Research on filter parameter optimization method of grid-connected photovoltaic system

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Abstract: With a large number of distributed energy and nonlinear loads such as photovoltaic and wind power are connected to the power grid, while improving the energy structure of the grid, it also greatly increases the harmonic content in the power grid, resulting in the decline of power supply quality and stability. In this paper, based on the analysis of the working principle of photovoltaic power generation system and the characteristics of the filter connected to the power grid, taking the inverter composed of high-frequency power electronic devices as an example, the principle of high-order harmonic generation is analyzed. According to this, a T-type filter is designed to suppress harmonics. The relationship between thd and filter parameters is studied, and the optimization method of T-type filter parameters is proposed Law.

1. Introduction
In the photovoltaic grid connected system, grid connected inverter is the core component. At present, the research of grid connected system mainly focuses on DC-DC and DC-AC two-stage energy conversion structure. Among them, the DC-DC converter adjusts the working point of PV array to track the maximum power; the DC-AC inverter mainly makes the output current in phase with the grid voltage, and obtains the unit power factor. DC-AC is the key link of the system. The structure of photovoltaic grid connected system is shown in Figure 1.

![Figure 1 The structure of photovoltaic grid connected system](image-url)
With the development of new power electronic devices, the rectifier and inverter in photovoltaic grid connected system are composed of a large number of nonlinear high-speed components, which are easy to cause grid current waveform distortion. When PWM control is used, power electronic devices work at a high switching frequency, which will produce a large number of high-order harmonics in the power grid, resulting in the decline of power supply quality[1]. The effective way to eliminate higher harmonic and reduce total harmonic distortion is to connect harmonic filter between power grid and inverter circuit. The structure and parameters of pure inductance filter and inductor capacitor filter are simple, but the high frequency harmonic attenuation effect is poor and the harmonic suppression effect is not ideal due to the uncertainty of the grid impedance. The effective way to solve this problem is to use T-type filter. Because of the characteristics of both passband and stopband, it can effectively filter out the high-frequency harmonics in the grid current without requiring large inductance and capacitance, so that the inverter can obtain high-quality grid connected current at low switching frequency[2].

2. The harmonic problem of inverter with high frequency power electronic devices

Take an inverter circuit with single inductor filter as an example, as shown in Figure 2. the following results can be obtained according to fig 2.

\[ V_L = V_{dc} - V_e = L \frac{\Delta i}{\Delta t} \]  
(1)

Where, \( V_e = U_m \cos \omega t \), represents the instantaneous value of the grid voltage. \( \Delta t \) represents SPWM pulse width. According to the pulse theorem, If the carrier period is \( T \), narrow pulse time is \( \Delta t \), Then the switching frequency \( f_k \) of the inverter is as follows[3].

\[ V_{dc}\Delta t = U_m T \cos \omega t = \frac{U_m \cos \omega t}{f_k} \]  
(2)

From equation (2), we can get:

\[ \Delta t = \frac{U_m \cos \omega t}{V_{dc} \pi f_k} \]  
(3)

Substitute formula (3) into formula (1), the current variation during the inductor current rising phase, namely: variation during the switch tube conduction. Ripple current expression can be obtained.

\[ \Delta i = \left( U_m \cos \omega t - \frac{U_m^2 \cos^2 \omega t}{V_{dc}} \right) / L f_k \]  
(4)

It can be concluded from equation (4): The ripple current is related to the higher harmonic which is determined by the switching frequency \( f_k \), AC side inductance L and DC side voltage. The value of inductance affects ripple current and power system loss, and The ripple current and its related loss decrease with the increase of inductance L. But the volume and loss of the inductor will increase with the increase of the inductance. Therefore, the influence of various factors should be taken into account in the selection of inductors, so as to achieve a balance between the conflicting factors. In engineering design, the ripple value of output current is determined first, and then the value of inductor L is determined. The ripple value is generally about 20% of the output current. \( \Delta I_L = 20\% I_o \), where, \( I_o \) is the grid current[4].
3. Design of T-type filter based on harmonic control

The inverter works in unipolar modulation mode. The switching period is  \( T_k \), and the on time in each switching cycle is  \( d(t)T_k \). DC bus voltage is  \( V_{dc} \), capacitor voltage is  \( V_c(t) \), inductor voltage is \( V_L \), so:

\[
\Delta I_L = \frac{V_{dc} - V_c(t)}{L} \times d(t)T_k = \frac{V_{dc} - V_c(t)}{L} \times \frac{d(t)}{f_k}
\]

\( V_c(t) = d(t)V_{dc} + (1 - d(t)) \times 0 \)  \( \quad \quad \quad \quad (5) \)

Formula (6) is substituted into formula (5), and the following formula is obtained:

\[
\Delta I_L = \frac{V_{dc} - V_c(t)}{L} \times \frac{V_c(t)}{V_{dc} \times f_k} = \frac{V_{dc} \times V_c(t) - V_c^2(t)}{L \times V_{dc} \times f_k}
\]

\( \Delta P_L = \frac{V_{dc} - 2V_c(t)}{L \times V_{dc} \times f_k} \)  \( \quad \quad \quad \quad (6) \)

Differentiating \( \Delta I_L \) with respect to time yields.

\[
\Delta P_L = \frac{V_{dc} - 2V_c(t)}{L \times V_{dc} \times f_k}
\]

Because the grid voltage and current have the same frequency and phase, therefore, when \( V_{dc} = 2V_c(t) \), \( \Delta I_L \) has a maximum value, namely:

\[
\Delta I_L = \frac{V_{dc} - 2V_c(t)}{4L \times f_k}
\]

And because: \( \Delta I_L = 20\% I_o \), therefore,

\[
\Delta I_L = \frac{V_{dc}}{4L \times f_k} = 20\% I_o
\]

The minimum inductance is:

\[
L_1 \geq \frac{V_{dc}}{80\% f_k}
\]

It can be seen that when the fundamental current flows through, the capacitance of T filter is in open circuit state, and the equivalent total inductance is \( L = L_1 + L_2 \), Inductance voltage \( V_L = I_L \omega L, \omega = 2\pi f, f = 50Hz \).

According to the three vector relation:

\[
V_{dc} = \sqrt{V_L^2 + V_e^2}
\]

Because the phase of current and voltage is not synchronous, the influence of phase angle between them should be considered. According to cosine law, the following equation can be obtained:

\[
V_{dc} \geq \sqrt{V_L^2 + V_e^2 - 2V_L V_e \cos \theta}
\]

Assuming that the phase difference between the inductance voltage and the grid voltage is \( \theta \), the following results can be obtained from equation (12).

\[
V_L \leq \sqrt{V_{dc}^2 - V_e^2}
\]

\( V_L = I_L \omega L \), by substituting formula (14), we can get the following results:

\[
L \leq \frac{V_{dc}^2 - V_e^2}{\omega I_L}
\]

If \( L_1 = L_2 = \frac{1}{2} L \), from equations (11) and (15), the value range of \( L_1 \) can be obtained as follows:

\[
\frac{V_{dc}}{80\% f_k} \leq L_1 \leq \frac{\sqrt{V_{dc}^2 - V_e^2}}{2\omega I_L}
\]
The larger the filter capacitance is, the greater the output reactive power will be, and the overall efficiency of the inverter will be reduced; if the filter capacitance value is reduced, the inductance value needs to be increased to obtain the same filtering effect, which will lead to larger inductance volume. In order to achieve the compromise effect[6], the general reactive power is 15% of the total power. Therefore, the value range of capacitance is calculated as follows[7]:

\[ C \leq 15\% \times \frac{P}{2\pi f v_{e}} \]  

(17)

4. Analysis of simulation results

The total harmonic distortion (THD) is related to the inductance \( L_2 \), the THD value decreases with the increase of \( L_2 \) value. Saber is used to simulate the filter. The modulation of the inverter is \( M=0.8 \). The simulation circuit of the filter is shown in Fig. 4[8,9].

![Schematic diagram of T-filter simulation circuit](image)

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![Simulation waveform of T-filter output](image)

When the capacitance value is \( C = 10\mu F \), the total inductance constant \( L = 1.5mH \), the ratio of \( L_1/L_2 \) under different circumstances, the simulation results of the filter are summarized as shown in table 1.

| \( L_1+L_2(\mu H) \) | \( L_1/L_2 \) | \( L_1(\mu H) \) | \( L_2(\mu H) \) | \( C(\mu F) \) | THD(%) |
|---------------------|---------------|----------------|----------------|-------------|--------|
| 1500                | 1             | 750            | 750            | 10          | 0.7460 |
| 1500                | 2             | 1000           | 500            | 10          | 0.8021 |
The simulation results are shown in Table 1. When the total inductance and capacitance of the filter are constant, THD will increase with the increase of $L_1/L_2$. If the total inductance and $L_1/L_2$ are constant, the capacitance gradually increases, the simulation results of the filter are shown in Table 2.

Table 2 THD changes with $C$

| L$_1$+ L$_2$(μH) | L$_1$/ L$_2$ | L$_1$ (μH) | L$_2$(μH) | C(μF) | THD(%) |
|-----------------|-------------|------------|------------|-------|--------|
| 1500            | 1           | 750        | 750        | 47    | 0.7890 |
| 1500            | 1           | 750        | 750        | 33    | 1.0245 |
| 1500            | 1           | 750        | 750        | 22    | 1.5360 |
| 1500            | 1           | 750        | 750        | 10    | 4.8010 |

Table 2 simulation results show that when the total inductance is constant and $L_1 / L_2$ is constant, the larger the capacitance value, the smaller the THD. The simulation results are shown in Fig. 5. When the filter resonates, equivalent to short circuit between inverter and grid side, the capacitance and inductance $L_2$ are connected in parallel and then connected in series with the inductance $L_2$ to form a resonant circuit. The resonant frequency is calculated as follows:

$$f_{res} = \frac{1}{2\pi} \sqrt{\frac{L_1+L_2}{L_1L_2C}}$$  \hspace{1cm} (18)

$L_1 = 1250\mu H$, $L_2 = 250\mu H, C = 10\mu F$, and substituting them into equation (18), the calculated resonance frequency is far away from the harmonic frequency of the grid output voltage.

5. Conclusions

On the basis of in-depth analysis of the causes of power grid harmonics, Taking T-type filter as an example, this paper studies and analyzes the relevant parameters and calculation formula of T-type filter. In order to ensure the filtering effect, the value range of T-type filter parameters is determined. The simulation results show that the filter can significantly eliminate the ripple and improve the quality of power supply.

Acknowledgments

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