A Comparative Study of Single-Phase Active Filters for Improving Power Quality

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Abstract

In this paper, single-phase active filters are investigated. A detailed analysis of distortions is presented in the first section of the paper. Harmonic producing sources are introduced and classified. The nonlinear loads are divided into two categories of current-based distortion sources and voltage-based distortion sources. A detailed analysis of distortions is presented in this study. Harmonic producing sources are also introduced and classified. Three different topologies of active filters including series, parallel, and series-parallel are discussed and their compensation principles are also explained. Simulations results are presented in last section of the paper. In terms of eliminating voltage and current harmonics, active filters are evaluated in this study.

1 Introduction

It has known that the increase of using nonlinear equipments in the power system has been caused the distortion of power quality and utility conditions. Moreover harmonic distortion problems have caused equipment overheating, overvoltages in the power system, measurement faults etc. Most of the more important international standards (IEEE 519, IEC61000 etc.) are defined power quality and limited the harmonics [1].

Table 1. Power quality problems in industrial systems [2].

<table>
<thead>
<tr>
<th>From AC supply to the load</th>
<th>From the load to the AC supply</th>
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<tbody>
<tr>
<td>Voltage sag &amp; swell</td>
<td>Current harmonics</td>
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<tr>
<td>Voltage unbalances</td>
<td>Reactive current</td>
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<tr>
<td>Voltage distortions</td>
<td>Current unbalance</td>
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<td>Voltage interruptions</td>
<td>Voltage notching</td>
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<td>Voltage oscillations</td>
<td>Voltage flicker</td>
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Different methods are proposed in literature for solving the harmonic problems. The one of these methods is passive filtering technique. Although this method has advantages of being simple, cheap and reliable, it has some problem its application.

- Passive filters only work the frequencies, which were previously adjusted.
- The source impedance has to known accurately, because of the fact that it strongly influences the compensation characteristic of the passive filter. Otherwise system configuration is varies.
- Resonance problem can possible due to the interaction between passive filters and the other loads or the source [3]-[6].

Because of the disadvantages and limits of passive filters, active power filters have been studied and developed recent years to solve harmonic problems. This paper is investigated on parallel, series and series-parallel active filters in power system. Their compensation characteristics are also explained in this study.
2 Current and Voltage Harmonic Sources

Current-based distortions are current harmonics, load unbalance, neutral current and reactive current. In this study, a diode rectifier, which loaded RL load, is used to produce current harmonics. This topology is showed in Figure 1. Diode rectifier’s voltage and current waveforms are given in Figure 2.

Voltage-based harmonics are voltage harmonics; voltage unbalance, voltage flicker and voltage sag & swell. Diode rectifier, which employed smoothing dc capacitor, is showed in Figure 3. It is given as an example for a voltage harmonic source.

Figure 1: Typical current-based harmonic source.
  a) Diode rectifier.
  b) Equivalent circuit for this system.

Figure 2: Typical voltage and current waveform for diode rectifier with RL load.

Figure 3: Typical voltage-based harmonic source.
  a) Diode rectifier.
  b) Equivalent circuit of this system.

Figure 4: Typical voltage and current waveform for diode rectifier with RC load.
3 Parallel Active Filters and Compensation Principles

The proposed parallel active filter is occurred a PWM inverter which placed in parallel with the load. It is essentially provides to compensate the harmonics of the supply current caused by nonlinear load. Parallel active filter injects a harmonic current with the same amplitude and reverse phase as that of the load into AC system [7]. The basic principle of parallel active filter compensating for a current harmonic source is showed in Figure 6.

\[
I_S = I_L + I_{AF}
\]  

In Figure 6, \(Z_S\) is source impedance and \(Z_L\) is equivalent impedance on the load side, which includes passive filter impedance, \(I_{Lh}\) is the equivalent harmonic current, \(V_{Sh}\) is the equivalent harmonic voltage due to the distorted utility voltage. If \(V_{Sh}\) is equal to zero (that means the utility has pure sinusoidal voltage) and \(Z_S\) is neglected, then active filter compensating current should be

\[
I_{AF} = I_{Lh}
\]
extracted. Therefore the parallel active filter compensates current harmonics caused by nonlinear load at Point of Common Coupling (PCC). To compensating load current harmonics and source voltage harmonics, active filter current should be obtained by

\[ I_{AF} = I_{Lh} + \left( \frac{V_{Sh}}{Z_L} \right) \quad (3) \]

Here, source impedance \( Z_S \) is also neglected. Figure 8 shows the basic principle of parallel active filter compensating load voltage harmonics.

\[ I_{AF} = \left( \frac{V_{Sh} - V_{Lh}}{Z_L} \right) \quad (5) \]

4 Series Active Filters and Compensation Principles

The proposed series active filter is occurred PWM inverter, which is placed in series between the ac source and the load to force current or voltage become sinusoidal. The series active filter is to present high impedance to harmonic current or voltage and it behaviors like a short circuit to fundamental current or voltage. Therefore harmonic current
flow is blocked from the load to the ac source and from the ac source to the load side. Also series active filter injects voltage into the system for compensating voltage harmonics \[8\]-\[11\]. The basic principles of the series active filter compensating for a harmonic current source is showed Figure 10.

![Series active filter for current harmonic source.](image)

**Figure 9:** Series active filter for current harmonic source.

![Compensating current harmonics of load.](image)

**Figure 10:** Compensating current harmonics of load.

\[a)\] Equivalent circuit of compensation principle.
\[b)\] For fundamental component.
\[c)\] For harmonics component.

The series active filter should be produced \(V_{AF}\) voltage to cancel the load current harmonics.

\[V_{AF} = Z_L \cdot I_{Lh} \] \(\text{Equation 6}\)

Here \(Z_L\) is load impedance and \(I_{Lh}\) is load current harmonics. It is assumed that source voltage harmonics \(V_{Sh}\) is equal to zero and source impedance is neglected. If we want to cancel load current harmonics and source voltage harmonics, the series active filter should inject

\[V_{AF} = V_{Sh} + Z_L \cdot I_{Lh} \] \(\text{Equation 7}\)

Voltage into the system. Here, \(V_{Sh}\) is source voltage harmonics. The basic principle of series active filter compensating for voltage harmonics is showed Figure 12.
The series active filter should be produced $V_{AF}$ voltage to compensate the load voltage harmonics.

$$V_{AF} = -V_{Lh}$$  \hspace{1cm} (8)

Here it is assumed that $V_{Sh}$ source voltage harmonics is equal to zero and $Z_S$ and $Z_L$ source and load impedance respectively. If we want to compensate source voltage harmonics, active filter voltage should be obtained by

$$V_{AF} = V_{Sh} - V_{Lh}$$  \hspace{1cm} (9)

5 Series-Parallel Active Filters (Unified Power Quality Conditioners)

Combined series-parallel PWM converter topologies are used for power quality improvement in distribution/transmission power systems. They are capable of compensating voltage and current harmonics of load or source. The series converter controls the injected voltage and the parallel converter controls the injected current in the conventional UPQC systems [12].
The series active filter is placed near the source and the parallel active filter is placed near the load in Figure 13. The series active filter injects voltage to compensate voltage harmonics of the source and the parallel active filter injects current to compensate current harmonics of the load.

![Series-parallel active filter for current harmonic source.](image)

The parallel active filter is placed near the source and series active filter is placed near the load in Figure 14. While the parallel active filter injects the current for compensating current harmonics of the source and improving the power factor, the series active filter injects the voltage for compensating voltage harmonics of the load into the line.

![Series-parallel active power filter for voltage harmonic source.](image)

It is shown that basic circuit of series-parallel active filter (unified power quality conditioner - UPQC) for current harmonic source load and voltage harmonic source load in Figure 15. The parallel active filter compensates current harmonics caused by nonlinear load and the series active filter helps in compensating the voltage harmonics caused by nonlinear load.
Figure 15: Series-parallel active filter for current and voltage harmonic source load.

6 Control Strategy of Proposed Parallel Active Filter for Current Harmonics

The proposed parallel active filter is based on a single-phase inverter with four controllable switches a standard H-bridge converter. The AC side of the inverter is connected in parallel with the nonlinear load through a filter inductance. The parallel active filter injects harmonic current to the line with same amplitude of and opposite phase to the load’s harmonic current. It is assumed that supply voltage is pure sinusoidal and supply impedance is neglected in this simulations and the control strategy of parallel active filter is defined that assumption.

Figure 16: Overall control scheme of parallel active filter.

To implement closed loop control algorithm of parallel active filter, voltage and current are sensed at various points in the single-phase system as shown Figure 16. For extracting reference current of the active filter, it is used a band
pass filter as shown Figure 17. Here, $I_L$ consists fundamental and harmonics components, which is showed $\tilde{I}_L$ and $\tilde{I}_L$, respectively.

![Figure 17: Extracting parallel active filter reference current.](image)

To regulation of dc bus voltage of the parallel active filter, the sensed DC link voltage ($V_{DC}$) of the converter’s dc side is compared with its reference DC voltage ($V_{DC*}$). The error is processed in a PI controller as shown Figure 18. Consequently, the result is added to reference current, Figure 19. Voltage control of DC bus is performed by adjusting the small amount of real power flowing into the DC capacitor thus compensating for the converter and system losses.

![Figure 18: DC bus controller of parallel active filter.](image)

The error signal between actual current and sensed parallel active filter current is processed through a PI controller, after that the output voltage error is compared with a fixed amplitude and frequency triangular wave. This comparison generates the PWM switching signals for the switches used in parallel active filter, Figure 19.

![Figure 19: The control scheme of parallel active filter.](image)

### 7 Control Strategy of Proposed Series Active Filter for Voltage Harmonics

The proposed series active filter is based on a single-phase inverter with four controllable switches a standard H-bridge converter. The AC side of inverter is connected in series to transmission line thorough a single-phase transformer with turns ratio 1/1. A diode bridge rectifier with smoothing capacitor is considered as a nonlinear load. The proposed series active filter provides harmonic voltage with the same amplitude and opposite phase to the load harmonic voltage.
This control method achieved to elimination of voltage distortion caused by nonlinear load and harmonic current isolation. Here, it is assumed that the source voltage has pure sinusoidal waveform and source impedance is also neglected.

To realize control scheme of series active filter, voltages are sensed at various point of single-phase system as shown Figure 20. It is shown that extraction of reference voltage of series active filter in Figure 21.

To regulation of dc bus voltage of series active filter, the sensed dc link voltage of series active filter ($V_{DC}$) is compared with its reference dc voltage ($V_{DC^*}$). The error is processed in a PI controller then it is added to reference voltage to produce of gating signals as shown figure 22.

The error signal between actual voltage and the sensed series active filter voltage is processed through a PI controller then the output error is compared with a triangular wave. This comparison generates switching signals for series active filter, Figure 23.
8 Simulation and Experimental Results

Proposed parallel active filter, which controlled current-detecting method, is used for current harmonics elimination caused by the nonlinear load as shown Figure 16. Diode rectifier, which loaded RL load, is used as a nonlinear load in this topology. Load current harmonics are sensed a current sensor. Switching frequency is 50 kHz. Source voltage is pure sinusoidal and 110V, 60 Hz but PCC is includes current harmonics because of the nonlinear load, as shown Figure 24. Here, parallel active filter compensates current harmonics at PCC as shown Figure 25.

Figure 24: Voltage and current waveforms before parallel compensation.
- Upper trace load voltage, voltage at PCC and source voltage.
- Lower trace load and source current.

Figure 25: Voltage and current waveforms after compensation.
- First trace load, pcc and source voltage.
- Second trace compensated source current.
- Third trace load current.
- Forth trace parallel active filter current (compensation current).
Proposed series active filter, which controlled voltage-detecting method, is used for voltage harmonics elimination as shown Figure 20. Diode rectifier, which loaded big capacitive load, is used as a nonlinear load in this topology. Voltage harmonics are sensed by voltage sensor from load side. Switching frequency is 100 kHz. Source voltage is pure sinusoidal and 110 V, 60 Hz but PCC is includes voltage harmonics because of the nonlinear load as shown Figure 26. Here, series active filter compensates PCC voltage harmonics as shown Figure 27. Here, series active filter only corrects input voltage harmonics in this topology.

![Figure 26: Voltage and current waveforms before series compensation.](image)
Upper trace load voltage and voltage at PCC.
Lower trace load and source current.

![Figure 27: Voltage and current waveforms after series compensation.](image)
First trace compensated pcc voltage.
Second trace load voltage.
Third series active filter voltage (compensation voltage).
Last trace source and load current.

Another proposed series active filter is used for elimination of input (source) voltage harmonics. Source voltage includes 3., 5., 7. harmonics as shown Figure 28. Figure 29 is showed that elimination of input voltage harmonics by series active filter. Proposed series-parallel active power filter compensates input voltage and current harmonics at PCC as shown Figure 30.
Figure 28: Voltage and current waveforms before series compensation.
Upper trace source voltage, voltage at PCC, load and line voltage.
Lower trace load, line and source current.

Figure 29: Voltage and current waveforms after series compensation.
First trace pcc voltage and source voltage.
Second trace compensated line and load voltage.
Third trace source, load and line current.
Last trace series active filter compensation voltage.

Figure 30: Voltage and current waveforms after series-parallel compensation.
First trace source voltage.
Second trace compensated load voltage and line voltage.
Third trace compensated source and line current.
Fourth trace series active filter compensation voltage.
Fifth trace parallel active filter compensation current.
Last trace load current.
9 Conclusions

In this study, harmonics, their causes, and effects have been discussed. Series, parallel and series-parallel active filters and their compensation principles have also been discussed. Compensation principles of three kinds of active filters are explained and control strategies are analyzed. Their simulation results are also given in this study. While parallel active filter compensated current harmonics caused by the nonlinear load, series active filter compensated voltage harmonics caused by distorted input voltage or the nonlinear load. However, series-parallel active filters compensated input voltage and output current harmonics.

References


