Current mode Controller Design for Single Phase grid connected Inverter Using Proportional Resonant Control Strategy

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Abstract
This paper presents the design of controller based on proportional resonant strategy for single-phase grid connected inverter. The control design is carried out using Sisotool, which is provided in Matlab. By using this tool, users can examine the effects of changing the gain control values to system's transient response and stability, simultaneously. Hence, simplify and speed up the control design process. To evaluate the performance of the designed controller, the inverter is simulated under several types of load disturbances. From the result, it is shown that the designed controller exhibits a good transient response i.e. fast rising and settling time with small overshoot when subjected to step load disturbance.

Keywords – grid - connected inverter, film capacitor, PR controller, transient and steady state response.

I. INTRODUCTION

In recent years, distributed generation has been put on the agenda, distributed generation has the merits of less pollution, high reliability, high energy efficiency and installation flexibility, it can solve many potential problems of the large scale centralized power effectively, however, electricity produced by distributed power generation can’t supply to AC load directly, grid-connected interface equipment must be inserted¹.

Power inverter is an important part of many DC to AC conversion equipments such as uninterruptable power supply (UPS), induction motor drive and automatic voltage regulator (AVR) systems. In these systems, it is the major requirement for the power inverter to be capable of producing and maintaining a stable and clean sinusoidal output voltage waveform regardless of the type of load connected to it. The main key to successfully maintain this ability is to have a feedback controller [1].

Currently, grid-connected inverter generally use control strategy of the output current control, nowadays, the most commonly used method have PID control and so on. It has the merits of good control performance, robustness, and simple algorithm, clear physical meanings of parameters, easy to implement and high reliability, so it is widely applied in industry field as yet but conventional control can’t reach perfect control effects for sine reference current, because this method has relatively more rise and settling time. In order to settle this problem, PR controller is designed in this paper.

II. MODEL OF SINGLE PHASE GRID CONNECTED INVERTER

Figure 1, shows the equivalent circuit of a single-phase full bridge inverter with connected load. In this study, control based on the proportional resonant strategy theory is presented.

Figure 1: Full bridge single phase PV inverter

A full bridge configuration with SPWM unipolar voltage switching scheme is used as the switching circuit of the inverter. By selecting the full bridge configuration, the minimal allowed DC-link voltage can be set to be the peak value of the AC grid voltage (plus margins). Thus, power MOSFETs, instead of higher voltage IGBTs, can be used as the switching devices which enable use of a high switching frequency (> 20 kHz) without introduction of excessive switching loss.
A. Output Filter Design

A third order LCL filter, Figure 2, was used to meet the aforementioned harmonic reduction target. A switching frequency of 30 kHz was selected based on considerations for the filter size and the practical implementation of the digital controller.

\[
v_{i}(t) \text{ stands for the terminal voltage, which consists of a fundamental component and higher order harmonics components. Solving the grid current in Laplace domain using superposition yields the following transfer functions:}
\]

\[
I_g(s) = \frac{sC_fR_d + 1}{s^3L_iL_gC_f + s^2C_fR_d(L_i + L_g) + s(L_i + L_g)} \quad (1)
\]

\[
I_g(s) = \frac{s^2L_iC_f + sC_fR_d + 1}{s^3L_iL_gC_f + s^2C_fR_d(L_i + L_g) + s(L_i + L_g)} \quad (2)
\]

Consider the equation (1) in the output filter design the terminal voltage \(v_i(t)\) contains a fundamental component and higher frequency components which could result in higher frequency distortions on the grid current \(i_g(t)\). Therefore, Equation (1) is used as the output filter transfer function as:

\[
H_f(s) = \frac{I_g(s)}{V_i(s)} = \frac{sC_fR_d + 1}{s^3L_iL_gC_f + s^2C_fR_d(L_i + L_g) + s(L_i + L_g)} \quad (3)
\]

The RMS value of the higher order frequency components of \(v_i(t)\) can be calculated as:

\[
|V_{h}(j\omega_g)| = \frac{1}{\sqrt{2}} \cdot \frac{1}{\sqrt{2}} \cdot \frac{V_{dc}}{2} \cdot \frac{1}{2} \cdot |V_{dc}| \cdot V_{dc} \quad (4)
\]

Combining equation (3) and (4), the RMS value of the harmonic current can be expressed as:

\[
|I_g(j\omega_g)| = \frac{1}{\sqrt{2}} \cdot |H_f(j\omega_g)| \cdot k(h) \cdot V_{dc} \quad (5)
\]

Remember that \(|I_g(j\omega_g)|\) cannot exceed 0.3% of the rated current of the inverter. Therefore, the RMS value of the rated grid current \(I_{g \text{ rated}}\) the following relationship can be derived:

\[
|H_f(j\omega_g)| \cdot k(h) \cdot V_{dc} \leq 0.3\% \quad (6)
\]

Rewrite for \(|H_f(j\omega_g)|\) then:

\[
|H_f(j\omega_g)| < \frac{0.3\% \cdot \sqrt{2} \cdot I_{g \text{ rated}}}{V_{dc} \cdot k(h)} \quad (7)
\]

For worst case \(k(h)\) at \(2m_r - 1\) is 0.37.

\[
|H_f(j(376614))| = |H_f(j(376614))| - 70dB = 2.87 \times 10^{-4} \leq 70dB \quad (8)
\]

With the transfer function of the filter derived in equation (3), the generic magnitude plot of \(H_f(s)\) can be drawn as shown in figure 3 at \(\omega = 376614\), the magnitude of \(H_f(j376614)\) from the magnitude plot of \(H_f(j\omega)\) should at most be -70dB. This is the guideline of choosing the values for \(L_i, L_g, C_f\) and \(R_d\). Finally, the LCL filter components are chosen following this guideline and the values of each component are shown in Table 1.

<table>
<thead>
<tr>
<th>Li</th>
<th>Lg</th>
<th>C_f</th>
<th>R_d</th>
</tr>
</thead>
<tbody>
<tr>
<td>300\mu H</td>
<td>100\mu H</td>
<td>30\mu F</td>
<td>1.5\Omega</td>
</tr>
</tbody>
</table>

III. CONTROL SYSTEM DESIGN

The design of the controller for the inverter can be divided into two parts: 1) current controller, and 2) DC voltage controller.

A. CURRENT CONTROLLER

A single phase feedback current loop is used to regulate the grid current. A proportional resonant (PR) control strategy is used as a compensator to track a sinusoidal current reference signal.
The plant model of the inverter can be derived by combining equation (1) and (2), which yields:

$$I_g(s) = G_f(s) \left( \frac{s^2 L_g C_f + s C_f R_d + 1}{s C_f R_d + 1} V_g - V_t \right) \quad (9)$$

Where,

$$G_f(s) = \frac{s C_f R_d + 1}{s^3 L_i L_g C_f + s^2 C_f R_d (L_i + L_g) + s (L_i + L_g)} \quad (10)$$

The equation (9) can be simplified to equation (11).

$$I_g(s) = G_f(s) (V_g - V_t) \quad (11)$$

![Figure 4: Current controller block diagram](image)

Given the plant model, a PR compensator, $G_t(s)$ is then added to the closed loop.

According to Figure 4, the relationship between the input and the output of the current loop can be derived as:

$$I_g(s) = H_t(s) I^{ref}(s) + H_v(s) V_g(s) \quad (12)$$

Where,

$$H_t(s) = \frac{G_t(s) G_f(s)}{G_t(s) G_f(s) - 1} \quad (13)$$

$$H_v(s) = \frac{G_f(s)}{1 - G_t(s) G_f(s)} \quad (14)$$

To successfully track the $i^{ref}(t)$ signal without steady state errors, the magnitude of $H_t(j\omega)$ in Equation (3.5) has equal to 1 at the fundamental frequency of the $i^{ref}(t)$.

For non-ideal PR controller the transfer function of $G_t(s)$ is given by:

$$G_t(s) = K_p^v + \frac{K_i^v s}{s^2 + 2\zeta \omega_n s + \omega_n^2} \quad (15)$$

The closed loop gain of the current control loop with the PR compensator can be simply obtained by Equation (4.9). The PR compensator's parameters and system's parameters are chosen in Table 2.

$$T_t(s) = G_t(s) G_f(s) = \left( \frac{K_p^v + \frac{K_i^v s}{s^2 + 2\zeta \omega_n s + \omega_n^2}}{s C_f R_d + 1} \right) \frac{s C_f R_d + 1}{s^3 L_i L_g C_f + s^2 C_f R_d (L_i + L_g) + s (L_i + L_g)} \quad (16)$$

![Table 2: PR compensator's parameters and system's parameters](image)

The bode plot of the compensated loop gain is shown in Figure 5.

![Figure 4: Compensated current loop gain](image)

### B. DC VOLTAGE CONTROLLER

The DC-link voltage can be regulated by a closed loop voltage controller. Figure 5 is a simplified power stage diagram which is used to analyze the DC voltage behavior.

![Figure 5: Inverter power stage diagram](image)

For voltage loop modeling, the differential equation on DC side is:

$$C_{dc} \frac{dv_{dc}(t)}{dt} = i_{dc}(t) \quad (17)$$

From the power balance equation:

$$I_{dc} = \frac{V_g}{2v_{dc}(t)} i_g \cos \phi = \frac{V_g}{\sqrt{2}v_{dc}(t)} i_g \cos \phi \quad (18)$$

$$i_{dc,\text{ripple}}(t) = \frac{\frac{V_g}{\sqrt{2}} i_g \cos(2\omega_d t - \phi)}{2v_{dc}(t)} \quad (19)$$

A simple PI controller is used as the DC voltage loop compensator, which has the form of:

$$G_v(s) = K_p^v + \frac{K_i^v s}{s} \quad (20)$$

A selection of $K_p^v = 0.1$ and $K_i^v = 1$ yields a phase margin of $60^\circ$ in the compensated loop as shown in Figure 6.
IV. SIMULATION RESULT

Figure 8 shows the MATLAB/SIMULINK simulation setup for the current and voltage loop of the DC/AC inverter.

Table 3: Inverter current loop simulation power stage parameters.

<table>
<thead>
<tr>
<th>TABLE III</th>
<th>INVERTER SPECIFICATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>Values</td>
</tr>
<tr>
<td>Grid nominal voltage $V_{gn}$</td>
<td>250V (RMS)</td>
</tr>
<tr>
<td>DC-link nominal voltage $V_{dce}$</td>
<td>400V (RMS)</td>
</tr>
<tr>
<td>Bridge side inductor $L_b$</td>
<td>300 μH</td>
</tr>
<tr>
<td>Bridge side inductor $L_g$</td>
<td>100 μH</td>
</tr>
<tr>
<td>Filter capacitor $C_f$</td>
<td>30 μF</td>
</tr>
<tr>
<td>Filter damping resistor $R_d$</td>
<td>1.5Ω</td>
</tr>
<tr>
<td>Switching frequency $f_{sw}$</td>
<td>30kHz</td>
</tr>
</tbody>
</table>

Figure 7 shows the steady state response of the inverter.

(a) Grid current and voltage are in phase

(b) Grid current lags the voltage by 90°

Figure 7: Steady state response of the current loop simulation
The transient response of the current loop simulation results are shown in Figure 9 for the output grid current steps up from 0A to 10A (RMS). Simulations are done in two different circumstances where in Figure 9(a), the current the grid voltage is in phase with the grid voltage and in Figure 9(b), the current lags 90°.

![Figure 9: Step response of the current loop simulation](image)

The grid voltage $v_g(t)$, inverter output current $i_{gn}(t)$ and the current input command $i_{gll}^{ref}$ and $i_{gel}^{ref}$ are shown from top to bottom of each sub-figure. It can be observed that the current step response has a settling time less than 2ms and a percentage overshoot that is less than 30%.

V. CONCLUSION

In this paper a current mode PR controller for a single-phase grid connected inverter has been designed. The control structure is comprised of two loops and has been arranged in a cascaded fashion. Two system variables namely the grid current and the output voltage are sensed as the feedback variables. The MATLAB/SIMULINK has been used to tune and design the PR control parameters for both loops. The performance is verified by subjecting the inverter system with steady and transient responses. The simulation results have shown that the controller is capable of producing good output voltage regulation.

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