A New Method based on PIR Controller to Reject Torque and Current Ripple under Fluctuating DC Voltage for High-speed Train Traction Drives

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***Abstract*-- In the traction drive system for high-speed train, a substantial ripple of DC bus voltage may negatively affect the performance of the traction drives. A new method to reject the torque and current ripple (beat components) in induction motor, which resulted from the DC bus pulsation, is presented in this paper. Based on the internal model principle, proportional-integral-resonant (PIR) controllers are used in the d-q currents loops instead of the PI controllers. Without bulky LC filters and the effects of sampling accuracy to the ripple eliminating common methods, the introduced method is economic and easy to implementation. In this paper, a PIR controller is derived and simulated using the parameters of CRH$_2$ in China. The simulation results of show that the torque and current ripple can be eliminated obviously by using the new method.**

***Index Terms*—PIR controller, high-speed train traction drives, rejection method, fluctuating DC voltage.**

I. INTRODUCTION

In the 'AC-DC-AC' high-speed train traction drive system, shown in the Fig.1, including a single-phase PWM rectifier, DC link and three-phase converter, the voltage ripple at the DC bus is mostly at doubled grid frequency because of the single-phase line supply. The pulsation generates low-frequency harmonic components in the output inverter voltage, motor stator currents and output torque (beat components) further[1-3].

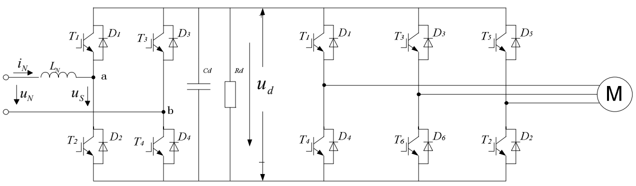

Fig.1 'AC-DC-AC' high-speed train traction drive system

Using the LC resonance filter installed in the DC link, which is tuned at twice the grid frequency, the pulsating power is absorbed by the filter[4], However, it is very difficult to set such bulky equipment in the traction application and it will reduce the power density of the whole system.

In contrast to the hardware solutions, so-called beat-less control can also reduce the current and torque ripple with low cost and high power density. It is possible to modify the modulation strategy of the output inverter by the measurement of varying DC link voltage. This feed-forward compensation is easy and effective by changing the pulse widths according to the actual DC link voltage[5-8]. In [9], a repetitive observer is proposed to predict the DC link voltage for higher performance, so as to overcome the measurement error by low sampling frequency, ZOH and delay.

In this paper, a new method is presented using PIR controllers instead of the PI controllers in the d-q currents loops, as to promoting the controlling loops, avoids the disadvantages of the methods mentioned above..

II. ANALYSIS OF PIR CONTROLLER

In a closed controlling loop, if the external command signal or the disturbing signal is periodical, the mathematic model of the periodical signal should be set in the feedback loop to reaching for precise control. So, for tracking the sine-wave signal or eliminating the sine-wave disturbance, the resonant segment should be set in the controlling loop[10-11].

As the harmonics in d-q currents of the induction motor are focused at doubled grid frequency resulted from the DC bus voltage ripple, a resonant component at the doubled frequency should be set to eliminate the harmonics in the d-q currents, and then, the torque ripple at low frequency can be eliminated. PIR controller is usually used as the expression bellow in s-domain:

$$G_d(s) = k_p + \frac{k_i}{s} + \frac{k_r s}{s^2 + \omega_n^2} \quad (1)$$

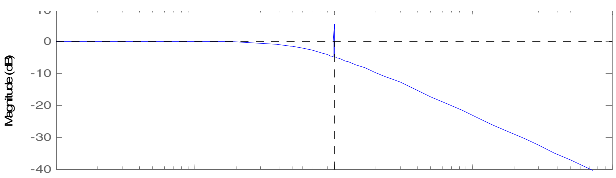

Fig.2 frequency response of PIR controller

The frequency response as Fig.2 shows that the gain of the transfer function at the resonant frequency can be proximately infinite.

Similarly, the resonant component can be used to inhibit the specific harmonics of the controlled signal. In a negative feedback closed-loop system, shown as Fig.3,

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when there are harmonics at or near a specific frequency in the controlled signal caused by the harmonic disturbances, the resonant frequency of the resonant one should be set at the harmonic frequency which is supposed to be eliminated. Considering the performance in Fig.2, adding a resonant one will help traditional PI controller reject the sine-wave disturbance with less steady state error. The resonant segment can produce a negative offset component at the resonant frequency, which is larger than the harmonics proposed to be eliminated. As a result, using the PIR controller can get a good inhibition of the harmonics at the specific frequency.

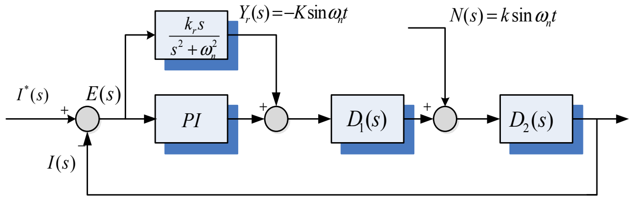

Fig.3 harmonics eliminating principle of PIR controller

The harmonics eliminating frequency response of a typical PIR controller with resonant component is shown in Fig.4, the gain of the transfer function at the resonant frequency is minimal, and the well filtering performance can be achieved at the specific frequency.

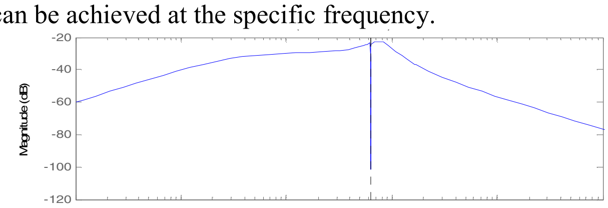

Fig.4 harmonics eliminating frequency response of PIR controller

In the practical application of the controller, the transfer function should be transformed into the discrete domain, Tustin transformation method is equivalent to the mathematical trapezoidal integration method, the transform equation involved with s and z can be expressed as follows:

$$s = \frac{2}{T}\frac{z-1}{z+1} \tag{2}$$

The resonant segment in discrete domain is shown as follows:

$$D(z) = \left.\frac{k_r s}{s^2+\omega_n^2}\right|_{s=\frac{2}{T}\frac{z-1}{z+1}} = \frac{2Tk_r}{4+T^2\omega_n^2}\frac{z^{-1}+z^{-2}}{1+\frac{2T^2\omega_n^2-8}{4+T^2\omega_n^2}z^{-1}+z^{-2}} \tag{3}$$

Tustin transform mapping ensures that the frequency characteristic of the controller does not produce aliasing in discrete domain, but distortion happens inevitably in the frequency characteristic of the controller. High accuracy of the performance at the resonance point is needed of the resonant segment, and we need to ensure that the response characteristics at the resonant frequency meet the requirements, so a modified Tustin transformation is used in this paper.

$$s = \frac{\omega_n}{\tan(\omega_n T/2)}\frac{z-1}{z+1} \tag{4}$$

Considering the delay effect of the low switching frequency in the high-speed traction drive system, the zero of the transfer function of the controller should be designed for an appropriately delay compensation, to reach a better performance. In the field-oriented control of induction motor, if the delay of the plant in a control loop is considered, the resonant link zero should be designed for the cancellation with the discrete transfer function pole of the motor windings, or as close as possible to offset its cause of delay.

For example, transfer the transfer function of the induction motor equivalent circuit into discrete domain as follows, further to design the zero position of the resonant controller.

$$C(z) = \left.\frac{1}{R+Ls}\right|_{s=\frac{2}{T}\frac{z-1}{z+1}} = \frac{T}{RT+2L}\frac{1+z^{-1}}{\frac{RT-2L}{RT+2L}+z^{-1}} \tag{5}$$

In addition, the tiny fluctuations of the grid frequency will lead to fluctuations of secondary pulse frequency of the DC link voltage, which may weaken the effectiveness of the resonant segment for eliminating the harmonics in the controlled signal. Therefore, increasing the damping coefficient appropriately can be considered to increase the gain of the transfer function at the frequencies near the resonant frequency. When $\omega = \omega_n$, the gain of the transfer function is k_r :

$$D(s) = \frac{k_r\omega_n\zeta s}{s^2+\omega_n\zeta s+\omega_n^2} \tag{6}$$

III. CONTROL STRATEGY FOR INDUCTION MOTOR BASED ON PIR CONTROLLER

A secondary pulse($2\omega_m$) in the DC link voltage exists resulted from the single-phase PWM rectifier, Therefore, the inverter output AC voltage contains not only the voltage of the desired frequency(ω_o), it also contains harmonics at the two frequencies of ($2\omega_m \pm \omega_o$).

When the harmonics frequencies of the motor voltage supply are ($2\omega_m \pm \omega_o$), the current will have the same frequency harmonics, according to the expression of the phase voltage the fundamental current can be assumed as:

$$i_{ai} = I_i\sin(\omega_o t - \varphi) \tag{7}$$

The lower-frequency harmonics of the stator currents expressions are as follows:

$$i_{h1} = k_1 I_i\cos\left[(\omega_o - 2\omega_m)t - \varphi\right] \tag{8}$$

$$i_{h2} = k_2 I_i\cos\left[(\omega_o + 2\omega_m)t - \varphi\right] \tag{9}$$

Where φ is the fundamental power factor angle, k_1 and k_2 are the amplitude ratios of the lower-frequency harmonics of the fundamental current.

Then the motor phase currents can be derived to the following expressions through coordinate transformation：

$$i_d = -I_i\sin\varphi + k_1 I_i\cos(2\omega_m t + \varphi) + k_2 I_i\cos(2\omega_m t - \varphi) \tag{10}$$

$$i_q = I_i\cos\varphi - k_1 I_i\sin(2\omega_m t + \varphi) + k_2 I_i\sin(2\omega_m t - \varphi) \tag{11}$$

From equation (10) and (11), It`s obvious that the harmonic component in the d-axis current and q-axis current contains the same frequency ($2\omega_m$) as the secondary ripple frequency of the DC link voltage.

Known by the model of the motor synchronous rotating coordinate system, the motor torque can be expressed as:

$$T_e=\frac{n_p L_m^2}{L_r}i_{sq}i_{sd} \tag{12}$$

Then,

$$T_e=\frac{n_p L_m^2}{L_r}\times I_i^2\begin{bmatrix}-\frac{1}{2}\sin 2\varphi+\frac{k_3k_4}{2}\sin(\alpha-\beta)\\ +k_3\cos\varphi\cos(2\omega_m t-\alpha)\\ -k_4\sin\varphi\sin(2\omega_m t-\beta)\\ +\frac{k_3k_4}{2}\sin(4\omega_m t-\alpha-\beta)\end{bmatrix} \tag{13}$$

where $k_3=\sqrt{(k_1+k_2)^2\cos^2\varphi+(k_2-k_1)^2\sin^2\varphi}$,

$k_4=\sqrt{(k_2-k_1)^2\cos^2\varphi+(k_1+k_2)^2\sin^2\varphi}$,

$\tan\alpha=\frac{k_2-k_1}{k_2+k_1}\tan\varphi, \tan\beta=\frac{k_1+k_2}{k_1-k_2}$。

It can be seen from the motor transient torque formula that the motor output torque containing the pulsating torque component with the frequency at $2\omega_m$ and $4\omega_m$, due to the existence of the DC link secondary ripple voltage.

Following the harmonics eliminating principle of PIR controller presented in Fig.3, to produce a negative offset component, which is larger than the harmonics proposed to be eliminated, adding a resonant one to a traditional PI controller is needed because of the roughly high gain at the resonant frequency. In the procedure of deriving the inverter output line-line voltage under fluctuating DC-link voltage presented in Fig.5, the negative offset component ($2\omega_m$) in d-q currents is transferred into a-b-c three-phase ac currents ($2\omega_m \pm \omega_o$) firstly, then the component exists in the output ac currents thronging the modulation procedure together with the fundamental reference wave, lastly, the large offset component eliminates the targeting harmonics in the currents and output torque powerfully.

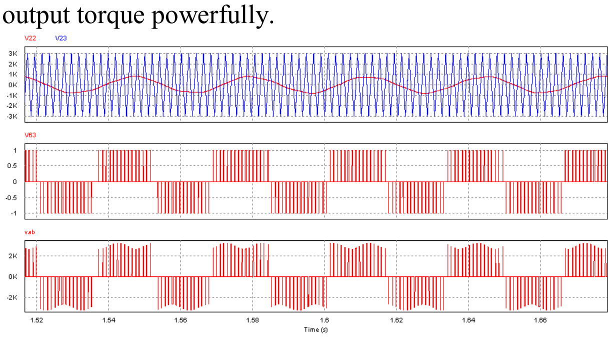

Fig.5 the procedure of deriving the inverter output line-line voltage under fluctuating DC-link voltage

It can be inferred that to control the inverter switching function so that the motor torque ripple can be reduced, we can try to control i_d and i_q to track their own instructions with no static error, no containing the harmonics result from DC link voltage ripple, when the excitation current and torque current motor torque, low-frequency ripple naturally be eliminated.

The filed-oriented control block and the d-q currents loop can be expressed as Fig.6, where the PI controller is replaced by the PIR controller. The transfer function of the PWM modulation of the converter can be expressed as proportional-inertia segment:

$$G_{PWM}(s)=\frac{k_{PWM}}{1+T_d s} \tag{14}$$

The disturbances inserted from DC-link ripple can be expressed as:

$$N(s)=k\sin 2\omega_m t \tag{15}$$

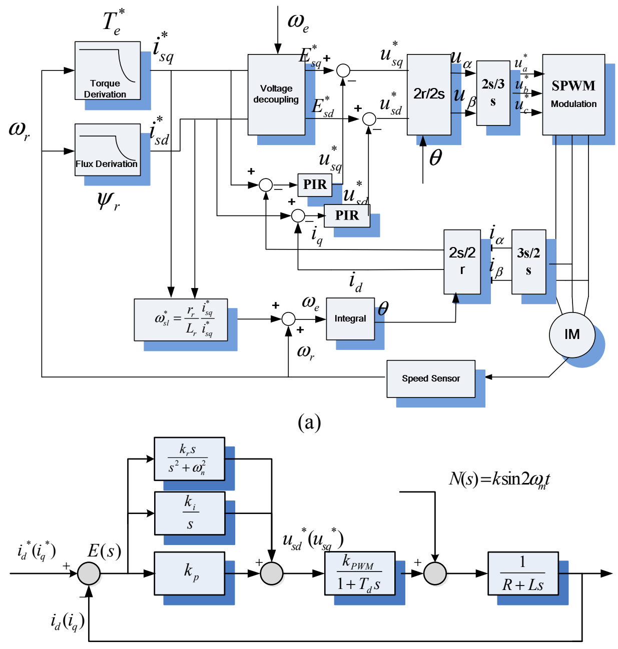

Fig.6 (a) filed-oriented control block with PIR controller, (b) control block of d-q currents loop with PIR controller

Considering the transfer function of the i_d controlling loop in Fig.6(b).the frequency response of the i_d^*-in-i_d-out system is shown in Fig.7. The gain at the resonance frequency of 100Hz (twice the grid-frequency) is nearly infinite. Further, analyzing the tracking performance, the error transfer function for disturbance rejection is shown as:

$$\Phi_{eN}(s)=\frac{E(s)}{N(s)}=\frac{-1}{R+Ls+(k_p+\frac{k_i}{s}+\frac{k_r s}{s^2+n^2\omega_r^2})\times\frac{k_{PWM}}{1+T_d s}} \tag{16}$$

The frequency response of the error transfer function is shown in Fig.8, a very small gain at the frequency of 100Hz (twice the grid-frequency), the inhibitory of disturbances from the DC link voltage ripple is very good.

Similarly, with the effectiveness of the disturbance rejection method applied in the i_q control loop, the inhibitory effect of the 100Hz harmonic of i_q is also reliable.

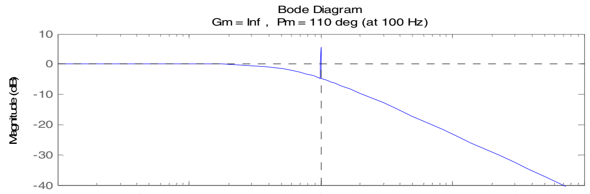

Fig.7 frequency response of promoted controlling loop

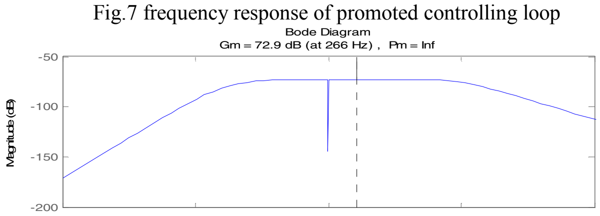

Fig.8 harmonics eliminating frequency response of promoted controlling loop

IV. SIMULATION RESULTS

The simulation model based on PSIM according to the parameters of CRH_2 high–speed train in China is built. In the simulation model, the DC link voltage is 3000V, assuming the 100Hz DC link ripple magnitude is 300V(10% from the DC link voltage) and the torque load of the motor is 314N.m.

Fig.9 shows the simulation results without and with the new control method (inverter output frequency):90Hz. When the fundamental wave of the inverter is set at 90Hz, the sub-harmonics components of stator currents are obviously reduced.

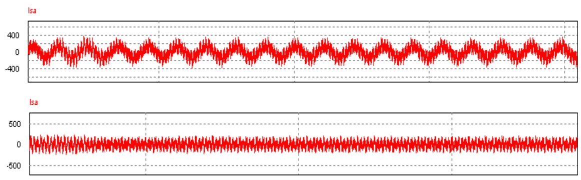

Fig.9 comparison of the stator currents simulation results

Fig.10 shows the simulation results without and with the new control method, when the motor speed is 1200r/min, the inverter output frequency is 40Hz , and the modulated carrier wave ratio is N = 9, including the simulation waves of the stator line-line voltage, stator current, output torque and d-q current. The above wave shows the simulation results when taking no restraining measures, and the following one shows the results when taking the proposed rejection method.

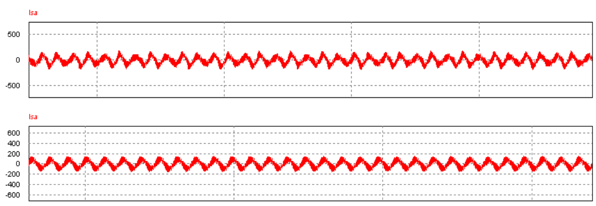

Fig.10 comparison of the stator voltages and currents simulation results

Fig.11 FFT comparison of the simulation waves

The stator currents has been better after taking the suppression measure, and the motor torque current, magnetizing current and torque are stable, their harmonic analysis shown in Fig.11, The 100Hz harmonics hardly exist in the motor d-q currents, and the motor torque pulsation is restrained significantly at 100Hz. The harmonics of the stator current at 60 (100-40) Hz and 140 (100+40) Hz are almost non-existent.

The following simulations are chosen at several different fundamental frequencies (30Hz, 40Hz, and 70Hz). The comparison of with and without the proposed method are presented in Tab.1.

Tab.1 comparison of the simulation results of fundamentals at several frequencies

The frequencies of the inverter output fundamental voltage and the harmonics (Hz)	Current magnitude (A) (without the new rejection method)	Current magnitude （A）（with the new rejection method）	Harmonics rejection percentage
fi:30	**82.52**	**82.52**	**0.00%**
fi-fr:70	**10.83**	**0.25**	**98.18%**
fi+fr:130	**8.76**	**0.25**	**97.12%**
fi:40	**72.11**	**72.11**	**0.00%**
fi-fr:60	**22.13**	**2.75**	**89.71%**
fi+fr:140	**10.83**	**0.40**	**94.67%**
fi:70	**81.34**	**81.34**	**0.00%**
fi-fr:30	**56.19**	**1.93**	**96.57%**
fi+fr:170	**14.34**	**1.4**	**90.24%**
The frequency of the inverter output fundamental voltage (Hz)	The sub-harmonics of the torque（at 100Hz）（N.m）（without the new rejection method）	The sub-harmonics of the torque（at 100Hz）（N.m）（with the new rejection method）	Harmonics rejection percentage
30	**125.53**	**0.80**	**99.37%**
40	**182.07**	**1.56**	**99.06%**
70	**297.32**	**0.23**	**99.92%**

In the rated load CRH_2 high-speed train simulation model, the proposed suppression method has good inhibitory effect on the harmonics caused by the DC link secondary ripple, in the stator current and motor output torque, and the harmonics can be reduced to very low level.

V. CONCLUSION

A novel rejection method of fluctuating DC link voltage for railway traction drives is presented. It employs PIR controllers to eliminate the low harmonics from fluctuating DC link voltage. In steady state, the pulse widths of the traction inverter can be regulated automatically by feedback control loop. Simulations show that this method can reduce the beat current of the traction motor to a negligible level with 10% voltage ripple in the DC link.

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