Improvement of Power Quality Using Hybrid Power Filter with Fuzzy Logic Controller

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Abstract—In this paper, we present a Hybrid Power Filter (HPF) which consists of a combined system of Passive Filter (PF) and Series Active Power Filter (SAPF) has been designed by MATLAB/SIMULINK approach for harmonic and reactive power compensation. This filter is a three level PWM voltage source inverter and we use a Fuzzy Logic Controller (FLC) algorithm to control the harmonic voltages. The viability of the proposed algorithm is validated in this work. This combined system of filter is able to compensate the reactive power (showed that source voltage is sinusoidal and in phase with source current), and harmonics (voltage & current) for three phase of the non linear load current proposed with RL load. For the following voltage related problems in the power grid voltage flicker and voltage unbalance in three-phase systems are minimized under norm. The proposed solution has achieved an improvement of power quality in distribution system;

Index Terms—active power filter, shunt passive power filter, power quality improvement, power factor, THD, fuzzy controller

I. INTRODUCTION

Power Quality is defined as the extent to which both the utilization and distribution distresses the electric power system affects the efficacy of electrical equipment. These power harmonics are called electrical pollution which will degrade the quality of the power supply. As a result, filtering process for these harmonics is needed in order to improve the quality of the power supply. Therefore, these harmonics must be mitigating. In order to achieve this, series or parallel configurations or combinations of active and passive filters have been proposed depending on the application type [1], [2]. Conventionally passive filters were used to reduce the Total Harmonic Deduction (THD) and compensate the reactive power. Passive filters were considered to most reliable, cost effective, robust, and can be easily maintained. But they suffer from certain disadvantages like create resonance with the system, they are bulky and the most prominent is that they are tuned for particular harmonic frequency [3].

Since the beginning of the 1980s, active power filters (APFs) have become one of the most habitual compensation methods [4]. A usual APF consists of a three-phase Pulse Width Modulation (PWM) voltage source inverter. The APF can be connected either in parallel or in series with the load. The first one is especially appropriate for the mitigation of harmonics of the loads called harmonic current source. In contrast, the series configuration is suitable for the compensation of loads called harmonic voltage source. However, the costs of shunt active filters are relatively high for large-scale system and are difficult to use in high-voltage grids.

In addition, their compensating performance is better in the harmonic current source load type than in the harmonic voltage source load type [5].

II. HYBRID POWER FILTER TOPOLOGY DESCRIPTIONS AND MODELING

A. Description of the HPF Topology

Fig. 1 shows the topology of the combined system of a series active power filter and shunt passive filter, acting as zero impedance for the fundamental frequency and as high resistor for the harmonics frequencies. The HPF, which is supplied by a low power PWM inverter, is connected in series with the main supply and the nonlinear load through the current transformer. The passive filter connected in parallel to the load is used to damp the 5th and the 7th harmonic of Vl because of their high amplitudes.

Figure 1. General configuration of a hybrid power filter

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The series APF acts as a voltage source and inject a compensating voltage in order to obtain a sinusoidal load voltage. The developments in digital electronics, communications and in process control system have made the loads very sensitive, requiring ideal sinusoidal supply voltage for their operation [5], [6].

B. Modeling

Fig. 2 shows the per-phase equivalent scheme of the studied topology.

\[
\begin{bmatrix}
V_s
\end{bmatrix}
= \begin{bmatrix}
V_{slp} & V_{slq} & V_{slr}
\end{bmatrix}
\]

where:
- \(e_c\), \(i_c\), \(L_c\), \(R_c\): Source voltage, source current, source inductance, and source resistance,
- \(V_c\): Line voltage,
- \(V_i\), \(i_i\): Load voltage and load current,
- \(V_{sl}\): Controllable voltage source representing the series active power filter,
- \(i_f\), \(C_f\), \(L_f\): Shunt passive filter current, passive filter capacitance, and passive filter inductance.

This equivalent scheme is modeled by (1) and (2):

\[
\begin{align*}
V_{sl} &= V_s - V_i \\
i_f &= i_t + i_i
\end{align*}
\]

where:

\[
\Delta V_{sl} = V_{slref} - V_{sl}
\]

The voltage error is given by:

\[
V_{slref} = V_{sh} - V_{lh}
\]

\[
V_{sh}, V_{lh}, i_{sh}: \text{represent, respectively, the harmonic components present in } V_s, V_i \text{ and } i_i.
\]

C. APF Voltage References Determination

The harmonic component \(V_{slh}\) of \(V_{sl}\) is defined by:

\[
V_{slh} = V_{sl} - V_{slf}
\]

First, we extract the \(p-q\) components of \(V_{sl}\):

\[
\begin{bmatrix}
V_{slp} \\
V_{slq}
\end{bmatrix} = C_{pq} \begin{bmatrix}
V_{slh} \\
V_{lh}
\end{bmatrix}
\]

\(C_{pq}\), \(C_{32}\) representing the Park matrix and Concordia matrix given respectively by:

\[
C_{pq} = \begin{bmatrix}
\sin(\omega t) & -\cos(\omega t) \\
-\cos(\omega t) & -\sin(\omega t)
\end{bmatrix}
\]

\[
C_{32} = \begin{bmatrix}
1 & -1/2 & -1/2
\end{bmatrix}
\]

Next, decomposition of \(V_{sl}\) and \(V_{slq}\) into continuous components \(V_{slp}, V_{slq}\) and alternative components \(\tilde{V}_{slp}, \tilde{V}_{slq}\):

\[
\begin{align*}
V_{slp} &= V_{slp} + \tilde{V}_{slp} \\
V_{slq} &= V_{slq} + \tilde{V}_{slq}
\end{align*}
\]

\(V_{slp}, V_{slq}\) are obtained via a second order low-pass filter.

Then, the obtained three-phase fundamental components are presented below:

\[
\begin{bmatrix}
V_{slfa} \\
V_{slfb} \\
V_{slfc}
\end{bmatrix} = C_{32} C_{pq}^{-1} \begin{bmatrix}
\tilde{V}_{slp} \\
\tilde{V}_{slq}
\end{bmatrix}
\]

Finally, this algorithm can be represented as shown in the block diagram of Fig. 3.

D. Inverter Control Using PWM

The control method is aimed to control PWM inverter to produce the desired compensation voltage, in the output of series filter. This method is achieved by implementing a fuzzy logic controller [7]-[9] which starts from the difference between the injected voltage \(V_{inj}\) and the calculated reference voltage \(V_{sl}\) that determines the reference voltage of the inverter (modulating wave).

This reference voltage is compared with two carrying triangular identical waves shifted one from other by a half period of chopping producing the control signal to control the on-off of the IGBT [10], [11].

Fig. 4 shows the general block diagram of voltage control used.

The control of inverter arm constituting the series active filter is summarized in the two following steps.

- Determination of the intermediate signals \( V_{i1} \) and \( V_{i2} \).
- If \( \text{error} \geq \text{carrying} \) \( \Rightarrow V_{i1} = 1 \)
- If \( \text{error} < \text{carrying} \) \( \Rightarrow V_{i2} = 0 \)

Determination of control signals of the switches \( T_0 \) (\( j = 1, 2, 3, 4 \)).
- If \( (V_{i1} + V_{i2}) = 1 \Rightarrow T_{11} = 1, T_{12} = 1, T_{13} = 0, T_{14} = 0 \)
- If \( (V_{i1} + V_{i2}) = 0 \Rightarrow T_{11} = 0, T_{12} = 1, T_{13} = 1, T_{14} = 0 \)
- If \( (V_{i1} + V_{i2}) = -1 \Rightarrow T_{11} = 0, T_{12} = 0, T_{13} = 1, T_{14} = 1 \)

E. Fuzzy Control Application

The FLC concept was proposed in 1965 that was based on a logical system called fuzzy logic. It is much closer in spirit to human thinking and natural language. FLC was deduced from fuzzy set theory. Fuzzy sets boundaries were undefined, ambiguous and useful for approximate systems design [12], [13]. FLC is used for the HPF in closed loop to control a constant DC voltage, improve the performance and reduce the THD of the current.

The (\( e \)) and its derivation (\( de \)) are used as inputs for fuzzy process.

Fig. 5 shows the synoptic scheme of fuzzy controller, which possesses two inputs (the error (\( e \))).

\[
(\frac{V_{\text{ref}}}{V_{\text{inj}}}) \text{ and (} \frac{\text{derivative}}{V_{\text{inj}}}, \text{and one output (the command (} \frac{c_{\text{de}}}{)})) \text{.} \ [9]
\]

Mainly, the three main features of FLC are Fuzzification, Fuzzy Inference Mechanism (Knowledge base) and Defuzzification.

- **Fuzzification:** The conversion process of a numerical variable to a linguistic variable.
- **Rule Elevator:** FLC uses linguistic variables as a control gain. The basic operations of FLC requires AND (\( \cap \)), OR (\( \lor \)) and (NOT (\( \neg \))) for evaluation fuzzy set rules.
- **Defuzzification:** The conversion process of linguistic variable to a numerical variable.
- **Database:** stores the definition of the triangular membership function for the fuzzifier and defuzzifier.
- **Rule Base:** stores the linguistic control rules required by rule evaluator. The 25 rules in this proposed controller are shown in Table I. is based on the error (\( e \)) sign, variation and knowing that (\( e \)) is increasing if its derivative (\( de \)) is positive, constant if (\( de \)) is equal to zero, decreasing if (\( de \)) is negative, positive if (\( V_{\text{ref}} > V_{\text{inj}} \)), zero if (\( V_{\text{ref}} = V_{\text{inj}} \)), and negative if (\( V_{\text{ref}} < V_{\text{inj}} \)).

### Table I. Rules Base of Fuzzy Control

<table>
<thead>
<tr>
<th>( C_{de} )</th>
<th>( BN )</th>
<th>( N )</th>
<th>( Z )</th>
<th>( P )</th>
<th>( BP )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( e )</td>
<td>( BN )</td>
<td>( N )</td>
<td>( Z )</td>
<td>( P )</td>
<td>( BP )</td>
</tr>
<tr>
<td>( f_{BP} )</td>
<td>( f_{N} )</td>
<td>( f_{Z} )</td>
<td>( f_{P} )</td>
<td>( f_{BP} )</td>
<td></td>
</tr>
<tr>
<td>( f_{BN} )</td>
<td>( f_{N} )</td>
<td>( f_{Z} )</td>
<td>( f_{P} )</td>
<td>( f_{BP} )</td>
<td></td>
</tr>
</tbody>
</table>

With: (\( BN \)): Big negative; (\( N \)): Negative; (\( Z \)): Zero; (\( P \)): Positive and (\( BP \)): Big positive

Fig. 6 shows the membership function of FLC used for the error (\( e = V_{\text{ref}} - V_{\text{inj}} \)) and its derivative (\( de \)), and one output (the command (\( c_{de} \))).

![Figure 6. Membership function of FLC used](image)

III. Simulation Results

The simulation is carried out using a program working in MATLAB/SIMULINK environment. For non linear load we use a three phase diode rectifier with RL load.

The simulation parameters are shown in the Table II.

### Table II. System Parameters

<table>
<thead>
<tr>
<th>Source</th>
<th>( e_i )</th>
<th>230 V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load</td>
<td>( L_i )</td>
<td>5,5 mH</td>
</tr>
<tr>
<td>Load</td>
<td>( R_i )</td>
<td>3,6 Ω</td>
</tr>
<tr>
<td>Passive filter</td>
<td>( L_{dC} ), ( C_{dC} )</td>
<td>13,5 mH .30 ΜF</td>
</tr>
<tr>
<td>Passive filter</td>
<td>( L_{dC} ), ( C_{dC} )</td>
<td>6,75 mH .50 ΜF</td>
</tr>
<tr>
<td>Switching Frequency</td>
<td></td>
<td>10KH</td>
</tr>
<tr>
<td>Current sensor gain</td>
<td></td>
<td>5</td>
</tr>
</tbody>
</table>

A. Without Filtering

In Fig. 7 we present the waveform of the load current, load voltage, and the delay between voltage and current that represents the absorbed reactive power or power factor of the system.

![Figure 7. Waveforms of load (current, voltage), and their delay](image)
Fig. 8 shows the waveform of the three voltages on the same graph. In this figure we see that there are disruptive phenomena appear as flicker and voltage imbalance.

Fig. 9 shows the harmonic spectrum of current without filtering.

The harmonic spectrum of current shows that the harmonics of order 5, 7, 11, 13...; are the most predominant harmonic and have larger amplitudes; because they are harmonics characteristics (following relationship $6K \pm 1$; k is an integer number); and return to the non linear load used (Three phase rectifier PD3).

B. With Passive Filter (PF) Only

The simulations results with passive filter only are presented in Fig. 10, Fig. 11 and Fig. 12.

Fig. 12 shows the harmonic spectrum of current with passive filter only.

After the use of the passive filtering (two resonant filter to rank harmonics 5 and 7); we clearly see the elimination of the current harmonics of order 5 and 7.

C. With Hybrid Power Filter (HPF)

The simulations results after filtering by using hybrid power filter are presented in Fig. 13-Fig. 16.
In Table III and Table IV we present the simulations results before and after filtering for currents and voltages harmonics.

**TABLE III. SIMULATION RESULTS OF HARMONICS CURRENTS**

<table>
<thead>
<tr>
<th>Harmonic Currents</th>
<th>Without Filtering</th>
<th>With PF Only</th>
<th>With HPF</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>19.00 %</td>
<td>0.26 %</td>
<td>0.19 %</td>
</tr>
<tr>
<td>7</td>
<td>12.29 %</td>
<td>0.32 %</td>
<td>0.03 %</td>
</tr>
<tr>
<td>11</td>
<td>6.63 %</td>
<td>2.19 %</td>
<td>1.54 %</td>
</tr>
<tr>
<td>13</td>
<td>4.93 %</td>
<td>1.74 %</td>
<td>1.27 %</td>
</tr>
<tr>
<td>17</td>
<td>3.35 %</td>
<td>0.71 %</td>
<td>0.97 %</td>
</tr>
<tr>
<td>19</td>
<td>2.03 %</td>
<td>0.77 %</td>
<td>0.59 %</td>
</tr>
<tr>
<td><strong>THDI</strong></td>
<td><strong>24.46 %</strong></td>
<td><strong>3.40 %</strong></td>
<td><strong>2.19 %</strong></td>
</tr>
</tbody>
</table>

**TABLE IV. SIMULATION RESULTS OF HARMONICS VOLTAGES**

<table>
<thead>
<tr>
<th>Harmonic Voltages</th>
<th>Without Filtering</th>
<th>With PF Only</th>
<th>With HPF</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1.14 %</td>
<td>0.85 %</td>
<td>0.67 %</td>
</tr>
<tr>
<td>7</td>
<td>0.48 %</td>
<td>0.76 %</td>
<td>0.28 %</td>
</tr>
<tr>
<td>11</td>
<td>4.08 %</td>
<td>3.42 %</td>
<td>2.42 %</td>
</tr>
<tr>
<td>13</td>
<td>3.34 %</td>
<td>2.77 %</td>
<td>1.94 %</td>
</tr>
<tr>
<td>17</td>
<td>2.12 %</td>
<td>3.50 %</td>
<td>1.29 %</td>
</tr>
<tr>
<td>19</td>
<td>1.88 %</td>
<td>2.03 %</td>
<td>1.07 %</td>
</tr>
<tr>
<td><strong>THDv</strong></td>
<td><strong>7.49 %</strong></td>
<td><strong>6.74 %</strong></td>
<td><strong>4.27 %</strong></td>
</tr>
</tbody>
</table>

It summarizes in the Table V: harmonic minimization rate with the use of only passive filtering (PF) and hybrid Power filtering (HPF).

**TABLE V. EFFICIENCY OF THE FILTERS USED**

<table>
<thead>
<tr>
<th>Harmonics Currents</th>
<th>Harmonics Voltages</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>With PF Only</td>
</tr>
<tr>
<td>5</td>
<td>98.63 %</td>
</tr>
<tr>
<td>7</td>
<td>97.4 %</td>
</tr>
<tr>
<td>11</td>
<td>68.33 %</td>
</tr>
<tr>
<td>13</td>
<td>64.71 %</td>
</tr>
<tr>
<td>17</td>
<td>78.81 %</td>
</tr>
<tr>
<td>19</td>
<td>62.07 %</td>
</tr>
<tr>
<td><strong>THD</strong></td>
<td><strong>86.1 %</strong></td>
</tr>
</tbody>
</table>
IV. DISCUSSIONS

After the simulation results, we note that with the use of passive filtering (Filter 5 and 7) that there a total elimination of harmonic 5th and 7th which have large amplitudes; The harmonic 5 is reduced from 19% to 0.26% with rate of 98.63%; the harmonic 7 from 12.29% to 0.32% with rate of 97.4% and for the current THD is reduced from 24.46% to 3.40% with rate 86.1% For the voltage THD is reduced from 7.49% to 6.74% with rate of 10.01%

The obtained results for hybrid filter showed clearly that the use of is better than utilization of passive filter only especially for mitigation of voltages harmonics from 7.49% to 4.27 with rate of 36.98% under norm (5%). and the same for the current THDI from 24.46% to 2.19% (Under Standard) with rate of 91.05% [14].

In Fig. 7 shows the delay between current and source voltage is big but the Fig. 13 illustrates the delay reduction between source current and voltage; i.e. power factor correction when the hybrid filter is connected.

In Fig. 8 we see that it to be disruptive phenomena associated with voltage as imbalance and flicker and after use a Hybrid Filter we note that these phenomena are reduced (Fig. 14) and this because the injected voltage by this filter.

V. CONCLUSION

In this paper we have presented the three-phase hybrid active power filter for compensation of harmonic currents generated by the non-linear load. The fuzzy logic control based HPF for three-phase system is modeled and simulated in MATLAB/SIMULINK environment. The main objective of this research work has been accomplished.

The total harmonic distortion of the supply current and voltage has been decreased at a high level in the simulation. Which is an achievement to meet the IEEE 519 recommended harmonic standard. In fact, not only the harmonics were reduced to an acceptable rate, but also the transient response time was minimized. Moreover, the utility power factor was corrected, unbalanced voltage and flicker is minimized.

REFERENCES


Dr. Yacine Djeighader was born in 1980 in Annaba, Algeria. He received the BS degree, MS degree and Ph.D. degree in Electrical Engineering from Annaba University, Algeria in 2003, 2006 and 2011 respectively. Presently he is Assistant Professor in Electrical Engineering in Souk Ahras University, Algeria; His fields of interest are Power Quality, Power System, FACTS, Power Electronic.