A SERIES ACTIVE POWER FILTER FOR HARMONIC VOLTAGE SUPPRESSION

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Abstract - This paper proposes a terminal harmonic voltage compensator using a series active filter which reduces or even eliminates harmonic voltage content supplied to critical loads or consumers. Consisting of a voltage-fed PWM inverter with a LC filter, it is inserted in series between an AC supply and a load. The compensation principle and theoretical analysis are described. Simulation results of an active filter, applied to a 3000W load, are presented which validate its purpose. Experimental results obtained from an active series filter prototype are shown to confirm the theory and feasability of the proposed system.

INTRODUCTION

It is known that the wide use of polluting loads in industrial, commercial and residential environments yields a voltage distortion in the electrical network. This harmonic pollution has drawn the attention of power electronics researchers and engineers to find solutions for that problem, Peng et al (1) and Singh et al (2). A voltage filtering system (Fig. 1) is needed to provide a sinusoidal voltage to many critical loads, consumers or even to obey specific standards regulations and recommendations.

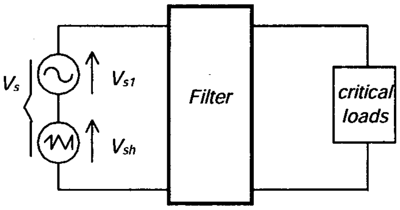

Figure 1: Voltage filtering structure.

Passive filtering is a possible solution, but presents several drawbacks. Another possibility would be an ac/dc/ac system which produces sinusoidal voltages. However it needs more than one stage of conversion and implies in higher costs. Another option is the use of active filters, conceptually established in the 70's. A series active filter is the appropriate choice to improve voltage waveforms. Unfortunately, few works on series active filters have been published, in comparison with the number of publications on, for instance, shunt filters. Among these works, one topology, proposed by Campos et al (3), describes the use of a series filter requiring a power source (usually a dc link) that is supplied by a shunt filter (or an auxiliary source). Still regarding series active filters, a second work proposes its use in harmonic current compensation, Nastran et al (4), while a third one, combined it with a passive element resulting in a hybrid voltage filter, Koczara and Dakyo (5). According to (5), the main problem of the hybrid filter is determining its reference signals (current and voltage).

This work proposes a series active filter topology acting as harmonic voltage compensator without an auxiliary source to supply the dc link. Its control strategy is simple and its elements and control signals are determined in a straightforward manner.

SYSTEM CONFIGURATION

The proposed harmonic voltage compensator is shown in Fig. 2. It is composed of a full-bridge voltage source inverter and a LC filter. It is connected in series between the AC mains and the load, which are, respectively, represented by an ideal voltage (V_s) and a current source (I_L). The voltage source has a fundamental voltage (V_{s1}) and some harmonic voltages (V_{sh}).

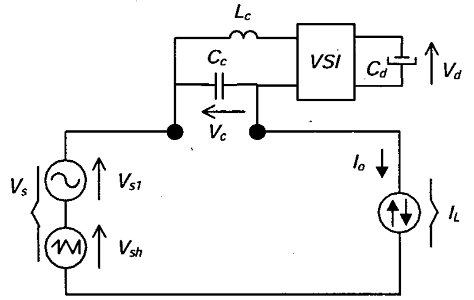

Figure 2: The proposed harmonic voltage compensator.

The series active filter and its control strategy is depicted in Fig. 3. The main idea is to generate a voltage V_c (over the capacitor Cc) which is able to cancel the harmonic contents of V_s. The inner voltage loop compares the harmonic voltage reference (V_{shr}) to the harmonic voltage of the capacitor Cc. This produces an error which is injected into an appropriate voltage

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controller. Its output is then compared to a triangular waveform, generating drive signals to the switches.

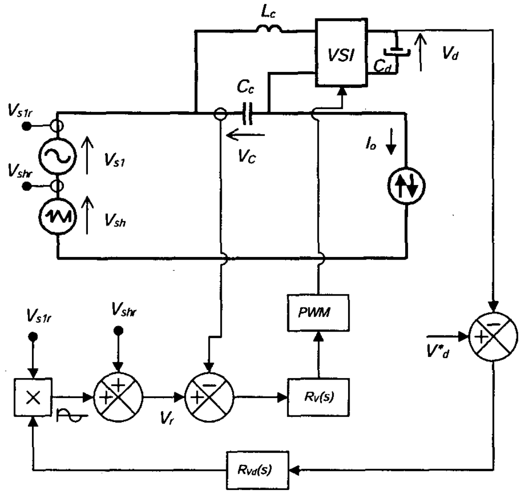


Figure 3: The harmonic voltage compensator and its control strategy.

The outer voltage loop is responsible for keeping the average voltage on the DC side of the inverter constant. It takes a sample of V_d and compares it to the reference V_d. The resulting error is injected into an adequate voltage controller. Its output is then multiplied by a sinusoidal signal proportional to and in phase with the fundamental input voltage. The result of this multiplication, added to V_{shr} yields the reference voltage V_r. The latter enables the filter operation (including information about the compensating voltage V_c and the switching and conducting losses in the inverter).*

SIMPLIFIED THEORETICAL ANALYSIS

The inductor L_c

According Fig. 4 (b), for a switching period T_s an average value for $v_{ab}(t)$ is obtained by using (1).

$$Vab_{avg} = \frac{1}{Ts}\left(\int_0^{DTs} V_d\,dt + \int_0^{(1-D)Ts} -V_d\,dt\right) = V_d(2D-1) \qquad (1)$$

$$fs = \frac{1}{Ts} \qquad (2)$$

$$\Delta t = DTs \qquad (3)$$

Where f_s is the switching frequency and Δt is the conduction interval of two switches. A $v_c(t)$ voltage, containing all needed harmonic components to cancel the voltage V_{sh} is produced across capacitor C_c. Admitting that a squared waveform is present at V_s, then (4) is written for capacitor C_c.

$$v_c(\theta c) = \frac{4V_q}{\pi}\cdot\left[\sum_{u=2}^{v}\frac{1}{2u-1}\cdot sin[(2u-1)\cdot\theta c_u]\right] \qquad (4)$$

Neglecting the switching frequency, it is possible to consider that the voltage $v_{ab}(t)$ has the same content of the V_{sh} voltage, as shown in (5).

$$v_{ab}(\theta ab) = \frac{4V_q}{\pi}\cdot\left[\sum_{n=2}^{m}\frac{1}{2n-1}\cdot sin[(2n-1)\cdot\theta a_n]\right] \qquad (5)$$

Therefore, using (1) in (5), after isolating the duty cycle, D, yields (6).

$$D(\theta a) = 0.5\cdot\left[1+\frac{4V_q}{\pi V_d}\cdot\left[\sum_{n=2}^{m}\frac{1}{2n-1}\cdot sin[(2n-1)\cdot\theta a_n]\right]\right] \qquad (6)$$

While switches S1 and S4 are on, from the circuit (Fig. 4 (a)), we can find (7). For one switching period, (8) is obtained.

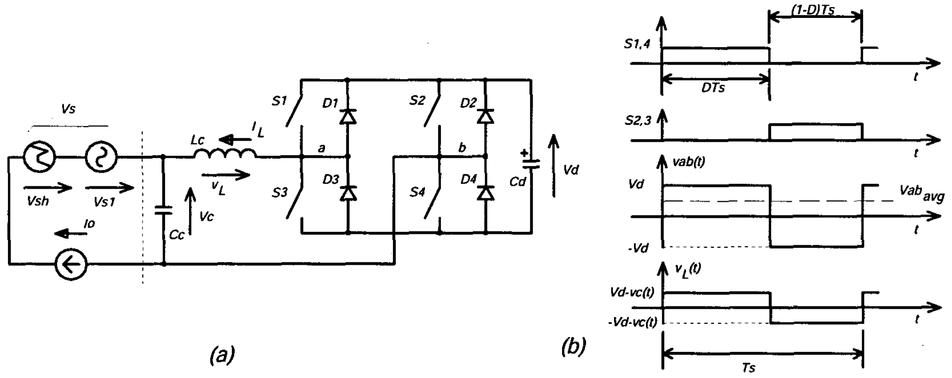


Figure 4: Series active filter circuit (a) and waveforms for a switching period (b).

$$L_c \frac{d(i_L)}{dt} = V_d - Vc(\theta c) \tag{7}$$

$$L_c \frac{\Delta i_L}{\Delta t} = V_d - Vc(\theta c) \tag{8}$$

From (3), (4) and (6) replaced in (8) yields (9) and (10).

$$\overline{\Delta i_L} = 0.5 - \left(\frac{2M_i}{\pi}\right)^2 \left[\sum_{n=2}^{m} \alpha_n \sin(\gamma_n \theta a_n)\right]\left[\sum_{u=2}^{v} \alpha_u \sin(\gamma_u \theta c_u)\right] \tag{9}$$

$$M_i = \frac{V_q}{V_d} \quad \theta a = \theta c = \varpi t \quad \alpha_n = \frac{1}{2n-1}$$

$$\alpha_u = \frac{1}{2u-1} \quad \gamma_n = 2n-1 \quad \gamma_u = 2u-1 \tag{10}$$

$$\theta a_n = \theta a \quad \theta c_u = \theta c \quad \overline{\Delta i_L} = \frac{L_c \Delta i_L}{V_d T_s}$$

where: ω - the frequency of the fundamental voltage V_I; M_i – the modulation index.

From (9), when it reaches its maximum value, the L_c can be determined by (11).

$$L_c \geq \frac{\overline{\Delta i_{L\,max}} \cdot Vd}{\Delta i_{L\,max} \cdot fs} \tag{11}$$

The transfer function $\Delta V_C(s)/\Delta D(s)$

Yet, from Fig. 4 (a), it is possible to write (12).

$$\frac{di_L(t)}{dt} = \frac{V_d(2D-1) - V_C}{L_c} \tag{12}$$

Then, introducing a small perturbation in the duty cycle D, (12) can be written as (13).

$$\frac{d(i_L)}{dt} + \frac{d(\Delta i_L)}{dt} = \frac{V_d(2D-1) - Vc}{L_c} + \frac{2V_d \Delta D - \Delta Vc}{L_c} \tag{13}$$

Comparing (12) to (13), yields (14)

$$\frac{d(\Delta i_L)}{dt} = \frac{2V_d \Delta D - \Delta Vc}{L_c} \tag{14}$$

From the circuit of Fig. 4 (a), the equations (15) and (16) are settled.

$$\Delta i_L = \Delta i_{Cc} \tag{15}$$

$$\Delta V_C = \frac{1}{C_c} \int \Delta i_{Cc}(t) \tag{16}$$

Using the Laplace transform over (14), (15) and (16) and after some algebraic operations, the transfer function (17) is obtained.

$$\frac{\Delta V_c(s)}{\Delta D(s)} = \frac{2 \cdot V_d}{1 + s^2 \cdot L_c \cdot C_c} \tag{17}$$

A two poles and two zeros voltage controller will be used along with (17). Its transfer function is defined by (18).

$$H_i(s) = \frac{Vo}{Vc'} = \frac{(1 + sRizCi) \cdot (1 + sRfzCf)}{(sCf(Rip + Riz)) \cdot \left(1 + sCi\left(\frac{RipRiz}{Rip + Riz}\right)\right)} \tag{18}$$

DESIGN AND SIMULATION RESULTS

Design procedure

A simulation example of a series active filter employing the two level modulation technique is presented in this section. A simplified design procedure to calculate some of its components is used. Its specifications are: V_{speak} = 311 V, P_o = 3000 W, f_{line} = 60 Hz, Vd = 100 V, fs = 40 kHz, Δi_{Lmax} = 10% i_{speak}. Considering that the active filter, placed in series with the load rated up to 3000 W, is ideal (no losses) the resulting input peak current is given by:

$$i_{speak} = \frac{2 \cdot P_o}{V_{speak}} = \frac{2 \cdot 3000}{311} = 19.29A$$

$$\Delta i_{L\,max} = 0.1 \cdot i_{s\,peak} = 1.929A$$

The maximum inductor L_c current ripple is 10% of the input peak current and its maximum parameterized current ripple is 0.5. Then, the L_c value is determined and shown below:

$$\overline{\Delta i_{L\,max}} = 0.5$$

$$Lc \geq \frac{\overline{\Delta i_{L\,max}} \cdot Vd}{\Delta i_{L\,max} \cdot fs} = \frac{0.5 \cdot 100}{1.929 \cdot 40 \cdot 10^3} = 648\mu H$$

The transfer function is calculated and results:

$$G_i(s) = \frac{\Delta V_c(s)}{\Delta D(s)} = \frac{2 \cdot V_d}{1 + s^2 \cdot L_c \cdot C_c} = \frac{200}{1 + s^2 \cdot 19.5 \cdot 10^{-9}}$$

Following a graphical procedure all voltage controller components are calculated. Their values are:

$$Riz = 47\,k\Omega \qquad Ci = \frac{1}{2\pi\ fz1\,Riz} = 3.75\,nF$$

$$Rip = 1.46\,k\Omega \qquad Rfz = 265.8k\Omega$$

$$Cf = \frac{Ci\,Rz}{Rfz} = 662\ pF$$

The carrier signal peak-to-peak voltage (V_{Tpp}) is 10 V and the AC mains voltage transducer gain (K_{is}) is 0.1.

The Bode diagram of Gi(s), Hi(s) and Fi(s)=Gi(s)Hi(s) is presented in Fig. 5. The open loop transfer function (Fi(s)) presents a crossover frequency of 10 kHz and a phase margin of about 58°.

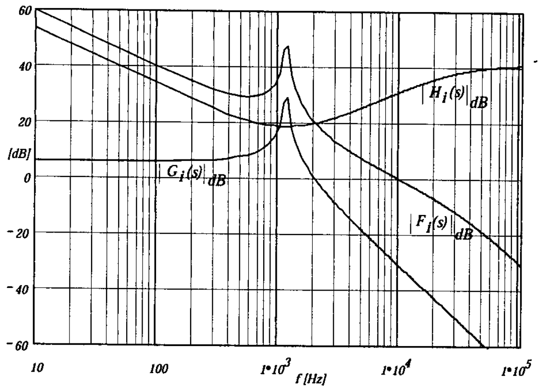


Figure 5: Bode diagram of Gi(s), Hi(s) and Fi(s).

Simulation results

A series active filter was prepared and simulated by the Pspice program. Its power stage diagram is presented in Fig. 6 where S1 to S4 are ideal switches with a conducting resistance of 0.3 Ω. Elements E1 and E2 are voltage transducers. They read the reference and the controlled voltage signals.

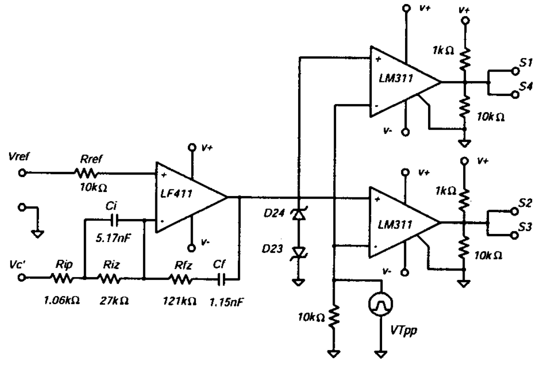


Figure 6: Simulated control circuit.

In Fig. 6 the control circuit is shown. Only the inner voltage loop was simulated due to the slow dynamics of the outer voltage loop.

A simplified diagram of the series active filter and two loads are presented in Fig. 7. The first simulation was performed using a load consisting of a sinusoidal current source (I_{o1peak} = 19 A) while the second one used a R-L load (about 3000 W).

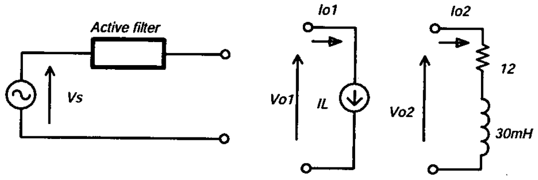


Figure 7: Series active filter connection diagram and loads.

Fig. 8 presents simulation results related to the current source load showing the voltages at the input side of the series active filter: the distorted input voltage (V_s) and its fundamental component (V_{s1}). The voltage across capacitor Cc is also shown (V_c). It cancels the distortions of the input voltage yielding a sinusoidal signal (V_{o1}) over the load (I_L source). The current (I_{o1}) and voltage (V_{o1}) loads are in phase.

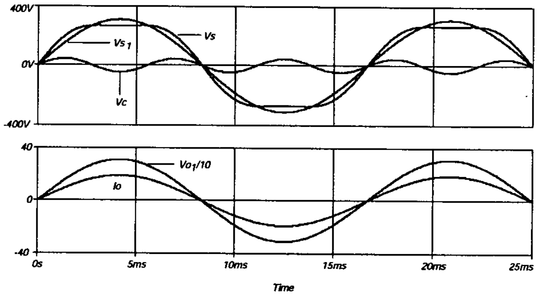


Figure 8: Voltages and currents for current source load.

Fig. 8 presents a simulation results related to the R-L load. The distorted voltage (V_s) and its fundamental component (V_{s1}) at the AC mains port and also the conditioning voltage (V_c) are shown. The latter cancels the distortions of the input voltage, yielding a sinusoidal signal (V_{o2}) over the R-L load. The current (I_{o2}) is displaced 43° from the voltage (V_{o2}).

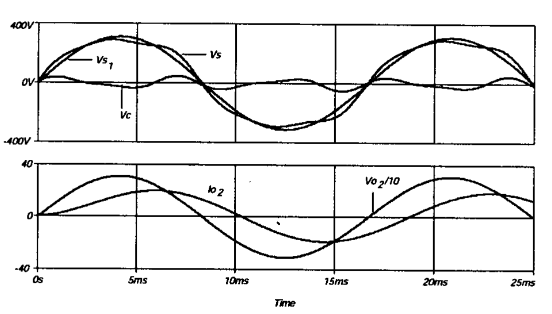
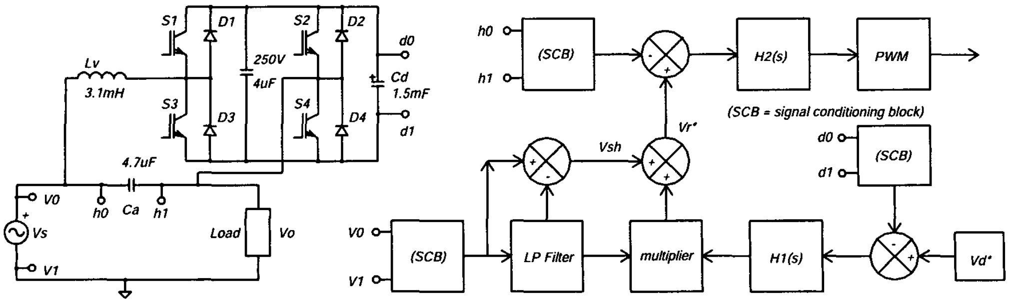


Figure 9: Voltages and currents for R-L load.

The simulation results confirm the ability of the series active filter to generate all required harmonic voltages to cancel the ac mains harmonics content.



(a) (b)

Figure 10: Active filter power stage (a) and system control (b) diagrams.

EXPERIMENTAL RESULTS

To verify the principle of operation and the control strategy, a 800 W, 20 kHz active series filter has been implemented. Its power stage and control system diagrams are presented in Fig. 10. Its major parameters and components are:

$V_s = 220$ *Vrms*
$V_d = 250$ *V*
S_1, S_3, D_1 *and* D_3: *SKM50GB063D*
S_2, S_4, D_2 *and* D_4: *SKM50GB063D*
$C_d = 1.5$ *mF/350 V*
$C_c = 4.7\,\mu F/250$ *V*
$L_c = 3.1$ *mH*

The control system (Fig. 10 (b)) was implemented using the Hall-effect transducers, operational amplifiers and others discrete components. From Fig. 11 to 15, the experimental results of the active filter inserted between an AC supply source and R-load can be observed. The R-load is equal to 40 Ω.

In Fig. 11 are presented: the input voltage, V_s, *and the output voltage,* V_o. *It is noticed that the output voltage has better shape when compared to* V_s.

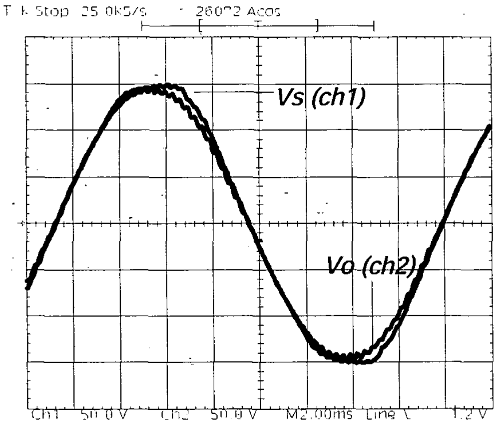


Figure 11: The input, V_s, *and output voltages,* V_o.

The output current, I_o, *and the voltage,* V_s, *are shown in Fig. 12. The active filter does not introduce any displacement effect between the input and the output voltages. Then, the current* I_o *remained in phase with the input voltage.*

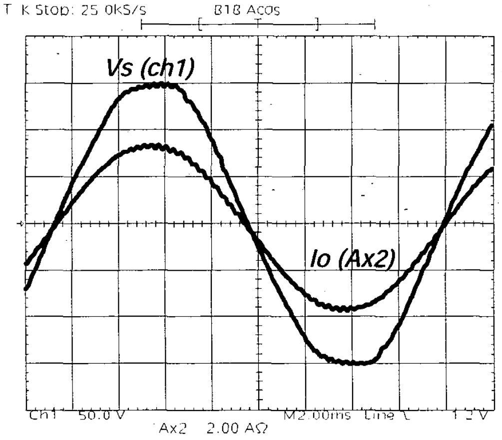


Figure 12: The input voltage, V_s, *and output current,* I_o.

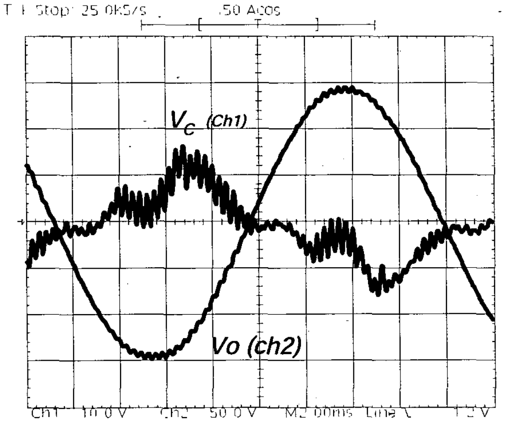


Figure 13: The output, V_o, *and capacitor* V_c, *voltages.*

The capacitor voltage, V_C, and the voltage, V_o, are presented in Fig. 13. The V_C voltage is the one that cancels the harmonic content of the input voltage V_s.

In Fig. 14 the control signal are shown. They are: the 20 kHz triangular voltage, V_T, and the compensating voltage signal, V_{cnt}.

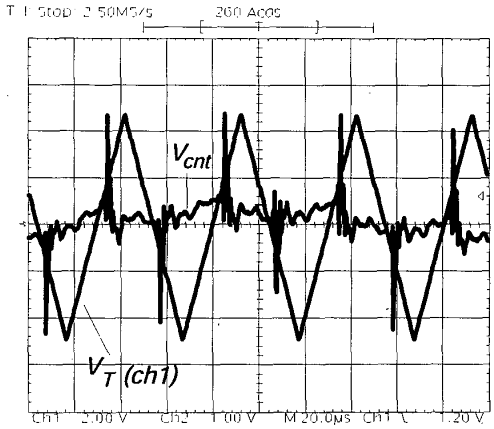


Figure 14: The control, V_{cnt}, and triangular, V_T, voltages.

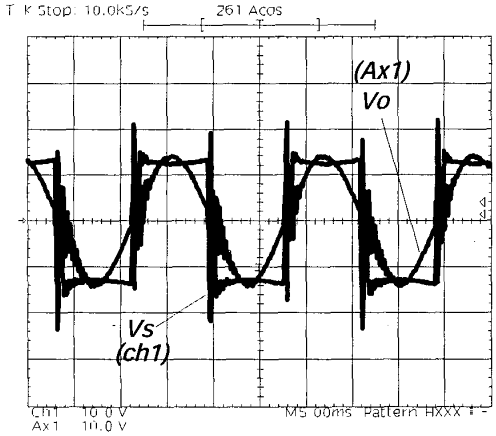


Figure 15: The input, V_s, and output, V_o, voltages.

The AC supply source was replaced by a square wave generator. And Fig. 15 shows the source voltage, V_s, and the output voltage V_o. The active series filter removed the harmonic content of V_s, delivering to the load a sinusoidal voltage.

CONCLUSION

The proposed series active filter acting as harmonic voltage compensator, its operating principle and its control strategy were presented. A sinusoidal waveform, from a distorted voltage source, was delivered to the load after being processed by the filter according the simulation results.

The filter topology is simple and its components are determined in a straightforward manner. Experimental results of an active filter connected between AC supply source and R-load confirmed the theoretical analysis.

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