Discrete Kalman Filter Applied in Reference Current Estimation for control of Single Phase Shunt Active Power Filter

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Abstract—A new control strategy for current reference generation in single phase shunt active power filters for current harmonic compensation is proposed in power systems. A digital Kalman filter is used as a current reference generation technique to compensate harmonics, related to the load and unbalance. Its capability of prediction avoids the effects of computational lags derived from digital signal processing. A voltage source inverter with hysteresis band current control scheme is used to form the active power-filter (APF), which uses minimum measured variables to make it cost effective. A diode rectifier feeding capacitive-resistive load is considered as a nonlinear load on ac mains for elimination of harmonics. Main purpose of this paper is to improve the filtering performance and make the source current sinusoidal and in phase with the source voltage under distorted supply voltages.

Keywords-Active Power Filters(APFS);Kalman digital algorithm;PWM;current control.

I. INTRODUCTION

The increasing use of nonlinear loads has implied in harmonic injection on power systems and it has become an important issue for electric utility companies. The distorted current implies in voltage distortion, heating, misoperation of protective equipment, increased losses among other effects[1,2]. In order to avoid the circulation of nonlinear currents continues to increase the levels of distortion of the power signal, therefore its negative effects, the use of specialized equipment to cancel the harmonic current becomes more and more important. Moreover, the distorted line voltage must be taken account as a factor in the design of the harmonic current compensators. The shunt active power filters are a possible alternative to minimize the nonlinear load effects on the power system. They permit to compensate harmonics generated by nonlinear loads. To achieve the compensation objectives, reference generation is important for the design and control of active filters. The use of such filters protects electrical equipment which could be affected by poor power quality and avoids the propagation of generated disturbances in the power systems.

Fig. 1 shows the basic circuit of shunt active power filter, based on voltage source converter, for the compensation of the current harmonics generated by nonlinear load. Hysteresis carrierless PWM current control is employed to generate gating pulses to the switches of the APF. The dc based load fed from diode bridge rectifier with a capacitor is a nonlinear load on the ac mains. The cancellation of the current harmonics is accomplished by their injection in the point of common coupling(PCC) in opposite phase. The harmonic current detection unit is used to obtain the reference signal and will have a decisive influence on the efficiency and performance of the APF.

There are different techniques for obtaining APF reference current, which can operate in the frequency domain or in the time domain. These first are based on the application of the DFT or FFT, which relies on some basic assumptions, summarized in [3]. If one fails to fulfil the basic assumptions of DFT or FFT algorithms, they will lead to incorrect results. The DFT method [10] permits the direct extraction of each one of the harmonic components of the load current and simplifies the cancellation in the selective mode. In the time domain the common methods applied are based on the instantaneous reactive power theory (pq-theory) and synchronous reference frame theory. The pq-theory suffers from the influence of the distortion of the main voltage according to [5]. The synchronous frame method presents the best performance under the presence of unbalance and voltage distortion, but complicates the harmonic current cancellation in selective mode due to the necessary synchronisation signal for each one of the harmonics that must be cancelled.

Several modulation techniques such as sinusoidal pulse width modulation (SPWM), random pulse width modulation(RPWM), delta modulation(DM) have been proposed to control the output of the inverters. The SPWM technique has some disadvantages in high switching stresses on the semiconductor devices and also its effect of the harmonic content on the input side is high as well. The amplitude of fundamental frequency component is very low in the RPWM and DM method as specified in [15].

In this paper a new control strategy based upon Kalman filter is proposed, which is utilised to create the compensation current reference derivation. Both source voltage and load current estimations are taken into considerations in this reference current derivation. This method takes advantage of both frequency and time domain methods and is insensitive to line voltage distortions. Here we propose the hysteresis band current control technique to generate gate pulses, which is very simple and robust in control. It can be able to limit the maximum switching frequency and improve both current and voltage of the operated inverter.
The main contribution of this paper is the application of new control strategy based on Kalman algorithm to estimate the compensation current reference and the modulation technique based on hysteresis based current control to enhance the power quality of the waveform i.e. to shape the output ac voltage and currents to be as close to sine wave as possible. Section II and III of this paper represent the proposed technique in reference current estimation and modelling of single phase active power filter with RC load respectively. The new control strategy of the APF is described in IV and sectionV gives software implementation of the proposed technique based on matlab programming. SectionVI describes conclusion part of the proposed scheme with references and Appendixes.

II. PROPOSED KALMAN ALGORITHM IN REFERENCE CURRENT ESTIMATION

A. Recursive Kalman Algorithm

A first-order autoregressive model [4] with processing noise and measurement noise can be expressed as

\[ x(k) = \phi x(k-1) + w(k) \]

\[ z(k) = Hx(k) + v(k) \]  

(1)
\( (2) \)

Where (1) is the signal model and (2) is the measurement equation, \( x(k) \) vector is the time varying(state variable) at instant \( k \). \( \phi \) is the state transition matrix, \( w(k) \) is the noise processes vector, \( z(k) \) is the measurement of the signal, \( H \) is the observation matrix and \( v(k) \) the vector of white noise with zero mean and variance \( \sigma_v^2 \).

For each measurement (sample), the estimation carried out for each of the state variables is expressed by

\[ \hat{x}(k) = \phi \hat{x}(k-1) + K(k)[z(k) - H\hat{x}(k-1)] \]  

(3)

Where \( K(k) \) is the vector that corresponds to the filter gains(kalman gains) for each of the variables that adjusts the estimation for the least squares, and be expressed as

\[ K(k) = P(k/k-1)H^T[HP(k/k-1)H^T + R(k)]^{-1} \]  

(4)

Where \( R(k) \) is the weighted matrix corresponding to noise measurement covariance at instant \( k \), \( P(k/k-1) \) is the values of the covariance estimated with the error at instant \( k \) calculated with value of real covariance obtained at instant \( k-1 \).

\[ P(k/k-1) = \phi P(k-1) \phi^T + Q(k-1) \]  

(5)

Where \( Q(k-1) \) is the weighted matrix corresponding to noise process covariance and denotes the covariance of the vector \( w(k-1) \) and \( P(k-1/k-1) \) is the real value of the covariance of the error at instant \( k-1 \).

\[ P[k/k] = P(k/k-1) - K(k)HP(k/k-1) \]  

(6)

B. Predictive Kalman algorithm

The recursive Kalman algorithm is modified to obtain a predictive estimation of the state variables, where the prediction equations advance the estimated value of the state variables in one-step .

Here, the digital filter is based upon:

\[ \tilde{e}(k + 1/k) = \phi \hat{e}(k/k - 1) + G(k) \]  

(7)

Where

\[ G(k) = K(k)[x(k) - H\hat{e}(k/k - 1)] \]  

(8)

and

\[ K(k) = \phi P(k/k - 1)H^T[HP(k/k - 1)H^T + R(k)]^{-1} \]  

(9)

\[ P(k + 1/k) = [\phi - K(k)H]P(k/k - 1)\phi^T + Q(k) \]  

(10)

Where, \( P(k + 1/k) \) is the values of the covariance estimated with the error at instant \( k+1 \) calculated with the value of the real covariance obtained at instant \( k \).

C. State variable representation of signal using a stationary Reference axes

Voltage and current signals in power systems can be described using state equations which take into account the frequency components in-phase and in-quadrature. Since each frequency component requires two state variables, total number of state variables is 2n. These state variables are defined as follows

\[ x1(t) = A_i(t) \cos \theta_i \]  

\[ x2(t) = A_i(t) \sin \theta_i \]  

\[ x3(t) = A_i(t) \cos \theta_i \]  

\[ x4(t) = A_i(t) \sin \theta_i \]  

\[ \ldots \]  

\[ x2n - 1(t) = A_n(t) \cos \theta_n \]  

\[ x2n(t) = A_n(t) \sin \theta_n \]  

Where,

\( A_i(t) \) is the amplitude of the ith harmonic at time t,

\( \theta_i \) is the phase angle of the ith harmonic relative to reference.

The state-equation description of the nth harmonic component in these fixed reference axes with angular frequency, as defined by (1) and (2), is

\[ x_n(k) = \begin{pmatrix} x_{np}(k) \\ x_{nq}(k) \end{pmatrix} \]  

(12)

\[ \phi_n = \begin{pmatrix} \cos(n\omega \Delta t) & -\sin(n\omega \Delta t) \\ \sin(n\omega \Delta t) & \cos(n\omega \Delta t) \end{pmatrix} \]  

(13)

\[ H_n = \begin{pmatrix} 1 & 0 \end{pmatrix} \]  

(14)

Where \( x_{np} \) and \( x_{nq} \) are, respectively, the in-phase and in-quadrature components of the nth harmonic of a distorted signal. For a complex signal model, which is composed of nth
harmonics (a 2 × n order filter), has the state equations with transition matrix Φ and observation matrix H are of following type:

$$x_n(k) = \begin{pmatrix} x_{1p}(k) \\ x_{1q}(k) \\ \vdots \\ x_{np}(k) \\ x_{nq}(k) \end{pmatrix}$$

$$\Phi = \begin{pmatrix} 1 & 0 & \cdots & 0 \\ \vdots & \ddots & \vdots & \vdots \\ 0 & \cdots & 1 \end{pmatrix}$$

$$H_n = (1 \ 0 \ \cdots \ 1 \ 0)$$

$$V_i = V_{r(n)} - V_{dc(n)}$$

(20)

Where

$$K_p$$ and $$K_i$$ are proportional and integral gain constants of the voltage regulator, $$V_{r(n)}$$ and $$V_{e(n)}$$ are the output of controller and voltage error at nth sample instant. This output $$V_{o(n)}$$ of the voltage controller is limited to safe permissible value and resulting output is taken as peak of supply current $$i_{max}$$.

III. OPERATION AND MODELLING OF SINGLE PHASE ACTIVE POWER FILTER

Figure 1 shows the basic circuit of the APF scheme including nonlinear load. The APF is a standard voltage source inverter having an energy storage capacitor on the dc side. Hysteresis based current control is used to generate gating pulses to the switches of APF. The dc based load fed from diode bridge rectifier with a capacitor is a nonlinear load on the ac mains. This load draws a pulsating peaky-nonsinusoidal current from the ac source. The APF is used to eliminate harmonics and to improve the power factor of supply.

A. Voltage Controller

P-I (proportional-integral) controller is used to regulate the dc capacitor voltage of the APF. The dc bus capacitor voltage $$V_{dc(n)}$$ is sensed with set reference voltage $$V_{r(n)}$$. The resulting voltage error $$V_{e(n)}$$ at nth sample instant is expressed as:

$$V_{e(n)} = V_{r(n)} - V_{dc(n)}$$

(21)

B. Current Controller

The carrierless PWM hysteresis current controller contributes the switching pattern of the APF devices. The PWM voltage of the APF in terms of switching functions:

$$V_a = V_{dc}(SA - SB)$$

Where $$SA$$ and $$SB$$ are switching functions of the APF devices. $$SA$$ is taken as one if $$S_1$$ is ON and $$SA$$ is considered zero if $$S_2$$ is ON. Similarly $$SB$$ is taken as one or zero when $$S_3$$ or $$S_4$$ are ON. Switch ‘S’ consists of IGBT with antiparallel diodes. So, either diode may conduct in ON state.

C. Active Power Filter

The AFP current $$i_c$$ can be expressed by the equation,

$$i_c = \frac{V_c}{\sqrt{R_c^2 + (\omega L_c)^2}}$$

(23)

Where $$R_c$$ and $$L_c$$ are the resistance an inductance of the APF inductor and $$V_c$$ represents

$$V_c = V_{in} - V_{e}$$

(24)

D. Nonlinear Load

Here a typical diode rectifier with capacitor-resistive load is taken as nonlinear load shown in Figure 1.1. It has two operating modes i.e., when diodes are in conducting or non-conducting state.

When diodes are conducting, the ac source is connected to the load and basic equation is:
\[ R_{SL}i_L + L_{SL}pL + V_L = V_s \]  
(25)

Where \( p \) denotes differential operator and the charging equation is:

\[ pV_L = (i_d - i_g)/C_L \]  
(26)

Where \( R_{SL} \) and \( L_{SL} \) are source impedance elements and \( V_L \) is the voltage across load capacitance \( C_L \). An \( i_d \) is the current drawn from ac source into rectifier load. An \( i_g \) is magnitude of \( i_L \) and \( i_d \) is resistive load current \( (V_L/R_L) \). Equation (25) may be expressed in state space derivative form as:

\[ pL = (V_S - V_L - R_{SL}i_L)/L_{SL} \]  
(27)

When diodes are not conducting \( i_L \) and \( i_g \) will be zero and charged capacitor with voltage \( V_L \) will feed the load. Equation (26) will be modified for this discharging mode of operation.

**IV. DESIGN OF PROPOSED APF CONTROL DIAGRAM**

The block diagram of the designed control system is given in Appendix B. The computational lag inherent to digital signal processing is avoided with the use of a predictive Kalman filtering loop.

The two Kalman filter estimators are described using a waveform with known harmonic contents. The waveform consists of the fundamental, the third, the fifth, the seventh, the ninth, the eleventh, the thirteenth, the fifteenth, the seventeenth, the nineteenth, the twenty-first harmonics.

The current estimator is based on the first 10 odd current harmonics, applied to the nonlinear load current waveform and it gives instantaneous values of in-phase and in-quadrature components of the harmonics and this gives the signal \( i_{R1} \) after multiplication with the output \( i_{max} \) of the PI-controller. This is used as a component of the reference current \( i_R \).

The voltage estimator is based on the first 5 odd voltage harmonics, applied to the supply voltage \( V_s \), and it gives the instantaneous values of the in-phase fundamental component with per-unit value, \( \hat{E}_{1P} \). This is another component of reference current \( i_R \). The Hysteresis current controller technique is provided to voltage source inverter to improve the output voltage and current.

The compensating current \( i_c \) is obtained as a voltage difference \( V_c \) on the inductor branch \( (L_c, R_c) \). This voltage is difference between voltage source converter output \( V_o \) and and the line voltage \( V_L \).

**V. MATLAB IMPLEMENTATION WITH RESULTS**

A matlab program is developed according to control unit design of Appendix A. The simulation parameters used for implementation are given in Table I.

As the Kalman filter model started with no past measurement, the initial process vector was selected to be zero. The initial covariance matrix was selected to be diagonal matrix with the diagonal values equal to 10 \( pu^2 \). The noise variance was selected to be 0.05 \( pu^2 \). The state variable covariance matrix \( Q \) was also selected to be 0.05 \( pu^2 \).

**Table I.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistance of APF inductor ( R_c )</td>
<td>1.0 ohm</td>
</tr>
<tr>
<td>Inductance of APF inductor ( L_c )</td>
<td>2.5 mH</td>
</tr>
<tr>
<td>Load capacitance ( C_{L} )</td>
<td>2200 ( \mu )F</td>
</tr>
<tr>
<td>Source resistance ( R_{SL} )</td>
<td>0.25 ohm</td>
</tr>
<tr>
<td>Source inductance ( L_{SL} )</td>
<td>0.25 mH</td>
</tr>
<tr>
<td>DC bus capacitance ( C_{c} )</td>
<td>660 ( \mu )F</td>
</tr>
<tr>
<td>Load Resistance ( R_L )</td>
<td>37.0 ohms</td>
</tr>
<tr>
<td>Proportional controller ( K_p )</td>
<td>0.061</td>
</tr>
<tr>
<td>Integral controller ( K_i )</td>
<td>0.015</td>
</tr>
</tbody>
</table>

Fig. 2 shows the waveforms for
a) Applied Source voltage \( V_s \) of 100v peak to peak.

b) Rectified nonlinear load current \( i_L \).

![Fig. 2](image)

**Fig. 2** Applied source voltage and load current waveform

The estimated reference current \( i_R \) and its one component \( \hat{i}_{R1} \) are shown in the Fig. 3. It is clear that the reference current component \( \hat{i}_{R1} \) corresponding to load current and the estimated reference current \( \hat{i}_R \) are in same phase with each other.

**Table I.**

<table>
<thead>
<tr>
<th>Table I. Simulation Parameters</th>
<th>Value</th>
</tr>
</thead>
</table>
Fig.3 waveform of $i_{R1}$ and $i_R$

Fig.5 shows the compensating current $i_c$, which flows through the APF inductor ($R_c, L_c$). The waveforms for load current, compensating current and the source current after compensation are given in Fig.6. The result shows that the source current and the compensating current are in opposite phase with each other such that harmonics can be cancelled.

Fig.7 shows the waveforms for source voltage $V_s$ and source current $i_s$ before and after compensation. Before compensation (i.e. less than 300 ms), the source current was equal to the load current.

After compensation (i.e. more than 300ms), the source current becomes sinusoidal and in same phase with the source voltage, which is clearly shown in diagram. Table II shows the THD (%) value of the source current before and after compensation.

Table II (Source current THD% calculation)

| Source Current Before Compensation (THD) | 58.3 |
| Source Current After Compensation (THD) | 4.9 |

VI CONCLUSION

A new control strategy for single-phase shunt active power filter with discrete Kalman filter as a current reference generation technique and hysteresis based current controller method as a switching modulation technique has been developed. The Kalman algorithm makes it possible to obtain the estimate of the reference value for cancelling current harmonics which vary rapidly with time. The HBCC method can be able to produce output voltages and currents with higher qualities by switching and operating converters, hence power quality can be enhanced. The simulation results show the effectiveness of the proposed method.

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REFERENCES


APPENDIX A

APF CONTROL UNIT DESIGN


