Internal Model Controller Applied to LCL-type Grid-connected Inverters in Weak Grid

Kai Wang¹², Jingtao Huang¹, Shengguo Zhang¹, Yumei Li¹ and Fei Wu³

¹College of Electrical Engineering, Northwest Minzu University, Lanzhou 730030, China
²College of Electrical Engineering, Sichuan University, Chengdu 610065, China
³Huantai County Power Supply Company, Zibo 255000, China
E-mail:63322567@qq.com

Abstract. Power grid in remote areas may show the feature of weak grid with time-variable impedance. Robustness of control of grid connected inverter (GCI) to grid impedance is one of the key technologies. For grid connected inverters with voltage feed-forward and time delay, IMC (Internal Model Controller) is used so that the adaptability to the grid impedance is improved. Detailed IMC and its parameter design method are provided, theoretical analysis and simulation results verify that IMC has robustness of grid and LCL impedance.

1. Introduction

Renewable energy sources are seen as a reliable alternative to the traditional energy sources such as oil, natural gas, or coal. With increasing penetration of renewable energy sources in the power grid, due to the long transmission line, long cable, multi-stage transformer and other factors, SCR (Short circuit capacity ratio) of power grid in remote areas or microgrid for distributed generation may be small, impedance of power grid may be large, and the power grid is in a weak state [1].

Impedance correction and robust controller are generally adopted to improve the adaptability of weak power grid. Virtual series/parallel impedance is adopted to correct the magnitude and phase of output impedance in [2], but this method is sensitive to the change of grid impedance [3], and the correction unit contains differentiation which is easy to introduce high frequency noise. Reference [4] points out that predictive controller and resonance controller can lead to a large number of harmonics and are not suitable for weak power grids. In [5], $H_{\infty}$ theory is adopted to design robust controller, the design process is complex, and the actual control variable may be large when the impedance of the power grid disappears [2]. In [6], $\mu$ synthesis algorithm of $H_{\infty}$ needs complex weight function for higher order controller, and is difficult in engineering application. In [1], adaptive control is adopted to improving the adaptability of weak power grid. On-line detection of grid impedance increases the cost and complexity of the algorithm, and interferes the grid current. IMC has better transient characteristics than PR [7], suppression of LCL resonance with resistance load may cause instability when load decreases, and weak power grid is not taken into account. The above method can adapt to a certain range of grid impedance, the disadvantage is either interference or complex design.

In this paper, IMC is used to improve the robustness of grid-connected inverter system in weak power grid. Firstly mathematical model of single-phase grid-connected inverter is established,
Secondly structure and parameter design method of IMC is given. Thirdly theoretical analysis of robust performance is carried out by root locus. Finally simulation results verify the correctness of the theoretical analysis.

2. Mathematical Model

Figure 1 shows the general block diagram of grid connected inverter. \( L_1, C \) and \( L_2 \) constitute LCL filter. Weak power grid consists of inductance and grid voltage in series. The influence of LCL parasitic resistance on system stability can be neglected [8], and grid resistance is beneficial to system stability [9], so this paper considers the most serious conditions and ignores the resistance in impedance. PLL (Phase Locked Loop) measures phase of PCC (Common Connection Point), \( I^* \) and phase are combined to reference signal \( i^*_g \). Deviation current \( e \) is obtained by Grid current and reference current. Controller \( G_c(s) \) regulates \( e \), and grid voltage proportional feedforward (proportional coefficient is \( 1/K \)) reduces grid current harmonics from background voltage harmonics. PWM converts control signal into AC power signal, the average model is

\[
G_{in}(s) = Ke^{-T_{d}e}
\]  

(1)

Where \( K \) is the ratio of DC voltage \( V_{dc} \) to triangular wave amplitude, \( T_d \) equals one and a half sampling cycle [10].

![Figure 1. System structure of GCI.](image)

Closed-loop control block diagram and simplified diagram can be obtained in figure 2 and 3.

![Figure 2. Control block diagram of GCI.](image)

![Figure 3. Simplified block diagram.](image)

According to figure 3:

\[
G_{c1}(s) = Ke^{-T_{d}e}/[L_1L_2Cs^3 + (L_1 + L_2)s] \quad G_{c2}(s) = (L_4Cs^2 + 1)/[L_1L_2Cs^3 + (L_1 + L_2)s]
\]  

(2)

Transfer function from reference current to grid current is

\[
T_0(s) = \frac{i_g^*(s)}{i_g(s)} = \frac{G_c(s)Ke^{-T_{d}e}}{L_4L_2 + L_4 + L_2 + L_2}Cs^3 + (L_1 + L_2)s - L_2se^{-T_{d}e}
\]  

(3)

Transfer function from grid voltage to grid current is

\[
T_1(s) = \frac{u_{pcc}(s)}{i_g(s)} = \frac{K(L_4Cs^2 + 1 - e^{-2T_{d}e})}{L_1L_2Cs^3 + (L_1 + L_2)s}
\]  

(4)
3. Design of IMC

3.1 Structural Design of IMC

Figure 4 is the schematic diagram of the IMC system. $G_p(s)$ is control object corresponding to the dotted line frame section of figure 1. $G_{x1}(s)$ is mathematical model of control object, $G_{IMC}(s)$ is IMC, $d$ represents the noise caused by harmonics voltage. $G_{IMC}(s)$ and $G_{x1}(s)$ can be merged into equivalent IMC $G_e(s)$, which is shown in figure 5, and $G_e(s)=G_{IMC}(s)/[1-G_{IMC}(s)G_m(s)]$.

![Figure 4. Structure of IMC system.](image)

![Figure 5. Structure of equivalent IMC system.](image)

The design steps of the equivalent internal model controller are as follows:

Step 1: minimum phase part of mathematical mode.

$$G_{x1-}(s) = \frac{K}{L_4L_2Cs^3 + (L_4 + L_2)s}$$  \hspace{1cm} (5)

Step 2: The inverse of the minimum phase part and the low-pass filter constitute IMC. The order of the filter should ensure that IMC can be physically implemented.

$$G_{IMC}(s) = \frac{L_4L_2Cs^3 + (L_4 + L_2)s}{K(\lambda s + 1)^3}$$  \hspace{1cm} (6)

Step 3: equivalent IMC is deduced from $G_{x1}(s)$ and $G_{IMC}(s)$. Since $L_1L_2C$ is much smaller than $(L_1+L_2)$, square term in molecule is ignored.

$$G_e(s) = L_4L_2Cs^2 + (L_4 + L_2) \approx \frac{L_4 + L_2}{K(\lambda s^2 + 3\lambda^2 s + 3\lambda)}$$  \hspace{1cm} (7)

The minimum phase part $G_{x1-}(s)$ does not contain the voltage feedforward, nor approximates the delay in the mathematical model. In this way, the equivalent IMC does not cancel out the voltage feed-forward and delay in the control object, thus suppression effect of background harmonics and damping of LCL resonance from delay are retained [3][11][12].

3.2 Parameter design of IMC

Time constant $\lambda$ of filter is the only adjustable parameter of IMC. In [13] a parameter design method considering both robust stability and robust performance is adopted.

The performance index of the control system is expressed by Integral Squared Error (ISE). The smaller the ISE value, the better the robustness; robust stability performance index adopts M value, the smaller M value, the better robust stability.

$$ISE = \int_0^t e^2(t)dt$$  \hspace{1cm} (8)

$$M = \max_\alpha |\eta|$$  \hspace{1cm} (9)

Where $e(t)$ is the error between the reference current and the grid current. $\eta$ is a complementary sensitivity function, and definition is:

$$\eta = \frac{G_{1le}(s)G_p(s)}{1 + G_{1le}(s)[G_p(s) - G_{x1}(s)]}$$  \hspace{1cm} (10)

The design steps of parameter are as follows:

Step 1: delay time $T_d$ is selected according to sampling mode, control mode, hardware...
performance, etc.

Step 2: different value of $\lambda$ is selected to calculate parameters of the controller according to (8), then ISE is obtained by simulation with 0.1s.

Step 3: M value can be calculated corresponding to different $\lambda$ according to (9), and the frequency range is 20 kHz.

Step 4: the curve of ISE and M is drawn from step 2 and step 3, then $\lambda$ can be selected according to robustness and robust stability.

In figure 6, ISE and M is small when $\lambda=2.1\times10^{-5}$, robustness and robust stability meet the requirements.

4. Robustness Analysis

4.1 Power grid parameter

Figure 7 is bode diagram of $T_0$. When $L_g$ is small, negative crossing point is invalid by delay, when $L_g$ is large, voltage feedforward can damp peak of LCL below 0dB, so the system can guarantee stability. With the increase of $L_g$, negative crossing point of phase frequency curve moves left, and can not disappear, while negative crossing point of PI can disappear and instability comes. Therefore, IMC has a wider range of adapting to the reactance variation of power grid.

4.2 LCL parameter

Because of the nonlinearity of inductance and the discreteness of the filter capacitor, the actual value of LCL filter deviates from nominal value [10], and the effect of IMC may be worse. So root locus of closed-loop system is used to judge robust stability with LCL parameter deviation.

Figure 8 is root locus diagram when parameters of LCL change to $\pm20\%$ respectively with different $L_g$. With the increase of $L_g$, dominant poles become from two pairs to one pair, and are getting closer to the imaginary axis, so the stability margin decreases gradually which causes more harmonics, but the stability remains unchanged.
5. Simulation Results

In this paper, the simulation is carried out in MATLAB/Simulink, and the system parameters are shown in Table 1.

Table 1. Main simulation parameters.

| Parameter            | Value | Parameter            | Value |
|----------------------|-------|----------------------|-------|
| Rated power $P_N$    | 6kW   | Inverter-side inductor $L_1$ | 0.5mH |
| Grid Voltage $u_g$   | 220V  | Filter capacitor $C$  | 10μF  |
| Fundamental frequency $f_g$ | 50Hz | Grid-side inductor $L_2$ | 0.5mH |

5.1 Power grid Parameters

Figure 9 plots waveforms of voltage and current, plots FFT of current, gives THD of voltage and current with different $L_g$. With the increase of $L_g$, the low order harmonics increase gradually, the reason is that bandwidth decreases; when $L_g=13mH$, voltage harmonics exceeding limit, but there is no instability phenomenon; therefore, the internal model control has a wide range of adaptability to weak power grids, THD and amplitude errors are small.

5.2 LCL parameters

When the deviation of LCL parameters is $\Delta=\pm 20\%$, the scope of THD of grid-connected voltage and...
current with different $L_g$ is shown in table 2. Voltage distortion is more serious than current distortion when LCL parameters vary, the reason is that the inverter current is controlled. THD of voltage and current can meet the requirements when $L_g < 10.4$ mH. The simulation results are consistent with the theoretical analysis in quarter 2.2, which shows that the deviation of LCL parameters causes the change of THD, but it does not affect the stability of the system, and the control effect can meet the requirements.

| IMC | $L_g$(mH) | $\Delta L_1$ | $\Delta L_2$ | $\Delta C$ |
|-----|-----------|-------------|-------------|----------|
| THDi | 0 | 0.67% | 0.66~0.69% | 0.67~0.68% |
|     | 2.6 | 0.79~0.96% | 0.76~0.99% | 0.87~0.88% |
|     | 10.4 | 1.14~1.92% | 1.39~1.4% | 1.1~1.95% |
| THDu | 0 | 0% | 0% | 0% |
|     | 2.6 | 0.95~1.23% | 0.94~1.26% | 1.09~1.11% |
|     | 10.4 | 2.78~4.53% | 3.26~3.48% | 2.78~4.46% |

6. Conclusion
In this paper, IMC is used to enhance the adaptability of grid connected inverter to the variation of grid impedance. Structure and parameters of IMC are designed for LCL grid-connected inverters with common connection point voltage feedback and time delay. Robustness analysis is given and the simulation results show that IMC has good robustness.

Acknowledgments
The research was supported by the Fundamental Research Funds for the Central Universities (31920170018).

Reference
[1] Liu Guihua et al 2017 Adaptive Quasi-PRD Control Method of Grid-Connected PV Inverter in Weak Grid Power System Technology, 41(01) pp 112-117
[2] Yang D, Ruan X and Wu H 2014 A virtual impedance method to improve the performance of LCL-type grid-connected inverters under weak grid conditions Zhongguo Dianji Gongcheng Xuebao 34(15) pp 2327-2335
[3] Wang Zhenhao et al 2018 Analysis of resonant characteristics and resonance suppression strategy of weak grid with LCL-type inverter Advanced Technology of Electrical Engineering and Energy 37(6) pp 34-42
[4] XU Jinming, XIE Shaojun and Tang Ting 2014 An Adaptive Current Control for Grid-connected LCL filtered Inverters in Weak Grid Case Proceedings of the CSEE 34(24) pp 4031-4039
[5] Yang S et al 2010 A robust control scheme for grid-connected voltage source inverters IEEE Transactions on Industrial Electronics 58(1) pp 202-212
[6] Qian Qiang et al 2016 A Current Control Strategy to Improve the Adaptability to Utility for Inverters Proceedings of the CSEE 36(22) pp 6193-6201
[7] Chaves E N et al 2016 Internal Model Control design applied to single-phase grid-connected inverters Power Electronics Conference and Southern Power Electronics Conference IEEE
[8] Qiu Zhiling 2009 The Study on Key Techniques of Three-Phase Three-Line Grid-Connected Converter Based on LCL-filter (Hangzhou: Zhejiang University) p 17
[9] Hua Xiaojie 2014 Research on Stability of Grid-connected Inverter Control System under Weak Grid Condition (Nanjing: Nanjing University of Aeronautics and Astronautics) p 21
[10] Ruan X et al 2015 Control Techniques for LCL-Type Grid-Connected Inverters (Beijing: Science Press) pp 76-134
[11] Xu Dezhi 2015 Modeling, Analysis and suppression on Harmonic Interactions Between Gied-Connected Inverters and Utility Grid (Shanghai: Shanghai University) pp 88-91
[12] Li Jun, Li Yuling and Chen Guozhu 2012 A Stability Control Strategy for PWM Converter With Undamped LCL-Filter Journal of Electrical Engineer & Technology 27(4) pp 110-116
[13] PAN Lideng and PAN Yangdong 2010 Application and Maintenance of Advanced Control System (Beijing: China Electric Power Press) pp 214-217