Power Quality Improvement Using a Shunt Active Power Filter Based on the Hysteresis Current Controller

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Abstract— one of the main power quality concerns currently is the existence of harmonics. Shunt active power filters are widely applied in power distribution grids to mitigate current harmonics and compensate the reactive power. In this paper the instantaneous reactive power theory is used to detect reference compensation current for the controller of the shunt active filter and a hysteresis current controller is used to synthesize it precisely. Hysteresis current controller is one of the simplest current control methods and the most popular one for active power filter applications, but it suffers from an uneven switching frequency, to overcome this disadvantage a novel fuzzy hysteresis current controller is being used. The proposed controller is characterized by simplicity as a result of reducing the size of calculations that makes it acting faster and doesn’t rely on the load parameters. The system was modeled and simulated using MATLAB/SIMULINK. The results of simulation are presented and discussed they show the effectiveness of the proposed fuzzy hysteresis controller in improving the PWM performance and thus improve the shunt active power filter performance.

Index Terms— Shunt Active Power Filters, p-q theory, Hysteresis Band Current Controller, Fuzzy Logic, Harmonic Distortion

I. INTRODUCTION

Ideally an electricity supply should fixedly show a perfectly sinusoidal voltage signal at every customer location. However, for a number of reasons, utilities often find it difficult to maintain such desirable condition [1,2]. For example the widespread use of nonlinear devices likes (microprocessor, variable speed drives, uninterrupted power supplies and electronic lighting) which have become used on a large scale. These modern power electronic devices draw a significant amount of harmonics from the electrical grid; these non sinusoidal currents interact with the impedance of the power distribution lines creating voltage distortion at the point of common coupling (PCC) that can affect both the distribution system equipment and the user loads connected to it. As a result, the utilities obliged to reduce the total harmonic distortion (THD) at the point of common coupling below 5% as given in the IEEE 519-1992 harmonic standard. This can be achieved through the use of the harmonic filters whether passive or active filters [3-5]. The passive filtering is the simplest classical solution to mitigate the harmonic distortion, these filters consisting of R, L and C elements connected in various configurations. Although simple, these filters have many defects such as fixed compensation, bulky size and resonance so these filters may not be able to achieve the desired performance thus we need to use dynamic and adjustable devices to mitigate the power quality problems such as active power filters [6,7]. Active power filters are considered the most ideal solutions to the many of power quality problems such as harmonics, reactive power, regulate terminal voltage, flicker and improve voltage balance in three phase systems. Shunt active power filter is the most important configuration and widely used in active power line conditioners applications. It automatically adapts to changes in the grid and load fluctuations, can compensate for several harmonic orders and eliminating the risk of resonance between the filter and the grid impedance [8-14].

II. SHUNT ACTIVE POWER FILTER

Shunt active power filter based on voltage source converter (VSC) is an effective solution to current harmonics, reactive power and current unbalance. The basic principle of this filter is to use power electronics technologies to generate particular currents components that can cancel the current harmonic components from non linear load [15-17].

The performance of the shunt active filter depends on the reference compensating current detection algorithm and the current control technique used to drive the gating pulses of the active power filter switches to generate compensating current that should be injected into the power system to mitigate the current harmonics and compensate the reactive power [18-22]. The compensation characteristics of the shunt APF are shown in Fig. 1.
III. INSTANTANEOUS REACTIVE POWER THEORY

Estimation of reference compensating current can be done through two main approaches, time domain and frequency domain approach. A time domain method uses the conventional concepts of circuit analysis and algebraic transformations that require less calculation, thus simplifying the control function, in the opposite the frequency domain methods require a large amount of calculations and a lot of memory [23].

Reactive power theory is the most commonly used time domain methods where it is very efficient and flexible in designing controllers for active power filters. It's based on a set of instantaneous powers defined in the time domain, thus allowing the controller of the active filters to operate in real time. The following steps are used to calculate current harmonic components of the load current that are used as a reference signal for the shunt active power filter controller [24-26].

Step 1: transform the three phase load currents and phase voltages from the a-b-c coordinates to \( \alpha - \beta \)-0 coordinates by:

\[
\begin{bmatrix}
  i_{\alpha} \\
  i_{\beta} \\
  v_{\alpha} \\
  v_{\beta}
\end{bmatrix}
=egin{bmatrix}
  \frac{2}{3} & -\frac{1}{2} & -\frac{1}{2} \\
  0 & \sqrt{3}/2 & -\sqrt{3}/2 \\
  1 & 0 & 0 \\
  0 & 1 & 0
\end{bmatrix}
\begin{bmatrix}
  i_a \\
  i_b \\
  i_c \\
  v_a \\
  v_b \\
  v_c
\end{bmatrix}
\]

Step 2: calculate the values of the instantaneous real and imaginary powers by:

\[
p = v_{\alpha}^* i_{\alpha} + v_{\beta}^* i_{\beta}
\]

\[
q = v_{\beta} i_{\alpha} - v_{\alpha} i_{\beta}
\]

Step 3: for this step, as shown in Fig. 2. The high pass filter is used to extract the oscillating components of real power.

Step 4: The compensated currents produced by the shunt APF in \( \alpha - \beta \) coordinates are;

\[
\begin{bmatrix}
  i^{*}_{\alpha a} \\
  i^{*}_{\alpha b} \\
  i^{*}_{\alpha c}
\end{bmatrix} = \frac{1}{\sqrt{3}} \begin{bmatrix}
  1 & 0 & 0 \\
  0 & \sqrt{3}/2 & -\sqrt{3}/2 \\
  0 & 1 & 0
\end{bmatrix}
\begin{bmatrix}
  p \\
  q
\end{bmatrix}
\]

Step 5: these currents are transformed from \( \alpha - \beta \) coordinates to the a-b-c coordinates that are used as a reference signal for active power filter controller:

\[
\begin{bmatrix}
  i^{*}_{\alpha a} \\
  i^{*}_{\beta a} \\
  i^{*}_{\gamma a}
\end{bmatrix} = \begin{bmatrix}
  \sqrt{2}/2 & 1/2 & 0 \\
  \sqrt{2}/2 & -1/2 & \sqrt{3}/2 \\
  1 & 0 & -\sqrt{3}/2
\end{bmatrix}
\begin{bmatrix}
  i^{*}_{\alpha a} \\
  i^{*}_{\alpha b} \\
  i^{*}_{\alpha c}
\end{bmatrix}
\]

IV. HYSTERESIS CURRENT CONTROL

Current controller is the most critical part for the shunt active power filter performance that drawn more attention from industry and researchers [27]. It force power circuit of the shunt active filter to synthesize the compensating current precisely by drive the gating pulses of the active power filter switches [28].

There are various current control methods such as PI control, sinusoidal PWM and hysteresis control. Hysteresis current controller has proven to be the most suitable for all the application of current controlled voltage source converters in shunt active power filters [29-33]. It derives the switching signals of the active power filter switches by comparing the current error signal with a constant hysteresis band as shown in Fig. 3.
The current controller is designed to the three phases and the switching logic for each phase is developed as follows [5,23,34-36]. If the error current exceeds the upper limit of the hysteresis band, the upper switch of the inverter arm is turned off and the lower switch is turned on. As a result, the current starts to decay. If the error current crosses the lower limit of the band, the lower switch is turned off and the upper switch is turned on. As a result, the current gets back into the hysteresis band.

The main problem when applying the conventional hysteresis band current controller is its uneven switching frequency and that leads to audio noises, high switching losses, injection of high frequency ripple current to the system and difficulty in designing suitable filters to remove these high frequency components. To avoid these unsatisfactory features adaptive hysteresis band has been recommended in the literature [37-44] to control the modulation frequency.

1) During the switching period (t1):

The current ramps from lower hysteresis band -HB to the upper hysteresis band +HB and the inverter side voltage is +0.5Vdc.

\[
\frac{di_{a}^{+}}{dt} = \frac{1}{L} (0.5 V_{dc} - v_s(t))
\]  

(7)

2) During the switching period (t2):

The currents ramps from upper hysteresis band +HB to the lower hysteresis band -HB and the inverter side voltage is -0.5 Vdc.

\[
\frac{di_{a}^{-}}{dt} = -\frac{1}{L} (0.5 V_{dc} + v_s(t))
\]  

(8)

From the geometry of Figure 4, we can write

\[
\frac{di_{a}^{+}}{dt} - \frac{di_{a}^{-}}{dt} = 2HB
\]  

(9)

\[
\frac{di_{a}^{-}}{dt} - \frac{di_{a}^{+}}{dt} = 2HB
\]  

(10)

\[
t_1 + t_2 = T_s = \frac{1}{f_{sw}}
\]  

(11)

Where \( t_1 \) and \( t_2 \) are the respective switching intervals, and \( f_{sw} \) is the modulation frequency. Adding (9) and (10) and substituting (11), we can write:

\[
t_1 \frac{di_{a}^{+}}{dt} + t_2 \frac{di_{a}^{-}}{dt} = \frac{1}{f_{sw}} \frac{di_{a}^{*}}{dt}
\]  

(12)

Subtracting (10) from (9), we get

\[
4HB = t_1 \frac{di_{a}^{+}}{dt} - t_2 \frac{di_{a}^{-}}{dt} - (t_1 - t_2) \frac{di_{a}^{*}}{dt}
\]  

(13)

Substituting (8) in (13)

\[
4HB = (t_1 + t_2) \frac{di_{a}^{*}}{dt} - (t_1 - t_2) \frac{di_{a}^{*}}{dt}
\]  

(14)

Substituting (8) in (12) and simplifying

\[
t_1 - t_2 = \frac{\frac{di_{a}^{*}}{dt}}{f_{sw} (\frac{di_{a}^{*}}{dt})}
\]  

(15)

Substituting (15) in (14), gives

\[
HB = \left[ \frac{0.125 V_{dc}}{f_{sw} L} (1 - \frac{4L^2}{V_{dc}^2} (v_s(t) + S)) \right]
\]  

(16)

Where \( f_{sw} \) is the switching frequency; 0.5 Vdc is half of the total bus voltage; L is the output load inductor; \( v_s(t) \) is the supply voltage; S is the slope of reference current and \( HB \) is the hysteresis band.

The adaptive HB should be derived instantaneously during
each sample time to keep the switching frequency remains nearly constant, this can be achieved with the help of fuzzy logic controller as stated in literature [20,23,45,46], which $S$ and $V_s(t)$ are taken as input variables to the fuzzy controller and the HB is the output. But if the reference current is assumed to be smooth, the following equations can be written in the switching intervals $t_1$ and $t_2$:

$$\frac{2HB}{t_1} = 0.5 v_{dc}^2 - v_s(t)$$  \hspace{1cm} (17)$$

$$\frac{-2HB}{t_2} = -0.5 v_{dc}^2 - v_s(t)$$  \hspace{1cm} (18)$$

Combining (17) and (18) and solving for the switching period $T$ gives:

$$T = \frac{2LHBv_{dc}}{(0.25v_{dc}^2 - v_s^2(t))}$$  \hspace{1cm} (19)$$

$$f_{sw} = \frac{(0.25v_{dc}^2 - v_s^2(t))}{2LHBv_{dc}}$$  \hspace{1cm} (20)$$

For a fixed hysteresis band current controller the parameters of equation (20) are constant except for the supply voltage that changes over each fundamental cycle causing uneven switching frequency for the voltage source converter, therefore, if $HB$ can be varied in response to $v_s(t)$ a constant switching frequency can be achieved [47,48]. In next section fuzzy logic based adaptive hysteresis current controller will help to fix the switching frequency.

V. THE PROPOSED FUZZY LOGIC FOR HYSSTERESIS CURRENT CONTROLLER

The fuzzy logic controller is one of the advantageous control methods for systems facing difficulties in obtaining mathematical models or having performance restrictions with traditional linear control methods. In a fuzzy logic controller, the control signal is determined from the assessment of a set of linguistic rules (if-then rules), these rules are obtained from our understanding of the process to be controlled. To design fuzzy controller, variables that can represent the dynamic performance of the system to be controlled must be taken as the inputs to the controller [49]. Subsequently the supply voltage $v_s(t)$ and its derivative $\Delta v_s(t)$ are chosen as inputs to the fuzzy controller, and the hysteresis band ($HB$) is taken as the output as shown in Fig. 5

VI. SIMULATION RESULTS

This section introduce the details of simulations that have been implemented using MATLAB/SIMULINK, to shows the performance of the proposed shunt active power filter to mitigate the current harmonics and compensate reactive power in the distribution grid. Test system that was used to carry out the analysis consists of a three-phase diode bridge rectifier with RL load Connected to three-phase three wire distribution system and shunt active power filter connected to the system by an inductor $L$. The control strategy of the shunt active filter based on p-q theory to generate the reference compensation current, hysteresis band current controller to drive the gating signals of the shunt active filter switches and PI controller to regulate the voltage of dc side capacitor of the shunt active filter. The values of the circuit components used in the simulation are given in Table I. The system performance was analyzed without the shunt active filter and Fig. 6 gives the details of source voltage, source current, load current, harmonic spectrum of the supply current, real and reactive power supplied by the source to the load. It is seen that line current is distorted due to nonlinear load and the total harmonic distortion (THD) of the supply current is 24.44%, this current distortion resulting from the dominance of 5th, 7th, 11th and 13th harmonic spectral components. Real and reactive power supplied from the source to the load have constant values and a superposition of oscillating components, These oscillating components are related to the presence of harmonics.
Table I System parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply Phase to Phase Voltage</td>
<td>400 V</td>
</tr>
<tr>
<td>Grid Frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Supply Line Parameters</td>
<td>Rs=0.01Ω &amp; Ls=1mH</td>
</tr>
<tr>
<td></td>
<td>R=13Ω &amp; L=100mH</td>
</tr>
<tr>
<td>Rectifier Side Inductance</td>
<td>1mH</td>
</tr>
<tr>
<td>Filter Coupling Inductance</td>
<td>4mH</td>
</tr>
<tr>
<td>Filter Capacitance</td>
<td>2mF</td>
</tr>
<tr>
<td>Reference DC Voltage</td>
<td>700V</td>
</tr>
<tr>
<td>Fixed Hysteresis Band Limit</td>
<td>0.7 A</td>
</tr>
<tr>
<td>Proportional gain KP</td>
<td>0.89</td>
</tr>
<tr>
<td>Integral gain KI</td>
<td>197</td>
</tr>
<tr>
<td>Sampling Time</td>
<td>5e-6</td>
</tr>
</tbody>
</table>

Fig.6. Simulation results without SAPF (a) source voltage (b) supply current (c) load current (d) harmonic spectrum of the line current (e) load real power (f) load reactive power
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A. PERFORMANCE OF FIXED HYSTERESIS BAND CURRENT CONTROLLER BASED SAPF

The system performance was analyzed and the resulting waveforms source voltage, source current, load current, reference current, filter current, tracking shunt active filter for phase (a), supply current, harmonic spectrum of the supply current, real and reactive power supplied by the source to the load are shown in Fig. 7(a)-(i) respectively. As shows the shunt active power filter (SAPF) shows a good filtering process which leads to compensate harmonic components from the source current, as it is clear from Table II and harmonic spectrum analysis of the supply current, THD of the source current has decreased from 24.44% to 2.63% that is less than 5% which is in compliance with IEEE 519-1992 standard for harmonics under non linear loads. As well shows the undesired portions of the real and reactive power of the load that related to the presence of harmonics have been compensated by the SAPF and the source supplies only fundamental real power and zero reactive power to the load. In spite of that when applying the conventional hysteresis band current controller the Shunt APF operates in uneven switching frequency as it is shown in Fig. 8. This uneven switching frequency Leads to audio noises, high switching losses, injection of high frequency ripple current to the system and makes the design of suitable filters to remove these high frequency components is difficult, difficulty in determining convenient switching device and calculate its switching losses. To avoid these unsatisfactory features, adaptive hysteresis band current controller with the changeable hysteresis band will be used based on the fuzzy logic.
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shown in Fig. 9(a)-(i) respectively. The THD of the supply current has decreased from 24.44% to 3.03% as it is clear from Table III and harmonic spectrum of the compensated source current and we can see that the reactive power drawn by the load becomes zero and the source supplies only fundamental real power to the load, this means that all the undesirable current components of the load are being eliminated. As shown in Fig.10. The switching frequency becomes nearly constant and the switching ripple components of the source current has been concentrated to a narrow range around (10 KHz to 13 KHz)
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C. PERFORMANCE OF PROPOSED FUZZY HYSTERESIS BAND CURRENT CONTROLLER BASED SAPF

Three linguistic variables are set to the inputs and output of the controller as NL (Negative Large), ZE (Zero), PL (Positive Large) for inputs and PS (Positive small), PM (Positive Medium), PL (Positive Large) for output, triangular membership functions as shown in Fig. 11, have been used for input and output variables because of its simplicity, the fuzzy rules are given in Table IV. Fig. 12 (a)-(e) highlights the performance of proposed fuzzy hysteresis current controller, gives the details of source voltage, source current, load current, reference current, filter current, tracking shunt active filter for phase (a), supply current, harmonic spectrum of the supply current, real and reactive power supplied by the source to the load. The THD of the supply current has decreased from 24.44% to 2.66% as it is clear from Table V and harmonic spectrum of the compensated source current and the undesirable portions of the real and reactive powers of the load that related to the presence of harmonics have been compensated by the SAPF and the source supplies only fundamental real power and zero reactive power to the load. It is seen from Fig. 13, that the switching frequency becomes nearly constant and the switching ripple components of the source current has been concentrated to a narrow range around (15 KHz), this means that the proposed fuzzy hysteresis band current controller has worked properly and the modulation frequency of the shunt active power filter is held in 15 KHz. Hence select the appropriate filter to mitigate the ripple components in the filter current, determine convenient switching device and calculate switching losses has become easier.

Table IV Fuzzy inference rule

<table>
<thead>
<tr>
<th>Vr (t)</th>
<th>PL</th>
<th>Z</th>
<th>NL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 10 (a) switching patterns of S1 (b) FFT analysis of the source current in high frequency range.
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<table>
<thead>
<tr>
<th>$\Delta V_s(t)$</th>
<th>PS</th>
<th>PS</th>
<th>PS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z$</td>
<td>PM</td>
<td>PL</td>
<td>PM</td>
</tr>
<tr>
<td>NL</td>
<td>PS</td>
<td>PS</td>
<td>PS</td>
</tr>
</tbody>
</table>

Fig. 11 Membership functions of the input variables and output variable
(a) Source voltage (b) rate of change of source voltage (c) hysteresis band
(d) Filter current (e) Source Voltage

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International Electrical Engineering Journal (IEEJ)
Vol. 7 (2016) No.5, pp. 2266-2278
ISSN 2078-2365
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VII. RESULTS AND ANALYSIS

The results obtained from the simulation is given in table VII. It shows that the three current controllers, fixed HCC, Traditional fuzzy HCC and Proposed fuzzy HCC have been found to meet the IEEE 519-1992 standard for harmonics under nonlinear loads where THD is less than 5% at the point of common coupling, with the following observations:

- The proposed fuzzy HCC gets better compensation than traditional fuzzy HCC.
- The modulation frequency is held nearly fixed with Traditional fuzzy HCC and got constant more and more using the proposed fuzzy HCC contrary to fixed HCC.
- The proposed fuzzy HCC acts faster than traditional Fuzzy HCC as a result of the use of simplified calculations (9 rules instead of 25 rules)

<table>
<thead>
<tr>
<th>THD%</th>
<th>Phase a</th>
<th>Phase b</th>
<th>Phase c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source current</td>
<td>2.67</td>
<td>2.64</td>
<td>2.69</td>
</tr>
<tr>
<td>Load Current</td>
<td>24.44</td>
<td>24.34</td>
<td>24.55</td>
</tr>
</tbody>
</table>

Table V Total harmonic distortion of source and load currents

Fig. 13 (a) switching patterns of S1 (b) FFT analysis of the source current in high frequency range.
The proposed fuzzy HCC forces the compensating current to track the reference compensation current more accurately.

The proposed fuzzy HCC characterized by removing reliance on variable parameters like reference current that is detected from load parameters and uses only fixed parameters like supply voltage that does not change in a real system.

Table VII Summary of total harmonic distortion of source current and switching frequency for each current controller

<table>
<thead>
<tr>
<th>Current Control Technique</th>
<th>THD %</th>
<th>Switching Frequency (KHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without Filter</td>
<td>24.44</td>
<td></td>
</tr>
<tr>
<td>FHCC</td>
<td>2.63</td>
<td>10.18</td>
</tr>
<tr>
<td>Traditional fuzzy HCC</td>
<td>3.03</td>
<td>10.13</td>
</tr>
<tr>
<td>Proposed fuzzy HCC</td>
<td>2.66</td>
<td>15</td>
</tr>
</tbody>
</table>

VIII. CONCLUSION

Shunt active power filter is the most effective solution to mitigate the current harmonics and compensate the reactive power. In this paper a novel current control strategy based on fuzzy logic for shunt APF was introduced to improve the current controller technique that is the backbone of the shunt active power filter operation. The simulation results have verified the effectiveness of this new technique to fix the modulation frequency of the shunt active power filter compared to the conventional current controller where the modulation frequency changing over a wide range causing many of undesirable effects.

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Strategies for Current harmonics cancellation in 3-ph 4wire SHAF


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