LCL-filter Optimization Design Considering Stability of Grid-Connected Inverters in Microgrid

Tiantian Chen  
Electric Power Research  
Institute of State Grid  
Shanghai Electric Power Company – China  
13881842533@163.com

Peng Zhang  
Electric Power Research  
Institute of State Grid  
Shanghai Electric Power Company – China  
pqlab_99@163.com

Ling Luo  
Electric Power Research  
Institute of State Grid  
Shanghai Electric Power Company – China  
scu_jaygc@163.com

Ling Pan  
Electric Power Research  
Institute of State Grid  
Shanghai Electric Power Company – China  
tanpengsc@gmail.com

ABSTRACT

As the existing optimized filter of grid-connected inverter design schemes give no consideration to the effect of grid impedances and current controllers, it will eventually cause the grid-connected LCL-filtered inverters lose stability when operating under the microgrid with small short-circuit ratio. This article thus presents a LCL-filter optimization design taking into account stability of grid-connected inverters. In the proposed approach, a multiple-objective optimal model is established, the objective functions of which are minimal damping power loss, minimal cost and optimum current tracking performance, and the constraint about stability is obtained by the impedance analysis method. PSO algorithm with compression factor is used to solve the optimization problem for its unique advantage on the convergence.

Compared with conventional design methods, such as optimized design of LCL filter for minimal damping power loss, the optimization in this article has a higher standardized satisfaction value, which means it can balance well cost and filtering performance and stability margin, especially suited for LCL filter parameters design under microgrid with small short-circuit ratio. For improving practical value of the proposed method, it is further demonstrated that the damp resistance has the most remarkable affect to the optimization results, so the precise selection of damp resistance is indispensable for achieving the desired performances. Moreover, the proposed method has a strong robustness for variation of the main circuit parameters, which makes the optimization design has a better practical value.

Finally, the comparative simulation results verify the effectiveness of the proposed method.

INTRODUCTION

In order to cope with the problem of climate deterioration and depletion of resources, the distributed power generation based on renewable energy such as wind energy and solar energy has been increasingly used in power system. As a connection unit of new energy power generation system and power grid, grid-connected inverter plays an important role in converting direct current into high-quality alternating current energy and feeding it into power grid, and it is widely used in network equipment because of its good performance in high-frequency harmonic suppression[1]-[2].

Combined with the actual experience, literature [3] introduced the general design method of LCL filter parameters in detail. But it just get the standard design parameters based on experience, and does not involve parameter optimization. Literature [4]-[5] proposed to design the filter parameters with the least damping loss or the smallest component energy storage.

The above optimization methods of LCL filter are all independently calculated under the ideal power grid. When operating under the microgrid, it is easy to cause the designed inverter to lose stability because of the excessive grid impedance [6]. In recent years, many documents take resonance suppression as an important consideration of filter parameter design. Literature [7] introduced the main resonance suppression methods and compared their performances, and the passive damping method has been widely used due to its good robustness and reliability. Literature[8] established a model about total harmonic distortion, and the generalized simple gradient method was used to achieve the minimum on the inductor with ensuring filtering performance, but the influence of grid impedance on system stability was not considered. A design method integrated with LCL filter and current controller optimizations is presented in [9] where the constraints of control performances to LCL parameters are considered.

Most LCL-filter designs do not take into account the effects of stability of inverters, which may cause inverters lose stability when operating under microgrid. A LCL-filter optimization design considering stability of inverters is proposed. First , the mathematical model of LCL grid-connected inverter is established, and the influence of grid impedance on inverter is studied by impedance analysis method. Furthermore , combining with the the constraints of LCL parameter design for inverter stability under microgrid and the requirements of other external characteristics of filter, a multi-objective optimization model with minimal damping power loss, minimal cost and optimum current tracking performance is obtained. Particle swarm optimization with compression factor is used to solve the problem. Finally, a comparative design example is given and the effectiveness of the proposed method is verified by the simulation results.

INFLUENCE OF GRID IMPEDANCE ON GRID-CONNECTED INVERTER UNDER
MICROGRID

Modeling of LCL Grid-Connected Inverter Output Impedance

Fig 1 shows the configuration of a LCL single grid-connected inverter, incorporated into the microgrid.

Fig.1 Grid-connected structure of single-phase inverter
Switches S1 and S2, S3 and S4 form the two bridge arms of the inverter bridge. The inverter-side filter inductor L1, the filter capacitor C and grid-side filter inductor L2 form the LCL filter of the grid-connected inverter. The damping resistor R is in series with capacitor to suppress the resonance peak. Cdc is the DC side energy storage capacitor. Then, iL is the output current, and upcc is the PCC voltage. The microgrid is equivalent to the series of voltage source uo and grid inductor Lg. As for internal control structure of the inverter, iref is the reference current, and um is the triangular carrier.

Fig.2 control block diagram of grid-connected inverter
The simplified control block diagram is shown in Fig. 2. The transfer function of using PI-controlled current regulator is expressed as

\[ G_{ig}(s) = K_p + K_i/s \]  
(1)

Where \( K_p \) is the proportional coefficient, and \( K_i \) is the integral coefficient. \( G_{inv} \) is the equivalent gain of the inverter, and its value is equal to the ratio of DC voltage to the triangular carrier amplitude.

According to the control block diagram, the output impedance \( Z_o \) can be modeled as

\[ Z_o(s) = \frac{L_1 s + L_2 s + L_1 L_2 C s^2 / (CRs + 1) + G_{inv} G_{dc}(s)}{1 + L_1 C s^2 / (CRs + 1)} \]  
(2)

**Influence of Grid Impedance on Stability**
The grid-connected inverter is denoted by the Norton equivalent circuit, in which a controlled current source is in parallel with the output impedance \( Z_o \). The microgrid is equivalent to the series of voltage source and grid impedance. The equivalent impedance network is shown in Figure 3.

Fig.3 Equivalent circuit of grid-connected inverters
The grid current \( I_g \) can be expressed as

\[ I_g(s) = \frac{U_{ref}(s) - U_{pcc}(s)}{Z_o(s)} \frac{1}{1 + Z_o(s)} \]  
(3)

The stability of the output current depends on the second term to the right of equation (2). \( H(s) \), which is defined as \( H(s) = 1 / (1 + Z_o(s) / Z_o(s)) \), is similar to a closed-loop transfer function with negative feedback, whose the positive gain is 1 and the feedback gain is \( Z_o(s) / Z_o(s) \). The root locus diagram of grid-connected system with different grid impedances is shown in Figure 4.

Fig.4 Root locus diagram of grid-connected system with different grid impedances
The increase of the grid impedance will cause the closed-loop pole of the grid-connected control system to gradually move to the right, and the stability of the grid will gradually decrease. The system will lose stability when there is a pole in the right half plane.

MULTIOBJECTIVE OPTIMIZATION MODEL FOR LCL FILTER PARAMETER DESIGN CONSIDERING GRID IMPEDANCE

**Establishment of Optimization Model**

Multiobjective optimization model can be expressed as

\[
\begin{align*}
\min \ f(x, u) &= \alpha_1 f_1 + \alpha_2 f_2 - \alpha_3 f_3 \\
&= \alpha_1 \left( 3I_g^2 R \right) + \alpha_2 \left( L_1 + L_2 \right) - \alpha_3 \left( 20 \log |F_{ref}| \right) \\
s.t. \ h_j(x, u) = 0 & \quad j = 1, 2, \ldots, p \\
g_k(x, u) \leq 0 & \quad k = 1, 2, \ldots, q
\end{align*}
\]  
(6)

Where the objective function \( f_1 \) represents the minimum damping loss, and \( f_2 \) represents the minimum total inductance \( L \). The objective function \( f_3 \) represents the
maximum loop gain at the fundamental frequency to ensure that the steady-state error is minimal. The weight coefficient $\omega_0$ is determined by the entropy weight method.

\[ u = [L_1, L_2, R, C, K_p, K_i] \] represents the control variable. 
\[ x = [f_c, T_0, I_0] \] represents the state variable. Among them, $f_c$ is the cutoff frequency of the equivalent open-loop system $G(s)$, which is defined as $G(s) = Z_g(s) / Z_0(s)$, and $T_0$ is the loop gain at the fundamental frequency, and $I_0$ is the valid values of harmonic current around the switching frequency of the filter capacitor.

Constraints include stability constraints, grid harmonic current constraints and filter capacitor reactive power constraints.

1) Equality constraints
\[ T_{0} = \frac{K_{\text{sum}}(K_p + K_i/j2\pi f_c)}{2\pi f_c(L_1 + L_2)} \] (7)
\[ Z_g(s) / Z_0(s) \] has an amplitude of 1 at the cut-off frequency $f_c$. 
\[ \left| \frac{Z_g(x, u)}{Z_0(x, u)} \right| = 1 = 0 \] (8)

2) Constraints about grid stability
In order to take into account the grid stability and dynamic response performance, the phase margin is usually 30° to 60° according to the actual engineering experience.
\[ 30 \leq g_3(x, u) = 180° - \left[ 90° - \arg Z_g(x, u) \right] \leq 60° \] (12)

For a inverter, which has a capacity of $P_N$, it needs to adapt to the maximum value of grid inductance is
\[ L_{g, \text{max}} = \frac{U_{\text{dc}}^2}{10 \times P_N \times 2\pi f} \] (13)

3) Constraints about harmonic current
The value of harmonic current near the switching frequency is less than 0.3% of the rated grid current. 
\[ g_4(x, u) = \left| \frac{\int_0^{T_f} |jw_nRC| + 1}{L_1 L_2 C(jw_n)} + (L_1 + L_2) CR(jw_n) \right| \leq 0.3\% I_N \] (14)

4) Constraints about total filter inductance
\[ \frac{U_{\text{dc}}}{4\sqrt{3} \Delta I_{\text{ripple, max}} f_{\text{sw}}} \leq g_5(x, u) = L_f \leq \sqrt{U_{\text{dc}}^2 / 3 - E_{\text{mp}}^2} / w_{\text{mp}} \] (15)

Where $\Delta I_{\text{ripple, max}}$ is maximum allowed phase current ripple. $I_{\text{mp}}$ and $E_{\text{mp}}$ is peak phase current and peak phase voltage, respectively

5) Constraints about reactive power of capacitor
The reactive power of filter capacitor does not exceed 5% of rated power.
\[ g_6(x, u) = 3 \times 2\pi f U_{\text{dc}}^2 C \leq 5\% P_N \] (16)

**Solution of Optimization Model**

The particle swarm optimization with compressibility factor is helpful to enhance the convergence of PSO algorithm, and high-quality solutions can be searched in different areas. Each particle update their speed and location according to (17) and (18).
\[ v_{id}^{k+1} = \chi(wv_{id}^k + c_1 \text{rand}_1(p_{\text{best}}^k - x_{id}^k)) \] + $c_2 \text{rand}_2(g_{\text{best}}^k - x_{id}^k) \] (17)
\[ x_{id}^{k+1} = x_{id}^k + v_{id}^{k+1} \] (18)

Where $v_{id}$ and $x_{id}$ is the velocity and the position of particle $d$ in the $k$th iteration, respectively. $c_1$ and $c_2$ are acceleration factors. $\text{rand}_1$ and $\text{rand}_2$ are random numbers between [0, 1]. $\chi$ is a compression factor, which can be selected according to (19)
\[ \chi = 2/[2 - \wp -(\wp^2 - 4\wp)^{1/2}] \] (19)

Where $\wp = c_1 + c_2$, and $\wp > 4$.

**DESIGN EXAMPLE AND COMPARATIVE ANALYSIS**

**Design example**

We optimize the parameters of the following grid-connected inverter in Table I.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>value</th>
<th>Parameters</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_p$/Hz</td>
<td>50</td>
<td>$f_{\text{in}}$/kHz</td>
<td>3</td>
</tr>
<tr>
<td>$u_d$/V</td>
<td>220</td>
<td>$U_{\text{dc}}$/V</td>
<td>650</td>
</tr>
<tr>
<td>$P_N$/kW</td>
<td>10</td>
<td>$I_{\text{mp}}$/A</td>
<td>21</td>
</tr>
<tr>
<td>$f_{\text{c}}$/kHz</td>
<td>6</td>
<td>$\omega LC$</td>
<td>30%</td>
</tr>
</tbody>
</table>

In order to demonstrate the superiority of the proposed method in this paper, we gave the design results with optimized design for minimal damping power loss(method I) and proposed method(method II), which are shown in Tab II

<table>
<thead>
<tr>
<th>Parameters</th>
<th>method I</th>
<th>method II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_1$</td>
<td>13.1mH</td>
<td>12mH</td>
</tr>
<tr>
<td>$L_2$</td>
<td>3.9mH</td>
<td>4.2mH</td>
</tr>
<tr>
<td>$C$</td>
<td>10uF</td>
<td>6uF</td>
</tr>
<tr>
<td>$R$</td>
<td>5Ω</td>
<td>8.5Ω</td>
</tr>
</tbody>
</table>

The fuzzy membership function is defined to compare the optimization results quantitatively.
\[ \mu_i = \begin{cases} 1 & f_i < f_{i, \text{min}} \\ \frac{f_{i, \text{max}} - f_i}{f_{i, \text{max}} - f_{i, \text{min}}} & f_{i, \text{min}} \leq f_i \leq f_{i, \text{min}} \\ 0 & f_i > f_{i, \text{max}} \end{cases} \] (20)
The closer $\mu_i$ is to 1, the more satisfied the index $\mu_i$ is. Finally, the degree of the optimization result is judged by standardizing the satisfaction value $\mu$. According to (20), $\mu = 0.63$ for the method I, and $\mu = 0.8$ for the method II, which shows the proposed optimization can balance well cost and filtering performance and stability margin.

For the inverter designed by the proposed method in this paper, because the grid system has enough stability margin, which is showed in Fig. 7, the system work stably and has a high quality output current. These simulations validate the effectiveness of the proposed method.

**CONCLUSION**

This paper has presented a LCL-filter optimization design considering stability of grid-connected inverters in microgrid, and the particle swarm optimization with compressibility factor is used to find the optimal solution. According to the comparative analysis and simulation results, the proposed design method has a overall optimization to inverter parameters, which can balance well cost and filter performance and increase stability margin, especially suited for LCL filter parameters design under microgrid.

**REFERENCES**


