Distributed Control for the Parallel DC Linked Modular Shunt Active Power Filters under Distorted Utility Voltage Condition

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Basic Analogy (Concept)
Basic Analogy (Concept)
Active Power Filter

The main aim of the APF is to compensate for the harmonics and reactive power dynamically.

Figure 1: Non ideal-load current

Figure 2: Injected converter compensation current

Figure 3: Grid current after active power filtering
Introduction

- Parallel-APF configuration is used, instead of high capacity single units, to add flexibility and reliability during operation.

- Individual sub-controllers are used for each APF unit to determine distributed harmonic currents and reactive components with the PWM circuit. While all the Sub-Controllers are governed by one Main Controller. The control complexity is significantly reduced with use of the proposed controller.

- The proposed system has been verified under distorted and unbalanced grid voltages.
3. Topology of Proposed Parallel Modular APF’s

1. **Individual Sub-Control Units**

2. **Main Control Unit**

Fig. The power circuit of the common dc-linked modular APF and associated control units
3. Proposed Control Strategy

A- ) Main Controller

**Fig. Main Controller**
Therefore, the performance of the control method is dependent on the type of PLL algorithm used. In order to improve the efficiency of the PLL, the three-phase supply voltages \( (u_a, u_b, u_c) \) are transformed using the Clarke (or \( \alpha-\beta \)) transformation into a different coordinate system by using:

\[
\begin{bmatrix}
u_a \\
u_b \\
u_c
\end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix}
1 & -\frac{1}{2} & -\frac{1}{2} \\
0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\
1 & 1 & 1
\end{bmatrix} \begin{bmatrix}
u_a \\
u_b \\
u_c
\end{bmatrix}
\]

3. Proposed Control Strategy  A- ) Main Controller
3. Proposed Control Strategy  
A- ) Main Controller

\[ -\dot{u}_\alpha(s) = \frac{K_1}{s} [u_\alpha(s) - \dot{u}_\alpha(s)] - \frac{\omega}{s} u_\beta(s) \]

\[ -\dot{u}_\beta(s) = \frac{K_1}{s} [u_\beta(s) - \dot{u}_\beta(s)] + \frac{\omega}{s} u_\alpha(s) \]

\[
\begin{bmatrix}
u_\alpha \\
u_\beta \\
\bar{u}_0
\end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix}
1 & -\frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{3}} \\
0 & \frac{2}{\sqrt{3}} & -\frac{2}{\sqrt{3}} \\
1 & 2 & 1
\end{bmatrix} \begin{bmatrix}
u_a \\
u_b \\
u_c
\end{bmatrix}
\]
3. Proposed Control Strategy  A- ) Main Controller

**Fig.** PI Regulator for Inverter Losses Measurement
3.) Proposed Control Strategy  B) Sub Controller

Figure 9: The proposed sub-control system unit for each Inverter
Beside this, the un-balanced load currents are also important power quality issue that may reduce the performance of the APF.

For this reason, the obtained $i_d$ and $i_q$ components of the load current are also processed with STF in order to calculate balanced current components.

$$
\begin{bmatrix}
    i_d \\
    i_q \\
    i_a \\
    i_b \\
    i_c
\end{bmatrix} = \frac{2}{3}
\begin{bmatrix}
    \cos \theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\
    -\sin \theta & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \\
    \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}}
\end{bmatrix}
\begin{bmatrix}
    i_a \\
    i_b \\
    i_c
\end{bmatrix}
$$

$$
\ddot{i}_d(s) = \frac{K_2}{s} \left[ i_d(s) - \dot{i}_d(s) \right] - \frac{\omega}{s} \ddot{i}_q(s)
$$

$$
\ddot{i}_q(s) = \frac{K_2}{s} \left[ i_q(s) - \dot{i}_q(s) \right] + \frac{\omega}{s} \ddot{i}_d(s)
$$
3.) Proposed Control Strategy  B) Sub Controller

After obtaining the balanced and undistorted current components, the fundamental and harmonics components of instantaneous currents can be obtained by using equations,

\[ \tilde{i}_d = i_d - \bar{i}_d \]

\[ \tilde{i}_q = i_q - \bar{i}_q \]

In the most of the control method, a low-pass or high-pass filter is used to separate the fundamental and harmonic currents. However, there is no need for an additional filter in the proposed control method.
3.) Proposed Control Strategy  B) Sub Controller

Finally, the obtained current harmonic components are then transformed to the three phase converter reference currents using the inverse synchronous transform as given by,

\[
\begin{bmatrix}
    i_{ca}^* \\
    i_{cb}^* \\
    i_{cc}^*
\end{bmatrix}
= \sqrt{\frac{2}{3}}
\begin{bmatrix}
    \cos \theta & -\sin \theta \\
    \cos(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{2\pi}{3}) \\
    \cos(\theta + \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3})
\end{bmatrix}
\begin{bmatrix}
    \tilde{i}_d \\
    \tilde{i}_q
\end{bmatrix}
\]
3. Simulation Results

The proposed control method is simulated using MATLAB/Simulink and power system block set environment to verify the performance of the system. Three variable RL type non-linear load is used to see dynamic performances of the modular APF. Additionally, a load is used to create additional unbalance currents condition in the studied system. The used parameters in these work are given in Table I.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \omega, f )</td>
<td>Ideal Line to Neutral Volt. &amp; Freq.</td>
<td>240V, 50 Hz</td>
</tr>
<tr>
<td>( Z )</td>
<td>Grid Line Impedance</td>
<td>3 m( \Omega ), 2.6 ( \mu )H</td>
</tr>
<tr>
<td>( Z_i )</td>
<td>Load Line Impedance</td>
<td>10 m( \Omega ), 0.3 mH</td>
</tr>
<tr>
<td>( X_{in} )</td>
<td>Inverter Coupling Inductance</td>
<td>20 m( \Omega ), 1.6 mH</td>
</tr>
<tr>
<td>( C_{dc}, U_{dc} )</td>
<td>Common DC-LinkSize &amp; Voltage</td>
<td>5 m( \Omega ), 750V</td>
</tr>
<tr>
<td>( K_{p1}, K_{i1} )</td>
<td>Prop. &amp; Int. Gain (for d-link)</td>
<td>0.88, 78.96</td>
</tr>
<tr>
<td>( K_{p2}, K_{i2} )</td>
<td>Prop. &amp; Int. Gain (for PWM)</td>
<td>10.9, 48.887</td>
</tr>
<tr>
<td>( K_{p3}, K_{i3} )</td>
<td>Prop. &amp; Int. Gain (for PWM)</td>
<td>2, 3</td>
</tr>
<tr>
<td>( T_s )</td>
<td>Sampling Time</td>
<td>20( \mu )s</td>
</tr>
<tr>
<td>( K_{p}, K_{i} )</td>
<td>STF Gain</td>
<td>100, 40</td>
</tr>
<tr>
<td>( f_s )</td>
<td>Switching Frequency</td>
<td>14 kHz</td>
</tr>
<tr>
<td>Load 1</td>
<td>Non-Linear Load Res. and Inductive</td>
<td>7 ( \Omega ), 0.8 mH</td>
</tr>
<tr>
<td>Load 2</td>
<td>Non-Linear Load Res. and Inductive</td>
<td>10 ( \Omega ), 3 mH</td>
</tr>
</tbody>
</table>
3. Simulation Results

![Graphs showing simulation results with voltage values and time plots.](image)
Simulation Results

3. Operation with Single Inverter

Simulation Results
3. Operation with Dual Inverter

Simulation Results
Simulation Results

3. Operation with Triple Inverter

![Graphs showing simulation results](image-url)
Conclusion

In this paper, we have considered the design of a modular active power filter (APF) in order to distribute the total compensation current for unbalanced nonlinear loads.

This is achieved with a flexible and un-bulky solution that maintains low power loss for the required level of harmonic suppression and reactive power compensation.

The controller complexity of the modular APFs is significantly reduced with the use of the proposed control strategy.

The proposed system comprises a main controller and a number of sub-controllers.

The former is used to determine the required common signals for each sub-controller, whereas the sub-controllers themselves use the common signals to generate the required compensation for each branch.
Conclusion

A benefit of having a modular APF system comes from the fact that a faulty sub-unit can be isolated from the system for repair whilst the system is still in operation.

Another benefit offered by a modular system is the ability to modify the number of parallel branches depending on the power demand of the plant.

A major advantage of having the type of distributed controller scheme proposed in this paper is the elimination of the need for repeated signal processing required for each inverter.

The system under study was implemented on RT-LAB real-time experimental platform to evaluate the real-time performance of the system. The THD of the grid currents with use of proposed method are reduced to ~3 % under both grid voltage and frequency fluctuations conditions, which meets the IEEE 519-1992 recommended standard.
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Thank you