Optimal selection of output inductance in active power filters

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Abstract: APFs (Active Power Filters) are solid-state devices used to compensate nonlinear load harmonics and improve customer power quality. The selection of its designing parameters, especially the output inductance, affects its performance. The output inductance decides the reaction speed and compensation current of APF. By $\alpha\beta$ transformation, the model of APF on $\alpha\beta$ coordinates is erected. According to the mathematical analysis, the scope for output inductance selection in APF is determined. Within the range, optimal values are selected by simulation to make the total harmonic rate least. The calculated scope for output inductance selection effectively reduces the blindness in APF designing. Combined with values of other parameters in the system, the output inductance can be decided to improve the compensation performance.

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1 Introduction of active power filters

With the development of solid-state devices, the ability of mankind to control power energy is far better than ever, such as AC-DC, DC-DC, DC-AC and AC-AC transform. However, at the same time, it also produces power pollution. Harmonics and reactive components of line current reduce the efficiency of the power system and interfere to the communication network nearby[1]. As a substitution of traditional passive filters, active power filters, as shown in figure 1, can compensate the harmonics and reactive currents of the load currents at the same time dynamically. Simultaneously, it can compensate the harmonics concentrated or distributed without resonance[2].

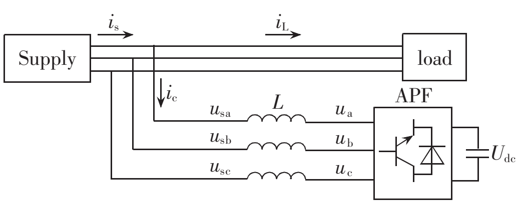

Fig.1 The structure of active power filters

Most attentions are paid to harmonics measurement and control of current loops[3]. But, the output inductor L affects the performance of current compensation in active power filter system. It directly decides the speed of tracking reference currents. If the inductor is larger, the output current of inverter changes more slowly, so the dynamics of the system will slow down. On the other side, the larger inductor increases the cost and size of the APFs. Whereas, the smaller inductance will speed up the reaction of the system, it also makes impulsion in the system, which will cause the device unstable[4]. How to choose the output inductance in different cases is very important for the design of APF.

In this paper, the authors present a method to compute the selection range of output inductance. The range reduces the blindfold search of the value of the output inductance during the designation. Based on the model of $\alpha\beta$ coordinates, the relationship between the inductance and the performance of APF is calculated. According to the relationship, the selection range of output inductance is achieved. The simulation results show the relationship between the values of output inductances and the THD (Total Harmonic Distortion) in different switch frequencies and load power factors, and the optimal inductance is in the range calculated.

2 Problem formulation

2.1 $\alpha\beta$ transformation

The transformation is from the three-phase i.e. a, b, c to $\alpha\beta$ coordinates. The equation is

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$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}=C_{32}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix},\ C_{32}=\sqrt{\frac{2}{3}}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \quad (1)$$

where C_{32} is the transform matrix.

Figure 2 gives the phasor graph of the $\alpha\beta$ transformation.

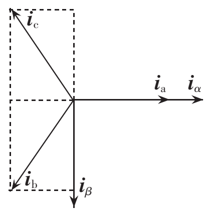

Fig.2 Phasor graph of $\alpha\beta$ transformation

2.2 THD

With the Fourier transformation, the current is able to divided into many components in different frequencies.

$$i(\omega t)=a_0+\sum_{n=1}^{\infty}c_n\sin(n\omega t+\varphi_n) \quad (2)$$

The fundamental wave is the current with power frequency and the others are called harmonics. The THD is defined as the following:

$$\mathrm{THD}=\frac{I_n}{I_1}\times 100\%,\ I_n=\sqrt{\sum_{n=2}^{\infty}I_n^2} \quad (3)$$

where I_n is the total of harmonics and I_1 is the fundamental wave.

For THD is one of the most important index in the harmonic analysis, it is considered as the optimal objective. The output inductance should be selected to make the THD of supply current minimum.

2.3 Model of APF

According to figure 1, the model of APF is:

$$L\begin{bmatrix} \mathrm{d}i_{ca}/\mathrm{d}t \\ \mathrm{d}i_{cb}/\mathrm{d}t \\ \mathrm{d}i_{cc}/\mathrm{d}t \end{bmatrix}=\begin{bmatrix} u_{sa} \\ u_{sb} \\ u_{sc} \end{bmatrix}-\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} \quad (4)$$

Where $i_{cj}, j=a,b,c$, is the compensation current; u_{si}, $i=a,b,c$, is the supply voltage; $u_i, i=a,b,c$, is tri-phase output voltage of the APF; L is the output inductance to be selected. On the $\alpha\beta$ coordinates, the model can be represented as:

$$L\begin{bmatrix} \mathrm{d}i_{c\alpha}/\mathrm{d}t \\ \mathrm{d}i_{c\beta}/\mathrm{d}t \end{bmatrix}=\begin{bmatrix} u_{s\alpha} \\ u_{s\beta} \end{bmatrix}-C_{32}\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} \quad (5)$$

The C_{32} is presented in equation (1).

3 Optimal selection of the output inductance

The compensation current given in equation (5) must track the reference signals of currents, so in any time, the following inequality stands:

$$\left|\frac{\mathrm{d}i_{c\alpha}}{\mathrm{d}t}\right|\geqslant\left|\frac{\mathrm{d}i_{c\alpha}^*}{\mathrm{d}t}\right|,\ \left|\frac{\mathrm{d}i_{c\beta}}{\mathrm{d}t}\right|\geqslant\left|\frac{\mathrm{d}i_{c\beta}^*}{\mathrm{d}t}\right| \quad (6)$$

where $i_{c\alpha}^*$ and $i_{c\beta}^*$ are the reference signals. That is to say, the actual currents should change faster than the given currents. From equation (5) and (6), we get:

$$\begin{aligned} &\frac{1}{L}\left|u_{s\alpha}-\sqrt{\frac{2}{3}}\left(u_a-\frac{1}{2}u_b-\frac{1}{2}u_c\right)\right|\geqslant\left|\frac{\mathrm{d}i_{c\alpha}^*}{\mathrm{d}t}\right| \\ &\frac{1}{L}\left|u_{s\beta}-\frac{\sqrt{2}}{2}(u_b-u_c)\right|\geqslant\left|\frac{\mathrm{d}i_{c\beta}^*}{\mathrm{d}t}\right| \end{aligned} \quad (7)$$

When the rights of the inequalities are maximum while the lefts of the inequalities are minimum, for this extreme case, the inequalities stand, we can say that the inequalities stand in all cases. That is:

$$\frac{1}{L}\left|u_{s\alpha}-\sqrt{\frac{2}{3}}\left(u_a-\frac{1}{2}u_b-\frac{1}{2}u_c\right)\right|_{\min}\geqslant\left|\frac{\mathrm{d}i_{c\alpha}^*}{\mathrm{d}t}\right|_{\max} \quad (8)$$

$$\frac{1}{L}\left|u_{s\beta}-\frac{\sqrt{2}}{2}(u_b-u_c)\right|_{\min}\geqslant\left|\frac{\mathrm{d}i_{c\beta}^*}{\mathrm{d}t}\right|_{\max} \quad (9)$$

As consequence, the following result gives the ranges of the output inductance:

$$L\leqslant\left|u_{s\alpha}-\sqrt{\frac{2}{3}}\left(u_a-\frac{1}{2}u_b-\frac{1}{2}u_c\right)\right|_{\min}\Big/\left|\frac{\mathrm{d}i_{c\alpha}^*}{\mathrm{d}t}\right|_{\max} \quad (10)$$

$$L\leqslant\left|u_{s\beta}-\frac{\sqrt{2}}{2}(u_b-u_c)\right|_{\min}\Big/\left|\frac{\mathrm{d}i_{c\beta}^*}{\mathrm{d}t}\right|_{\max} \quad (11)$$

The smaller L obtained in either (10) or (11) will be chosen to satisfy the inequality. The value of the output inductance is under the extreme case, so it is not optimal. For the best choice, numeric simulations are still necessary.

4 Simulation results

A three phase rectifier bridge is considered as a harmonics load. The parameters of the simulations are: frequency $f=50$ Hz; nominal voltage of each phase $U_s=220$ V (RMS); active power of the load $P_L=10$ kW; DC voltage $U_{dc}=600$ V.

As described above, when the compensation current crosses zero, the differential of the reference signal is maximum. Then,

$$\left|\frac{\mathrm{d}i_{cj}^*}{\mathrm{d}t}\right|_{\max}=\frac{\sqrt{2}}{\pi}\frac{P_L\omega}{U_s\lambda} \quad (12)$$

where the subscript j of the variable i_{cj} refers to both α and β, and λ is the power factor of the load.

The u_{sa} is the voltage vector on α coordinates, which is constant in amplitude. When the output voltage of APF is maximum, the left-hand side of inequality (8) is minimum[5-6]. Then,

$$\left|u_{s\alpha}-\sqrt{\frac{2}{3}}\left(u_a-\frac{1}{2}u_b-\frac{1}{2}u_c\right)\right|_{\min}=\left|\sqrt{2}U_s-\sqrt{\frac{2}{3}}\times\frac{2}{3}U_{dc}\right| \quad (13)$$

When load power factor is 1, from (10), the upper-limit of L should be $L\leqslant 2.3$ mH. In (11), we can calculate $L\leqslant 1.29$ mH. The smaller one will be chosen.

The value of the L from 0.1 mH to 4 mH is used to calculate the THD of the proposed APF system. The system is a current mode control. The control objective is to ensure the supply current is in a shape of sinusoidal whose phase is the same as the supply voltage, that is to say, the power factor is unity. The simulation results give the relationship characteristics between the THD of supply current and the output inductance. The power factor and the switching frequency also affect the THD of the supply current. Switching frequencies are set as 5 kHz, 10 kHz and 15 kHz, while the load power factors are set as 1, 0.7 and 0.5.

When the switching frequency is 5 kHz, the relationship between the THD of supply current and the output inductance with different power factor (1, 0.7, and 0.5) is shown as figure 3. Figure 4, 5 are the results when switching frequency is 10 kHz and 15 kHz respectively.

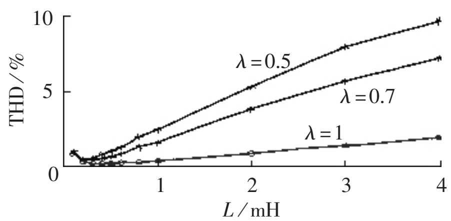

Fig.3 The relationship between output inductance and THD when switching frequency is 5 kHz

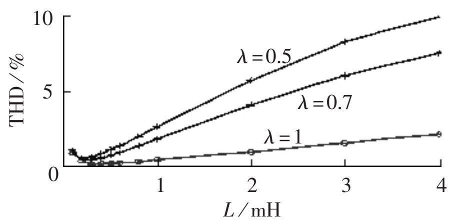

Fig.4 The relationship between output inductance and THD when switching frequency is 10 kHz

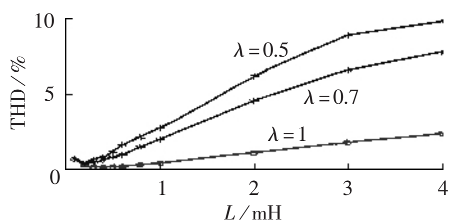

Fig.5 The relationship between output inductance and THD when switching frequency is 15 kHz

From the figure 3, 4 and 5, the switching frequency affects the THD less than the other two parameters do. So the switching frequency of solid-state devices can be ignored in the selection of output inductance.

Form (12), lower power factor of load makes the maximum inductance smaller. The increasing of the output inductance will make the shape of supply current worse. When power factor is low, the THD of supply current is very sensitive to the selection of the output inductance. Based on the upper-limit of the inequality as shown in inequalities (10) and (11), the output inductance can guarantee the compensation function with THD less than 5%. But if out of the range, the THD will be too large for the harmonic compensation. For example, in figure 3, when power factor is low, and the output inductance is large, THD of supply current will be more than 5%.

The simulation results also show that the THD of supply current does not decrease when the output inductance is smaller than 0.2 mH. It is because that the smaller output inductance makes the current change faster, just the same as the analysis above. But the value calculated is only a range for the selection of output inductance. The best choice of the output inductance should be affected by the other parameters of the systems. For example, with different power factor, the optimal inductance is not the same. When power factor λ is unity, the optimal value is from 0.2 to 1 mH, while 0.2 to 0.6 mH for $\lambda=0.7$ and 0.2 to 0.4 mH for $\lambda=0.5$.

Set the output inductance $L=0.5$ mH, switching frequency $f_{sw}=10$ kHz and power factor is unity. The shapes of the load current, supply current and compensation current of phase A are shown in figure 6 respectively. The spectrums of load current and supply current are shown in figure 7 and 8 respectively. The THD of the load current is 5.39%. With the APF, the THD of supply current is 0.21%.

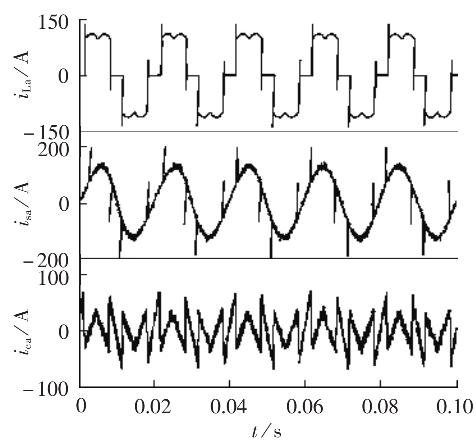

Fig.6 The load current, supply current and compensation current

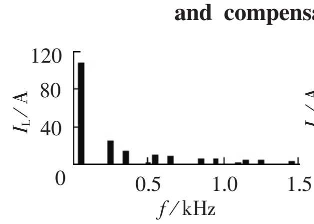

Fig.7 The spectrum of load current

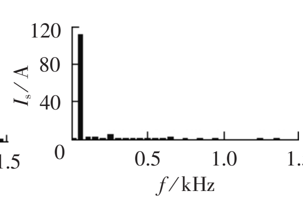

Fig.8 The spectrum of supply current

5 Conclusion

The selection of the output inductance should be more careful for its effect on the performance of APF. This paper has investigated how to choose the output inductance of APF. In order to reduce the blindness in selecting the inductance, the calculation based on APF model has been shown in the paper to get the selection range of the output inductance. The calculations give the upper-limit of the range. Because the value is computed in extreme case, it is not the optimal. Simulations are carried out to get the best choice. With the simulations, the relationship between the THD and the different inductance will show the optimal inductance. If power factor of the load is different, the optimal value of the output inductance is not the same. With the correct selection of the output inductance, the THD of supply current will be decreased compared with the THD of load current. So the APF compensates the harmonic current of the load current to promise the shape of current in the supply system.

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有源电力滤波器输出电感的最优选取

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摘要：有源电力滤波器作为消除谐波的新型电力电子装置,能有效提高用户的电能质量。其设计过程中参数的选取,直接关系到装置的补偿性能,尤其是输出电感的选取,是决定系统响应速度和补偿效果的关键。通过 $\alpha\beta$ 变换,建立了有源电力滤波器的数学模型。根据数学推导分析的结果,获得输出电感的选取范围。并以总谐波畸变率最小为目标,在给出范围内通过数字仿真,获得输出电感的最优值。由分析计算得出的输出电感选取范围,能够有效避免有源滤波器在设计过程中输出电感选择的盲目性,并可以根据系统中的具体参数,选取输出电感值,提高补偿谐波性能。

关键词：电能质量；谐波；有源电力滤波器

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