cdot$$

$$\begin{bmatrix} v_x(t) \\ v_y(t) \end{bmatrix} = [\boldsymbol{M}_{uv}^{+}(\omega_0)]^{\mathrm{T}} \cdot \begin{bmatrix} v_x(t) \\ v_y(t) \end{bmatrix} \tag{11}$$

According to Eqs. (7) and (11), the block diagram of the positive sequence harmonic detection using in-phase correlation filtering technique can be drawn as shown in Fig. 1.

In accordance with the frequency spectrum shifting theory, band pass or band elimination-filtering $\boldsymbol{B}_{\omega_0}(\omega)$ of a complex signal $\boldsymbol{f}(t)$ at a central frequency of ω_0 can be achieved by performing narrow band filtering $\boldsymbol{B}_0(\omega)$ of a complex signal $\boldsymbol{f}(t)\mathrm{e}^{-j\omega_0 t}$ at the central frequency of zero. Normally, the amplitude-frequency characteristics of the narrow band filter $\boldsymbol{B}_0(\omega)$ is required to be symmetric with respect to $\omega = 0$ and conventional low pass and high pass filters just possess such characteristics. Therefore, the block $\boldsymbol{H}_0(\omega)$ in Fig. 1 can be realized by a low pass filter when the fundamental signal of frequency ω_0 is to be filtered, or by a high pass filter when the total harmonics except the fundamental one with frequency of ω_0 is to be filtered.

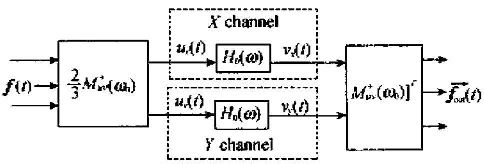


Fig. 1 Block diagram of positive sequence harmonic detection using the in-phase correlation filtering technique

In Fig. 1, the relationship between the output $\boldsymbol{f}_{\text{out}}(t)$ and the input $\boldsymbol{f}(t)$ can be derived using an impulse function. Assume the impulse response of $\boldsymbol{H}_0(\omega)$ is

$$h(t) = \boldsymbol{F}^{-1}[\boldsymbol{H}_0(t)] \tag{12}$$

In Fig. 1, for X and Y channels, we have

$$\left.\begin{aligned} v_x(t) &= u_x(t) * h(t) \\ v_y(t) &= u_y(t) * h(t) \end{aligned}\right\} \tag{13}$$

where $*$ is the operator of convolution integral. Consequently,

$$\boldsymbol{v}(t) = v_x(t) + jv_y(t) = \boldsymbol{u}(t) * h(t) \tag{14}$$

If the Fourier transform of $\boldsymbol{f}(t)$, $\boldsymbol{u}(t)$, $\boldsymbol{v}(t)$ and $\boldsymbol{f}_{\text{out}}(t)$ are $\boldsymbol{F}(\omega)$, $\boldsymbol{U}(\omega)$, $\boldsymbol{V}(\omega)$, and $\boldsymbol{F}_{out}(\omega)$, respectively, from equation (14), we have

$$\boldsymbol{V}(\omega) = \boldsymbol{u}(\omega) \cdot \boldsymbol{H}_0(\omega) = \boldsymbol{F}(\omega + \omega_0) \cdot \boldsymbol{H}_0(\omega). \tag{15}$$

Since

$$\boldsymbol{F}_{out}(\omega) = \boldsymbol{V}(\omega - \omega_0) = \boldsymbol{F}(\omega) \cdot \boldsymbol{H}_0(\omega - \omega_0) \tag{16}$$

we have

$$\frac{\boldsymbol{F}_{out}(\omega)}{\boldsymbol{F}(\omega)} = \boldsymbol{H}_0(\omega - \omega_0). \tag{17}$$

From Eq. (17) it can be found that the transfer function of the system shown in Fig. 1 is $\boldsymbol{H}_0(s - j\omega_0)$, which is the result of right shifting the spectrum of $\boldsymbol{H}_0(\omega)$ along the frequency axis by ω_0. As the amplitude-frequency characteristics of low pass and high pass filters are symmetric with respect to $\omega = 0$, this results in the narrow band filtering at the central frequency of ω_0.

Similarly, the block diagram of the negative sequence harmonic detection using in-phase correlation filtering technique can also be derived, which has the same structure as that shown in Fig. 1 with the frequency spectrum shifting matrix being

$$\boldsymbol{M}_{uv}^{-}(\omega_0) = \begin{bmatrix} \cos(\omega_0 t) & \cos\left(\omega_0 t + \frac{2}{3}\pi\right) & \cos\left(\omega_0 t - \frac{2}{3}\pi\right) \\ \sin(\omega_0 t) & \sin\left(\omega_0 t + \frac{2}{3}\pi\right) & \sin\left(\omega_0 t - \frac{2}{3}\pi\right) \end{bmatrix} \tag{18}$$

As the transfer function of the narrow band filter is $\boldsymbol{H}(\omega) = \boldsymbol{H}_0(\omega + \omega_0)$, this implies performing the narrow band harmonic filtering at the central frequency of $(-\omega_0)$.

IMPLEMENTATION OF HARMONIC DETECTION

As it has been demonstrated that the process of the in-phase correlation filtering used for providing frequency transformation and harmonic detection is accomplished by transforming the three-phase vector signal into the reference frame rotating at the frequency of ω_0. Therefore, the circuit in-phase correlation filtering of the harmonics, in a broad sense, should consist of a positive (P) and a negative (N) sequence channel with frequency spectrum shifting matrix being $\boldsymbol{M}_{uv}^{+}(\omega_0)$ and $\boldsymbol{M}_{uv}^{-}(\omega_0)$ respectively, and a zero sequence channel. However, for the harmonic detection of harmonics in AC excited generation systems, it is unnecessary to distinguish the positive and negative sequence components, since only the positive sequence fundamental component or the harmonic components in a broad sense need to be extracted. As a result, only P channel is needed as shown in Fig. 2. Meanwhile, a closed loop control is used to reduce the filtering error and improve the noise immunity. In order to keep the transfer function of the closed loop system the same as $\boldsymbol{H}_0(s)$, the original filter should be in the form of $\boldsymbol{H}_1(s) = [1 - \boldsymbol{H}_0(s)]/\boldsymbol{H}_0(s)$ which is a low pass system with a DC gain of infinity. Consequently, the P channel itself forms a band pass system with a central frequency of ω_0.

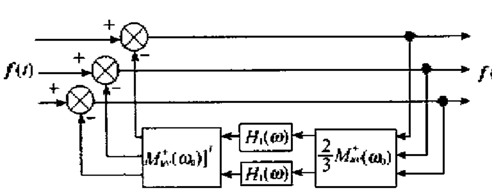


Fig.2 Block diagram for detecting the harmonics in a broadsense using in-phase correlation filtering

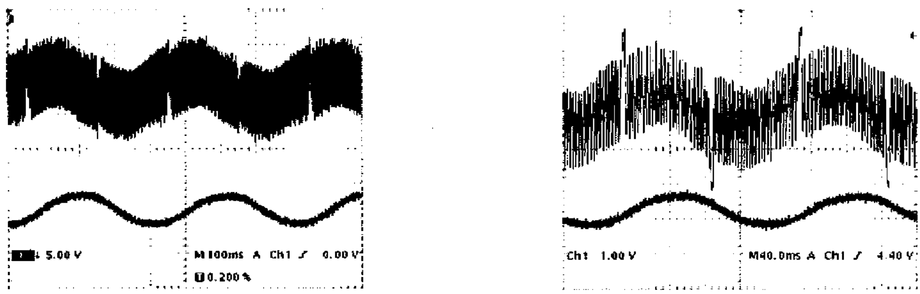
Compared to the conventional harmonic detection methods, the in-phase correlation filtering technique based on frequency shifting principle has the following advantages:

1. It increases the octave between the frequencies of the components to be detected and the fundamental frequency and, hence, it simplifies the design of the filter. For instance, when a high pass filter is used for eliminating the fundamental component with frequency of ω_0 to acquire the harmonic compensation signal, the cut-off frequencies of its band pass and band elimination are ω_p and ω_s, respectively. By the conventional design method, the high pass filter will be normally used because of the small normalized cut-off frequency of ω_p/ω_s which will result in poor dynamic response (Lou et al., 1995). In contrast, if the in-phase correlation filter technique is adopted, the normalized cut-off frequency of the filter can be increased to $(\omega_p - \omega_0)/(\omega_s - \omega_0)$ and this significantly simplifies the filter design.

2. When the fundamental frequency ω_0 of a signal varies, the equivalent central frequency of a band pass or band elimination filter used in the in-phase correlation filtering can be changed accordingly to achieve constant bandwidth, frequency controlled narrow band filtering. The values of $\cos\omega_0 t$ and $\sin\omega_0 t$ can be given externally or generated on-line by a phase-locked loop (PLL), which provides adaptive function for the harmonic detection of the signal whose fundamental frequency is varying(Wang, 2001).

3. The phase-frequency characteristic of an in-phase correlation filter has zero phase shift at the frequency of ω_0 and small phase error for the harmonic detection. Furthermore, accurate control of the central frequency ω_0 is not required and digital implementation is easy to realize.

The characteristics of this technique is a close match for the requirement of harmonic detection in the AC excited power generation system. In order to validate the effectiveness of this technique in a complicated power supply system like the AC excited generation system, experimental study on the harmonic detection and harmonic suppression for a prototype AC excited generation system was conducted. The AC excited generator was a 3-phase, 4-pole wound-rotor asynchronous machine excited from the rotor side by a 6-pulse 36-thyristor, triggered according to the cosine-intersection method. A type TMS320F240 DSP (digital signal processor) was adopted to implement the harmonic analysis and to generate the compensation signal, controlling the serial-active filter part of a hybrid power filter for harmonic suppression. Figs. 3 – 6 show some measured waveforms recorded from this experimental set-up. Use of a conventional FIR (Finite Impulse Response) filter as a low pass filter resulted in the Fig. 3(a) and (b) waveforms of the measured original signal to be detected taken from the rotor side of the generator and the detecting signal with fundamental frequencies of 2.5Hz and 5Hz, respectively. The results shown indicated clearly that a large phase shift exists between the two signals and varies with the fundamental frequency in the conven-

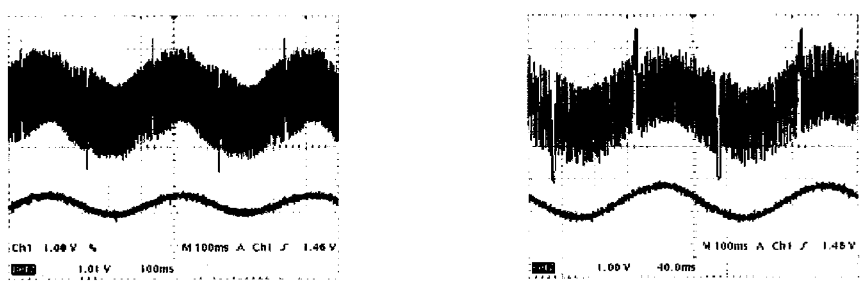


(a) (b)

Fig.3 Rotor voltage waveforms with ordinary FIR low-pass filtering, FIR order $n = 109$ (upper: original signal; bottom: filtering result)

(a) fundamental freq.: $f_0 = 2.5$ Hz; sampling freq.: $f_s = 0.75$ kHz; fundamental phase shifting: $\phi \approx 85°$ (10 V/div, 100 ms/div)

(b) fundamental freq.: $f_0 = 5$ Hz; sampling freq.: $f_s = 1.5$ kHz; fundamental phase shifting: $\phi \approx 65°$ (10 V/div, 40 ms/div)

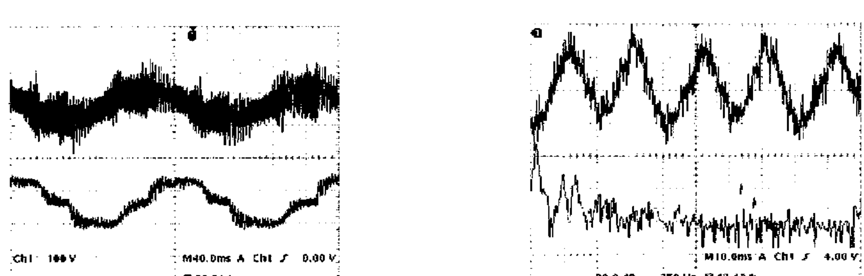


(a) (b)

Fig.4 Rotor voltage waveforms with low-pass filtering FIR of complex signal based on the in-phase filtering, FIR order $n = 109$

(a) fundamental freq.: $f_0 = 2.5$ Hz; sampling freq.: $f_s = 0.75$ kHz (10 V/div, 100 ms/div)

(b) fundamental freq.: $f_0 = 5$ Hz; sampling freq.: $f_s = 1.5$ kHz (10 V/div, 40 ms/div)



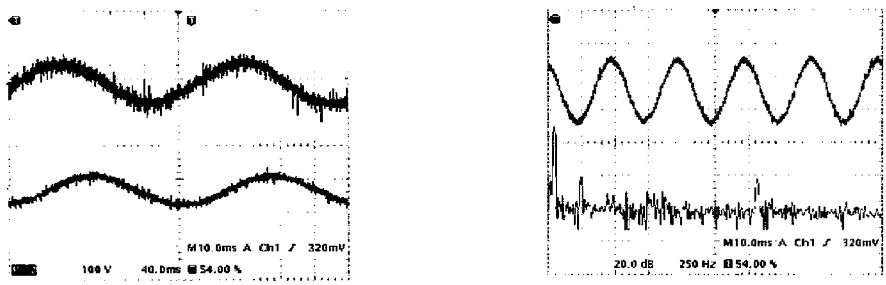
(a) (b)

Fig.5 Waveforms of the experimental AC excited generator connected into grid before filtering under the condition of $P = 1000$ W, $Q = 200$ VAR, $f_0 = 5$ Hz, $n = 1350$ rpm

(a) upper part: rotor voltage (10 V/div, 40 ms/div); bottom part: rotor current (5 A/div, 40 ms/div)

(b) upper part: stator current (5 A/div, 10 ms/div); bottom part: stator current spectrum (20 dB/div, 250 Hz/div)

tional detection method. For comparison, Fig.4 shows the experimental results using the in-phase correlation filtering technique under the same operation condition. Fig.4 shows that there is no phase distortion anymore, so that the detecting harmonic signals can be used as the true reference signals for the active filter. The effectiveness and suitability of the developed harmonic detection scheme for suppression of harmonics in the AC excited generator were tested. Fig.5 and Fig.6 show some waveforms and spectrum taken from the rotor and stator of the generator in the operational condition of connecting into the grid. From the results presented it can be concluded that the harmonic detection method based on the in-phase correlation filtering technique and the hybrid serial-active power filter are quite effective and practical for the detection of harmonics in the cycloconverter excited power generation system.



(a) (b)

Fig.6 Waveforms of the experimental AC excited generator connected into grid after filtering under the same condition as in Fig.5

(a) upper part: rotor voltage (10 V/div, 40 ms/div); bottom part: rotor current (5 A/div, 40 ms/div)

(b) upper part: stator current (5 A/div, 10 ms/div); bottom part: stator current spectrum (20 dB/div, 250 Hz/div)

CONCLUSIONS

The in-phase correlation filtering technique based on the frequency shifting principle is proposed in this paper. It was shown to have the advantages of simple structure, ease of design and ability of self-tuning. This harmonic detection technique is suitable for application to the power system which has a variable fundamental frequency, rich low order harmonics and sub-harmonics whose frequencies are lower than the fundamental frequency. The experimental results showed the effectiveness of this technique for detection of harmonics in AC excited generation systems.

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