DETECTION AND COMPENSATION OF TORQUE HARMONICS IN DRIVE WITH INDUCTION MOTOR AND GEAR

Abstract: In many solutions of drives, the torque transmission systems are used for torque converting from the motor shaft to the load. Properties of torque transmission system are a reason of mechanical vibration occurring in drive system. Analysis of drive vibration, usually measured by the accelerometer, makes it possible to create diagnostic system for detection of mechanical faults of drive. In many applications, an introducing of vibrations to drive system is undesirable. Mechanical vibrations of drive can be reduced by generation of appropriate torque components in electric machine. Proper compensation of mechanical vibration requires information about amplitudes and frequencies of vibration harmonics. In drive system with gear, the reduction of mechanical vibration and early detection of gear damages require information about mutual position of toothed wheel and the torque transmitted by gear. Analysis of state variables of induction motor makes it possible to indicate the instants of toothed wheels meshing. It makes it possible to eliminate both: vibration and optical sensors in systems of detection of gear damages and compensation of mechanical vibration. The results of simulation and experimental researches on proposed detection and compensation method are presented in the paper. The experiments were provided for a drive with 10kW induction motor with gear and for a high-speed train drive with gear and 1.2MW asynchronous motor.

1. Introduction

The main task of drive systems is stabilization of speed of load shaft. Every change of load torque on motor shaft by generation of appropriate value of electromagnetic torque can be compensated. In many solutions of electric drive systems, the electromagnetic torque is transferred to load using mechanical torque transmitters like: gear transmission, belt transmissions, shafts, coupling elements. In drive systems with gear, the transmission error of gear introduces ripples to electromagnetic torque transmitted to load, and to load torque transmitted to motor. The transmission error of gear is an effect of variable stiffness of teeth and inaccuracy of mechanical work of toothed wheels [14, 15]. It is defined as difference between the actual position of the output gear, and the position it would occupy if the gear were perfect:

\[ T_E = \phi_r - \phi_o \]  

where \( T_E \) is a transmission error of gear, \( \phi_r, \phi_o \) are positions of both shafts of gear.

The mutual position of gear shafts can be measured using special optical system or accurate position encoders [4,11]. Mechanical oscillation of drive system, caused by gear, can be measured by using accelerometers [5,9,10,12]. The analysis of mutual shaft positions of gear or analysis of mechanical oscillation of drive system gives possibility to early detect of gear (and drive) damages [1,10].

The transmission error of gear has an influence on speed and torque oscillations occurring on gear output shaft. These oscillations can be reduced by modification of teeth profile [2,3]. In drive systems with electric motor and gear, the mechanical oscillations can be actively compensated by generation of appropriate torque harmonics in electric motor [4,8,15]. Proper compensation of torque ripples on gear output shaft requires information of mutual position of gear shafts. In this paper, the sensorless method of torque ripples detection, caused by gear transmission, is proposed. Presented method can be used in systems for early detection of gear damages and for active compensation of mechanical vibration. The results of simulation and experimental researches on proposed detection and compensation method are presented in the paper. The experiments were provided for a drive with 10kW induction motor with gear and for a high-speed train drive with gear and 1.2MW asynchronous motor.
with known frequencies. The first of them is an effect of unbalancing of mechanical elements of drive and the second is an effect of the transmission error created by the mesh [1, 10]:

\[ f_u = \frac{n_r}{60} \]  
\[ f_{TE} = \frac{z \cdot n_r}{60} \]  

where: \( n_r \) - speed of motor shaft, \( z \) – the number of teeth, oscillation frequencies: \( f_u \), \( f_{TE} \) – are connected with unbalance of mechanical elements of drive and transmission error respectively.

In [8] the simplified model of gear was proposed:

\[ \frac{d\omega_r}{dt} = \frac{1}{J_r}(T_{em} - T_r) \]  
\[ \frac{d\omega_o}{dt} = \frac{1}{J_o}(T_r - T_o) \]  
\[ \frac{d\phi_r}{dt} = \omega_r \]  
\[ \frac{d\phi_o}{dt} = \omega_o \]  

\[ T_r = K \cdot (\phi_r - \phi_o) + D \cdot (\omega_r - \omega_o) \]  

where: \( \omega_o, \omega_o \) are angular speeds of driven shaft and output shaft of gear, \( T_{em} \) is the torque of driving motor, \( T_r \) is the load torque on motor shaft, \( T_o \) is the load torque of drive, \( D \) is damping coefficient and \( K \) is the stiffness coefficient, described as the function of position of driven wheel [13]:

\[ K = K_s + K_D \cdot \sin\left(z \cdot \phi(t)\right) \]  

where: \( K_s \) is mean value and \( K_D \) maximum value of stiffness coefficient.

The simplified gear model was used in simulation research of drive with induction machine. In drive system with electric motor and gear, the change of stiffness coefficient of toothed wheels meshing introduces ripples to electromagnetic torque, transmitted to load, and to load torque, transmitted to electric motor. These changes of load torque on induction motor shaft cause oscillation of rotor speed and electromagnetic torque generated in induction motor (fig. 1). The amplitudes of rotor speed oscillations and torque oscillations are too small to compensate the load torque ripples, introduced by gear, in speed or torque control loop.

3. Sensorless detection of gear transmission error

Analysis of speed or torque transients makes it possible to indicate the instant of meshing and makes it possible to detect mutual position of gear shafts (fig.1). In sensorless control system of induction motor, the rotor speed and rotor flux components are estimated in observer system. The electromagnetic torque, generated in AC motor, can be obtained from:

\[ T_{em} = L_m \cdot \frac{\dot{\psi}_m}{L_r} \]  

where: \( \dot{\psi}_m \) and \( \dot{\psi}_r \) are estimated rotor flux components, \( L_m \) is mutual inductance, \( L_r \) is rotor inductance, \( J \) – motor inertia.
Using of speed observer, proposed in [7] make it possible to estimate the mechanical oscillations, caused by gear. The transient of rotor speed of 10 kW induction motor, estimated in speed observer and the mechanical vibrations of drive, measured by accelerometer, are presented on fig 2. The electromagnetic torque of electric motor was transmitted to load using gear transmission. The reduction ratio of gear: \( n_1/n_2 = 27/54 \). Because of damping of high frequency speed oscillation in speed observer, analysis of mechanical vibration in high-speed drive can be done using electromagnetic torque, estimated in speed observer. The transient of estimated value of electromagnetic torque of 1.2MW AC motor are presented on fig 3. The reduction ratio of gear used in drive system: \( n_1/n_2 = 25/75 \).

### 4. Sensorless detection of gear faults

In the paper [1,10] the method for detection of gear damages is proposed. Presented solutions bases on analysis of mechanical oscillation spectrum and decomposition of measured vibration signal in angular position domain. Presented method makes it possible to indicate the cracked teeth of gear. It is possible to replace the signal from vibration sensor by the electromagnetic torque or speed estimated in speed observer. The transients of speed and electromagnetic torque of induction motor and the results of FFT analysis of electromagnetic torque are presented on fig 4. In presented case, one of teeth of toothed wheel was cracked. Analysis of oscillation of estimated value of torque, generated in AC motor, make it possible to indicate the cracked teeth of gear without any additional sensor.

![Fig. 5. Multiscalar control system of induction motor with active compensation of mechanical vibrations](image-url)
5. Compensation of mechanical vibration in drive with gear

The change of meshing stiffness of toothed wheels is one of reasons of mechanical vibration of drive system with gear transmission. The transmission error of gear increase in case if only one pair of teeth is transforms the torque and decreases if two or more pairs transform the torque. Compensation of mechanical vibrations in drive with gear require information about mutual position of both wheels of gear. The mutual position of toothed wheels can be measured using optical sensors or position encoder. Analysis of mechanical variables, estimated in speed observer (fig. 2, fig. 3) makes it possible to detect the changes of stiffness coefficient of teeth. The components of electromagnetic torque generated in induction machine, used for compensation of mechanical vibrations, should be synchronized with changes of stiffness coefficient of toothed wheels. On fig.5 the control system of induction motor, with active compensation of mechanical vibration, is proposed. The control system is based on multiscalar control system of induction motor proposed in [6]. In presented solution, the second derivative of estimated speed is used for elimination of constant variable from signal. The phase locked loop is used for synchronization of compensation torque with signal from speed observer. The results of compensation of mechanical vibration in drive with 10kW AC motor and gear are presented on fig .6.

6. Summary

In this paper a method of sensorless detection of mechanical vibration of drive with gear is proposed. Presented method bases on analysis of speed and electromagnetic torque. Both variables are estimated in speed observer, used in sensorless control system of induction motor. Proposed method can be used in systems for detection of gear damages and for active compensation of mechanical vibration in drive system with gear. The results of simulation and experimental researches on proposed detection and compensation method confirm its correctness.

7. References

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