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A High Precision Selective Harmonic Compensation Scheme for Active Power Filters

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Abstract: This study proposes a high precision selective harmonic compensation scheme for active power filters, which compensates selective current harmonics detected by Kalman filter and harmonic current is tracked by a novel PI controller-recursive integral PI controller. As Kalman filter can detect each order harmonic separately, the compensation on delay time arouse from digital implementation is performed. Since traditional PI is subjected to inherent steady-state error, a recursive integral PI regulator is proposed to compensate for the harmonic current, which can eliminate steady-state error. The proposed scheme improves the stability of APF, prompts the precision of harmonic compensation and is applicable to both single phase and three phase inverters. The effectiveness of the scheme is verified by simulation.

Key words: Active power filter, Kalman filter, recursive integral PI, selective harmonic compensation

INTRODUCTION

The significant growing use of the semiconductor in recent decades has led to a corresponding increase in harmonic pollution in power grid. It is an important issue to keep electrical resources pure in modem electric utility operation. Negative effects of harmonic currents and voltages, such as increased I^2R losses and the reduction of the lifespan of sensitive equipment, has prompted the establishment of a number of standards and guidelines (IEC61000-3-6, G5/4, G5/4, IEEE Std519-1992) regarding acceptable harmonic levels.

Active Power Filter (APF) is a very useful tool for eliminating harmonic pollution in power grid (Fang Peng, 2001). APF eliminates power system harmonics through injecting current to the power supply side lines that is equal to the load harmonic current, therefore the system side will almost have no harmonic current remaining. Compared with traditional passive filters, APF has significant advantages such as good controllability, fast response and high control accuracy. The general block diagram of a shunt APF is outlined in Fig. 1.

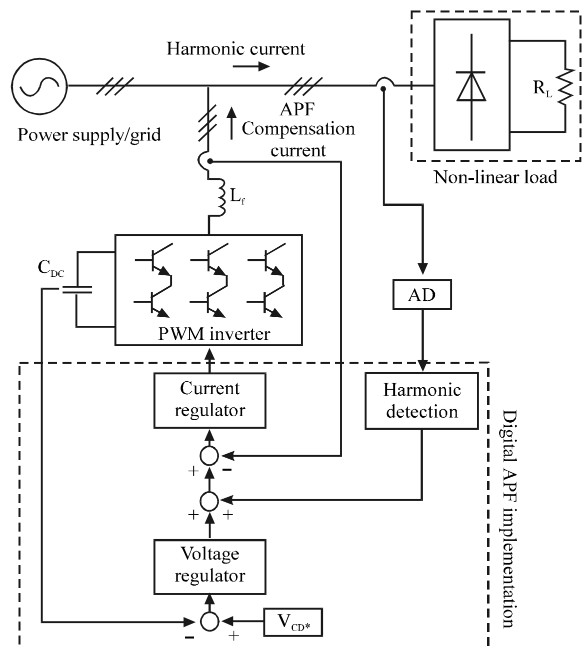

Fig. 1: General block diagram of a shunt APF

Among various current compensation schemes, compensation of selected current harmonics has significantly increased in this years. This scheme has several merits as follows.

Improving stability margin: The high order harmonic compensated by digital APF causes phase shift and the phase delay even is 180°, which will cause control instability of APF. And the capacitor load always leads to oscillation between the load and the line impedance. This approach keeps the orders harmonic near the resonance frequency out of compenated amount (Mattavelli, 2001).

Reducing APF rating: If the target harmonic source exceed capability of APF, the main selective order harmonic can be selectively compensated. The

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compensation capability is only used to eliminate the desired harmonic components.

Possibility of compensating delay: Delay time arouse from digital implementation deteriorates the performance of APF (Le Roux and Van Wyk, 2000). Compensation of selected current harmonics detects the selective order harmonic separately, so delay time can be compensated in each order harmonic phase.

Prompting the precision of harmonic compensation: The high orders current harmonic amount is tiny and to compensate for them will even deteriorate the compensation result. Selective harmonic compensation does not compensate for high order harmonic and will improve the control accuracy.

Detecting harmonic separately is the premise of selective harmonic compensation. Several techniques have been presented for the estimation of selective harmonics. Some of them are synchronous harmonic dq frame (Bhattacharya *et al.*, 1998), FFT (Williams and Hoft, 1991), RDFT (Dolen and Lorenz, 2000), Kalman filtering (Girgis *et al.*, 1991), neural networks (Van Schoor *et al.*, 2003) and Wavelet (Driesen and Belmans, 2002), synchronous harmonic dq frame is limited to three phase wire, which requires a careful implementation if the line voltages are not balanced and sinusoidal and there are three major pitfalls in the application of FFT namely, aliasing, leakage and picket-fence effect; RDFT is a faster and more efficient than the popular FFT algorithm, however, sensitive to line frequency; Neural Networks and Wavelet are difficult to implement; Among them, Kalman filter has advantage of immunity to measurement noise, fast response to non-stationary harmonics, none steady-state phase-lag and the most of all, ability of detecting selective harmonic current.

Excpet detection methods, the current tracking is another key of APFs. In virtue of fixed inverter switching, ramp comparator controller is widely employed. However, inherent phase and amplitude errors arise, even in the steady-state condition. In this study, a novel harmonic current tracking algorithm, recursive integral PI regulator, is presented. According to the periodic character of the reference signal, the recursive integral PI algorithm achieves zero steady-state error. The transfer function of recursive integral PI is given in this study which is identical with repetitive control. And a internal model which can generate the required reference input is included in the regulator.

This study proposes a high precision selective harmonic compensation scheme based on Kalman filter and recursive integral PI controller.

KALMAN HARMONIC DETECTING ALGORITHM

Kalman filter is a optimal estimation algorithm which can extract the signal from the noises and is able to track time varying parameters. In this study, harmonic is estimated by Kalman filter. A noise free current including n order harmonic can be represented by:

$$\begin{aligned} s(t) &= \sum_{h=1}^{n} M_h(t)\sin(h\omega_0 t + \theta_h) \\ &= \sum_{h=1}^{n} \left(M_h(t)\sin\theta_h \cos(h\omega_0 t) + M_h(t)\cos\theta_h \sin(h\omega_0 t)\right) \end{aligned} \quad (1)$$

So, let state variable x_{2h-1} be $M_h(t)\sin\theta$ and x_{2h} be $M_h(t)\cos\theta$.

$$M_h(t) = \sqrt{x_{2h-1}^2 + x_{2h}^2} \quad (2)$$

$$\theta_h = \mathrm{acrtg}\left({x_{2h-1}}/{x_{2h}} \right) \quad (3)$$

ω_0 is base angular frequency. $M_h(t)$ is the magnitude of h order harmonic. θ_h is phase angle. If set the synchronous signal be zero crossing of voltage, θ_h represents power angle.

The signal model for Kalman filter is defined as:

$$\begin{aligned} X_{k+1} &= AX_k + W \\ y_k &= CX_k + v \end{aligned} \quad (4)$$

Where:

- X_k = 2n by 1 process state vector at step k, representing $[x_1\ x_2, ..., x_{2h-1}, x_{2h}, ..., x_{2n-1}, x_{2n}]_k^T$
- A = 2n by 2n state transition matrix
- W = The discrete variation of the state variables due to an input white noise sequence. It can be described by a covariance matrix Q(k) where $E[W(k)W(k)^T] = Q(k)$
- y_k = 1 by 1 vector measurement at step k
- C = 1 by 2n matrix giving the ideal (noiseless) connection between the measurement and the state vector
- v = 1 by 1 measurement noise vector assumed to be a white sequence with known covariance structure and uncorrelated with the W sequence; The noise is usually described by its variance r, where, E[v v] = r

According to the Eq. 5, the A and C in state variable equations can be expressed as:

$$A=\begin{bmatrix}1 & 0 & \dots & 0\\ 0 & 1 & \dots & 0\\ \dots & \dots & \dots & \dots\\ 0 & 0 & \dots & 1\end{bmatrix}_{2n} \quad C=\begin{bmatrix}\sin(\omega_0 t)\\ \cos(\omega_0 t)\\ \dots\\ \sin(h\omega_0 t)\\ \cos(h\omega_0 t)\\ \dots\\ \sin(n\omega_0 t)\\ \cos(n\omega_0 t)\end{bmatrix}_{2n}^{T} \tag{5}$$

The convergence rate and steady precision of Kalman filter is related to the value of Q and r. The bigger value of Q or smaller value of r will make convergence rate higher, but the steady precision poorer and vice versa.

And let white noise covariance matrix be:

$$Q=0.002^2\begin{bmatrix}1 & 0 & \dots & 0\\ 0 & 1 & \dots & 0\\ \dots & \dots & \dots & \dots\\ 0 & 0 & \dots & 1\end{bmatrix}_{2n} \tag{6}$$

measurement noise variance be:

$$r = 0.05^2$$

and let initial process vector be:

$$X_1=[0 \quad 0 \quad \dots \quad 0]_{2n}^{T} \tag{7}$$

The amount of initial error covariance $\hat{P}_1$ affects the initial convergence rate of Kalman filter, so let the matrix be:

$$\hat{P}_1=[10 \quad 10 \quad \dots \quad 10]_{2n}^{T} \tag{8}$$

The recursive process includes time update and measurement update. The state varliable X_k is estimated as described by Girgis *et al.* (1991) and the magnitude of h order harmonic is calculated by Eq. 6. Then, magnitude M_h multiplicities sin $(\omega_0+\theta_h)$, where, ω_0 origins from Phase-Locked Loop (PLL) and θ_h is obtained from Eq. 7. Figure 2 shows the general block of Kalman filter extract h order harmonic current.

Kalman filter for selective harmonic detection has been simulated with Matlab/SimPowerSystems using the parameters shows in Table 1. The harmonic source is 3-phase bridge uncontrolled diode rectifier. 5th, 7th, 11th, 13th, 17th and 19th order harmonic are selectively detected. As the Fig. 3 and 4 shown, the Kalman filter has high convergence rate and high precise steady-state value.

The digital APF implementation induces the time delay, including A/D sample time, PWM dead zone, execution time of harmonic detection and current tracking algorithm (Le Roux and Van Wyk, 2000). As Fig. 5 shown, the delay deteriorate the effect of harmonic compensation, especial for the high order harmonic, so compensation on delay time will prompt the precision of harmonic compensation.

Kalman filter detects the fixed order harmonic, so compensation on delay time in phase is feasible. Assume the delay time is Δt and a leading angle $h\omega_0\Delta t$ is compensated which is outlined by dashed line in Fig. 2. The Eq. 8 is corrected as:

Table 1: Converter and control parameters

AC mains line voltage (E)	310 V
AC frequency (f_0)	50 Hz
DC capacity (C_{DC})	3360 μF
DC link voltage (V_{DC})	800 V
Carrier frequency (f_c)	10 kHz
Sampling. frequency (f_s)	10 kHz
AC side (L_f)	12 mH
Nominal source capability	2000 kW
Selected frequencies	5th, 7th, 11th, 13th, 17th, 19th
Recursive integral PI K_p	1
Recursive integral PI K_i	0.1
Load (R_L)	40 Ω

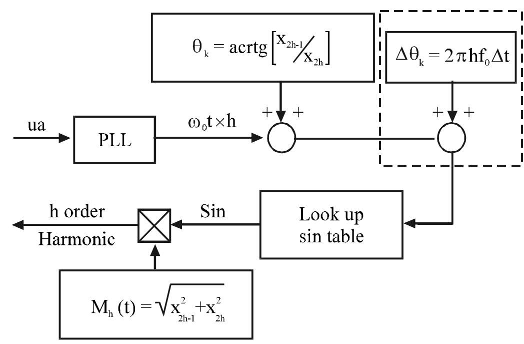

Fig. 2: General block of Kalman filter extract h order harmonic current

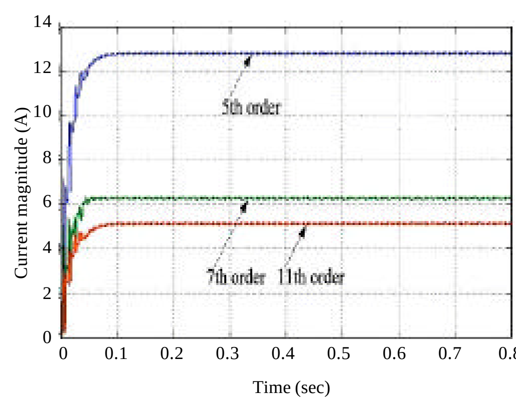

Fig. 3: Estimated magnitude of the 5th, 7th and 11th harmonics

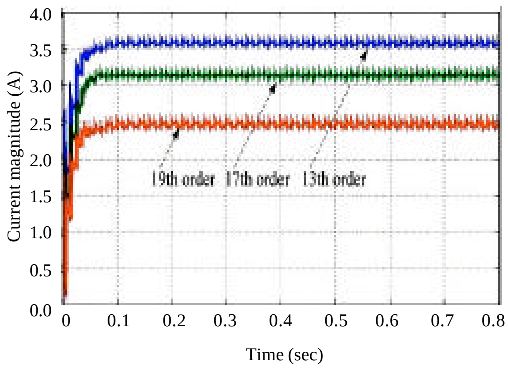

Fig. 4: Estimated magnitude of the 13th, 17th and 19th harmonics

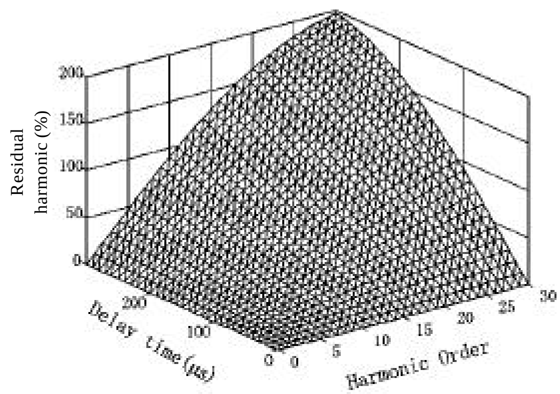

Fig. 5: Relation between residual harmonic and time delay of the digital APF

$$\theta_h = \mathrm{acrtg}\left(X_{2h-1}/X_{2h}\right) + h\omega_0 \Delta t \tag{9}$$

A NOVEL PI CONTROLLER FOR HARMONIC CURRENT TRACKING-RECURSIVE INTEGRAL PI

Harmonic current is periodic signal described in Eq. 1 and to track harmonic current, the traditional PI will lead to inherent steady-state error in magnitude and phase. This paper proposes an improved PI controller, a recursive integral PI controller, to eliminate steady-state error.

The traditional PI discrete equation is expressed as:

$$u(k) = Kp \times e(k) + Ki \times \sum_{h=0}^{k} e(k) \tag{10}$$

and a new recursive integral PI discrete equation is:

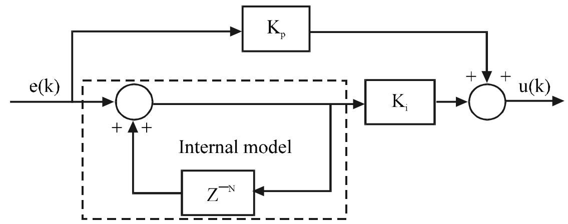

Fig. 6: Block diagram of recursive integral PI

$$u(k) = Kp \times e(k) + Ki \times \sum_{h=0}^{U} e(k - hN) \tag{11}$$

where, u(k) is recursive integral PI regulator k time output. e(k) is k time error. K_p is proportional coefficient. K_i is integral coefficient. N is sample point number per base period. U is integer part of k/N.

The integral part of conditional PI demonstrates the accumulation of error from time 0 to k. While, the recursive integral PI calculates the integral error of same point of every base period.

The (k-N) time regulator output is:

$$u(k - N) = Kp \times e(k - N) + Ki \times \sum_{h=0}^{U-1} e(k - (h+1)N) \tag{12}$$

From Eq. 11 and 12, the incremental amount of u(k) is represented as:

$$\Delta u(k) = Kp \times e(k) - Kp \times e(k - N) + Ki \times e(k) \tag{13}$$

The incremental form derived from Eq. 12 and 13 is expressed as:

$$\begin{aligned} u(k) &= u(k - N) + \Delta u(k) \\ &= u(k - N) + Kp \times e(k) - Kp \times e(k - N) + Ki \times e(k) \end{aligned} \tag{14}$$

The transfer function of recursive integral PI derived from Eq. 14 is expressed as Eq. 15. Recursive integral PI controller satisfies the internal model principle, which includes the periodic information of reference and agrees with the repetitive controller which has the same transfer function.

$$G = \frac{U(z)}{E(z)} = Kp + \frac{Ki}{1 - z^{-N}} \tag{15}$$

Figure 6 shows the block diagram of recursive integral PI. The open-loop transfer function of the system includes a mathematical model which can generate the required reference input.

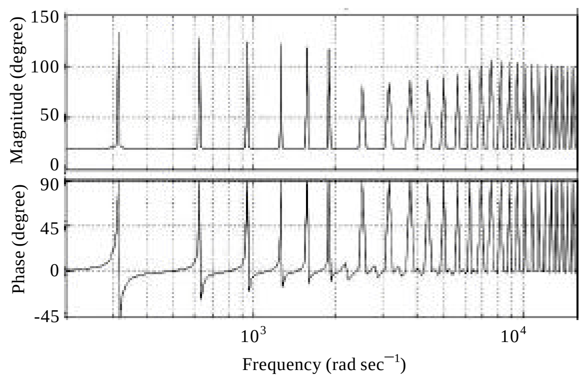

Fig. 7: Bode diagram of transfer function G

The Bode diagram of transfer function G is showed in Fig. 7 (f_s = 10 kHz, ω_0 = 314 rad sec^{-1}, K_p = 1, K_i = 0.1). It is observed that G has a sufficient amount of phase margin, 90°, at $\omega = n\omega_0$ (n = 1, 2, ...). The gain of the transfer function is theoretically infinite at the resonant angular frequency, guaranteeing the reduction of the error to zero as time elapses. Obviously, the performance of the regulator is sensitive to line frequency, so a PLL that precisely tracks supply-frequency variations is suggested in practical implementation. Then the resonant angular frequency will vary with line frequency.

VERIFICATION ON PROPOSED SCHEME

The system of Fig. 1 has been simulated with Matlab/SimPowerSystems using the parameters of Table 1. A comparison between the traditional PI compensating whole harmonic and selective harmonic compensation is made, respectively shown in Fig. 8 and 9. 5th, 7th, 11th, 13th, 17th and 19th order harmonic are selectively compensated. The superior performance after compensation on delay is also shown in Fig. 10.

Figure 8 and 9 shows that the tracking current of recursive integral PI regulator is more precise, which can be confirmed by the line current spectrum. Figure 10 describes the behavior of the proposed scheme with 50 μsec time delay compensated. As compared Fig. 9 with Fig. 10, the time delay deteriorates the performance of APF and compensation on delay improve the performance of APF and compensation on time delay prompts the precision of harmonic compensation. The line current spectrum shown in Fig. 10 shows that the 5th, 7th, 11th, 13th, 17th and 19th order harmonic current are almost fully eliminated. All indicate that a significant superiority of proposed scheme can be obtained.

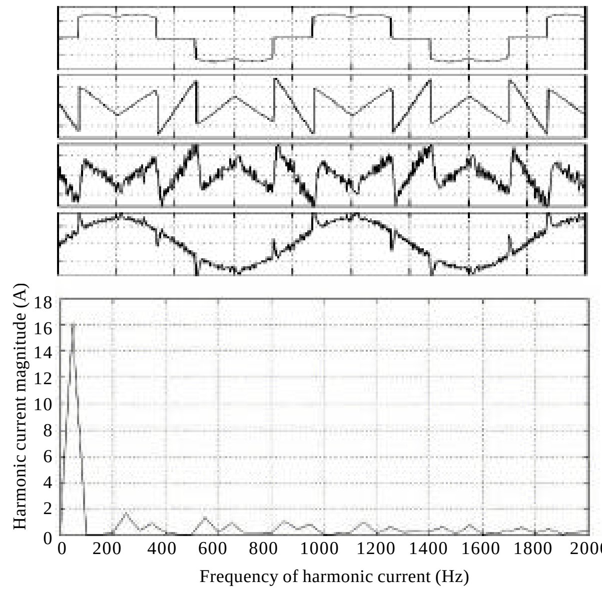

Fig. 8: APF behavior using traditional PI whole harmonic compensation with 50 μs digital delay. From top to bottom: load current (10A/div), whole harmonic current (8A/div), active power filter current (8A/div), line current (10A/div), line current spectrum

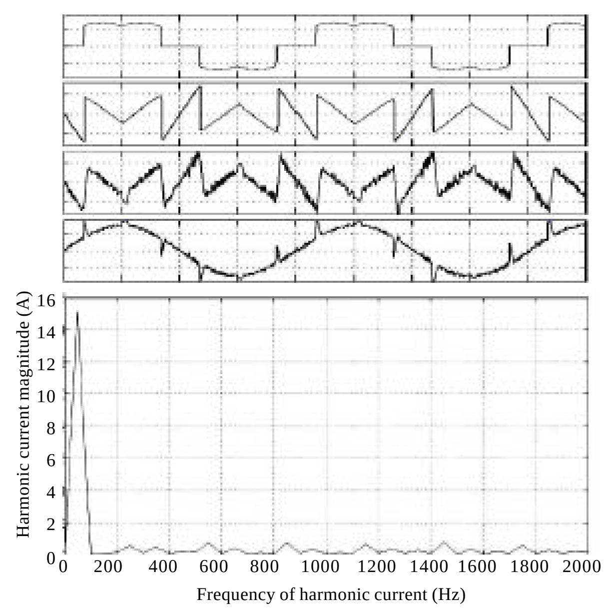

Fig. 9: APF behavior using recursive integral PI whole harmonic compensation with 50 μs digital delay. From top to bottom: load current (10A/div), whole harmonic current (8A/div), active power filter current (8A/div), line current (10A/div), line current spectrum

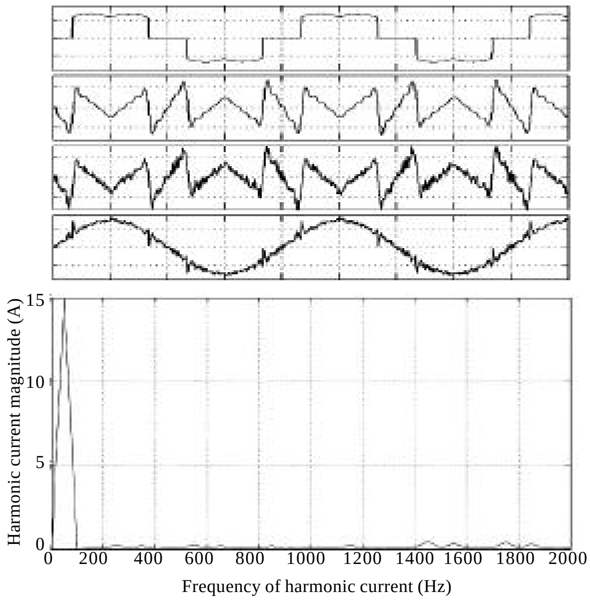

Fig. 10: APF behavior using proposed scheme with 50 μsec digita delay compensation. From top to bottom: load current (10A/div), 5, 7, 11, 13, 17, 19 order harmonic current (8A/div), active power filter current (8A/div), line current (10A/div), line current spectrum

CONCLUSION

This study has proposed a selective harmonic compensation for APFs using Kalman harmonic detection method and recursive integral PI regulator scheme. Thanks to the virtue of Kalman filter, the detection method is immune to measurement noise and delay compensation is implemented with a leading phase angle. Compared with traditional PI, recursive integral PI, which is familiar with repetitive control, eliminates steady-state error. The proposed scheme does not only improves the stability of APF, but also prompts the precise harmonic compensation. Moreover, its application area is not restricted in wire topology. The simulation results have demonstrated the effectiveness and advantages of the solution.

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