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Three-Phase For-Wire Shunt Active Filter With Unbalanced loads
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Abstract

The electrical power quality at low voltage alternative networks became a serious concern because of the increased use of non-linear loads and pollutants. This work is to improve the quality of electric current in such networks. Four-Wire Shunt Active Filter is studied; different loads (balanced and unbalanced) are discussed. We propose to identify harmonic and reactive currents at the base of Self-Tuning-Filters, which proved very good filtering performance, either in transient or steady state. The simulations demonstrate the importance of this work in harmonic filtering and reactive power compensation.

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Keywords ─ Shunt Active Filter (SAF), Total Harmonic Distortion(THD), Self-Tuning-Filter (STF), Unbalanced loads.

1. Introduction

Generally, harmonic currents are produced by power electronic equipment. These harmonic currents are the source of adverse effects for many types of equipment such as heating in distribution transformer and perturbation of sensitive control equipment.

Many solutions have been studied in the literature to mitigate the harmonic problems, such as the passive filters which cannot completely eliminate all of the harmonic currents, and the active filters which is developed and widely used to overcome to the drawbacks of the passive filters and improve power quality [1].

The identification approach is based on the Phase Locked Loop (PLL), which is not sensitive to the disturbances, specifically to the harmonic and unbalanced voltage [2], [3].

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As known, the performances of the active filter system mostly depend on the accuracy of the harmonic isolation and DC voltage control. Many works recently dealt with Active Power Filters for three-wire power system [7], and using Self-Tuning Filter to isolate harmonic currents without reactive power [1-2], [4-5]. This STF is used instead of classical harmonics extraction based on High Pass Filters or Low Pass Filters, it proved excellent performances.

This paper presents a new control scheme of 3-phase 4-wire Power Active Filter, to compensate harmonic and reactive power simultaneously, using Self-Tuning-Filter. The effectiveness of the proposed method is verified by computer simulation, and presented in this paper.

![Filter configuration](image)

**Fig. 1. Filter configuration**

2. System Configuration

2.1 Self-Tuning-Filter

In this paper, we propose to use Self-Tuning-Filter (STF) in the place of Low Pass Filter or High Pass Filter. The STF is introduced by Hong-sock Song in [6].

The STF principle is described in the Fig. 2 below.

![STF principle](image)

**Fig. 2 Self-Tuning-Filter**
From Fig. 2, the following expressions can be obtained:

\[
\dot{x}_a(s) = \left( \frac{K}{s} \right) \left[ x_a(s) - \dot{x}_a(s) \right] - \frac{\omega_f}{s} \ddot{x}_a(s),
\]

\[
\dot{x}_b(s) = \left( \frac{K}{s} \right) \left[ x_b(s) - \dot{x}_b(s) \right] + \frac{\omega_f}{s} \ddot{x}_a(s),
\]

(1) (2)

Where:

- \( x_a, x_b \): input signals in Clark axes
- \( \dot{x}_a, \dot{x}_b \): output signals in Clark axes (the fundamental of the input signals)
- \( K \): Selectivity parameter
- \( \omega_f \): Fundamental pulsation

### 2.2 Harmonics and reactive identification by the instantaneous power theory using STF

The load currents \( i_{L1}, i_{L2}, i_{L3} \) of the three-phase four-wire system are transformed into the \( \alpha - \beta \) axis as follows:

\[
\begin{bmatrix}
    i_a \\
    i_b \\
    i_0
\end{bmatrix} = \frac{1}{\sqrt{3}} \begin{bmatrix}
    1 & -\frac{1}{2} & -\frac{1}{2} \\
    0 & \sqrt{3} & -\sqrt{3} \\
    \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}}
\end{bmatrix} \begin{bmatrix}
    i_{L1} \\
    i_{L2} \\
    i_{L3}
\end{bmatrix},
\]

(3)

As known, the currents in the stationary frames can be respectively decomposed into DC and AC components by:

\[
\begin{align*}
    i_a &= \overline{i}_a + \overline{\overline{i}}_a \\
    i_b &= \overline{i}_b + \overline{\overline{i}}_b \\
    i_0 &= \overline{i}_0 + \overline{\overline{i}}_0
\end{align*}
\]

(4)

Then, the STF extracts the fundamental components at the pulsation \( \omega_f \) directly from the currents in the \( \alpha - \beta \) axis.

The \( \alpha - \beta \) harmonic components of the load currents are computed by subtracting the STF input signals from the corresponding outputs. The resulting signals are the AC components, \( \overline{\overline{i}}_a \) and \( \overline{\overline{i}}_b \), which correspond to the harmonic components of the load currents \( i_{L1}, i_{L2} \) and \( i_{L3} \) in the stationary reference frame.

If: \( i_0 = 0 \), (three identical loads) then the 0 harmonic component of the load is:

\[
\overline{i}_0 = i_0,
\]

(5)

which correspond to the harmonic component of the neutral current \( i_n \) in the stationary reference frame. For the source voltage, the three voltages \( v_{S1}, v_{S2}, v_{S3} \) are transformed to the \( \alpha - \beta \) reference frame as follows:

\[
\begin{bmatrix}
    V_a \\
    V_b
\end{bmatrix} = \frac{1}{\sqrt{3}} \begin{bmatrix}
    1 & -\frac{1}{2} & -\frac{1}{2} \\
    0 & \sqrt{3} & -\sqrt{3} \\
    \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}}
\end{bmatrix} \begin{bmatrix}
    V_{S1} \\
    V_{S2} \\
    V_{S3}
\end{bmatrix},
\]

(6)

Then, we applied the STF to these \( \alpha - \beta \) voltage components. This filter allows suppressing the harmonic components of the distorted mains voltages and consequently leads improve the harmonic isolator performances.

After the computation of the fundamental component \( \overline{\overline{V}}_{a\beta} \) and the computation of the harmonic currents \( \overline{i}_{a\beta} \), we calculate the alternative instantaneous real power \( \overline{\overline{p}}(t) \) and the instantaneous imaginary power \( \overline{\overline{q}}(t) \) as follows [8-9]:

\[
\overline{\overline{p}}(t) = i_a \overline{V}_a + i_b \overline{V}_b,
\]

(7)

\[
\overline{\overline{q}}(t) = i_b \overline{V}_a - i_a \overline{V}_b,
\]

(8)
And so we identify harmonics and reactive power at the same time. The references of current in the $\alpha - \beta$ reference frame are calculated by:

\[
\begin{align*}
    i_{ref}^\alpha &= \frac{1}{\sqrt{3}} \left( \bar{v}_a \times (\bar{p} + p_{DC}) - \bar{v}_b \times q \right), \\
    i_{ref}^\beta &= \frac{1}{\sqrt{3}} \left( \bar{v}_b \times (\bar{p} + p_{DC}) + \bar{v}_a \times q \right), \\
    i_{ref}^0 &= i_0,
\end{align*}
\]

(9) (10) (11)

Where: $p_{DC}$ is a small amount of active power absorbed from or realised to the DC capacitor so as to regulate the DC bus voltage. Then the filter reference current in the 1, 2, 3 coordinates are defined by:

\[
\begin{bmatrix}
    i_{ref}^1 \\
    i_{ref}^2 \\
    i_{ref}^3
\end{bmatrix} = \frac{1}{\sqrt{3}} \begin{bmatrix}
    1 & 0 & \frac{1}{\sqrt{3}} \\
    0 & -\frac{\sqrt{2}}{2} & \frac{1}{\sqrt{3}} \\
    \frac{1}{\sqrt{2}} & -\frac{\sqrt{2}}{2} & 0
\end{bmatrix} \begin{bmatrix}
    i_{ref}^\alpha \\
    i_{ref}^\beta \\
    i_{ref}^0
\end{bmatrix},
\]

(12)

Fig. 3 below describes the identification scheme.

3. Simulation Results

Fig. 4 presents the system of loads studied.

3.1 Balanced loads

The simulation parameters are defined in Tab. II. For the loads we consider three identical loads powered by three non-controlled rectifiers. Fig. 5 shows the simulation results for the system of load depicted in the Fig. 5. Before inserting the APF (between 0 and 0.1 s), the Total Harmonic Distortion (THD) of the source (and the load) current is equal to 28.94%. At 0.1 s the APF is inserted and the source current becomes perfectly sinusoidal.
With classic low pass filter the obtained THD of the supply currents is 1.99 % after compensation. Using STFs the THD is reduced to 0.97 %, (K = 50 for the STF). At 0.2 s the same system of load is inserted. And the supply currents remain quickly sinusoidal.

For the inverter of the active power filter we used two topologies; three-leg (with split DC capacitor) and for-leg inverter. The THDs that we mentioned (1.99 % and 0.97 %) are those of the three-leg configuration. The THDs obtained by the for-leg topology are 2.00 % with low pass filter and 1.07 % with STF.

When we compare between the three-leg and the for-leg topologies, we find the results shown in Tab. I. In this simulation the same balanced system of loads of the period between 0.1s and 0.2s is used:
Fig. 5 Simulation results of STFs under three balanced loads:
(a) Supply and loads currents, (b) 1st phase filter current, (c) Neutral currents,
(d) Harmonic current spectre of 1st phase load, (e) Harmonic current spectre of 1st phase of supply

Table 1: Simulation results for the three and for-leg topologies

<table>
<thead>
<tr>
<th></th>
<th>Between 0.1s and 0.15s</th>
<th>Between 0.25s and 0.29s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3-leg</td>
<td>4-leg</td>
</tr>
<tr>
<td>THD (%)</td>
<td>3.27</td>
<td>4.07</td>
</tr>
</tbody>
</table>

The results of Tab. 1 show that for transient regime the three-leg topology gives the best THD and for steady
regime for-leg topology gives the best THD. For-leg topology is the best because in this topology the neutral is
piloted directly (by hysteresis command) so the THD is best. In three-leg topology the neutral is indirectly piloted so
the THD is high. The simulation results verify the effectiveness and the performances of the proposed harmonic
isolation under balanced load in harmonic elimination for different topologies of rectifier.

3.2 Unbalanced loads

To examine the effectiveness of the STF, simulations under unbalanced system of load are done. This new system
is described below: Resistive load ($R_{d1} = 26 \, \Omega$) powered by dimmer connected between phase 1 and neutral ($\alpha_1 = 60^\circ$), Inductive load ($R_{d2} = 26 \, \Omega$ et $L_{d2} = 30 \, mH$) powered by rectifier, Resistive load ($R_{d3} = 26 \, \Omega$) powered by
dimmer connected between phase 3 and neutral ($\alpha_3 = 30^\circ$).

Fig. 6 shows the simulation results for this system. The THDs of loads are respectively: 32.41 %, 11.87 % and
13.01 %. While the THDs of supply currents are respectively: 3.83 %, 3.43 % and 2.34 %. $I_n$ is the neutral load
current; it contains the third order harmonic, and odd multiple of three harmonics. $I_{ns}$ is the neutral supply current, it
is became zero after compensation.
Fig. 6 Simulation results under three unbalanced loads:

(a) Source and loads currents, (b) Neutral currents, (c) Filter currents, (d) Harmonic current spectres of loads, (e) Harmonic current spectres of supply
3.3 Reactive power compensation

In this simulation STFs are used to compensate reactive and harmonics of source current. The same parameters of the balanced load case are used. Fig.8.a demonstrates that there is a phase difference between source voltage and source current (before compensation). Fig.7.b demonstrates that there is no difference of phase between source voltage and current (phase 1), it means that power factor is became equal to 1 (after compensation).

(a) Before reactive power compensation                                               (b) After reactive power compensation

Fig.7 Supply voltage and current (phase 1)

4. Conclusion

In this paper we have presented a new three-phase for-wire active power filter based on STF extraction, to identify harmonic current and reactive power. The objective was to improve the dynamic of identification method and also selectivity. The advantages of this filter are:

STFs don’t introduce any displacement between input and output, at the fundamental pulsation. Good dynamic, and high selection of fundamental signal. Their selectivity is improved by reducing K. They can filtrate the voltages that are used to calculate instantaneous powers, to identify perturbation, and so PLL is not used. This method reduces the complexity of the control scheme and consequently facilitates the digital implementation of the control system. Those results demonstrate the good performances of the proposed control.

References