A Single-Phase Shunt Active Power Filter Based on Cycle Discrete Control for DC Bus Voltage

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Abstract:-A new control method for single-phase shunt active power filter (APF) is proposed. It integrates the DC bus voltage control and active power filter command current generation, according to the periodicity of source current and energy balance concept. The instantaneous harmonic compensation and linear DC bus voltage control are achieved, without complicated and involved control logic, by using cycle discrete control technique to DC bus voltage. A mathematical model of the scheme is developed. Detailed analysis and simulation in the PSCAD/EMTDC environment are presented. A laboratory prototype of this APF is developed to validate the result. Both of simulation and experimental results show the good behavior of this type of APF.

Key-Words:-Active power filter, Discrete control, Harmonic and Reactive power, PWM.

1 Introduction
Over the years, power electronics devices have become widespread in the industrial as well as in the domestic world such as cycloconverters, variable speed drives, personal computers. These non-linear loads draw reactive power and harmonic currents along with active power from ac mains. The reactive power and harmonic components of load current cause poor power factor, poor utilization of distribution system, overheating which deteriorate life expectancy of other equipments and cause low efficiency, disturbance to other consumers and interference to communication network. Conventionally, passive L-C filters and capacitors are employed to compensate harmonics and lagging power-factor of the linear and non-linear loads. But they have many demerits like fixed compensation, large size, resonance, noise, and increased losses [1,2,3]. Having the features of good transient response, accurate compensation, and eliminating resonance, APF has been used to replace the passive filters step by step ,and generated tremendous interest among the researchers.

Various types of active power filters are reported in the literature. References [4,5] introduce an APF based on instantaneous reactive power theory. Adaptive method for the harmonic extraction is utilized in the APF introduced in references [6,7]. It is a common observation that the calculation of harmonic decreases the response speed of APF. In order to maintain the DC bus voltage, general continuous PI control method is used in voltage control loop, which effects the compensation precision [1,8]. In paper [8], a LPF is used to get average value of DC capacitor voltage, this results in 2–3 cycle delay in response time. The non-linear PI controller for voltage loop makes the APF control more complex [9]. The approximating methods [10] can get linear control for DC bus voltage, but the overall performance is poor.

This paper proposes a new APF control technique, and in the proposed method, cycle discrete control is applied to DC voltage control loop. The salient feature of the proposed method is that it keeps the source current synchronized to the mains voltage, irrespective of the load transient. According to energy balance concept, the output of cycle discrete controller is equal to the magnitude of required active current to compensate the load active power and APF losses. The cycle discrete control method ensures that the source active current maintain perfect sinusoid path in each cycle, even during transient. This new method can minimize the source active current distortion at load fluctuations ,and in this control structure, there are no delay elements like LPF, hence the harmonic compensation is instantaneous.

2 Problem Statement
Fig.1 shows the power storage circuit diagram of the single-phase shunt voltage-mode APF. The filter consists of a PWM voltage source, inverter linked to
the point of connection through a filtering inductor $L_f$ and capacitor $C_f$. It is operated in a controlled current boost-type inverter mode, and the current drawn from the utility $i_s$ is made to follow a sinusoidal reference current $i_{rf}$ in a fixed hysteresis band.

![Fig.1 Basic Circuit of the active power filter](image)

### 2.1 Classic Operation Principle of APF

Under normal circumstances, the utility can be assumed to be an ideal sinusoidal voltages source.

$$u_s(t) = V_{sm} \sin \omega t$$  \hspace{0.5cm} (1)

Where $\omega$ is the fundamental frequency of the utility source voltage. In the case of a nonlinear load, the load current consists of fundamental component and the higher-order harmonic as follows:

$$i_L(t) = \sum_{n=1}^{\infty} I_n \sin(n \omega t + \theta_n)$$  \hspace{0.5cm} (2)

From Fig.1, it can be found that the desired compensation current generated by power inverter can be represented as:

$$i_c(t) = i_L(t) - i_s(t)$$  \hspace{0.5cm} (3)

In the classic control methods of active power filters, load current and source current is sensed to calculate the harmonic and reactive current. Owing to the losses in the inverter such as switching loss, capacitor leakage current etc., the utility not only provide the real power needed by the load but also the additional power required by the inverter to maintain the capacitor voltage at a prescribed value, hence the classical PI controller and LPF are often used in voltage loop [8]. Fig.2 shows one of classic schemes of generating single-phase APF output reference current reported in various papers e.g. [11].

In the Fig.2, the DC component $I_{pl}$ obtained after LPF is equal to the peak value of active current of load current. The signal $\Delta I_p$ is the output of classical PI controller for the DC-bus voltage. If $\Delta I_p$ is free of harmonic, then $I_p$ is a fixed value throughout one cycle. However, a classical PI controller is applied, $\Delta I_p$ is not free of harmonics. And consequently, signal $i_p$ can not be pure sinusoidal waveforms. Typical waveform of compensated source current in this case is shown in Fig.3. When the load current changes suddenly, $I_p$ varies as the load current. Since $i_p$ doesn’t not change at the zero cross point of source voltage probably, hence distortion occurs in source current as shown in Fig.4 [10,12].

![Fig.2. One of the classic schemes of generating single-phase APF output reference current](image)

![Fig.3. Compensated source current waves: $I_L$ is load current; $I_s$ is source current](image)

![Fig.4. Source current in transient state: $I_L$ is load current; $I_s$ is source current](image)

### 3 The Proposed Active Power Filter

#### 3.1 Principles of Operation

![Fig.5 The power flow diagram of single-phase shunt APF](image)

The power flow of single-phase shunt APF system is shown in Fig.5. At full compensation, source provides active power $P_s$ which is equal to the sum of APF loss power $P_L$ and active power of the load $P_L$. The load’s reactive power $q_L$ is provided by the APF. From equation.1 and 2, $P_s$ and $q_L$ can be expressed as:

$$P_s = I_s \cos \theta V_{sm} \sin^2 \omega t$$  \hspace{0.5cm} (4)

$$q_L = I_s \sin \theta (V_{sm} \sin^2 \omega t) + \sum_{n=2}^{\infty} V_{sm} \sin(\omega t) I_n \sin(n \omega t + \theta_n)$$  \hspace{0.5cm} (5)

Integrating the reactive power of load $q_L$ in one fundamental cycle, we can get:

$$\int_0^T q_L \, dt = \int_0^T (I_s U_s \sin(\omega t) \cos(\omega t) + \sum_{n=2}^{\infty} U_s \sin(\omega t) I_n \sin(n \omega t + \theta_n)) \, dt = 0$$  \hspace{0.5cm} (6)

Where $T$ is the fundamental period of the utility. Integrating $P_s$ in one fundamental cycle results in following equation:
\[
\int_0^T P_s \, dt = \frac{T}{2} I_c \cos \theta V_{on} \quad (7)
\]

In a voltage-source inverter, the DC bus capacitor is used as an energy storage element of the system. Eqns. 6 and 7 show that the reactive power \( q_L \) results in energy exchange between AC source and DC-side capacitor by inverter. The DC bus voltage fluctuates with the energy exchange. Whereas, the integration of \( q_L \) in one fundamental period \( T \) is zero, so the reactive power doesn’t effect the \( T \) periodically sampled value of DC bus voltage. However integration of active power \( P_s \) is not zero, that is, if the DC bus capacitor provides active power for the load and inverter, then the periodically sampled value of DC bus voltage can not be constant. The \( T \) periodically sampled value of DC-bus voltage can supply the active power flow information, and the amplitude of the mains current can be obtained by using a voltage regulation circuit of the DC capacitor.

### 3.2 Model of Proposed Active Power Filter

![Fig.6](image)

**Fig.6** Simplified model of single-phase shunt APF

![Fig.7](image)

**Fig.7** The waveform of signal \( i^*_P(k) \)

Generally, the APF output current consists of three components: load current \( i_L(t) \), source current \( i_s(t) \) and the fundamental active current \( i_A \) which represents the loss of inverter. A simplified APF model of full bridge inverter acting as power storage is shown in Fig.6(a). The AC component of capacitor current \( i_{dc}(t) \) doesn’t change the periodically sampled value of DC-bus voltage, whereas the DC component of current \( i_{dc}(t) \) changes it. So the model in Fig.6(a) can be simplified to a DC side of inverter shown in Fig.6(b). In this model the DC side capacitor current is given by \( i_{dc}(t) = i_L(t) - i^*_P(t) \). The current \( i^*_P(t) \) is equivalent to the sum of load current \( i_L(t) \) and current \( i_A \), which is DC component of current \( i_{dc}(t) \) and harmonic current. The DC current \( I^*_P(k) \) multiply \( \pi/2 \) is the amplitude of source fundamental active current \( i_A \) as shown in Fig.7. According to model in Fig.6(b), if DC current \( I^*_P(k) \) can completely compensate the DC component of \( i^*_P(t) \), the periodically sampled value of DC-bus voltage is maintained at a fixed value at the end of each cycle. Hence the APF just provides the harmonic and reactive component of load current meanwhile.

The equation mathematical model of the APF can be obtained as shown in Fig.8. In this model, the current \( i^*_P(k) \) can be considered as a disturbance. As the signal \( I^*_P(k) \) is a cycle discrete value, a zero-order hold with fundamental sampling period is used in the model. The transfer function of DC side capacitor plant \( G(s) \) is

\[
G(s) = \frac{1}{CS} \quad (8)
\]

Where \( C \) is the DC side capacitor. It can easily be verified that the discrete transfer function between the \( I^*_P(k) \) and DC bus voltage can be written as:

\[
G(z) = \frac{1}{T C} \cdot \frac{1}{z-1} \quad (9)
\]

Where \( T=0.02 \)ms is the period of system.

### 3.3 Design of Cycle Discrete Controller

The integration of the capacitor current \( i_{dc}(t) \) in one fundamental cycle can be written as following:

\[
\int_{(K-1)T}^{KT} \frac{d}{dt} I^*_P(t) \, dt = \int_{(K-1)T}^{KT} \left( i_L(t) - I^*_P(t) \right) \, dt
\]

\[
= \int_{(K-1)T}^{KT} (I_L(k) - I^*_P(k)) \, dt = T(I_L(k) - I^*_P(k)) = \Delta U_{dc} C
\]

That is

\[
I_L(K) - I^*_P(K) = \frac{T}{C} \Delta U_{dc}
\]

\[
= \frac{T}{C} (u_{dc}(k) - u_{dc}(k-1)) = u(k)
\]

Where \( I_L(K) \) is the average value of currents \( i_A \) during the interval \([K-1]T \) , \( KT \). From eqn.11, the reference current input to the inverter to maintain DC bus voltage can be written as

\[
I^*_P(k) = I^*_P(k-1) + u(k)
\]

The structure of this controller is illustrated in Fig.9.

![Fig.9](image)

**Fig.9.** Cycle discrete controller for DC-bus voltage using capacitor current

From Fig.9, the discrete transfer function \( D(Z) \) can be given as

\[
D(z) = C / T \quad (13)
\]
Eqn.13 is a P controller shown in Fig.10, and for \( C = 10000 \mu F \), P is 0.5. In Fig.11, the open-loop frequency response of this control system shows that the gain margin is 3 dB and phase margin is 45\(^\circ\) respectively. Fig.12 shows the good step response with one cycle delay and no steady error. In case of the disturbance, the output of this system will have an error shown in Fig.13.

To eliminate the disturbance, a cycle discrete PI controller is used, which is shown in Fig.14. When the PI controller parameters \( K_P \) and \( K_I \) is 0.45 and 0.1, gain margin of 6 dB and phase margin is 50\(^\circ\) is obtained respectively shown in Fig.15. Fig.16 shows the step response of this system. In Fig.17 it can be found that this close-loop system with cycle discrete PI controller can maintain the DC bus voltage near the reference value in spite of the disturbance.

3.4. Control Block Diagram

The basic control block diagram of the proposed scheme for single-phase APF is shown in Fig.18. It can be found that the DC bus voltage is sampled at the positive going zero-crossing instants. In this way, the high frequency disturbances in the whole system can be reduced[13]. The periodically sampled value of DC bus voltage \( U_{dc}(k) \) is compared with a reference voltage \( V_{ref} \). The compared output is fed to cycle discrete controller to generate the desired amplitude of source current \( I_P(k) \). As the \( U_{dc}(k) \) is sampled at the positive going zero-crossing point of source voltage, it is ensured that the error information which passed to the cycle discrete controller is sampled only at the positive going zero-crossing point of source voltage. The desired amplitude \( I_P(k) \) of source current is set at the beginning of each cycle, and is kept constant throughout the cycle. The desired source current and the
detected source current are fed to the current control loop to generate the desired output current $i^*_c(t)$. The actual output current $i_c(t)$ is made to follow $i^*_c(t)$ within a hysteresis band. Since the amplitude of $I_p(k)$ is maintained constant throughout a sampled cycle of the source voltage, the source current remains distortion free and is in phase with the source voltage during both steady state and transient operation. Hence, the compensation process is instantaneous.

4 Simulation and Expereriment Results

4.1 Simulation Results

Simulation studies are carried out to predict the performance of proposed APF by PSCAD/EMTDC [14]. In the simulation, the system structure of APF is shown as fig.1, the nonlinear load is represented by antiparallel thyristors. The width of the hysteresis window is maintained at 0.5A, and the switching frequency is 10 KHz.

4.2 Experiment Results

On the basis of the proposed control structure, a single-phase shunt APF prototype(220V/30KW) based on TMS320LF2812DSP is developed. The DC side capacitor $C=10000 \mu$F, filtering inductance $L_f=0.1mH$ and capacitor $C=30uF$. DC-bus reference value $U_{ref}=500V$. The nonlinear load is represented by full-wave diode rectifier. The system structure is shown in Fig.21. Fig.22 show the steady-state performance of APF. It can be found that although the DC bus voltage has ripple ,it is stable and near the set value. It’s fluctuation frequency is twice of the fundamental frequency of the AC source [1]. Furthermore the source current is almost sinusoidal. Fig.23and 24 show the harmonic spectrum of source current and load current. It is found that the THD of load current is approximately 50%, and the source current THD is less than 5%. Fig.25 is the transient performance of proposed APF .When switch K2 opens suddenly, the load current decreases and the DC-bus voltage will rise a little for 3 period nearly. In the transient process, the source current doesn’t show any distortion.
5 Conclusions

A new type of single-phase shunt APF technique is proposed in this paper. The cycle discrete controller is used to simplify the APF control structure and to realize the linear control for the DC-bus voltage. The merits of this APF are: (a) Simplified the calculation of the active component of load current. (b) The control of DC-bus voltage is linear. (c) The AC source current maintain sinusoidal, even during the variation of load current. (d) System is stable under large fluctuation in load current. The feasibility of the above scheme is verified by PSCAD/EMTDC simulation and experimental results.

References: