Influence of Active/Reactive Power Control on Harmonics of Wind Unit Converters and Photovoltaic Inverters

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Abstract: Wind units and photovoltaic inverters are the central generation devices of new energy power generation. Hence, the research on harmonic mechanisms and feature influencing factors of new energy power generation units is essential for its safe and stable operation. This paper analyzes harmonic and inter-harmonic mechanisms of wind units/photovoltaic inverters and studies the influence of active and reactive power output of wind farms and photovoltaic plants on harmonic features of wind units/photovoltaic inverters. Simulation results and harmonic test data verify the theoretical analysis of harmonic mechanisms and influencing factors of photovoltaic inverters and directly-driven wind unit converters.

1. Introduction
New energy power generation is attracting more attention to reduce the pollution due to consuming fossil energy. In a wind power system, nonlinear loads mainly include switching power supplies, rectifiers, inverters, etc. [1], while the photovoltaic power system includes solar panels, inverters, controllers, step-up transformers, etc., among which inverters and step-up transformers are mainly sources of power harmonics [2-7]. Based on electrical structures of inverters of photovoltaic and directly-driven wind units, this paper studies the influence of power unit output and filter structure on harmonic features of wind units/photovoltaic inverters, and builds a simulation model with relevant research results. The simulation result verifies the theoretical analysis.

2. The influence of active and reactive power output of power units on harmonic features.
The steady-state phase diagram of the grid-connected inverter is shown in Figure 1 [8], where \( U_g \) denotes valid value of AC-side phase voltage; \( I_o \) denotes grid-connected current; \( \phi \) denotes power factor angle; \( U_{inv} \) denotes valid value of inverter's output voltage; \( L_1 \) and \( L_2 \) denote reactance value of filter; \( L_g \) denotes grid-side impedance; \( \omega_1 \) denotes grid fundamental frequency under which the capacitive current of filter is negligible [9].

![Figure 1 Steady-state relationship of variables of grid-connected inverter.](image-url)
According to cosine theorem, the modulation degree is:

\[
M = \frac{2\sqrt{2}}{U_{dc}} \sqrt{P^2 + Q^2 - 2(\omega_1 L_1 + \omega_2 L_2 + \omega_3 L_3)^2 + \frac{2}{3}Q(\omega_1 L_1 + \omega_2 L_2 + \omega_3 L_3)} + U_g^2
\]  

(1)

As can be seen from Equation (1), when the output power of the inverter increases (or decreases), the modulation ratio of the inverter will also increase (or decrease). Therefore, the power unit output indirectly influences harmonic amplitude output by the inverter through changing the modulation ratio of the inverter.

Fundamental component:

\[
H_1 = \frac{\sqrt{3}}{2} MU_{dc}
\]

(2)

Harmonic amplitude \(H_h\) whose frequency is \(n\omega_c \pm k\omega_r\) is:

\[
H_h = \frac{4U_{dc}}{m\pi} J_m \left( \frac{m\pi M}{2} \right) \sin \left( \frac{n\pi}{3} \right)
\]

(3)

Where \(m\) denotes even number except for integer multiples of 3 when \(n\) equals 1, 3, 5, ……; \(m\) denotes odd number except for integer multiples of 3 when \(n\) equals 2, 4, 6, ……

If only sideband harmonics around the one-multiple and two-multiple frequency of the carrier frequency is taken into account, it can be seen from the Equation (3) that the relationship between harmonic amplitude and modulation ratio is:

\[
H_h = \begin{cases} 
2\frac{\sqrt{3}U_{dc}}{\pi} J_1 \left( \frac{\pi M}{2} \right), & m = 1, \ n = 2 \\
\frac{\sqrt{3}U_{dc}}{\pi} J_2 \left( \frac{\pi M}{2} \right), & m = 2, \ n = 1 
\end{cases}
\]

(4)

When the carrier frequency is taken as 2000Hz and DC-side voltage is taken as 1000V, sideband harmonics at the one-multiple (mainly 38th and 42th harmonics) and two-multiple frequency (mainly 79th and 81th harmonics) of the carrier frequency can be derived according to Equation (4).

3. The influence of filter structure on harmonic features

The filter in the main circuit plays an import role in the grid-connection inverters. AC-side filters in the inverter usually have two types of structures, i.e. LCL filter and L filter, as shown in Figure 2, where \(U_{inv}\) denotes inverter PWM output voltage\([10-11]\).

![Figure 2 two typical structures of filter.](image)

In Figure 2, \(L_1\) denotes inverter-side filter inductance, \(L_2\) denotes grid-side filter inductance, \(L_g\) denotes grid equivalent inductance. The equivalent resistance on inductors can be neglected. \(C\) denotes filter capacitor and \(R_d\) denotes capacitor branch resistance. The grid inductance \(L_g\) is connected in series in the circuit and it can be merged with the inductance \(L_2\) or \(L\). Without regard to grid voltage, the transfer function of inverter output grid current \(i_2\) and inverter output voltage \(U_{inv}\) in the two kinds of filters is shown as follows:
As seen from Equation (5) and (6), the LCL filter is third order while L filter is first order. At high frequency, the attenuation effect of LCL filter is better than that of the L filter. Figure 3 indicates Bode diagrams of the two kinds of filters in which the inductance value \(L_1+L_2\) of the LCL filter equals the inductance value \(L\) of the L filter. It also illustrates that when the total inductance values of two kinds of filters are equal, the gain of these filters is nearly identical at low frequency; while at high frequency, LCL filter attenuates with the slope of -60dB and L filter attenuates with the slope of -20dB. Therefore, the effect of LCL filter is better than that of L filter.

\[
G_{LCL}(s) = \frac{R_0Cs + 1}{L_1L_2Cs^3 + (L_1 + L_2)R_0Cs^2 + (L_1 + L_2)s}
\]  
\[
G_{L}(s) = \frac{1}{Ls}
\]

Equation (7) indicates that a resonance point exists in the transfer function \(GLCL(s)\) and its resonant frequency \(\omega_{res1}\) is:

\[
\omega_{res1} = \sqrt{\frac{L_1 + L_2}{L_1L_2C}}
\]

Equation (8) indicates that resonant frequency is related to capacitance and inductance of the filter. Figure 4 shows the curves of filter transfer functions when capacitance and inductance change. It can be concluded that when filter capacitance and inductance increase, the resonant frequency decreases, vice versa.
4. Simulation analysis

4.1. Influencing factor simulation of power unit output

The active and reactive power of an inverter with a capacity of 100kVA are set respectively as follows: (1) $P=10\text{kW}, Q=10\text{kVar}$; (2) $P=40\text{kW}, Q=10\text{kVar}$; (3) $P=10\text{kW}, Q=40\text{kVar}$; (4) $P=80\text{kW}, Q=40\text{kVar}$. The corresponding modulation ratios are 0.6782, 0.7095, 0.8393 and 0.9419 and the simulation results are shown in Figure 5. It can be seen that when the modulation ratio falls in the range of 0.6-1.0 (modulation ratio $M$ is usually not lower than 0.6). As $M$ rises, the sideband harmonic amplitude at one-multiple frequency increases while the sideband harmonic amplitude at two-multiple frequency decreases. The simulation results are almost consistent with theoretical calculation.

4.2. Influencing factor simulation of power unit output

The result of harmonic simulation for output current of filters is shown in Figure 6 when LCL and L filters are adopted respectively. The parameters of LCL filter are set as follows. $L_1=3\text{mH}, L_2=1\text{mH}, C=20\text{uF}$ while the parameter of the L filter is set as follows. $L=4\text{mH}$. As seen from Figure 6, the harmonic amplitude of high order current yielded by the LCL filter is obviously lower than that yielded by L filter, which proves that the LCL filter performs better than the L filter. Nevertheless, the LCL filter will also introduce extra resonance points. Such resonant peaks actually exist in Figure 3, whose resonant frequency is related to capacitance and inductance and the peak value is related to the resistance $R_d$ in the capacitor branch. It can be seen from the figure that the peak value decreases along with the increase of $R_d$. Therefore, it is suggested to raise the resistance of $R_d$, but an excessively high resistance will affect the impedance of high-frequency capacitance branches and weaken the filtering effect of high-frequency waves. Besides, $R_d$ can also lead to power loss because of heating.
5. Conclusion
Power unit output mainly affects the modulation ratio of the new energy generation inverter and then affects the harmonic output of the inverter. The larger the power unit output is, the higher the modulation ratio will be. Low-frequency harmonic amplitude produced by the modulation of PWM increases while the high-frequency one decreases. The filter has a better filtering effect on high-frequency harmonics than on low-frequency harmonics. Hence in practice, the less the power unit output is, the better the result will be. The filtering effect of the filter on harmonic modulation is also determined by the structure of the filter and component parameters. LCL filters generate a better effect than L type filters. The capacitance and inductance of a filter will affect the resonant frequency of filtration and might amplify some sub-harmonics produced by the inverter, so suitable parameters shall be selected in accordance with actual operation parameters.

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