Analysis and suppression of torsional vibration in electromechanical coupling transmission system of high-speed train

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Abstract: The high-speed train transmission system is a complex electromechanical coupling system. In this study, the torsional vibration of a train transmission system was studied. The centralised mass model of the mechanical structure of the coupling system was established. The natural vibration characteristics of the mechanical mechanism system were analysed. The results show that the natural vibration frequency of the universal shaft was 4.08 Hz, the natural vibration frequency of the pinion was 7.24 Hz, the natural vibration frequency of the big gear was 35.6 Hz, and the natural vibration frequency of the wheelset was 107.48 Hz. The traction motor model was built, and by considering the electromechanical coupling of the system, a torsional vibration suppression strategy for harmonic components in the motor is proposed. The effectiveness of the suppression strategy was verified by MATLAB/Simulink model simulation.

1 Introduction

With the acceleration of China’s high-speed trains, the dynamic environment of vehicle operation is gradually deteriorating, and the problems encountered in the development of the transmission system, which is the main transmission component of vehicle traction, are also more complex [1]. In literature [2], it is proposed that the dynamic meshing characteristics of the transmission system affect the overall dynamic characteristics of the train, and the electromechanical magnetic coupling vibration is also a typical problem [3]. In the course of high-speed train running, the phenomenon of motor torque fluctuation and torsional vibration of various parts such as the driving device is universal [4]. In literature [5], the influence of the creep slip rate of a train wheelset on the train transmission system is deeply studied, and the optimised controller makes the train to have the best adhesion in the running process. Liu et al. [6] take the traction power supply system of high-speed trains as the main research object, analysed the influence of the harmonic of the traction power supply system on the drive system and carried out experimental verification. In order to solve the existing problems, the mechanical structure and electrical control factors will be considered, and the model of high-speed train electromechanical coupling transmission system will be established. On top of that, a strategy of the inhibition of harmonic current will be proposed. The strategy will reduce the vibration of the motor output electromagnetic torque and torsional vibration of the transmission system. Finally, the simulation model will be built to verify the effectiveness of the suppression strategy.

2 Torsional vibration analysis of the mechanical structure of the transmission system

2.1 Construction of transmission system structure model

The electromechanical coupling transmission system of a high-speed train is a complicated electromechanical coupling system, which mainly includes the motor, universal shaft, gearbox, wheelset and suspension device [7]. The simplified schematic diagram is shown in Fig. 1.

In order to facilitate the analysis and calculation, the centralised mass model was established based on a simplified structure, as shown in Fig. 2. The following basic assumptions were made for the model. First, only the vibration of the motor rotor was considered, and the vibration of the motor and bearing was ignored. Second, the mechanical transmission efficiency of the drive system was not considered. Third, each drive element was thought of as a concentrated mass. Finally, the torsional damping in the system was ignored.

Here $J_i$ is the moment of inertia of the corresponding part, $k_i$ is the torsional rigidity, $\theta_i$ is the torsional angular displacement of the corresponding part, $T_m$ is the input torque of the system and $T_r$ is the output torque of the system.

Fig. 1 Simplified diagram of a transmission system

Fig. 2 Centralised quality model of the transmission system
2.2 Analysis of natural vibration characteristics of transmission system

The natural vibration characteristic is the most direct way to reflect the vibration characteristic of the system itself [8]. According to the centralised mass model established above, the natural vibration characteristics of the mechanical structure are analysed. Also, the equation of the system without considering damping was established:

\[ J\ddot{\theta} + K\theta = 0 \]  

(1)

The inertia matrix of the system is

\[ J = \begin{bmatrix} J_1 & 0 & 0 & 0 & 0 \\ 0 & J_2 & 0 & 0 & 0 \\ 0 & 0 & J_3 & 0 & 0 \\ 0 & 0 & 0 & J_4 & 0 \\ 0 & 0 & 0 & 0 & J_5 \end{bmatrix} \]  

(2)

The torsional stiffness matrix of the system is

\[ K = \begin{bmatrix} k_1 & -k_1 & 0 & 0 & 0 \\ -k_1 & k_1 + k_2 & -k_1 & 0 & 0 \\ 0 & -k_1 & k_5 + k_2r_2^2 & -k_4r_2^2 & 0 \\ 0 & 0 & -k_4r_2^2 & k_5 + k_2r_2^2 & -k_4 \\ 0 & 0 & 0 & -k_4 & k_3 \end{bmatrix} \]  

(3)

The character root form of the system is

\[ \theta_i = A\sin(\omega t + \varphi) \]  

(4)

Substituting (4) into (1), then

\[ (K - \omega^2 J)A = 0 \]  

(5)

Here \( A \) is the amplitude column vector and \( \omega \) is the free vibration frequency of each inertia.

Then, in order to have a non-zero solution

\[ |K - \omega^2 J| = 0 \]  

(6)

The key parameters needed in the process of solving the equation are shown in Tables 1 and 2.

Substituting the parameters into (6), we obtained the natural frequencies of each part of the system, as shown in Table 3.

The values in the table can be known, during the transmission process from the motor to the wheelset, the natural vibration frequency of components rapidly increased from 4.08 to 107.48 Hz. In the process of increase, the natural vibration frequency of the transmission from the big gear to the wheelset increased by 66.9% compared with that of the fast one.

3 Torsional vibration analysis of electrical system of transmission system

3.1 Control system of three-phase asynchronous machine

Three-phase asynchronous traction motor adopts space vector pulse-width modulation (SVPWM) method; the control strategy is rotor field-oriented vector control (RFOC). The specific control block diagram is shown in Fig. 3.

Performing Clack transform and Park transform on the three-phase current of the motor. The current component \( i_s^d \), which is associated with the motor flux, and the current component \( i_s^q \), which is associated with the motor torque, were obtained. The PI adjustment was used to realise the current closed-loop control. The stator voltages \( u_{s^d} \) and \( u_{s^q} \) were output from the current regulator. The stator voltages of the two-phase coordinate system \( u_{s^\alpha} \) and \( u_{s^\beta} \) were given by the Park inverse transformation. Finally, SVPWM was used in switching pulse signal, which was input to the inverter, to control the output of the three-phase asynchronous machine.

At this time, the relationship between electromagnetic torque and stator current was

Table 1: Moment of inertia

| Inertia | \( J_1 \) | \( J_2 \) | \( J_3 \) | \( J_4 \) | \( J_5 \) |
|---------|---------|---------|---------|---------|---------|
| values, kg\( \cdot \)m\(^2\) | 15      | 2.4     | 1.1     | 12.48   | 947.5   |

Table 2: Torsional rigidity value

| Stiffness | \( k_1 \) | \( k_2 \) | \( k_{mr} \) | \( k_3 \) |
|-----------|---------|---------|---------|---------|
| values, N\( \cdot \)m/rad | \( 9.192 \times 10^5 \) | \( 3 \times 10^4 \) | \( 3.85 \times 10^5 \) | \( 2.2167 \times 10^4 \) |

Table 3: Natural frequency of the torsional vibration of the transmission system

| Frequency | \( \omega_1 \) | \( \omega_2 \) | \( \omega_3 \) | \( \omega_4 \) |
|-----------|---------|---------|---------|---------|
| values, Hz | 4.08    | 7.24    | 35.6    | 107.48  |

Fig. 3: RFOC block diagram of asynchronous motor

J. Eng., 2020, Vol. 2020 Iss. 14, pp. 980-984

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Here \( n_p \) is the number of the magnetic poles of the motor. \( L_m \) is the mutual inductance between the stator and the rotor. The subscript letters ‘s’ and ‘r’ are the stator and the rotor, respectively. The subscript letters ‘\( \alpha \)’ and ‘\( \beta \)’ are the two-phase stationary coordinates, \( \alpha \)-axis and \( \beta \)-axis, respectively.

### 3.2 Modelling the electromechanical coupling transmission system

The motor model of RFOC was combined with the mechanical structure of a centralised mass model. The simulation model of the electromechanical coupling transmission system, which considering the motor control factors, was obtained. As shown in Fig. 4, the torque of the mechanical structure was fed back to the motor model as the input of load torque.

Assuming that the load torque increased from 100 to 150 N m, the simulation model output is shown in Fig. 5.

For the three-phase rectified motor load, the generated harmonic current is \( 6n \pm 1 \)th harmonic. In a harmonic magnetic field, the amplitude of the harmonics will decrease with the increase of the harmonic order. Therefore, the amplitude of the lower harmonics is relatively large. Namely, the amplitude of the 5th, 7th, 11th and 13th harmonics is relatively large [10]. The 6th harmonic in the motor three-phase current is composed of the \( 6n \) \( \pm 1 \)th harmonic and the \( 6n \pm 1 \)th harmonic. That means the sixth harmonic of harmonics is made up of the fifth and seventh harmonics. Here, the steady-state voltage equation of the fifth harmonic in the synchronous rotation coordinate system is

\[
\begin{align*}
\frac{\text{d}}{\text{d}t} u_\delta &= 5\omega L_q i_q \delta + R_s i_d \\
\frac{\text{d}}{\text{d}t} u_q &= -5\omega L_d i_d + R_s i_q 
\end{align*}
\]

(8)

Fourier analysis was performed for the current output by the motor in Fig. 5. Using the special electrical simulation system module fast Fourier transform (FFT) analysis toolbox function of MATLAB to perform the spectral analysis of the output harmonics. The analysis results are shown in Fig. 6.

According to the specific causes and properties, harmonic torque can be divided into two types: stable harmonic torque and oscillating harmonic torque. Usually, the additional stable harmonic torque can be ignored in practical applications. Therefore, the harmonic contained in the motor is mostly oscillation harmonic torque [9].

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\frac{\text{d}}{\text{d}t} u_q &= -5\omega L_d i_d + R_s i_q 
\end{align*}
\]

(8)

Similarly, the steady-state voltage equation of the seventh harmonic wave in the synchronous rotation coordinate system can be obtained, as shown in the following equation:

\[
\begin{align*}
\frac{\text{d}}{\text{d}t} u_\delta &= -7\omega L_q i_q \delta + R_s i_d \\
\frac{\text{d}}{\text{d}t} u_q &= 7\omega L_d i_d + R_s i_q 
\end{align*}
\]

(9)

According to the analysis results, the current output by the high-power asynchronous traction motor of high-speed train contained a large part of harmonic components during the working process, and most of harmonics were made of 5th, 7th, 11th and 13th harmonics. The results are consistent with the above theoretical analysis.
4.1 Theory of harmonic suppression

The amplitude of the lower harmonics is large, especially the fifth and seventh harmonics have a great influence on the output of the motor. Therefore, the most effective method to suppress the harmonics of the motor system is to suppress the fifth and seventh harmonics. To suppress these two harmonics, first, the fifth and seventh harmonics were extracted from the three-phase current of the motor by means of low-pass filtering. The specific extraction method was shown in Fig. 7. According to (8) and (9), the control block diagram of the fifth and seventh harmonics suppression algorithm was built, as shown in Fig. 8.

4.2 Analysis and verification of simulation

In order to verify the effectiveness of the suppression algorithm, we used MATLAB/Simulink to build a simulation model.

Assuming that the given load torque was 100 N m, and the given rotor speed was 1200 rad/s. The comparison diagram of the simulation waveform before and after harmonic suppression is shown in Fig. 9.

After adding a harmonic suppression module, the fluctuation of the output three-phase current decreased. The curve of the current is smoother than that before suppression. The rotor current cycle time was shorter. The output efficiency of the coupling system was improved. The rotor speed output efficiency of the coupling system was improved. Comparing the output electromagnetic torque, the amplitude of the fluctuation of torque was obviously reduced. It can be proved that the harmonics in the output three-phase current was obviously suppressed, and the effectiveness of the suppression algorithm was verified.

5 Conclusion

(i) The torsional vibration of a high-speed train exists in the process of power transmission. The centralised quality model of the transmission system was established and the natural vibration frequency was solved. The natural vibration characteristics were analysed. The natural vibration frequency of the system increased during the transmission process.

(ii) The torsional vibration in the coupling transmission system is mainly due to the harmonic components in the motor system, and the lower order harmonic amplitude is larger. Among them, the fifth and seventh harmonics affect the torsional vibration of the coupling system greatly.

(iii) Presenting a method to suppress the fifth and seventh harmonics using low-pass filtering and PI control. A simulation model is built to verify the suppression strategy. The simulation results show that the suppression strategy achieves a good suppression effect. The torsional vibration in the electromechanical coupling transmission system of high-speed trains can be effectively suppressed.
Acknowledgments

Funding from the National Natural Science Foundation of China (grant no. 61503163), the ‘333 project’ of Jiangsu Province (grant no. BRA2016440), the Key University Science Research Project of Jiangsu Province and Jiangsu University (grant no. 18KJA580004), Jiangsu University ‘blue and blue project’ and Postgraduate Research & Practice Innovation Program of Jiangsu Province (grant no. SJCX18_1058) is gratefully acknowledged.

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Fig. 9 Comparison diagram of simulation waveform before and after harmonic suppression

(a) Comparison of stator current $I_a$ (A), (b) Comparison of rotor speed $\omega$ (rad/s), (c) Comparison of electromagnetic torque $T_e$ (N m)