New feed-forward control strategy of single-phase grid-connected inverter

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Abstract. Traditional proportional feed-forward strategy can well restrain harmonic disturbance from grid background, but in the weak grid, positive feedback channel and grid-connected current inner-loop are coupling with each other by grid impedance, and robustness is substantially decreased. According to the above situation, a kind of new feed-forward control strategy is proposed, and adding more resonant link on positive feedback channel of point of common coupling voltage to change full pass characteristics of positive feedback channel which only make positive feedback channel have feedback effect on the frequency of main grid background harmonics. Inverter can both have great robustness and harmonic suppression ability in weak grid. In the end, the effectiveness and correctness of proposed control strategy is verified by the simulation model of single-phase grid-connected inverter.

1. Introduction

As one of the main operation devices of renewable energy, distributed generation has attracted the attention of scholars and experts all over the world because of its advantages which include clean environmental protection and support of economic operation of distribution network, and distributed generation has become the contemporary key research direction [1-2]. However, due to the wide distribution of distributed generation, the public grid is gradually transformed into a weak grid with time-varying inductive impedance and rich background harmonics. The change of grid impedance seriously affects the robustness of grid connected inverter, and the background harmonics will cause the grid current distortion[3-4]. The grid connection of distributed generation stipulates that the inverter must operate stably under the grid impedance corresponding to the short circuit ratio of 10 [5].

In reference [6], it is pointed out that the all pass characteristic of traditional proportional feedforward strategy is the main reason for the poor robustness of grid-connected inverter in the weak grid, and proposes a control strategy which add a resonant link in the feed-forward channel to improve the robustness of grid-connected inverter in weak grid. In reference [7], the series parallel virtual impedance is used to reshape the output impedance of the inverter. The harmonic suppression ability and robustness of the inverter are obviously improved, but the correction part includes differential term and introduces high frequency noise. Reference [8] introduces a negative feedback into the traditional proportional feed-forward positive feedback channel to offset the voltage drop on the inductive grid impedance, so as to correct the inductive component of the voltage at the point of common coupling (PCC).

According to the above research of adaptability of grid connected inverter in weak grid. Firstly, the control model of grid-connected inverter in weak grid is established, and the shortcomings of traditional proportional feed-forward strategy in weak grid are deeply analyzed. Then, a new feed-forward strategy is proposed. The proportional feed-forward strategy only has feedback effect at the low harmonic...
frequency of grid by adding multiple resonance links in the positive feedback channel. Finally, the simulation model of single-phase grid-connected which has 5kW output power is built to verify the effectiveness and correctness of the proposed strategy.

2. Control model of grid-connected inverter

As shown in figure 1, it is the model diagram of a single-phase LCL-type grid-connected inverter. The LCL filter is composed of inverter-side inductance $L_1$, grid-side inductance $L_2$ and filter capacitor $C$; $U_{dc}$ is DC voltage; $U_{inv}$ is output voltage; $U_{pcc}$ is common coupling point voltage; $i_L$ is output current; $i_C$ is capacitive current; $i_g$ is grid current; the public grid is equivalent to grid voltage $u_g$ in series with grid impedance $L_g$ (because the resistive component of the grid impedance is conducive to system stability, in order to consider the worst case, the grid impedance in this paper is purely inductive); $k_c$ is the active damping coefficient; $\theta$ is the fundamental phase information extracted by phase locked loop (PLL), $\theta$ is combined with current amplitude $I^*$ to generate command current $I_{ref}$; $G_c$ is the current controller; The inverter adopts bipolar sinusoidal pulse width modulation.

![Figure 1 Control structure graph with single-phase LCL-type grid-connected inverter](image)

Because digital control will produce control delay, it is composed of one beat delay caused by sampling and calculation and half beat delay caused by pulse width modulation (PWM). However, double sampling method has been proposed in the reference [9], which can completely eliminate the influence of sampling calculation delay to the system robustness and active damping $k_c$ performance, while PWM half beat delay has little influence on them. This paper mainly studies the background harmonic suppression and robustness improvement in low frequency band. For the convenience of analysis, the control delay factor is not considered temporarily.

Figure 2 is the block diagram of dual current feedback control without grid impedance. In figure 2, $k_{pwm}$ is equivalent to the gain coefficient of inverter bridge, which can be approximated as $U_{dc}/U_{tri}$, where $U_{tri}$ is the amplitude of triangular carrier. Because the grid voltage $u_g$ contains rich background harmonics, the common coupling point voltage $u_{pcc}$ is regarded as harmonic interference signal.

![Figure 2 Dual-current feedback control graph without grid impedance](image)

The transfer function from $i_{ref}$ to $i_g$ can be obtained from figure 2:

$$G_{i_{ref} \rightarrow i_g}(s) = G_c(s)k_{pwm}/[s^2L_2C + s^2L_2Ck_{pwm} + (L_1 + L_2)s]$$

(1)

The transfer function from $u_{pcc}$ to $i_g$ can also be obtained from figure 2:

$$G_{u_{pcc} \rightarrow i_g}(s) = [s^2L_2C + sk_{pwm} + 1]/[s^2L_2C + s^2L_2Ck_{pwm} + (L_1 + L_2)s]$$

(2)
It can be seen from figure 2 that the grid current \( i_g \) is composed of the closed-loop transfer function of two input signals \( i_{\text{ref}} \) and \( u_{\text{pcc}} \), so the output signal \( i_g \) can be expressed as:

\[
i_g(s) = \frac{G_{i_{\text{ref}}-i_{\text{ref}}}(s)}{1 + G_{i_{\text{ref}}-i_{\text{ref}}}(s)} \cdot i_{\text{ref}}(s) - \frac{G_{u_{\text{pcc}}-i_{\text{ref}}}(s)}{1 + G_{u_{\text{pcc}}-i_{\text{ref}}}(s)} \cdot u_{\text{pcc}}(s)
\]

In formula (3):

\[
u_{\text{pcc}}(s) = u_g(s) + i_g L_g s
\]

In addition, in order to conveniently analyze the influence of grid impedance \( L_g \) to grid current \( i_g \) of inverter, it is equivalent to a part of grid-side inductance \( L_2 \). Then figure 3 is the dual current feedback control block diagram with grid impedance, and formula (5) is the open-loop transfer function from \( i_{\text{ref}} \) to \( i_g \) with grid impedance.

3. Robustness analysis of proportional feed-forward strategy

Proportional feed-forward strategy has become a necessary control strategy which introduce a positive feedback channel at PCC point, the distorted voltage harmonic of grid is introduced into the modulation wave to achieve the goal of counteracting the harmonic disturbance of grid. The control block diagram is shown in figure 4.

In figure 4, \( k_g \) is the proportional feed-forward coefficient of network voltage, equal to \( 1/k_{\text{PWM}} \). The open-loop transfer function of the system with proportional feed-forward strategy can be deduced from figure 4.

\[
G_{i_{\text{ref}}-i_{g}}(s) = G_c(s) k_{\text{PWM}} \left[ s^2 L_1 (L_2 + L_g) C + s^2 (L_2 + L_g) C k_c k_{\text{PWM}} + (L_1 + L_2 + L_g) s \right]
\]

In formula (7), \( k_p \) is the open-loop gain, \( k_r \) is the fundamental frequency gain coefficient, \( \omega_i \) is the damping coefficient, and \( \omega_o \) is the fundamental angular frequency. \( kp=0.072, kr=15, \omega_i=3.14, \omega_o=314. \)
Figure 5 is the open-loop characteristic diagram corresponding to formula (6). It is easy to find that the system phase margin PM decreases greatly with the increase of grid impedance $L_g$. When $L_g=0$ mH, the phase margin PM of system is 58.7°, the system open-loop dynamic response is good. But when $L_g$ increase to 3.1 mH (the impedance value of the grid corresponding to the short-circuit ratio of 10), the phase margin PM has been seriously insufficient to 3.39°, the background harmonic near the cut-off frequency is greatly amplified. This is because $f_{\text{res}}$ of the conjugated pole of the open-loop resonance decreases rapidly and approaches the cut-off frequency $f_c$. As shown in formula (8), the phase at the frequency of the pole passes through -180° sharply. So the pole has a great attenuation effect on the phase near the frequency $f_c$.

$$f_{\text{res}} = \frac{1}{2\pi} \sqrt{\frac{L_1 + L_2}{L_1(L_2 + L_g)C}} \tag{8}$$

4. New feed-forward control strategy

4.1. The implementation principle of the proposed strategy

It can be seen that the reason why the robustness of the grid-connected inverter is greatly reduced is that the frequency of resonant conjugate pole decreases rapidly with the increase of the grid impedance $L_g$ and approaches the open-loop cut-off frequency.

Therefore, a new feed-forward strategy is proposed to make the positive feedback channel only maintain the feedback characteristics at the low harmonic frequency of the grid, and then slow down the decline rate of the resonant conjugate pole frequency by attenuating the amplitude gain of the other frequency bands of the positive feedback channel, which can not only maintain the high output impedance amplitude of the traditional proportional feed-forward at the low harmonic frequency, but also improve robustness of the inverter in weak grid. Figure 6 is the control block diagram of the new feed-forward strategy.
As shown in figure 6, multi-resonant $G_\alpha(s)$ is added to the traditional proportional feed-forward positive feedback channel to change the all pass characteristics of the positive feedback channel. The multi-resonant $G_\alpha(s)$ can keep the amplitude gain of the 3rd, 5th, 7th and 9th harmonic frequency in positive feedback channel, while the other frequency bands keep attenuation characteristics. Figure 7 is the bode diagram of $G_\alpha(s)$. The expression of transfer function of $G_\alpha(s)$ is shown in formula (9). In formula (9), $\omega_f$ is the resonant depth coefficient, taking 15$\pi$.

$$
G_\alpha(s) = \sum_{m=1}^{4} \frac{\omega_f s}{s^2 + \omega_f s + \left(2m+1\right)^2}\omega_f
$$

Figure.7 Bode graph with multi-resonant link

From the control block diagram shown in figure 6, we can get the open-loop transfer function of the new feed-forward strategy, as shown in formula (10).

$$
G^{*}_{\text{m}_2 - \text{m}_1}(s) = G_\alpha(s)k_{\text{pwm}}/\left[\left(s^3L_1\left(L_2 + L_5\right) + s^3(L_2 + L_5)Ck_c k_{\text{pwm}} + (L_4 + L_2 + L_5 - L_5)G_\alpha(s)k_{\text{pwm}}\right)s\right]
$$

(10)

From formula (10), the resonance frequency $f_{\text{res},n}$ expression of the conjugate pole can be obtained. As shown in formula (11), it can be found that the resonance frequency expression of the new strategy is consistent with resonance frequency expression of non-feed-forward strategy in the middle and high frequency range.

$$
f_{\text{res},n} \approx \frac{1}{2\pi \sqrt{\frac{L_1 + L_2 + L_5}{L_1\left(L_2 + L_5\right)C}}} \quad (f > 1000Hz)
$$

(11)

Figure 8 compares the change trend of resonant frequency of the proportional feed-forward strategy and the new feed-forward strategy. It can be concluded that the change of the grid inductance $L_g$ has little effect on the conjugate pole of the new feed-forward strategy in the medium and high frequency band due to the introduction of the resonant link $G_\alpha(s)$, and the attenuation effect of the conjugate poles is eliminated to the open-loop phase margin, and the robustness of system is significantly improved.
proportional feed-forward strategy
new feed-forward strategy

![Figure.8 Variation trend of pole resonance frequency with the increase of grid inductance](image)

4.2. Analysis of the open-loop characteristics of the proposed strategy

The open-loop bode diagram of the system with the new feed-forward strategy can be obtained from formula (10), as shown in figure 9. It is not difficult to find that the frequency of the resonant conjugate pole decreases slowly in the range of 0–3.1 mH of the grid impedance $L_g$, the system always keeps a good open-loop phase margin. Therefore, the robustness of the new feed-forward strategy is obviously stronger than proportional feed-forward strategy.

![Figure.9 System open-loop bode graph with new feed-forward strategy](image)

5. Simulation verification

In order to verify the effectiveness and correctness of the proposed strategy in this paper, a simulation model of single-phase LCL-type grid-connected inverter based on MATLAB/Simulink.

| Table 1. System parameters of single-phase LCL-type grid-connected inverter |
|--------------------------|--------------------------|
| parameter                | value                    |
| DC bus voltage $U_{dc}$/V | 400                      |
| grid voltage $u_g$/V     | 220                      |
| fundamental frequency $f_o$/Hz | 50               |
| carrier frequency $f_{sw}$/kHz | 15              |
| filter inductance $L_1$/mH | 0.6                   |
| filter inductance $L_2$/mH | 0.36                   |
| filter capacitor $C$/uf  | 5                       |
| output power $P_o$/kW    | 5                       |
| active damping coefficient $k_d$ | 0.09              |
| delta carrier amplitude $u_{tri}$/V | 3                 |
is built. The simulation parameters are shown in Table 1. At the same time, 3, 5, 7, 9, 11, 13, 17, 19 and 21 harmonic sources are connected in series to the grid voltage $u_g$, and the content is 10%, 5%, 3%, 3%, 2%, 2%, 1%, 1% and 1% of the fundamental amplitude.

Figure 10 shows the simulated grid current waveforms of the two strategies when $L_g=0\text{mH}$. It can be seen from Figure 10(a) that the proportional feed-forward strategy has good background harmonic suppression ability without inductive impedance. The new feed-forward strategy shown in Figure 10(b) has better harmonic suppression ability at the 3rd, 5th, 7th and 9th harmonic frequencies, the effectiveness of the proposed strategy is proved.

![Figure 10](image)

**Figure 10** Grid current wave graph of two strategies when $L_g=0\text{mH}$

Figure 11 shows the grid current waveforms of the two strategies when $L_g=1.5\text{mH}$. As shown in Figure 11(a), the grid current in the proportional feed-forward strategy is distorted. It aggravates the harmonic voltage distortion at PCC point and affects the operation of other grid-connected equipment. As shown in Figure 11(b), the grid current quality of the proposed strategy is also slightly affected by the grid impedance $L_g$, but still satisfy the requirements of grid-connected.

![Figure 11](image)

**Figure 11** Grid current wave graph of two strategies when $L_g=1.5\text{mH}$

It can be seen from Figure 12 that when the grid impedance $L_g=3.1\text{mH}$ (impedance value corresponding to short circuit ratio of 10), the grid current of the proportional feed-forward strategy has been seriously distorted. But the total harmonic distortion rate (THD) of the proposed strategy is 4.63% when $L_g=3.1\text{mH}$, and satisfies the requirements of grid-connected. It proves that proposed strategy has a good robustness when the grid impedance changes in a wide range.
6. Conclusion

1) In the weak grid, the robustness of the proportional feed-forward strategy will be greatly reduced because the frequency of the resonant conjugate pole decreases rapidly with the increase of the grid impedance.

2) A new feed-forward strategy is proposed, and proposed strategy changes the all pass characteristics of the traditional proportional feed-forward positive feedback channel by adding multiple resonant links. Final study results show that proposed strategy has good robustness and harmonic suppression ability in weak grid.

References

[1] Blaabjerg F, Teodorescu R, Liserre M, et al. Overview of control and grid synchronization for distributed power generation systems[J]. IEEE Transactions on Industrial Electronics, 2006, 53(5): 1398-1409.

[2] WU Weimin, LI Yuan, HE Yuanbin, et al. Damping methods for resonances caused by LCL-filter-based current-controlled grid-tied power inverters: an overview[J]. IEEE Transactions on Industrial Electronics, 2017, 64(9): 7402-7413.

[3] Yang D, Ruan X, Wu H. Impedance shaping of the grid-connected inverter with LCL filter to improve its adaptability to the weak grid condition[J]. IEEE Transactions on Power Electronics, 2014, 29(11): 5795-5805.

[4] XU Jinming, XIE Shaojun, QIAN Qiang et al. Adaptive Feedforward Algorithm Without Grid Impedance Estimation for Inverters to Suppress Grid Current Instabilities and Harmonics Due to Grid Impedance and Grid Voltage Distortion[J]. IEEE Transactions on Industrial Electronics, 2017, 64(9):7574-7586.

[5] XU Jinming, TANG Ting, XIE Shaojun. Research on low-order current harmonics rejections for grid-connected LCL-filtered inverters[J]. IET Power Electronics, 2014, 7(5): 1227-1234.

[6] WANG Jing, SONG Yulun, Monti A. A study of feedforward control on stability of grid parallel inverter with various grid impedance[C]. Proceedings of the 2014 IEEE 5th International Symposium on Power Electronics for Distributed Generation Systems(PEDG), 2014:1-8.

[7] Chen C, Xiong J, Wan Z, et al. A Time Delay Compensation Method Based on Area Equivalence For Active Damping of an LCL-Type Converter[J]. IEEE Transactions on Power Electronics, 2017, 32(1): 762-772.

[8] Guo L, Zhang Y, Yonghui L I, et al. Research on active damping strategy of LCL filter in three-phase voltage source PWM rectifier[J]. Power System Protection & Control, 2017, 45(4): 132-138.

[9] Chayjani S, Majid, Monfared, et al. Design of LCL and LLCL filters for single-phase grid connected converters[J]. IET Power Electronics, 2016, 9(9): 1971-1978.
[10] GENG Yiwen, QI Yawen, DONG Wenming. An Active Damping Method With Improved Grid Current Feedback[J]. Proceedings of the CSEE, 2018, 38(18): 5557-5567.