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Induction motors in traction drives, service tests

Silniki indukcyjne w napędach trakcyjnych, badania eksploatacyjne

Abstract

Electric multiple units (EMUs) EN57 are fitted with two cage induction motors to each bogie. Two motors driving one bogie are supplied from a common DC/AC inverter. These motors become damaged after a short service period; the end-rings start to break away, start to break away. The results of service tests conducted during normal train runs are presented in the paper. The investigation possibilities were limited to recording load currents and vibrations of four motors installed at two bogies of one car. It has been concluded that the reason for rotor winding damage may be traced back to the simultaneous impact of four factors: 1) transmission of load torque by mechanical gearbox; there is a backlash between the pinion mounted at the motor shaft and the toothed gear mounted at the drive bogie axle; 2) rigid assembly of the motor in the bogie frame and vibrations transmitted from the drive wheels to motor; 3) variable components of electromagnetic torque generated by higher harmonics of inverter voltage and current; 4) parallel operation of two unmatched motors supplied from common inverter.

Keywords: cage induction motors, traction drive systems, service tests, rotor winding failure.

Streszczenie

W zespołach trakcyjnych EN57 na wózkach jezdnych są zabudowane po dwa silniki indukcyjne klatkowe. Dwa silniki jednego wózka są zasilane z jednego falownika DC/AC. Silniki po krótkim okresie eksploatacji ulegają awarii, urywają się pierścienie zwierające pręty uzwojenia wirnika. W artykule przedstawiono wyniki badań eksploatacyjnych silników w czasie normalnej jazdy pociągu. Możliwości badawcze ograniczały się do rejestracji prądów obciążenia i drgań czterech silników zabudowanych na dwóch wózkach jezdnych jednego wagonu. Ustalono, że przyczyną uszkadzania się uzwojenia wirników jest równoczesne oddziaływanie czterech czynników: 1) przenoszenie momentu obciążenia przez przekładnię mechaniczną, która ma luz między kołem zębatym osadzonym na wale silnika i kołem zębatym sprzęgniętym z wałem kół jezdnych wózka; 2) sztywny montaż silnika na ramie wózka i drgania przenoszone z kół jezdnych na silnik; 3) składowe zmienne momentu elektromagnetycznego generowane przez wyższe harmoniczne napięcia i prądu falownika; 4) praca równoległa dwóch niesparowanych silników zasilanych ze wspólnego falownika.

Słowa kluczowe: silniki indukcyjne klatkowe, trakcyjne układy napędowe, badania eksploatacyjne, uszkadzanie się uzwojenia wirnika.

1. Introduction

Electric multiple units (EMUs) have been in operation for several decades, and nowadays, they are subjected to overhauls and modernisation – Fig. 1 [7]. In the drive car, DC drive units are replaced with AC drive units [1]. The motor car contains two drive bogies. Each bogie is fitted with two type LK 450 X6 cage induction motors. Motors M1 and M2 are mounted in the first bogie, and motors M3 and M4 in the second bogie. The pinions of the mechanical gearbox are mounted at motor shafts. The large toothed gears are mounted at drive wheels' axles. The two motors belonging to a single bogie are supplied from one common DC/AC power electronics converter, which is located below the car floor. After a relatively short service period, LK 450 X6 motors start to fail; the end-rings break away. Research has been undertaken at the KOMEL Institute in order to identify the reasons for damages of rotor windings [8].

Fig. 1. Electromotive unit EN57 [7]

2. Drive system of EN 57 EMU

The drive system is composed of: two inverters, four motors M1 ÷ M4 and four mechanical gearboxes. Three-phase squirrel cage induction motors LK 450 X6 are used, with the number of pole pairs $p = 3$. The rated data is [9]:

- nominal power/one-hour rating– 250/300 kW,
- rated voltage at 50 Hz – 2340 V,
- rated/maximum current – 78/160 A,
- rated/maximum frequency – 50/120 Hz,
- rated/maximum rotational speed – 987/2400 rpm,
- rated/maximum torque (at 50 Hz) – 2419/4400 N·m,
- breakdown torque (at 50 Hz) – 6600 N·m,
- efficiency ≥ 0.94,
- cos φ ≥ 0,84,
- forced cooling,
- Degree of Protection IP22,
- operating temperature– 30÷40°C.

A photo of the LK 450 X6 motor is shown in Fig. 2.

Fig. 2. Induction motor LK 450 X6 [8]

The motors are supplied from inverters converting the traction network 3 kV DC voltage into AC voltage by the pulse width modulation (PWM) method. Inverter FT-500-3000-UF is manufactured as HV IGBT 6.5 kV design – Fig. 3 [8]. The braking resistor is made of stainless steel. According to the manufacturer, the inverter fulfils the requirements set by UIC and EC standards (regulations) as to operational safety and electromagnetic compatibility. The AC voltage is controlled from a minimum value (train starting) to the rated value U_N = 2340 V. By changing the inverter's output frequency and voltage, two ranges of motor speed control are achieved (Fig. 4):

- control in the range from zero speed to rated speed (n_N = 987 rpm), torque is constant; this is obtained by a simultaneous change of the frequency and voltage ($f_{min} \le f \le f_N$, $U_{1min} \le U_1 \le U_{1N}$),
- control in the range from rated speed to maximum speed (n_{max} = 2400 rpm), power is constant; this is obtained by changing the frequency, while voltage is kept constant ($f_N \le f \le f_{max}$, U_N).

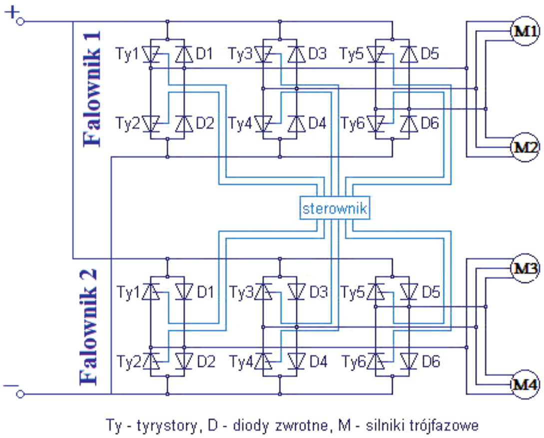

Fig. 3. Electric scheme for drive car – supply circuit of LK 450 X6 motors

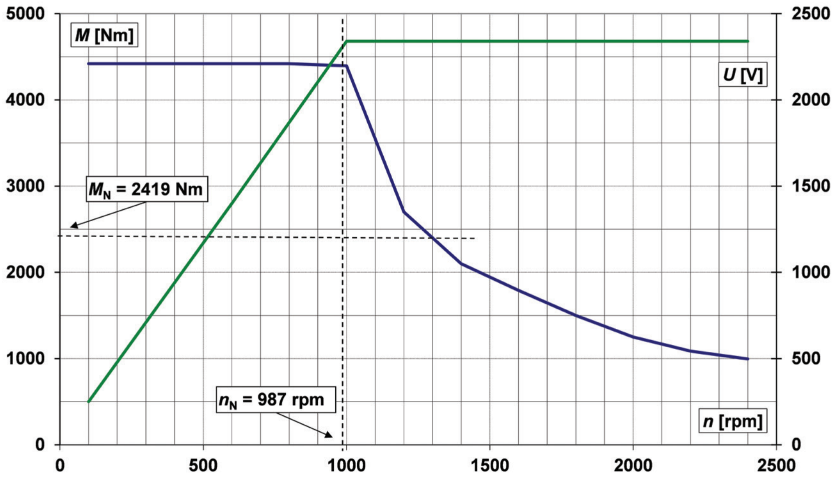

Fig. 4. Torque and electric voltage vs. speed – motor curve

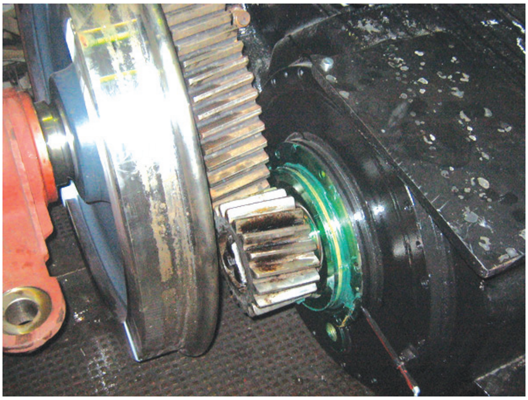

Fig. 5. Mechanical gear

The mechanical gear is simple and consists of a pinion and a large gear. The pinion with a number of teeth $Z_1 = 19$ is mounted at the motor shaft. The large gear with a number of teeth $Z_2 = 70$ is mounted at the bogie's drive wheel axle. The complete gear is shown in Fig. 5 [8].

3. Design of the LK-450 X6 motor

The traction motor is composed of three main parts:

- magnetic circuit, comprising the stator laminations, rotor laminations and the air-gap between these laminations,
- stator and rotor windings, placed in lamination slots,
- mechanical structure, i.e. shaft where rotor laminations are placed, body holding stator laminations, bearing plates and bearings.

The rotor winding is made of non-insulated copper bars placed in the slots of rotor laminations. Outside the core assembly, the bar ends are fast attached to copper short-circuiting end rings.

Different specimens of LK450 X6 motors are characterised by innate tolerance of the rated parameters. This tolerance is due to:

- differences in the magnetising curves of lamination steel,
- dimensional tolerance in winding wires,
- bearing slackness,
- working tolerances of mechanical working: laminations, shaft, bearing plates and body.

Magnetic circuits of LK-450 X6 are made of lamination steel M350-50A. In accordance with standard EN 10106:2007 (see Table 1), this steel is characterised by:

- maximum lossiness (total - at 50 Hz and 1.5 T): 3.50 W/kg,
- minimum magnetic polarisation (in AC magnetic field of 2500 A/m intensity): 1.5 T,
- maximum loss anisotropy (at 50 Hz and 1.5 T): ±12%.

Different batches of laminated steel may be characterised by even better parameters than the limits cited above. The magnetic circuits of motors where different batches of steels are used, will also differ from each other.

Moreover, bearing slacknesses are also present [10]:

- bearing D: minimum 0.145 mm, maximum 0.190 mm and
- bearing N: minimum 0.075 mm, maximum 0.110 mm.

The tolerances and backlashes are summed up in the airgap between stator and rotor; this also acts as a gap in magnetic circuit. The designed motor's air-gap is equal to 1.2 mm; if backlashes and tolerances are taken into account, then the real air-gap may range from 1.02 to 1.43 mm. Within this range, air-gaps in individual motors may differ from each other. The total tolerance of the magnetic air-gap determines the electrical and mechanical parameters' tolerances of individual motors. However, each motor's rated parameters are defined taking into account allowable tolerance. Allowable tolerances are specified in standard PN-EN 60034-1: 2011E, item 12, Table 20 [4]. In the case of machines with ratings above 150 kW, the tolerances are as follows:

- efficiency $\eta = -10\% \cdot (1 - \eta_N)$,
- total losses (–10%)
- $\cos\varphi = -\frac{1}{6}(1 - \cos\varphi_N)$,
- slip, at full load and when motor is heated ±20%,
- current when rotor is braked +20 %,
- rotational torque when rotor is braked: (–15% do +20%),
- minimum rotational torque (–15%)
- breakdown torque (–10%).

The rated parameters of brand-new motors are contained within the tolerance limits given above. However, individual motors may differ as to their rated parameters. That is why motors dedicated to parallel operation should be matched, which means that their parameters should be nearly the same. A selection of motors for parallel operation may be done on the basis of no-load current, when motors are supplied with the rated voltage at a 50 Hz frequency. The measured values of no-load current are provided by the manufacturer (performance tests run at the manufacturing plant). The appropriate matching (coupling) of motors should be conducted by companies assembling motors in bogies.

LK 450 X6 motors are subject to numerous failures during operation. The failures are due to breakdowns of end-rings, short-circuiting the rotor bars. When the rotor is rotating, the torn ring damages the stator winding outhangs. Photos illustrating the points of junction of rotor bars to the end-rings, for a new motor and motor with a damaged ring, are shown in Fig. 6 [8].

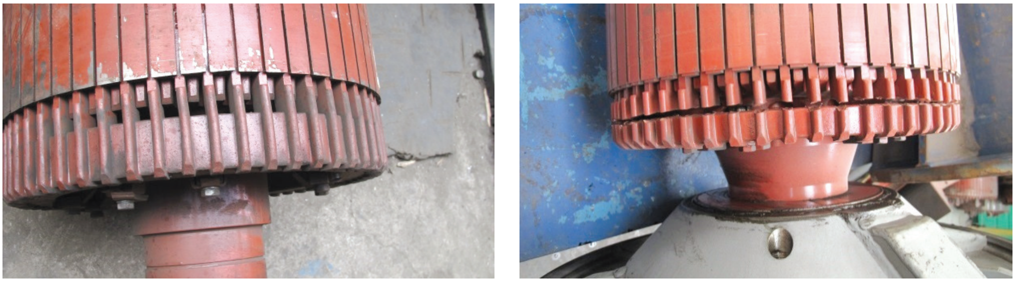

Fig. 6. Junction of rotor winding bars to end-rings: in a brand-new motor (left) and a worn motor with a torn end-ring (right)

4. Operational tests of LK 450 X6 motors

Traction motors LK 450 X6 operating in EMUs EN57 were subjected to tests. The trains were operated by two regional companies, G and W [8]. The tests were conducted during normal commercial train operation. The following phase current waveforms were recorded:

- currents of motors M1 and M2, bogie #1, supplied from inverter 1, and
- currents of motors M3 and M4, bogie #2, supplied from inverter 2.

The transformation of DC voltage into AC voltage is achieved with the pulse width modulation (PWM) method. The inverter voltage is distorted; it contains a fundamental (1st) harmonic as well as higher harmonics. This is a natural effect. The fundamental current and voltage harmonics generate useful electromagnetic torque. This torque is constant, and this corresponds to the conditions present in DC traction motors supplied with DC voltage. Higher harmonics of voltage and current generate variable torques [3], which have an adverse effect on the drive system. The torques at motor shafts were not recorded during the tests, since it was not possible. We were only able to record currents and mechanical vibrations of motors.

5. Current measurements

Examples of current waveforms are shown in Fig. 7. These were recorded for phases A, B, C of the M1 motor, train company W. The harmonic spectrum of the M1 motor phase A current is shown in Fig. 8. Fundamental harmonics of voltage and current generate useful electromagnetic torque; higher harmonics of voltage and current generate variable/ disturbance torques.

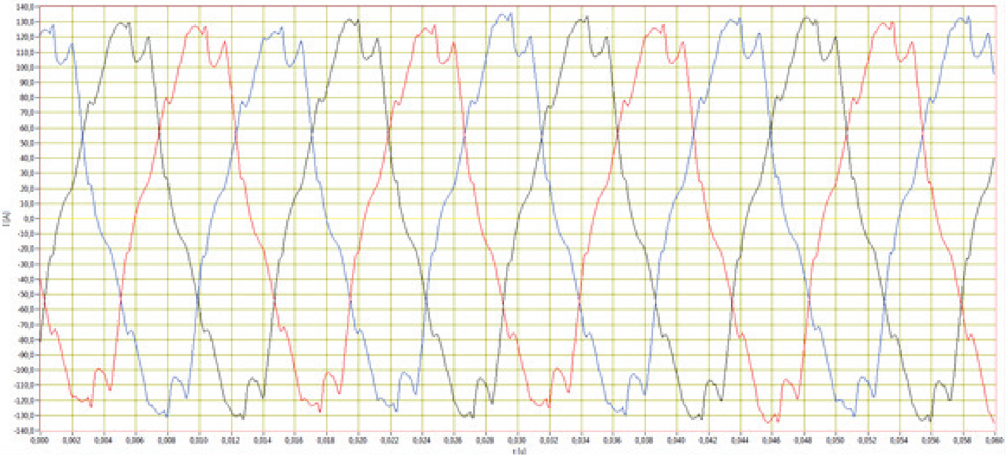

Fig. 7. Examples of phase current waveforms (phase A, B, C) for motor M1, train operator W. The fundamental frequency was f = 69.44 Hz, this corresponded to 58% of the train's maximum speed; the load current was 87A (RMS-value), i.e. 1.12 I_N

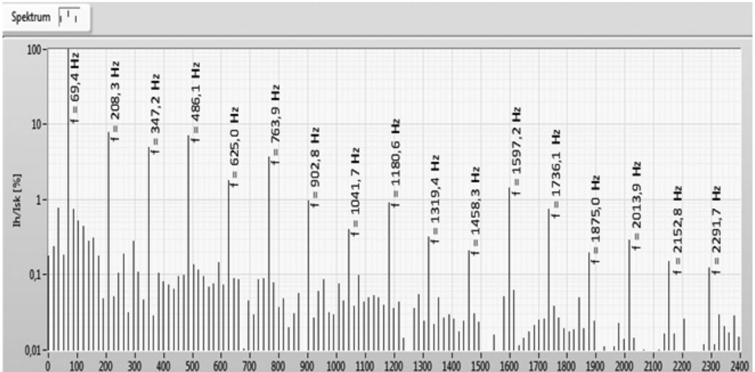

Fig. 8. Harmonic spectrum of motor M1 current, phase A (current waveforms are shown in Fig. 7)

When the AC frequency and load torque are changed, the motor current and voltage waveforms change, and their harmonic spectra change accordingly. The current distortion (deformation relative to sine wave) is much greater when the load current (torque) is small. This occurs when the train runs at a constant speed. Waveforms of M3 and M4 motor currents are shown in Fig. 9. These waveforms were recorded with the train running at a constant speed close to the maximum speed. It may be observed that motors M3 and M4 are loaded almost uniformly. This proves that these motors were adequately selected (matched).

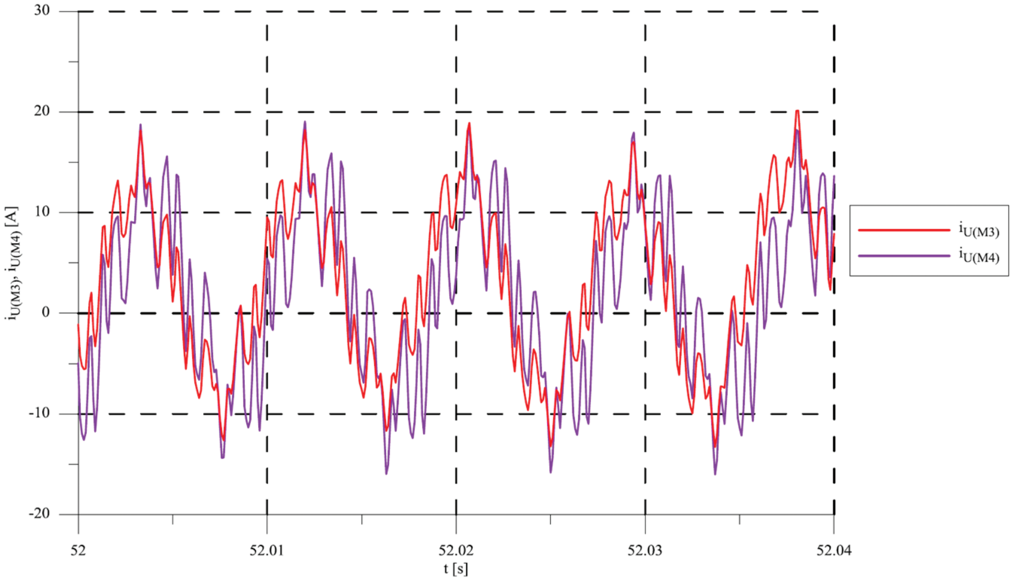

Fig. 9. Examples of phase current waveforms (phase A, B, C) for motors M3 and M4, bogie #2, train operator W. The fundamental frequency was f = 114.9 Hz, this corresponded to 96% of the train's maximum speed; load currents were I_{M3}=8.38 A; I_{M4}=8.49 A (RMS-values), i.e. 22% of I_N

Harmonic spectra of M3 and M4 motor currents are shown in Figs. 10 and 11.

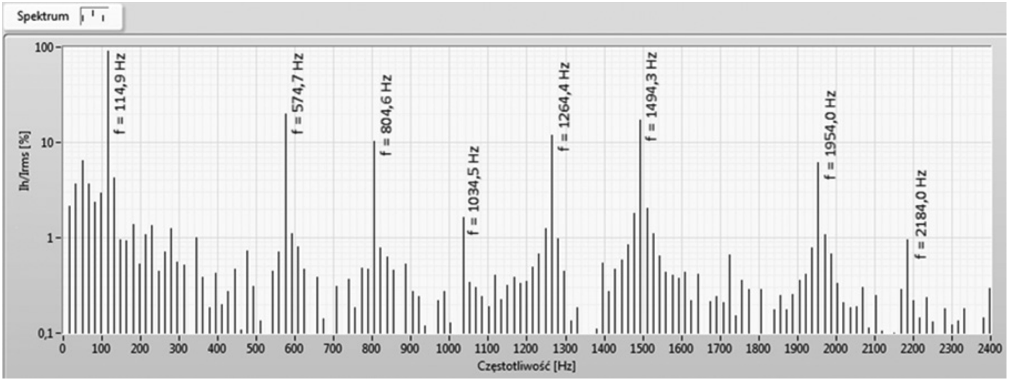

Fig. 10. Harmonic spectrum of the M3 motor current (current waveform is shown in Fig. 9)

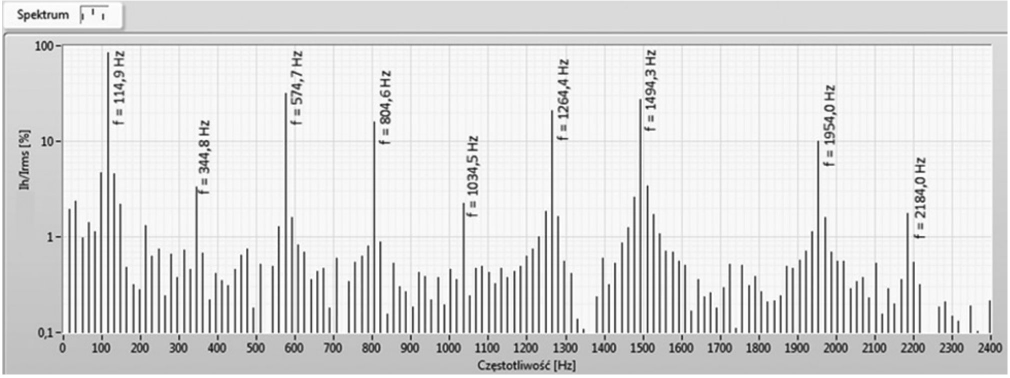

Fig. 11. Harmonic spectrum of the M4 motor current (current waveform is shown in Fig. 9)

In the harmonic spectrum of the M4 motor current, we may observe harmonic $f = 344.8$ Hz. This is not present in the harmonic spectrum of M3 motor current.

Voltage and current higher harmonics generate variable electromagnetic torques, which add up to useful torque generated by fundamental harmonics. Under load conditions, the motor currents are more distorted, which may result in negative instantaneous values of the torque. When torque is negative, the instantaneous value of the motor's rotational speed decreases. The pinion (mounted at motor shaft) gets out of contact with the large toothed gear (mounted at the wheel axle), since this large gear rotates at a constant speed. This constant speed of the large toothed gear is due to the car's inertial mass. When the instantaneous value of electromagnetic torque is positive, then the pinion accelerates and strikes at the large toothed gear. In this way, rotor elements, including end-rings which short circuit rotor bars, are subjected to sudden (surge) circumferential accelerations $\left(\frac{d\omega}{dt}\right)$.

Higher harmonic content in the load current of induction motors supplied from DC/AC inverters is normal. The beauty of power electronics converters lies in the fact that the generated variable voltage is distorted (non-sinusoidal), which results in distorted motor current waveforms (see Figs. 7 and 9) and the generation of higher harmonics of electromagnetic torque.

Motors in one bogie drive two separate bogie axles, and are connected by the track rails via the drive wheels. This is a parallel operation of motors supplied from a common converter and driving a common system of mechanical axles. If motor pairs M1 and M2, M3 and M4 are installed randomly, their parameters may differ within the allowable tolerance range. Differences in the motor parameters have an adverse effect on their parallel operation. This is the case observed in the investigated drive of bogie #1; it is confirmed by recorded courses of current RMS values of motors M1 and M2 operating in parallel. Here are some examples of RMS values of said motors M1 and M2:

- train accelerating under maximum load, M1 motor current attains 115 A, while M2 motor current is 87 A; the difference in load currents is 28 A, which is equal to 28% of the average current value,

- constant speed run, M1 motor current attains 110 A while M2 motor current is 15 A; the difference in load currents is 95 A, which is equal to 153% of the average current value,
- dynamic braking, M1 motor current attains 140 A, while M2 motor current is 25 A; the difference in load currents is c. 115 A, which is equal to 147% of the average current value.

These results prove that M1 and M2 motors are badly matched; the differences in load currents are very high. These large discrepancies may cause the occurrence of operational conditions where motor M1 should drive the bogie, while motor M2 would break the bogie. This phenomenon might be verified by load torque measurements; these were not possible during our tests. The load currents of M3 and M4 motors do not display such high disparities; the motors are matched correctly.

5.1. Backlash in the mechanical gearbox

The transmission of drive torque from the motor shaft to the drive axle is not elastic. The pinion is mounted at the motor shaft, and a large gear is mounted rigidly at the drive wheel axle; this is shown in Fig.5. The toothed gear is characterised by backlash. The induction motor supplied from the inverter generates a constant component of torque as well as variable torques; this is a normal effect of power electronics supply [3]. Variable components of electromagnetic torque affect the operation of gears. The pinion rotates in a non-uniform manner and tries to transmit this kind of motion to the large gear. The large gear, which is rigidly mounted at the drive wheel axle, maintains a constant speed due to high inertia of the car. The clearance between gear teeth causes clattering and mutual grinding of gear teeth; thus, the clearance increases with service time. Within the backlash range, the rotor of the motor will accelerate and decelerate due to variable components of the torque. When teeth come into contact, a surge-like braking of the rotor takes place. The derivative of angular rotor speed generates dynamic torque, which acts upon constructional elements of the rotor, including the end-rings, short-circuiting rotor winding bars. Shearing torque, which affects the junction of rings to bars, is equal to $J_p \frac{d\omega_m}{dt}$, where J_p is the moment of inertia of the end ring, and w_m is the angular speed of the rotor. This torque results in fatigue cracking of the junction between end rings and winding bars. The backlashes should be totally absent from the torque transmission path, and the toothed gear, together with the motor, should be elastically decoupled from the drive wheels and car mass [2, 3].

5.2. Vibrations transmitted to the motors by the bogie

On the outside of the motor body, there is a half-sleeve of a slide bearing; this contains the shaft of the bogie drive wheels – see Fig. 12. The motor is mounted to the bogie frame in the so-called axle hung nose suspended system. Moreover, it is affixed to the bogie frame via rubber pads with two ears and a special arm. The motor constitutes a partial load of the wheelset axle, via an axle slide bearing. This impacts the motor operation unfavourably, since vibrations of the drive wheel are transmitted directly to the motor.

Standard PN-EN 61373 (IEC61373) [5] sets requirements as to resistance to mechanical shock and vibrations of mechanical, pneumatic, electric and electronic equipment of the rolling stock.

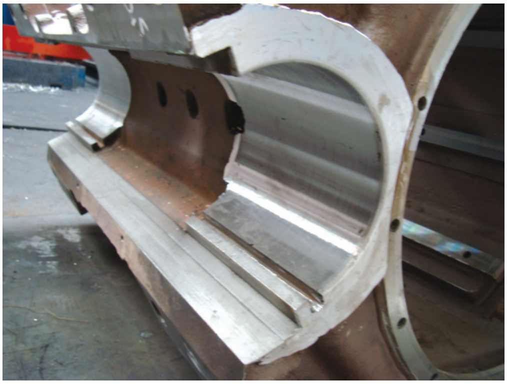

Fig. 12. Half-sleeve of a slide bearing – element of motor body

Technical requirements on the testing of railway vehicle equipment elements subjected to shocks and vibrations arising from the railway common operational conditions are defined in the standard. Maximum RMS-values of vibration accelerations occurring in service, in accordance with Appendix A.3 of the standard (category 3 – equipment mounted at wheelset axis) are [5]:

- in the vertical axis – 43 m/s^2 (*c.* 4.3 g),
- in the lateral axis – 39 m/s^2 (*c.* 3.9 g),
- in the longitudinal axis – 20 m/s^2 (*c.* 2.0 g).

From these requirements, we may conclude that during operation, the LK450 X6 motor may be subjected to maximum vibrations with an acceleration equal to 43 m/s^2 (*c.* 4.3 g). Under these conditions, the motor should be able to operate for 10 minutes without damage. During commissioning of the motors, the motor manufacturers run a test of the LK 450 X6 motor resistance to external vibrations as high as 50 m/s^2. The standard also provides regulations for the simulation test of durability at an increased vibration level. This simulation test should be conducted with the motor held at standstill, vibrations equal to 300 m/s^2 and a frequency range of 5÷150 Hz. The simulation test lasts 15 h (3 separate tests, each lasting 5 h, different directions).

The simulation tests of the motor's rotor construction have been conducted in at the KOMEL Institute. These tests included an investigation of the resistance to mechanical shock and vibrations. The stresses attained 50 MPa. Strength calculations for the rotor have also been run, as well as those for a portion of the rotor winding composed of a rotor bar and a segment of the short-circuiting end-ring, with the shock attaining an acceleration of 1000 m/s^2. This shock simulated the operating conditions set out in standard [5] and related to the equipment mounted on the axle. The maximum value of stresses in the rotor attained 100 MPa, and in bars at the point of junction with the end-ring, it was equal to 120 MPa. These stresses did not exceed allowable values for the material used in the construction of the rotor winding. The displacement of rotor elements, due to these stresses, reached a maximum value of 0.2 mm. Results of calculations confirmed the resistance of the LK 450 X6 motor rotor construction to shock loading equal to 1000 m/s^2.

Measurements of the vibration acceleration of the LK450 X6 motor were conducted on trains belonging to train operator W, during commercial runs. An example of vibration acceleration waveform is shown in Fig.13. We may observe that, during normal operation, the motors are subjected to vibrations with accelerations of up to 150 m/s^2. The LK-450 motors fulfil the requirements set in the PN-EN 61373 standard; however, real vibrations acting upon the motor and caused by external conditions attain values of 150 m/s^2, which means that they are three times as high (43 m/s^2) as vibration values given in the standard [5].

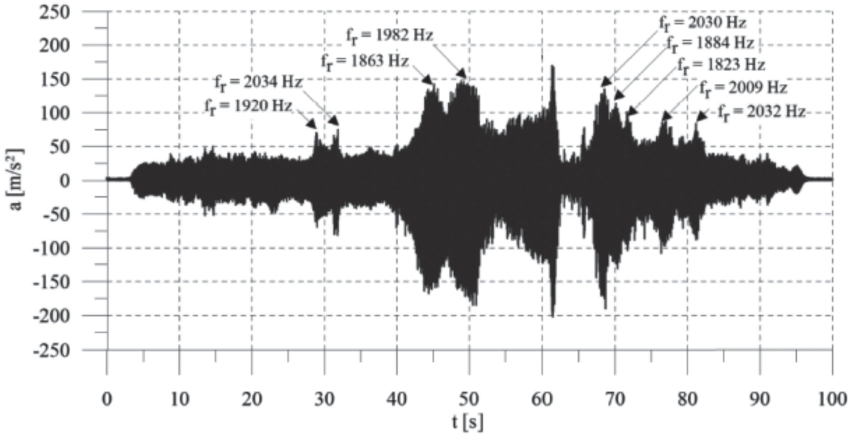

Fig. 13. Example of vibration acceleration, LK-450 motor, course recorded with train operator W

6. Conclusions

Exchanging the DC drive system present in electric multiple units EN57 for a drive system consisting of induction motors supplied from inverters is rational from the economic point of view, since AC drive is characterised by higher efficiency and lower energy consumption [1]. However, we must take into account the fact that apart from the constant torque, higher harmonic torques are also generated in induction motors supplied by inverters; this is an unavoidable natural effect [3]. Higher harmonic torques have not been generated in DC motors supplied by a constant voltage and controlled with resistors.

When the drive system was replaced, the mechanical structure of the bogie, composed of a mechanical gear and motor mounting, has not been changed. The toothed gears – a pinion at the motor shaft and a large gear at the drive axle, are mounted rigidly. The backlash of the toothed gear, together with variable components of motor torque, generates high dynamic torques.

The backlashes should be totally absent from the torque transmission path, and the toothed gear, together with the motor, should be elastically decoupled from the drive wheels and car mass.

LK 450 X6 motors are fitted with squirrel cage winding rotors consisting of copper bars short-circuited with copper end-rings. The end-rings are mounted on coil supports and they are protected from circumferential motion by wedges. The fatigue tearing of rings is due to circumferential acceleration.

At present, the mechanical structure of the bogie and harmonic components of motors' electromagnetic torque are the fundamental reasons for fatigue failures (breaking off) of end rings, which short-circuit rotor bars. The tearing away of the rings is accelerated by the fact that motors in the bogie are not matched (coupled) properly and that vibrations characterised by accelerations as high as 150 m/s2 are transmitted to the motor body via drive wheel axles and the bogie frame.

We have demonstrated that the ripping away of end-rings, short-circuiting rotor bars, is due to a simultaneous impact of four factors:

- variable components of electromagnetic torque generated by current's higher harmonics,
- parallel operation of two unmatched motors supplied from a common inverter,
- backlash in mechanical gearbox,
- vibrations transmitted to motors by the bogie.

Proposed changes in rotor winding.

The first proposed solution is to manufacture a rotor with a cast aluminium winding. Design calculations for such a motor have been conducted at the KOMEL Institute. It has been proven that it is possible to manufacture a motor with parameters identical to those of the LK 450 X6 motor, but with a cast aluminium winding. This sort of winding is compact, does not possess any clearances and hence it is more resistant to vibrations.

The second solution is to manufacture a rotor winding identical to the armature winding of a DC motor (without commutator and brushes). The rotor winding in slots is protected with wedges, and coil outhangs are secured with tapes [6]. This sort of protection works properly in DC motors, and therefore it might also be used in an induction motor. The electromagnetic calculations of such a motor have also been conducted at the KOMEL Institute and the motor's parameters have been proved to be identical to those of the LK 450 X6 motor.

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