A DSP ACTIVE FILTER FOR POWER CONDITIONING

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ABSTRACT

This paper presents a DSP controlled active filter for power conditioning. The active filter is designed to cancel lower order harmonics generated by nonlinear loads using a series resonant LC tank tuned to a high frequency along with a pulse-width modulation (PWM) rectifier topology. The PWM control of the active filter allows for independent control of lower order harmonics, both in amplitude and in phase, to efficiently cancel load generated harmonics for power quality improvement. The active filter control algorithm is simulated in Matlab and the harmonic cancellation process is verified through PSpice.

1. INTRODUCTION

Harmonics in power systems have received increased attention in recent years with the widespread application of advanced solid-state power switching devices in a multitude of power electronic applications. The ac power system has a substantial number of large harmonic generating devices, i.e. adjustable speed drives for motor control and switch-mode power supplies used in a variety of office equipment such as PCs, fax machines etc. These devices draw nonsinusoidal load currents consisting primarily of lower order 5^{th}, 7^{th}, 11^{th}, and 13^{th} harmonics that distort the system power quality. Power quality related disruptions, ranging from system malfunction and hardware damage to costly data loss and downtime, currently cost U.S. companies more than $25 billion annually [1-5]. With the widespread use of harmonic-generating devices, the control of harmonic currents to maintain a high level of power quality is becoming increasingly important.

A common remedial measure for reducing the effects of harmonics is passive filtering [6]. The addition of passive "LC" filters alters, or interferes, with the system impedance, and is known to cause resonance with other network impedances and can result in an excessive amplification of harmonics rather than harmonic reduction. In addition, passive filters cannot adapt to changing harmonic generating loads, thus for large systems containing multiple harmonic sources, a separate filter may be required for every major harmonic source.

In response to these concerns, numerous active filters have been proposed [7]. This paper proposes a highly efficient three-phase DSP controlled active power filter that can be implemented with minimal hardware expense. The filter is designed to counter the effects of harmonics on three-phase power distribution systems and thus improve the system power quality. The concept of this filter was verified in [8] and is being improved including DSP control and cancellation of additional 11^{th} and 13^{th} harmonics. The proposed filter employs a series resonant LC tank tuned to a high frequency along with a pulse-width modulated (PWM) rectifier topology to cancel the troublesome lower order i.e. 5,7,11,13 harmonics generated by nonlinear loads. The rectifier hardware is minimal, employing MOSFETs, and the LC resonant frequency is chosen to be high, thus resulting in smaller sizes of passive components. DSP implementation will allow real-time processing of the nonlinear load current to determine the harmonic content including magnitude and phase, using an FFT algorithm. The magnitude and phase information of the harmonics is passed to the PWM control algorithm of the filter for active cancellation of variable load-generated harmonics.

2. DESCRIPTION OF PROPOSED FILTER

The active filter is controlled using a PWM ac to dc converter employing six bi-directional switches as shown in Fig.1. The series resonant tank circuit consisting of L_o and C_o is tuned to a high resonant frequency, i.e. $f_o = 18*f_1$, where $f_1 = 60Hz$. The six-switch converter (Fig. 1) is suitably PWM controlled to generate an output current, I_o, at the resonant frequency. The output current, I_o, is reflected onto the filter input side, as a function of the PWM switching functions controlling the bi-directional switches. Thus the desired current harmonics are generated at the input of the filter to cancel the nonlinear load generated harmonics at the point of common coupling (PCC) with the utility (Fig. 2).

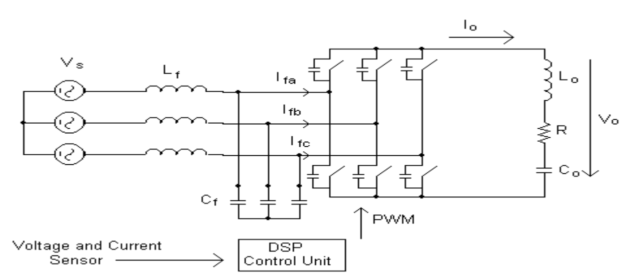


Figure 1. PWM series resonant active power filter with DSP control.

The PWM strategy provides active cancellation of lower order harmonics by controlling the input currents I_{fa}, I_{fb}, and I_{fc} to be at the desired harmonic frequencies, with variable amplitude and phase, and opposite to the load generated harmonics (I_a, I_b, I_c). It should be noted that the PWM switching frequency is chosen to be high and the switching frequency harmonics in I_{fa}, I_{fb}, and I_{fc} are filtered by the L_f and C_f components composing a small input low-pass filter (Fig. 1). Also, the resonant tank (L_o and C_o) losses are represented by the resistance 'R' in Fig. 1, which is minimal due to the high quality factors of the passive components. The active filter does not consume any real power other than due to switching losses, and is thus highly efficient. The PWM control of the active filter is simulated in Matlab to effectively cancel load-generated harmonics under varying load conditions. The active filter control algorithm is also verified through PSpice (Fig. 3) using the control signals generated in Matlab.

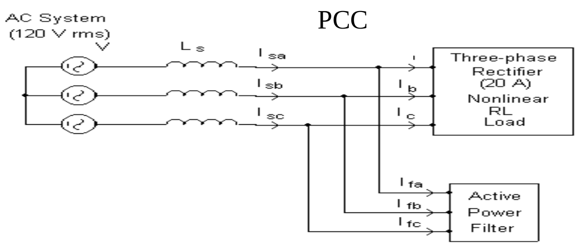


Figure 2. Simulation block diagram for nonlinear load harmonic compensation by proposed three-phase series resonant active power filter.

3. ANALYSIS

The proposed three-phase series resonant active filtering scheme uses a PWM ac to dc converter topology as shown in Fig. 1. The PWM control of the six bi-directional converter switches yields an output voltage, V_o, given by,

$$V_o = SW_1 * V_{ab} + SW_2 * V_{bc} + SW_3 * V_{ca} \qquad (1)$$

where SW_1, SW_2, and SW_3 are line-to-neutral switching functions, and V_{ab}, V_{bc}, and V_{ca} are line-to-line input voltages [9-10].
The output current, through the filter series resonant circuit, is given by,

$$I_o = \frac{V_o}{Z} \qquad (2)$$

where Z is the resonant circuit impedance. The resulting input current is given by,

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} (SW_1 - SW_3) * I_o \\ (SW_2 - SW_1) * I_o \\ (SW_3 - SW_2) * I_o \end{bmatrix} = \begin{bmatrix} S_1 * I_o \\ S_2 * I_o \\ S_3 * I_o \end{bmatrix} \qquad (3)$$

where S_1, S_2, and S_3 are the line-to-line switching functions, representative of the input line currents. As can be seen by eqn. 3, the output current, I_o, is reflected onto the input side according to the line-to-line switching functions S_1, S_2, and S_3.

The objective of the series resonant active filter is the cancellation of lower order harmonic currents by generating and injecting, harmonic currents of the same magnitude and frequency, and 180 degrees out of phase with the unwanted harmonics on an ac system. This objective is realized by PWM control of the active filter, and the tuning of the series resonant frequency, such that the product of the switching functions and the resulting output current will reflect the desired harmonic currents onto the input side. The DSP would realize the real-time control of the proposed active filter for active cancellation under varying nonlinear load conditions.

4. DESIGN APPROACH

The analytical method for the filter design approach leading to the cancellation of the 5^{th}, 7^{th}, 11^{th}, and 13^{th} harmonic currents is formulated in this section. The form of the filter switching functions for independent control of the the harmonic currents is as follows:

$$\begin{aligned} SW_1 = {} & A\sin(h\omega t + 30) + A'\sin((h-6)\omega t + 30) + A''\sin((h-8)\omega t + 30) \\ & + A'''\sin((h-12)\omega t + 30) + A''''\sin((h-14)\omega t + 30) \end{aligned} \qquad (4)$$

$$\begin{aligned} SW_2 = {} & A\sin(h\omega t - 90) + A'\sin((h-6)\omega t + 150) + A''\sin((h-8)\omega t + 270) \\ & + A'''\sin((h-13)\omega t + 30) + A''''\sin((h-14)\omega t + 150) \end{aligned} \qquad (5)$$

$$\begin{aligned} SW_3 = {} & A\sin(h\omega t + 150) + A'\sin((h-6)\omega t - 90) + A''\sin((h-8)\omega t - 210) \\ & + A'''\sin((h-12)\omega t - 90) + A''''\sin((h-14)\omega t - 210) \end{aligned} \qquad (6)$$

In eqns. (4)-(6), h is the frequency coefficient and determines the suitable PWM switching frequency and the series LC tank resonant frequency. The active filter is designed to reflect the output current, I_o, of order (h-1) onto the input side. Therefore, the series resonant LC tank is tuned to (h-1)*60 Hz, where a larger h increases the frequency of the PWM switching harmonics, and decreases the size of the passive components. The coefficients A, A', A'', A''', and A'''' determine the magnitudes of the reflected input harmonic currents. The "A" terms control the resonant frequency component of the output current, I_o, and the A', A'', A''', and A'''' terms independently control the 5^{th}, 7^{th}, 11^{th}, and 13^{th} harmonic currents at the input of the filter. In addition, the injected harmonics by the proposed filter are made negative and positive sequence in order to successfully compensate for the negative sequence 5^{th} and 11^{th} and positive sequence 7^{th} and 13^{th} harmonic currents generated by nonlinear loads.

The resulting output voltage, V_o, is found using eqns. (1) and (4)-(6) as given below:

$$V_o = \frac{3V}{2}\begin{pmatrix} A\cos((h-1)\omega t) - A'\cos((h-5)\omega t + 60) + \\ A''\cos((h-9)\omega t) - A'''\cos((h-11)\omega t + 60) \\ A''''\cos((h-15)\omega t) \end{pmatrix} \qquad (7)$$

where V is the amplitude of the line-to-line input voltage. By designing the series LC tank to resonate at the (h-1) harmonic, the (h-5), (h-9), (h-11), and (h-15) harmonic voltages will not carry any significant current. Therefore, the output current, I_o, will consist primarily of the (h-1) component, and is given as

$$I_o = \frac{3AV}{2R}\cos(h-1)\omega t \qquad (8)$$

where R represents the passive component losses.
The input current, I_{fa}, using eqn. (3), is given by,

$$I_{fa} = (SW_1 - SW_3) * I_o \tag{9}$$

Using eqns. 4-6 and 9, the simplified input current is given by,

$$I_{fa} = \left(\begin{array}{l} \frac{3\sqrt{3}A^2V}{4R}[\sin\{(2h-1)\omega t\} + \sin(\omega t)] + \\ \frac{3\sqrt{3}AA'V}{4R}[\sin\{(2h-7)\omega t + 60\} + \sin(-5\omega t + 60)] + \\ \frac{3\sqrt{3}AA''V}{4R}[\sin\{(2h-9)\omega t\} + \sin(-7\omega t)] + \\ \frac{3\sqrt{3}AA'''V}{4R}[\sin\{(2h-13)\omega t + 60\} + \sin(-11\omega t + 60)] + \\ \frac{3\sqrt{3}AA''''V}{4R}[\sin\{(2h-15)\omega t\} + \sin(-13\omega t)] \end{array} \right) \tag{10}$$

It can be seen that I_{fa}, consists of the following harmonics: 1^{st} (60Hz), 5^{th}, 7^{th}, 11^{th}, 13^{th}, (2*h*-15), (2*h*-13), (2*h*-9), (2*h*-7), and (2*h*-1). The fundamental (60Hz), and the lower order harmonics (5, 7, 11, 13), are independently controlled by the switching function coefficients of A, A', A'', A''', and A'''' respectively.

For a large *h*, i.e. *h* = 19, the higher order input harmonics of (2*h*-15), (2*h*-13), (2*h*-9), (2*h*-7), and (2*h*-1), become 23, 25, 29, 31, and 37, and can be easily filtered by the small input filter L_f and C_f components shown in Fig. 1. Also notice that for *h*=19, the LC tank resonates at 18*60 Hz = 1080Hz, resulting in small passive components.

5. RESULTS

Simulations were conducted using both Matlab and PSpice to evaluate the harmonic cancellation performance of the proposed three-phase series resonant active power filter. Fig. 3 shows the PSpice circuit of the active filter, employing MOSFETs. The nonlinear load system was also simulated in PSpice using a 30A three-phase adjustable speed drive type load with diode rectifier front-end. Fig. 4(a) shows the input current, I_a, and input voltage, V_a, waveforms for the nonlinear load. The FFT of the input current, I_a, is shown in Fig. 4(b). Notice the nonsinusoidal, nonlinear load current which is rich in harmonics as indicated in Fig. 4(b). The nonlinear load current was read in to Matlab and used to generate the PWM switching functions for the active filter.

The PWM switching functions are as given in eqns. (4)-(6), where the frequency coefficient variable, *h*, is 19, thus the series LC resonant frequency is (*h*-1)*60, or 1080Hz. The series resonant circuit components of L_o and C_o were selected as 2.17mH and 10μF respectively, and display series resonance at 1080Hz.

To generate the MOSFET gating signals, each modulating function, SW_1, SW_2 and SW_3 (eqns. (4)-(6)) is intersected with a triangle carrier wave (Fig. 5(a)) of frequency 10kHz to obtain a bi-level PWM signal as shown in Fig. 5(b). The tri-level line-to-line switching functions S_1, S_2 and S_3 are then obtained by successive subtractions of the line-to-neutral functions (SW_1, SW_2, SW3) as shown in eqn. 3 (Fig. 5(c)). Each tri-level line-to-line switching function is then divided into two positive signals, (d) and (e), by inverting the negative portion. The two positive signals generated by each line-to-line switching function S_1, S_2 and S_3 correspond to the top and bottom switch of the first, second and third leg of the active filter bridge respectively. Since there must always be a path for the inductive current to flow, when all the switches are off at the same time, an error control signal needs to be generated corresponding to the time that all of the switches are in the off state (Fig. 5(f)). Fig. 6 shows the nonlinear load current (a), the corresponding filter current (b), and resulting conditioned ac line current (c) as simulated in Matlab. Matlab was also used to generate the active filter gating signals to control the PSpice circuit shown in Fig. 3. The resulting active filter current and conditioned ac line current are shown in Fig. 7 (a) and (b) respectively.

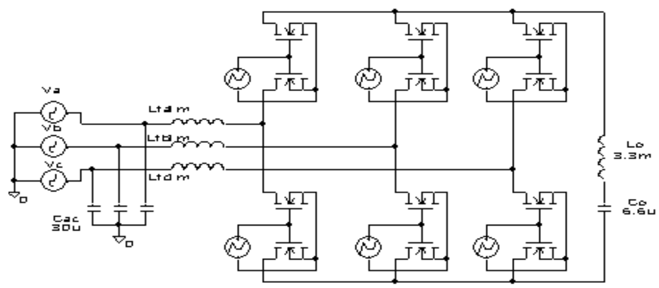
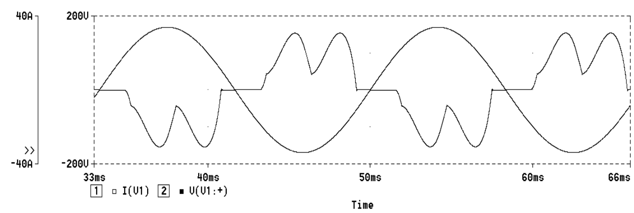
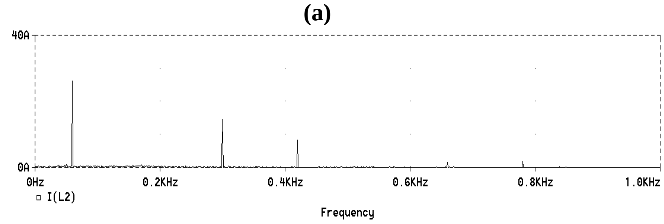


Figure 3. The active filter circuit diagram in PSpice.



(a)



(b)

Figure 4. (a) The nonlinear load current and voltage (b) FFT of the nonlinear load input current (TDD = 57%).

The common index used to determine the quality of power system currents and voltages is Total Demand Distortion (TDD), which is defined as:

$$TDD = \sqrt{\frac{\sum I_h^2}{I_L^2}} \tag{11}$$

where I_h represents the individual current harmonics and I_L is the maximum demand load current (fundamental) at the PCC (see Fig 2). The initial nonlinear load current as shown in Fig. 4 (b) has a TDD of 57%. After applying the active filter control algorithm in Matlab, the TDD of the ac line current is reduced to nearly 0% (Fig. 6). After the PSpice simulation, the TDD of the input ac line is reduced from 57% to 8% (Fig. 7). This would result in a significant improvement in the system power quality at the PCC.

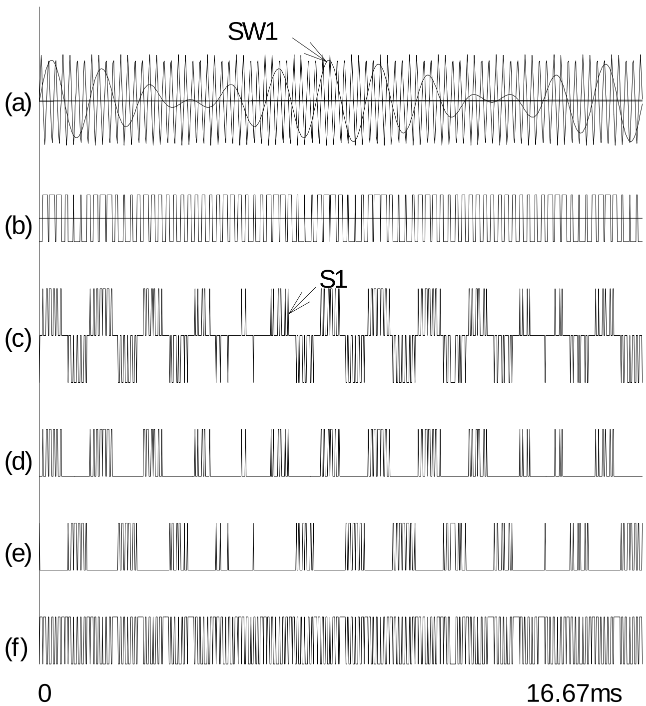


Figure 5. PWM control of the proposed active power filter. (a) Sine-triangle intersection (b) Bi-level PWM signal (c) Tri-level line-to-line switching function S_1 (d) Positive portion of S_1 (e) Negative portion of S_1 inverted (f) Control signal when all of the switches are in the off state.

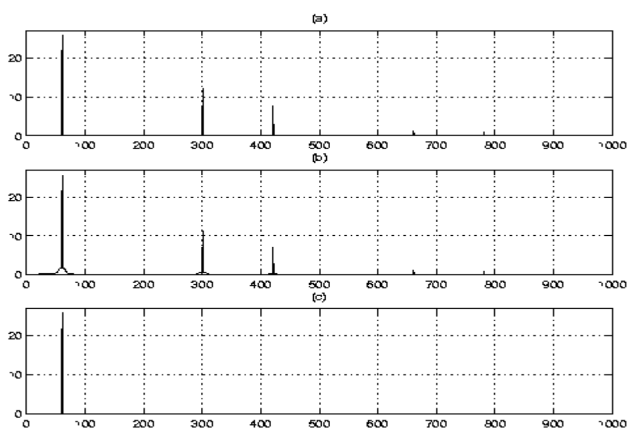
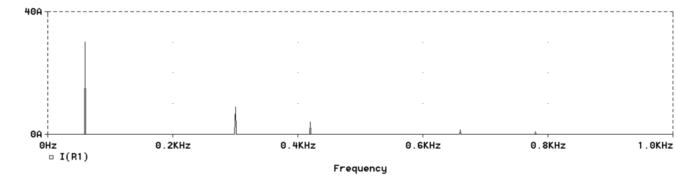


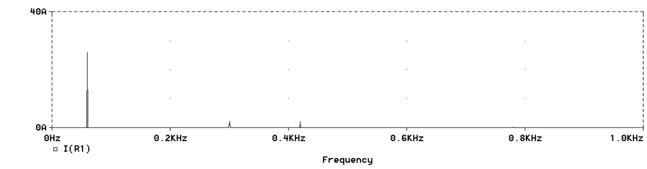
Figure 6. The Matlab simulation results (a) FFT of nonlinear load current (TDD = 57%) (b) FFT of the generated active filter current (c) the FFT of conditioned ac line current (TDD ≈ 0%).

6. CONCLUSION

In this paper, a DSP controlled three-phase active filter to cancel lower order harmonics generated by nonlinear loads for improved power quality is proposed. The proposed approach employs a PWM rectifier topology with a series resonant LC tank tuned to a high frequency. The PWM control of the active filter displays the ability to independently control several lower order harmonics, both in amplitude and in phase, to efficiently cancel load generated harmonics with minimal hardware expense. PSpice and Matlab simulation results verify the concept and the benefits of real-time DSP control. Implementation with a DSP will be demonstrated in the presentation.



(a)



(b)

Figure 7. The PSpice simulation results to cancel the load generated harmonics of Fig. 4 (TDD = 57%) (a) FFT of the generated active filter current (b) FFT of the conditioned ac line current (Now TDD = 8%).

7. REFRENCES

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