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Indirect Control of Single-Phase Active Power Filters using Harmonic Control Arrays

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Abstract

The ever increase of nonlinear loads in electric distribution networks causes many problems due to the high level of harmonic currents. This paper proposes a new technique for controlling a single phase shunt active power filter based on a selective compensation using the newly developed technique of harmonic control arrays. Simulation results confirm the appropriate selective harmonic compensation performance under different operating conditions.

Keywords: Harmonic control arrays, single-phase active power filter, selective compensation, electric distribution network**.**
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1. Introduction

Nowadays, nonlinear loads such as electrical variable speed drives, switch-mode power supplies, CFL and LED light bulbs, welding inverters and so on are increased in electric distribution networks. These loads draw a non-sinusoidal current from the grid and cause harmonic pollutions. Current harmonics in distribution networks have destructive impacts on system performance, such as increasing the neutral current in four-wire systems, over-temperature of system components, mechanical oscillation in electrical motors, insulation failure, unpredictable behavior of protection systems, over-temperature of transformers, interference with communications and etc. Therefore, one can say that the level of current harmonics has a direct relation with the cost of installation, maintenance and repair of the system [1]-[10].

Passive and active power filters (APFs) are used to reduce current harmonics in electric distribution networks. Despite of simplicity, passive filters suffer from disadvantages of large volume, high cost, and susceptibility to resonance in the network. Active power filters have attracted more tendency than other harmonic compensation techniques, due to the fast response and flexibility. These filters have the flexibility to compensate the desired harmonic orders and offer better harmonic compensation characteristics. The performance of an APF depends on the control method of the power electronic converter and the reference current generation. Till now, many different methods have been presented [11]-[17].

Harmonic Control Arrays (HCAs) method, which was first introduced in [18] and its application in power electronics was proposed in [19], is a suitable technique for controlling a system with AC signals. This method can track or reject desired harmonic components and is suitable for systems with periodic references or disturbance signals. This paper proposes the application of HCA method in indirect control of single-phase APFs with selective harmonic compensation. By this method, the specific power quality requirements and standards, such as the allowed level of total harmonic distortion (THD) in non-ideal networks with highly nonlinear loads can be fulfilled. Also, the suggested technique needs only one current sensor for measuring the grid current and two voltage sensors for measuring the grid and DC-link voltages. In the following, the system is first modelled then the adoption of the HCA to the

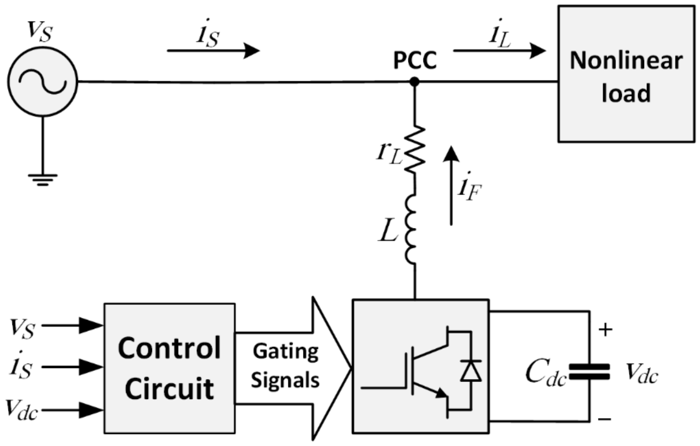

Fig. 1. Block diagram of the single-phase shunt active power filter.

specific problem of selective harmonic compensation of the single-phase APF is proposed. Finally, simulation results under various conditions for a typical system are presented, which confirm the theoretical achievements.

2. System Modeling

Fig. 1 shows the block diagram of a single-phase shunt APF. This block diagram consists of a single-phase full-bridge inverter, a DC-link capacitor and an inductive filter in the output. According to Fig. 1, the inductor voltage equation is:

$$v_{inv} = r_L i_F + L\frac{di_F}{dt} + v_S \tag{1}$$

Therefore, one has:

$$\left(r_L + L\frac{d}{dt}\right) i_F = v_{inv} - v_S \tag{2}$$

By applying the Laplace transform to (2), the inductor current is obtained as follows

$$I_F(s) = \frac{1}{Ls + r_L}\left(V_{inv}(s) - V_S(s)\right) \tag{3}$$

As can be seen, the transfer function from the inverter voltage to the inductor current is a first-order one. Also, it can be proven that the transfer function from the DC-link voltage to the grid current is also first-order [1]. In order to regulate the DC-link voltage, a proportional integral (PI) controller is used; while in order to control the inductor current (or the filter injected current to the grid) the harmonic control arrays (HCA) is utilized, which its implementation is described in the following section.

3. Indirect Current Control with HCAs

The nonlinear load current is composed of several harmonic components. The percentage of these components in each load is different, but often the low-order harmonics (third, fifth, seventh …) have significant percentages and also cause more serious problems. The harmonic load current equation can be written as

$$i_L(t) = i_{L_1}\sin(\omega t + \theta_1) + \sum_{n=2}^{\infty} i_{L_n}\sin(n\omega t + \theta_n) \tag{4}$$

where i_{L1} is the amplitude of the fundamental component and the second term in the right hand side of (4) shows the harmonic components, in which the even orders can usually be ignored.

Fig. 2 shows the indirect current control of the single-phase shunt APF, already well described in [15]-[17]. According to this technique, instead of directly extracting the fundamental and reactive current components from the load current, the desired compensated grid current is generated.

This will be done by using a PI DC-link voltage controller to generate the amplitude of the fundamental component of the reference grid current, while a phase locked loop (PLL) provides the phase information. The indirect control offers reactive power compensation and the unity power factor operation of the APF besides the elimination of harmonic currents.

The current controller has a major rule in successful operation of an APF, regardless of the reference current generation technique. A common disadvantage among all control methods is that the harmonic content of the load current and the grid voltage may be reflected in the grid current. So, in the indirect control, although the reference grid current is sinusoidal waveform in-phase with the grid voltage, the harmonic distortion and the THD value of the compensated grid current may be considerable. The main reason is that the reference current for the current controller block contains a wide range of harmonic contents, which may even be of the order of 25 or higher and a high control bandwidth is required.

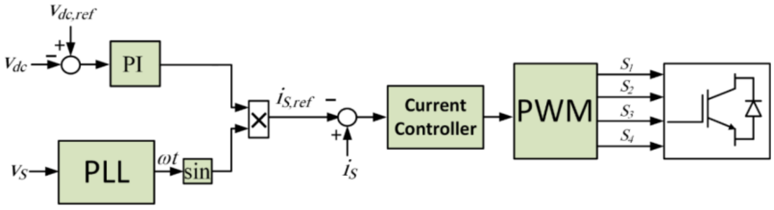

Fig. 2. Indirect control block diagram of the single-phase shunt APF

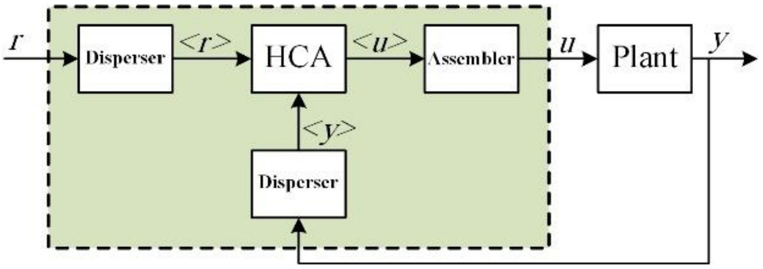

Fig. 3. Overall structure of the HCA method.

Table.1.
System Parameters

Parameter	***Symbol***	***Value***
DC-link voltage	V_{dc}	400 V
Grid voltage	V_S	220 V_{rms}
Inverter rating	S	5 kVA
Filter inductance	L	1 mH
DC-link capacitance	C_{dc}	2200 uF
ESR of the inductance	r_L	0. 25 Ω
Grid frequency	f	50 Hz
Switching frequency	f_{sw}	10 kHz
Sampling frequency	f_{samp}	20 kHz

The HCA method was first introduced in [18] as a recent solution for selective control of ac signals with harmonic contents. Its application to control the single-phase stand-alone inverter was then proposed in [19]. The essence of this paper is to adopt the HCA as the current controller of a shunt APF. By this method, the selected harmonic orders of the load current can be compensated. Fig. 3 shows the overall structure of the HCA method, which are briefly described in the following.

A) *Harmonic Disperser*

The harmonic disperser decomposes the harmonic components of the input signal as a function of time. The h^{th} harmonic of the input signal $x(t)$ is obtained by using the Fourier-series integral as

$$\langle x\rangle_h(t)=\frac{1}{T}\int_{t-T}^{t} x(\tau)e^{-jh\omega\tau}d\tau \qquad (5)$$

where T and ω = 2π/T are the mains period and angular frequency, respectively. The signal x(t) is assumed to be real in this paper. Harmonic dispersion of x(t) by considering the components from 0 to H is defined as

$$\langle x\rangle=\begin{bmatrix}\langle x\rangle_0\\ \langle x\rangle_1\\ \vdots\\ \langle x\rangle_H\end{bmatrix} \qquad (6)$$

where *H* is the design parameter and represents the maximum number of harmonics to be effectively attenuated.

Parameter *H* can be determined according to the required process and the processor computational power. If more harmonics are required for system control, the *H* can be increased. But in this case, the computational load is increased also and a compromise for computation management in a sampling period is needed. Although, by increasing the processor computational power and development of efficient algorithms, the implementation with a high number of harmonics will be possible, even in high sampling frequencies. In this paper, the system response for different values of *H* will be analyzed in simulation results section.

B) *Harmonic Assembler*

The harmonic assembler, rebuilds a signal from its harmonic components. By using the Fourier-series equation, the signal can be obtained as

$$x(t)=\sum_{h=-H}^{H}\langle x\rangle_h(t)e^{jh\omega t} \qquad (7)$$

By using (7), an equivalent representation with only non-negative harmonics is:

$$x(t)=\langle x\rangle_0(t)+2\,\mathrm{Re}\left\{\sum_{h=1}^{H}\langle x\rangle_h(t)e^{jh\omega t}\right\} \tag{8}$$

C) *Harmonic Controller*

The HCA controller in Fig. 3, by using of signals <r> and <y> produces <u> in an optimum way.

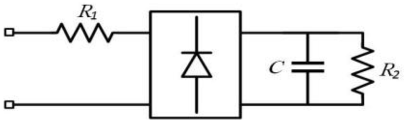

Fig. 4. Nonlinear load

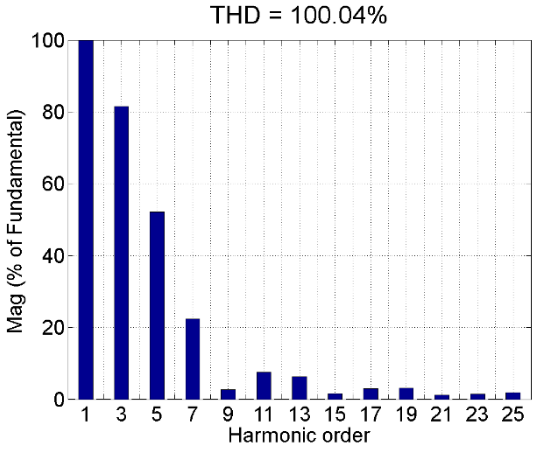

Fig. 5. Harmonic spectrum of the load current.

This is possible by using different control methods, such as the PI, fuzzy, sliding-mode, adaptive, robust control and … according to the designer selection. Therefore, the HCA method first extracts the harmonic components of the reference signal. Then the HCA controller regulates the individual harmonics. The final control signal is generated by assembling the controllers' outputs. In the present paper, the HCA controller is assumed as a simple PI controller. The dispersed signal passed through the HCA controller as follows

$$\langle u\rangle=K_P\langle e\rangle+K_I\int_{-\infty}^{t}\langle e\rangle dt \tag{9}$$

where $e = r - y$ is the error signal. It should be noted that the K_P and K_I are diagonal proportional and integral gain matrices with suitable dimension, which in a single-input single-output (SISO) system will be square matrices with $(H+1)\times(H+1)$ dimension. Therefore, despite of using classic PI controllers, an array of PI controllers exists. So, these controllers act as parallel on each harmonic to construct the final control signal.

In this paper, H is chosen as 3, 5 and 7 and simulation responses are analyzed. It should be noted that the even harmonics are not considered for the compensation.

4. Simulation Results

In order to confirm the proper performance of the proposed controller, simulation results of a typical single-phase shunt APF with parameters of table I in MATLAB/Simulink are reported.

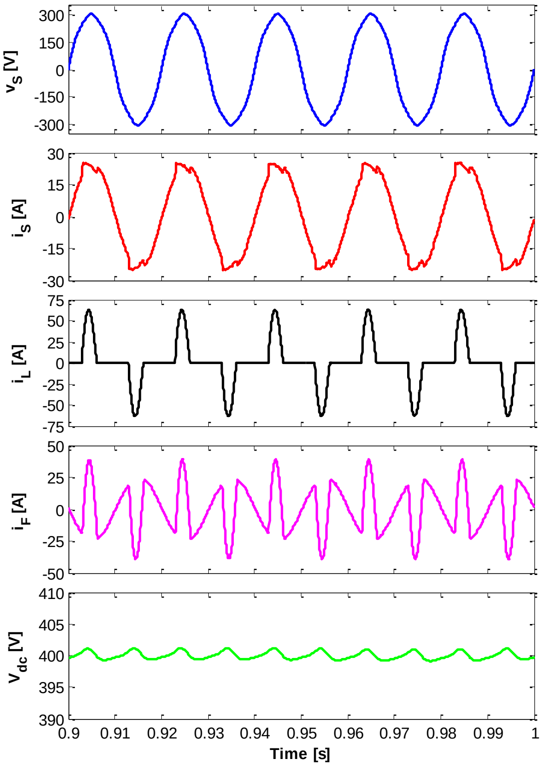

Fig. 6. Grid voltage, grid current, load current, filter current and DC-link voltage in steady-state.

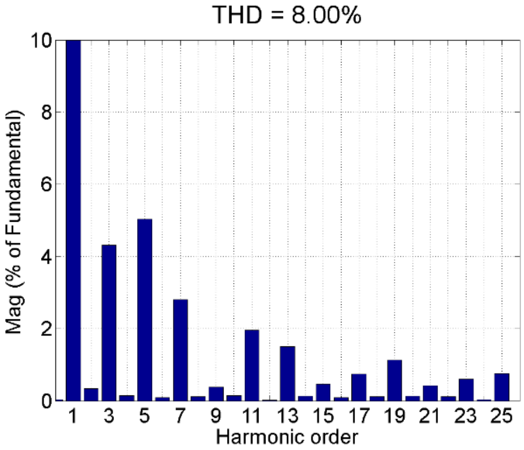

Fig. 7. Harmonic spectrum of the grid current under first harmonic component compensation.

A) *Steady-State Response*

In this section, the steady-state response of the system for a highly nonlinear load, which consists of a single-phase diode rectifier with a 20Ω resistor parallel with a 2200μF capacitor in DC-side is presented (shown in Fig. 4 with a small resistor before single-phase diode rectifier). The load current harmonic spectrum is drawn in Fig. 5 (THD=100%).

Also, the grid voltage is non-ideal and has 5% third harmonic and 3% fifth harmonic and its THD is 5.56%. Fig. 6 shows the grid voltage, grid current, load current, filter current and DC-link voltage in the steady-state.

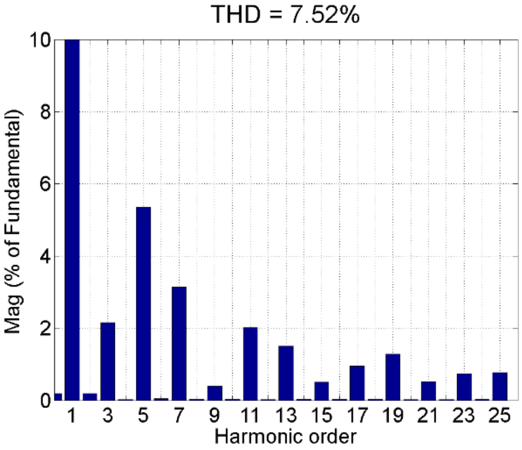

Fig. 8. Harmonic spectrum of the grid current under first and third harmonic components compensation.

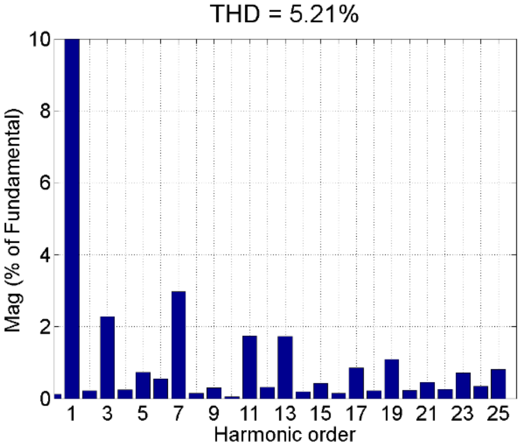

Fig. 9. Harmonic spectrum of the grid current under first, third and fifth harmonic components compensation.

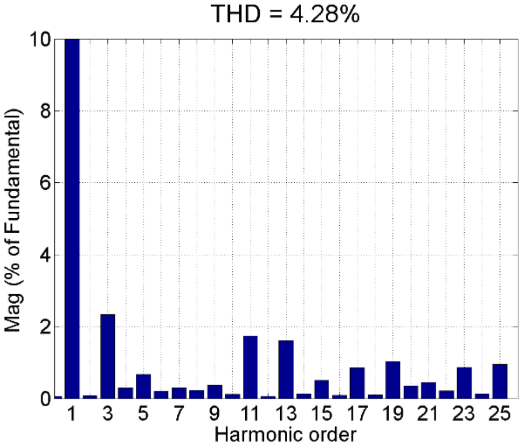

Fig. 10. Harmonic spectrum of the grid current under first, third, fifth and seventh harmonic components compensation.

This figure is plotted by assumption that the HCA controller compensates only the main component of the grid current. The corresponding harmonic spectrum of the grid current is shown in Fig. 7. As can be observed, the grid current THD is equal to 8% and this current has considerable third and fifth harmonics. Now, the third harmonic component is added for compensation to the HCA controller and the grid current harmonic spectrum is shown in Fig. 8. According to this figure, the third harmonic component is suppressed and the grid current THD is reduced to 7.52%. In the same way, by adding the fifth and seventh harmonic components to the suggested controller, the grid current harmonic spectrum will be yielded as Figs. 9 and 10. These results illustrate the correct performance of the proposed controller in selective harmonic compensation and suppression of the reference current.

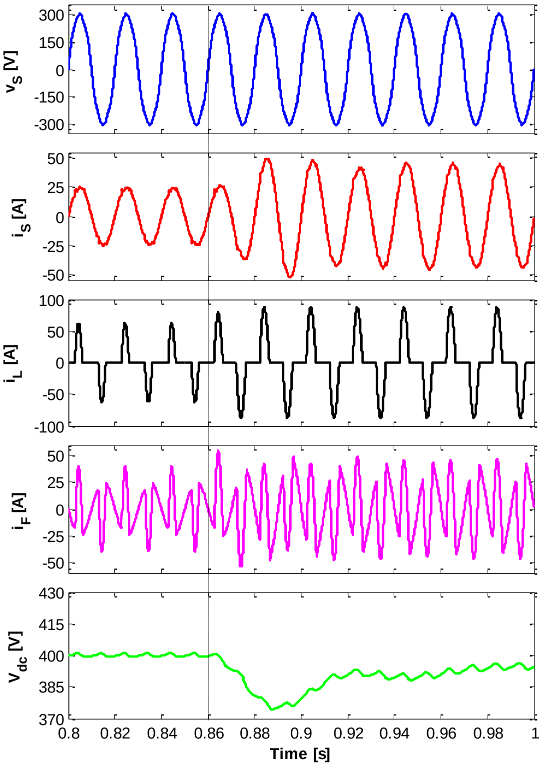

Fig. 11. Grid voltage, grid current, load current, filter current and DC-link voltage in transient condition for load sudden change

B) *Transient Response*

In this section, the transient response of the system in against load sudden change is analyzed. It is assumed that the HCA controller includes the first, third, fifth and seventh harmonic components for the compensation. Fig. 11 shows the system transient behavior in response to the load sudden increase. In this figure, in t=0.86s an equivalent resistor with R2 and parallel with it is connected in the DC-side of rectifier.

According to the results, the load increase has no effect on the current control system and current THD after compensation remains equal to 3.32%. Although the DC-link voltage has changed in the load change moment, it will recover in some cycles due to its slow controller.

5. Conclusion

This paper proposed a new technique for indirect controlling of single-phase APFs and improving the power quality of distribution networks. The suggested method (HCA) compensates the grid current harmonics in a selective manner, which lets highly attenuate the desired harmonics and improve the grid current quality. In order to confirm the proper performance of the HCA method simulations on a typical system in the MATLAB/Simulink were done. The results under different steady-state and transient tests prove the efficiency of the proposed method.

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