Active Power Filter Design Based on IPM

Detao Wang, Shandong Hoteam technology Co., Ltd, Jinan, China, detaowang@sohu.com
Xiaoling Wang, Semiconductor division, Mitsubishi Electric & electronics (Shanghai) CO., Ltd, Shanghai, China, wangxl@mesh.china.meap.com

Abstract:

This paper presents an interleaved active power filter (abbr. as APF) based on Mitsubishi 5th generation L1 series intelligent power module (abbr. as IPM). By adopting two pieces of interleaved switching IPMs, the prototype APF achieved high rated power, low power loss, high bus-bar voltage utilizing rate. In this paper, Mitsubishi IPM features, circuit topology of APF, control approach and system simulation result are introduced. Lastly the testing data, testing result, prototype APF outline are given.

1. Introduction

Power harmonic is becoming a great concern for power quality. Harmonic is normal power quality problem compared with voltage sag which belongs to transient power quality problem. With the development of economy and technology, power electronic equipments such as inverters, UPS, welding machine etc. are widely used. The operation of these equipments will inject harmonic current into power grid. The harmonic pollution from harmonic current will badly affect the operation of power supply equipments and power consumption equipments. Harmonic pollution will also decrease power factor and increase power loss. The application of APF will decrease the harmonic pollution effectively. APF will also compensate the reactive power and maintain active power balance. APF with less resonance operates more stably compared with passive power filter.

There are several ways to connect APF to power grid such as parallel connection, serial connection, parallel & serial connection etc.. Considering the stable operation of power grid, parallel connection is commonly used in harmonic suppression and reactive power compensation for low voltage side. In our design, parallel connection is used and the target system data for APF is shown in table 1.

<table>
<thead>
<tr>
<th>No.</th>
<th>Item</th>
<th>APF Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Input voltage</td>
<td>380V ± 15%</td>
</tr>
<tr>
<td>2</td>
<td>Rated compensation current</td>
<td>100A</td>
</tr>
<tr>
<td>3</td>
<td>Connection method</td>
<td>3 phase 3 wire or 3 phase 4 wire</td>
</tr>
<tr>
<td>4</td>
<td>Power supply frequency</td>
<td>50Hz/60Hz ± 5%</td>
</tr>
<tr>
<td>5</td>
<td>Filtering harmonic order</td>
<td>2-50 harmonic</td>
</tr>
<tr>
<td>6</td>
<td>Total harmonic compensation rate</td>
<td>≥ 90%</td>
</tr>
<tr>
<td>7</td>
<td>Filtering result</td>
<td>THDi ≤ 3%</td>
</tr>
<tr>
<td>8</td>
<td>Power loss</td>
<td>≤ 4%</td>
</tr>
<tr>
<td>9</td>
<td>Dynamic response time</td>
<td>≤ 30ms</td>
</tr>
</tbody>
</table>

Table 1. Target performance data

2. Inverter design

Inverter is the core for APF design. The parameters and operation points of inverter are important for the stability and reliability of APF system.
2.1. Topology for inverter

Several topology structures are commonly used currently, 3 phase 3 wire(4 wire) full bridge, 3 phase 4 wire 4 arm, multi level, inverter parallel etc. In our design, two shunt interleaved technology is used which will fulfill the requirements from APF completely. At first, low current ripple is required to reduce high frequency interference to power grid. Inverter must work with high switching frequency, normally 10kHz, which will lead to high power loss. Second, the output compensation current changing rate is high which can be achieved by applying high bus-bar voltage, however, power loss will go up. Decreasing output inductor can also be used which will increase the compensation current ripple.

Fig. 1 is the topology for two shunt interleaved inverter. Best performance is achieved in response time, power loss, output current ripple etc. The system cost decreases due to smaller output inductance and lower bus-bar voltage.

![Topology for inverter](image)

2.2. PWM interleaved modulation

PWM modulation is the key to realizing interleaved switching and reducing the output current ripple. Fig. 2 is the modulation circuit diagram for a phase. Dead time adjustment is not included in the diagram. $I_u$ is pulse width instruction signal. $T_1$ is triangle waveform. The phase for $T_2$ is opposite to the phase for $T_1$. PWM1, PWM2, PWM1’, PWM2’ are the driving signals for $T_1$, $T_2$, $T_1’$, $T_2’$.

![PWM interleaved modulation diagram and waveforms](image)

Fig. 2. PWM interleaved modulation diagram and waveforms

Fig. 3 is the simulation result for PWM interleaved modulation. From the simulation result, the ripple current from two inverters may reciprocally cancel greatly. From the modulation method, in low current increasing rate, current ripple decrease due to interleaved switching of two inverters. In high current
increasing rate, two inverters will increase simultaneously. Even when two inverters operate at the same time, high bus-bar voltage utilizing rate is achieved.

![PWM interleaved modulation simulation result](image)

Fig. 3. PWM interleaved modulation simulation result

### 2.3. DC bus-bar voltage

As a tied grid inverter, the higher bus-bar voltage applied, the faster responding time and better tracking capability will get. For IGBT, high rated voltage will lead to high power loss. Considering the cost and rated voltage requirement from IGBT and capacitors, the bus-bar voltage of inverter works at 800V. Bus-bar voltage is 150V higher than the peak voltage of 4 wire power grid voltage: 230V*1.414*2=650V, 234V higher than 3 wire peak voltage of power grid voltage: 400V*1.414=566V.

### 2.4. Power semiconductors selection

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Condition</th>
<th>Ratings</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>VCCPROT</td>
<td>Supply Voltage Protected by SC</td>
<td>V = 13.5 ~ 16.5V Inverter Part, Tj = +125°C Start</td>
<td>800</td>
<td>V</td>
</tr>
<tr>
<td>VCCsurge</td>
<td>Supply Voltage (Surge)</td>
<td>Applied between: P-N, Surge value</td>
<td>1000</td>
<td>V</td>
</tr>
<tr>
<td>Tso</td>
<td>Storage temperature</td>
<td>Tso = -40 ~ +125°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vdc</td>
<td>Isolation Voltage</td>
<td>60Hz, Sinusoidal, Charged part to Base, AC 1 min.</td>
<td>2500</td>
<td>Vrms</td>
</tr>
</tbody>
</table>

Table 2. Voltage limitation for Mitsubishi PM150CL1A120 IPM [1]

In table 2, the max. voltage for P-N for IPM (including surge) is 1000V, the surge voltage caused by IGBT switching is lower than 100V, as a result, the max. bus-bar voltage for inverter is 900V. The over voltage protection point for inverter is 900V to ensure the safe operation of IGBT. After studying the data sheet, Mitsubishi PM150CL1A120 IPM is a proper choice for APF inverter based on 800V bus-bar voltage. Two pieces of PM150CL1A120 IPM in parallel are applied in our design. The IGBT chips for IPM are full gate CSTBT™ type which could reduce power loss significantly. Compared with last generation L series IPM, L1 series IPM could achieve 15% power loss decrease under 10kHz switching frequency. The temperature sensor for L1 series of IPM is in the center of IPM chip, temperature protection acts more accurately and rapidly. Power cycling life for L1 IPM improved significantly by using new bonding technology. The internal circuit is shown in Fig. 4.
The power loss simulation result from Mitsubishi simulation software Melcosim_ver_09_10_01 is shown in table 3 under 10kHz switching frequency and 50A(rms) output current. Judging from the table, the power loss for PM150CL1A120 is lower which will only cover 2.15% of total inverter power.

<table>
<thead>
<tr>
<th>IPM</th>
<th>Power loss IGBT&amp;Diode</th>
<th>Total power loss</th>
<th>Power of inverter</th>
<th>Power loss ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM150CL1A120</td>
<td>IGBT 81</td>
<td>708</td>
<td>33000</td>
<td>2.15%</td>
</tr>
<tr>
<td></td>
<td>Diode 37</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PM150CLA120</td>
<td>IGBT 107</td>
<td>844</td>
<td>33000</td>
<td>2.56%</td>
</tr>
<tr>
<td></td>
<td>Diode 34</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3. IPM power loss analysis (Unit: Watt)

3. Control Algorithm

3.1. Control Algorithm introduction for APF

The principle diagram for APF is shown in Fig. 5. APF detects load current $i_L$ and separates harmonic in real-time and then instruction current signal is computed and produced. Generator gives driving PWM signal according to feedback signal from $i_D$ and $i_C$. PWM inverters generate the compensation current $i_C$. Grid current $i_S = i_L + i_C$ as shown in Fig. 5. If the APF compensation current $i_C$ is equivalent to load harmonic current and the phase of $i_C$ is opposite to load harmonic current, there is no harmonic in grid current.

3.2. Technology of harmonic separation

Two methods are used commonly in harmonic separation: instantaneous reactive power and Fast Fourier Transform. In our design Fast Fourier Transform is applied to separate harmonic of each order.

3.3. Instruction current adjustor

Considering the combination of software and hardware in our design, direct PWM control algorithm is applied in order to acquire good tracking performance. Direct PWM control algorithm is based on feedback and feedforward control. Parameters of output current $i_o$, bus-bar voltage $u_{dc}$, output inductance $L_o$, power voltage $u_a$ are known or measurable. This control algorithm is feedforward control with high stability.
4. Prototype machine and experimental result

4.1. Prototype machine outline and parameters

Based on above, a 400V/100A prototype machine is made. The real power is 69kVA. The product picture is shown in Fig. 6.

Fig. 6. Picture for prototype machine

4.2. Result for PWM interleaved control

Fig. 7, Fig. 8. are the output current waveforms. In Fig. 7, Fig. 8, the amplitude for \( i_a \), \( i_2 \) is 50A/division. For \( i_a \), the amplitude is 100A/division. According to the output current waveform, the output ripple current decreases greatly. Especially when the current rise rate is equal to current drop rate, the ripple current from two inverters may reciprocally cancel totally. In fact, the current waveforms shown in Fig. 8 appear easily in the operation of APF. The ripple current for Fig. 8 is larger than the ripple current in Fig. 7.

Fig. 7. Output current 1

Fig. 8. Output current 2

4.3. Harmonic compensation result

To test the harmonic filtering result, the prototype machine is tested with 3 wire rectifier load and 4 wire rectifier load.
4.3.1. APF in 4 wire connection, rectifier load in 3 phase 4 wire connection
APF compensation result is shown in Fig. 9, \( i_L \) is load current, \( i_C \) is compensate current, \( i_S \) is power source current.

![Fig. 9. 3 phase 4 wire rectifier load filtering result](image)

4.3.2. APF in 3 wire connection, rectifier load in 3 phase 3 wire connection
A better filtering result is achieved for both 4-wire rectifier and 3-wire rectifier load as shown in Fig. 9, Fig.10. The current THDf value is lower than 2% after filtering. By using interleaved switching technology, the output inductance is reduced and the current tracking capability for APF is improved. The accurate harmonic separation algorithm and optimized instruction current tracking controller contribute to the final filtering result.

![Fig. 10. 3 phase 3 wire rectifier load filtering result](image)

5. Conclusion
Mitsubishi electric L1 series IPM has the protection function of over current, over temperature and short circuit. The accurate speed control function and soft switching function assures safe operation of IPM under high bus-bar voltage. APF, as a grid tied inverter, needs to generate harmonic current and the harmonic current is opposite to the load harmonic current. There is high current rise rate with harmonic current, so high \( \frac{di}{dt} \) and high bus-bar voltage are required for APF. With the combination of L1 IPM and PWM interleaved switching technology, APF product achieves high cost efficiency and high quality.

6. Literature
[1] “The 5th Generation L1/S1 Series Intelligent Power Module Application Note”, (Ver1) by Mitsubishi electric