Circulating Current Inhibition Characteristic of the Parallel Inverters
Using Close-loop Adjustment of Instantaneous Voltage Feedback

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Abstract: This study investigated outputting circulation current inhibition characteristic that is controlled by the instantaneous feedback voltage in inverter parallel driving of the mine hoist. We established the transfer function of the parallel inverters controlled by the close-loop adjustment of the instantaneous voltage feedback. The influence of the parameters of the close-loop feedback circuit to the inhibition effects to the outputting circulation current are observed. After analysis of circulating current inhibition characteristic, the proportion integration (PI) controller is introduced into the close-loop adjustment by the instantaneous voltage feedback. The characteristic equation is gained to determine the PI parameters by the drawing of the Bode plots. The inhibition effects of the proposed controller are examined by the established simulation model of parallel inverter system. The harmonic distortion rate at the outputting voltage frequency values of 4Hz, 10Hz, 20Hz, 41Hz and 50Hz are all low than 2.32% by the outputting voltage instantaneous feedback.

Keywords: parallel inverters; circulating current; inhibition characteristic; close-loop adjustment

1. Introduction

Parallel inverter driving system of mine hoist differs from traditional driving inverter system, including parallel connection system of the two independent inverter unit to driving the motor, which can effectively increase the power levels and improve the reliability of the inverter driving system. When the inventers are in parallel structure, the total current of inverter parallel driving system is equal to the sum of currents of the two inverter units. If one of the inverter units goes wrong, the system can use the other one to drive the motor alone, keep the continuity and safety working of the equipment. However, if the two inventers have differences in the outputting voltage amplitude, frequency and phase, there will be a large circulating current between the two inventers. Especially when the dead times of the two inventers are different, it not only affect the amplitude and phase of the outputting voltage, but also cause the single harmonics, which will produce a huge harmonic circulating current. The harmonic circulating current has an impact on the system and consume large amounts of energy, cause waveform distortion of the output voltage and current and induce electromagnetic interference [1]. Therefore, it is significant to research on inhibition technology to the harmonic circulating current in inverter parallel driving system.

There are many available literature and referenced results about harmonic circulating current inhibition technology in inverter parallel driving system. The DC component generated in the inverter parallel system makes the inverter outputting filter inductor being saturation and uneven thermal and electrical stress of each electrical module, and then reduce the reliability of the parallel system [2]. In order to inhibit the DC circulating current, there are some methods to be developed such as voltage and current double closed loop controlling, three-state hysteresis controlling, filter circuit elimination and reference sine wave DC component regulating [3-5]. [6] analyzed the case of two inventers sharing a rectifier modules, a zero sequence circulation through the DC bus was produced, which consumed a lot of energy, reduce the efficiency of the system and cause saturation of filter reactor, so a separate rectifier inverter units in parallel was adopted. [7,8] analyzed the presence of harmonic circulating current have caused distortion of the outputting voltage and produced large amounts of harmonic, polluted the electrical grids and interfered the normal operation of other equipment. Following the
analysis some circulating harmonic inhibition methods have been introduced such as voltage instantaneous feedback controlling, repetitive controlling, deadbeat controlling and voltage and current double-loop controlling[9-10].

Considering the dispersion of dead zone of switching component of the circuit is the major reason of harmonic circulating current, and adopting regulation method of voltage instantaneous feedback to adjust and inhibit the harmonic circulating current, this paper proposes an inhibition method of harmonic circulating current in inverter driving system, which considers the outputting voltage error caused by a harmonic disturbance. The proposed method differs from the present studies that treated the dead zone of switching component of the circuit being equivalent to the resistance in series with the inverter outputting filter inductance.

2. Inhibition principle by the voltage instantaneous feedback

Fig.1 shows the regulation and control frame diagram of inhibition principle by the outputting voltage instantaneous feedback. $K_v$ is the coefficient of voltage feedback. The error of voltage is obtained by detecting the instantaneous voltage across the capacitor and comparing to the reference sine voltage signal $U_{ref}(s)$. The error of voltage generates a modulation wave by the regulator $T(s)$. After conducting a comparison of modulation wave to the carrier one, the SPWM wave is obtained. The SPWM wave is the driving signal to the inverter.

![Figure 1. The regulation and control frame diagram of inhibition principle of outputting voltage instantaneous feedback](image)

A transfer function of the inhibition principle by instantaneous outputting voltage feedback is established based on Fig.1, and is shown in Fig.2. In the model, $U_{ref}$ is the standard reference voltage, $T(s)$ is regulator of the instantaneous voltage feedback, $k_{PWM}$ is an equivalent gain for PWM, $k_v$ is the coefficient of voltage feedback, $r$ is the equivalent circuit resistance, $L$ is the filter inductor, $C$ is the filter capacitor, $U_o(s)$ is the outputting voltage.

![Figure 2. The function model of the inhibition principle of outputting voltage instantaneous feedback](image)

The transfer function of the closed-loop operation can be obtained:
\[ U_o(s) = \frac{K_{PWM} T(s)}{L s^2 + r C s + K_{PWM} K_v T(s) + 1} U_{ref}(s) - \frac{1}{L s^2 + r C s + K_{PWM} K_v T(s) + 1} U_e(s) - \frac{L s + r}{L s^2 + r C s + K_{PWM} K_v T(s) + 1} I_o(s) \] (1)

According to (1), the outputting voltage feedback regulator increases attenuation gain of the error of voltage caused by dead zone of switching component of the circuit, and has a good inhibiting effect on harmonic circulating current. Reasonable adjustment of \( T(s) \) parameters can improve the stability of the system and the quality of the outputting waveform. At the same time, the circuit parameters of \( L, C, r, K_r, K_{PWM} \) are selected appropriately to have an impact on the inhibition of harmonic circulating current.

Let \( B_e(s) = L C s^2 + r C s + K_{PWM} K_v T(s) + 1 \), then the (1) can be written by:

\[ U_o(s) = \frac{K_{PWM} T(s)}{B_e(s)} U_{ref}(s) - \frac{1}{B_e(s)} U_e(s) - \frac{L s + r}{B_e(s)} I_o(s) \] (2)

The harmonic circulating current (3) can be obtained by (2):

\[ I_H(s) = \frac{K_{PWM} T(s)}{L s + r + Z B_e(s)} \frac{U_{ref1}(s) - U_{ref2}(s)}{2} + \frac{1}{L s + r + Z B_e(s)} \frac{U_{e2}(s) - U_{e1}(s)}{2} \] (3)

Where, let \( H(s) = \frac{1}{L s + r + Z B_e(s)} \), we can see that the circulation error is mainly inhibited by \( H(s) \), the harmonic circulating current can be reduced by decreasing the gain of \( H(s) \) and increasing the \( B_e(s) \). According to (1), the increasing of \( B_e(s) \) reduce the outputting harmonic voltage. Meanwhile, according to \( H(s) \), inhibition effect is greater when the \( Z, L \) and \( r \) are larger. However, the voltage drop and the distortion of the outputting waveform will be greater when the parameters of \( Z, L \) and \( r \) are selected by too much large values, and the stability of the system will be affected by too large value of \( B_e(s) \). Thus, \( Z, L, r \) and \( B_e(s) \) should be selected by appropriate value. According to the expression of \( B_e(s) \), the \( B_e(s) \) is mainly controlled by \( T(s) \).

3. The determination of PI parameters of voltage instantaneous feedback

The \( T(s) \) is adjusted by adopting PI regulator that is a simple and effective method to be easily implemented. The expression of the \( T(s) \) can be written by:

\[ T(s) = K_p + K_i \frac{1}{s} \] (4)

Substituting (4) into (1), the characteristic equation can be obtained:

\[ B_e(s) = L C s^3 + r C s^2 + (K_{PWM} K_v K_p + 1)s + K_{PWM} K_v K_i \] (5)

It can be seen from (5) that the characteristic equation has three roots. The dominant roots are \( s_{1,2} = -\zeta \omega_n \pm j \omega_n \sqrt{1 - \zeta^2} \), \( \zeta \) is the damping ratio, \( \omega_n \) is the natural frequency. The no dominant root \( s_3 = -n \zeta \omega_n \), \( n \) is the normal number with the value ranging from five to ten. The characteristic equation of the system can be written:
According to the pole assignment method, the following expression can be obtained:

\[
K_p = \frac{(2n\zeta^2 + 1)\omega_n^2 LC - 1}{K_{PWM}K_p}
\]

\[
K_i = \frac{n\zeta\omega_n^3 LC}{K_{PWM}K_p}
\]

Formula (7) are the PI parameters of \( T(s) \) controller. It can be seen from formula (7) that \( K_{PWM} \), \( K_p \), \( L \), \( C \) are parameters of the inverter unit circuit, \( \zeta \), \( \omega_n \), \( n \) are the parameters to be determined. The parameters of inverter unit circuit are assumed as follows: \( L = 1 mH \), \( C = 30 \mu F \), \( r = 0.1 \Omega \), \( K_{PWM} = 33.3 \) and \( K_p = 0.0257 \). Substitution of formula (7) into the regulator \( T(s) \), the closed-loop transfer function of system can be written:

\[
U_o(s) = \frac{K_{PWM}K_p \omega_n s + K_{PWM}K_i}{LCs^2 + rCs^2 + (K_{PWM}K_p + 1)s + K_{PWM}K_p} U_{ref}(s)
\]

\[
- \frac{s}{LCs^2 + rCs^2 + (K_{PWM}K_p + 1)s + K_{PWM}K_p} U_i(s)
\]

\[
- \frac{LS^2 + rs}{LCs^2 + rCs^2 + (K_{PWM}K_p + 1)s + K_{PWM}K_p} I_o(s)
\]

The bode plots are drawn by formula (9), the system performance influenced by different \( \zeta \), \( \omega_n \), \( n \) are analyzed. Table 1 shows the PI coefficients of the \( T(s) \) regulator by different values of \( n \).

<table>
<thead>
<tr>
<th>n</th>
<th>4</th>
<th>6</th>
<th>8</th>
<th>10</th>
<th>12</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K_p )</td>
<td>0.979</td>
<td>1.837</td>
<td>2.696</td>
<td>3.554</td>
<td>4.413</td>
<td>7.848</td>
</tr>
<tr>
<td>( K_i )</td>
<td>12763.21</td>
<td>19144.81</td>
<td>25526.42</td>
<td>31908.00</td>
<td>38289.62</td>
<td>63816.00</td>
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The bode plot depending on the different values of \( n \) is drawn in Fig.3. According to the bode plot of \( G_1 \), the logarithmic amplitude-frequency characteristic coincide with substantially the horizontal axis in low-frequency range. The gain of a given reference voltage of \( U_{ref}(j\omega_0) \) is one when \( |G_1(\omega_0)| \approx 1 \), \( \omega_0 \) is the system operating frequency, the outputting voltage \( U_o(j\omega_0) \) can track the given reference voltage \( U_{ref}(j\omega_0) \). In the Fig.3, the arrow means the increasing direction of \( n \), with increasing of \( n \), the bandwidth of \( G_1 \) becomes wider.
with the moderate amplitude. According to the bode plots of $G$ and $Z$, the gain are relatively small in middle and low frequency ranges, which have a damping effect on the error voltage $U_e(s)$ caused by the dead zone and voltage drop of the circuit. The gain of $G$ and $Z$ decrease as the increasing of $n$.

Table 2 shows the PI coefficients of the $T(s)$ regulator by different values of $\omega_n$.

Table 2. The coefficients of $T(s)$ regulator under different $\omega_n$

<table>
<thead>
<tr>
<th>$\omega_n$</th>
<th>2000</th>
<th>3000</th>
<th>3500</th>
<th>4000</th>
<th>5000</th>
<th>7000</th>
</tr>
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<tbody>
<tr>
<td>$K_p$</td>
<td>-0.187</td>
<td>1.041</td>
<td>1.837</td>
<td>2.757</td>
<td>4.965</td>
<td>10.853</td>
</tr>
<tr>
<td>$K_i$</td>
<td>3572.00</td>
<td>12055.50</td>
<td>19144.81</td>
<td>28576.00</td>
<td>55812.51</td>
<td>153149.5</td>
</tr>
</tbody>
</table>

(a) G1 Bode Diagram
Figure 3. The impact on the system performance under different $n$

The bode plot depending on the different values of $n$ are drawn in Fig.4. According to the bode plot of $G_1$, the system is of the least stabilization when $\omega_n=2000$. The bandwidth of $G_1$ becomes wider than that of $n$ in middle and low frequency ranges as an increasing of $\omega_n$. Therefore, $\omega_n$ has a more impact on steady-state error of the system. According to the bode plots of $G_2$ and $Z$, the gains of $G_2$ and $Z$ are negative which inhibit the voltage error $U_e(s)$ caused by the dead zone and voltage drop of the circuit. The gain of $G_2$ and $Z$ become smaller with more effect of inhibition as increasing of $\omega_n$. 
Figure 4. The effect to the system performance under different $\omega_n$

Table 3 shows the PI coefficients of the $T(s)$ regulator by different values of the damping ratio $\zeta$. The bode plots depending on the different values of $\zeta$ are drawn in Fig.5. According to the bode plot of $G_1$, when $\zeta \geq 1.2$, the gains are positive near the corner frequency, the ability to recurrence signal decreases, the noise will be amplified at high frequency. Therefore, the most appropriate range of $\zeta$ is $0.5\sim1.0$. So let $\zeta=0.707$.

<table>
<thead>
<tr>
<th>$\zeta$</th>
<th>0.4</th>
<th>0.6</th>
<th>0.707</th>
<th>0.8</th>
<th>1.2</th>
<th>1.8</th>
</tr>
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<tr>
<td>$K_p$</td>
<td>0.085</td>
<td>1.120</td>
<td>1.837</td>
<td>2.558</td>
<td>6.680</td>
<td>15.95</td>
</tr>
<tr>
<td>$K_i$</td>
<td>10831.58</td>
<td>16247.37</td>
<td>19144.81</td>
<td>21663.16</td>
<td>32494.74</td>
<td>48742.11</td>
</tr>
</tbody>
</table>
Figure 5. The effect to the system performance under different $\zeta$. 

(a) G1 Bode Diagram

(b) G2 Bode Diagram

(c) Z Bode Diagram
In summary, the ability to track the given standard voltage becomes enlarged as increasing of $\omega_n$, becomes decreasing as the increasing of $n$ and $\zeta$. The changing of $\zeta$ has a more impact on the system compared to the changing of $n$. The ability to inhibit the harmonic voltage caused by the dead zone and the voltage drop of the circuit are enhanced as increasing of $\omega_n$, $n$ and $\zeta$. Considering above analysis, the parameters values are determined by $\omega_n = 3500$, $n = 6$ and $\zeta = 0.707$, which are substituted into (7), the PI coefficients of $T(s)$ regulator are determined as follows:

\[
\begin{align*}
K_p &= 1.837 \\
K_i &= 19144.81
\end{align*}
\] (10)

### 4. Numerical Simulation and results

Fig. 6 is a parallel inverter driving simulation model established by MATLAB/Simulink. The motor is driven by the two parallel inverter units after getting through the RLC filter. The parameters in the model are set as follows: DC voltage $V_1 = V_2 = 514 V$, RLC filter $R = 80\pi^2 \Omega$, $L = 3\pi^2 \Omega$, $C = 1.2\pi^2 F$, induction motor with parameters of 5.5KW, 400V, 1460rpm, 50Hz, 20nm and RMS of 50Hz.

![Image](image1)

**Figure 6. The simulation model of two frequency inverters in parallel**

Fig.7 is the SPWM simulation model with the dead zone, the dead time is set in the delay module. Fig.8 is the six bridge arms SPWM waveform when the dead time is set by ten milliseconds.

![Image](image2)

**Figure 7. The simulation model of SPWM with dead zone**
The speed map of mine hoist is divided into five stalls, corresponding five different frequency values are set by 4Hz, 10Hz, 20Hz, 41Hz and 50Hz. The inhibition effect of harmonic circulating current by instantaneous voltage feedback method is verified in the five frequencies. The difference of dead time of the two-conversion units is set by 3μs, and the simulation results are shown in Fig.9. The left figures of Fig.9 are the outputting voltage harmonic distortion rate by open-loop. The right figures are the outputting voltage harmonic distortion rate controlled by instantaneous outputting voltage feedback.
By comparing the results from Fig. 9, the using of the instantaneous outputting voltage feedback method inhibits effectively the harmonic circulating current at different frequencies. When the outputting voltage is frequency of 4Hz, the harmonic distortion rate of the outputting voltage is 5.05% under open-loop state, but the harmonic distortion rate is 2.32% controlled by the instantaneous outputting voltage feedback. When the frequency increases, the harmonic distortion decreases. The harmonic distortion rate reaches the minimum value at frequency 50Hz.

5. Conclusions

(1) By establishing the transfer function of the parallel inverters controlled by the close-loop adjustment of the instantaneous voltage feedback. The influence of the parameters of the close-loop feedback circuit to the inhibition effects to the outputting circulation current are observed. As increasing of the parallel inductance, the filter inductor and the equivalent circuit resistance, the inhibition effect of the outputting circulation current is more obvious. However, the drop and the outputting waveform distortion of the voltage should be greater when the parameters of the parallel inductance, the filter inductor and the equivalent circuit resistance are selected by too much large values. Furthermore, the inhibition effect of the outputting circulation current is mainly adjusted by the regulator of the instantaneous voltage feedback.

Figure 9. The contrast of harmonic distortion rate under different frequencies
(2) Through introducing the PI controller into the close-loop adjustment by the instantaneous voltage feedback, the characteristic equation is gained to determine the PI parameters. The Bode plots have been drawn to investigate the influence of the dominant roots of the characteristic equation to the inhibition effects of the controller, which determines the PI parameters by the selected values of the damping ratio, natural frequency and the normal number.

(3) In the established simulation model of parallel inverter system, the harmonic distortion rate at the outputting voltage frequency values of 4Hz, 10Hz, 20Hz, 41Hz and 50Hz are calculated to verify inhibition effects of the outputting circulation current by the close-loop controller of voltage instantaneous feedback. The harmonic distortion rate are all low than 2.32% controlled by the outputting voltage instantaneous feedback.

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