RESEARCH OF HARMONIC SPECTRUMS OF CURRENTS AND INDUCED VOLTAGES IN TRACTION DRIVE

VÝZKUM HARMONICKÝCH SPEKTER PROUDŮ A INDUKOVANÝCH NAPĚTÍ V TRAKČNÍM POHONU

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Summary: The paper deals with the research results of the harmonic spectrum of currents and induced voltages at traction drive. A permanent magnet synchronous motor is used at this drive. The harmonic spectrums of currents were analysed by a specialized device. The knowledge of subharmonic components of stator winding currents is the most significant finding of these researches. The frequencies of these components are given by frequency multiples of mechanical speeds. The subharmonic components also pass to the DC current at an input site of the traction inverter. This fact is particularly important from the viewpoint of the legislative requirements to electromagnetic compatibility of drive with railway interlocking devices.

Keywords: Permanent magnet synchronous motor, spectrum, harmonic component, subharmonic component, inverter.

Anotace: Článek prezentuje výsledky výzkumu harmonického složení proudů a indukovaných napětí trakčního pohonu, který využívá synchronní motor s permanentními magnety. Harmonické složení proudů pohonu bylo analyzováno pomocí specializovaného zařízení. Nejvýznamnějším poznatkem výzkumů je zjištění výrazných subharmonických složek proudů statorového vinutí. Frekvence těchto složek jsou dány násobky frekvence mechanických otáček. Subharmonické složky pronikají i do DC proudu na vstupní straně trakčního střídače, což je závažná skutečnost zejména z hlediska legislativních požadavků na elektromagnetickou kompatibilitu pohonu se železničním zabezpečovacím zařízením.

Klíčová slova: Synchronní motor s permanentními magnety, spektrum, harmonická složka, subharmonická složka, střídač.

1. INTRODUCTION

The development of power semi-conductor converters provides high quality to drive systems from the viewpoint of traction, dynamics and energy as well. Concurrently the

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problems of side noise effects of power semi-conductor converters have been opened due to this development. The magnitude and type of drive noise effects depend on many elements. It specifically concerns the whole concept of vehicle traction circuits, power converter construction, assembly of vehicular electro-equipment, traction circuit parameters, distribution of traction circuit parameters, switching properties of semi-conductor elements, PWM frequency, algorithm of PWM generation and durations of converter blanking times and so on. The harmonic spectrums of input currents from driving wheel vehicles are analyzed for the reason of possible parasitic effects on railway interlocking devices due to traction circuit operation. In the operation of traction circuits it is necessary to reduce the input current of a vehicle, particularly the harmonic components with frequencies used by interlocking devices. Under Czech Republic conditions it is necessary to use the particular frequencies 50 Hz, 75 Hz and 275 Hz. The standards specify the effective value limits of harmonic components at the defined frequencies. The other details about problems of power converters and EMC are in [1-7].

Traction drives with a permanent magnet synchronous motor (PMSM) are most often utilized for an individual drive of wheels or axels in a wheel vehicle. The three-phase bridge inverter with six power switched elements (in most cases IGBT) and six reverse diodes are used in a majority of applications for motor feeding. The inverter input circuit has voltage character and is created by the LC-network. These days at the Department of Electrical and Electronic Engineering and Signaling in Transport at the Jan Perner Transport Faculty, University of Pardubice the research of special characteristics of traction drives with PMSM from the viewpoint of noise effects in low-frequency areas are performed. The significant results of these works are presented in this paper. For researches, Jan Perner Transport Faculty is equipped with a special laboratory. This laboratory has a workplace containing traction PMSM (with characteristics: nominal power 58 kW, nominal speed 650 rpm, nominal torque 852 Nm, nominal phase current 122 A, system 3x368 V, nominal frequency 238 Hz, number of poles 44, the other information is in [8]). The workplace circuit diagram is shown in Fig. 1.

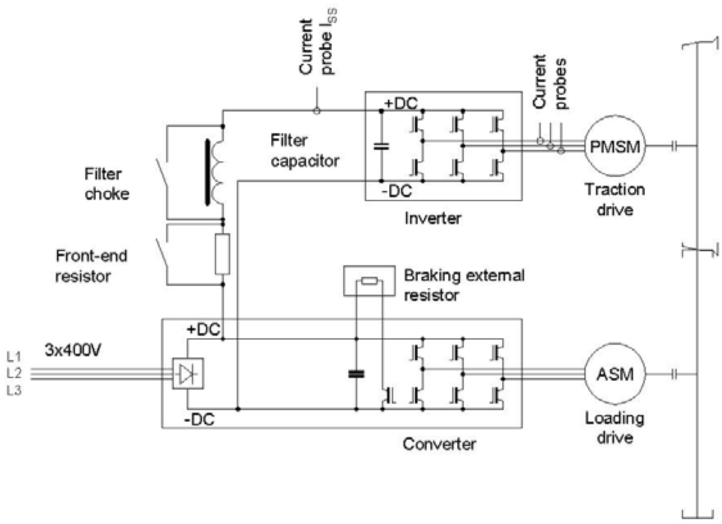

Fig. 1 - The workplace circuit diagram

The research aim was to map out harmonic spectrum of the stator phase currents and currents at an inverter input filter choke of the traction motor. A further aim was to find the significant properties of frequency spectrums and comprehend effects of various conditions of drive operation - motor/generator mode, load magnitude, various parameters of inverter input filter, inverter blanking time, softening DC source of inverter by series front-end resistance, effect of rotation direction.

2. RESEARCH OF SPECTRUMS

2.1 The conditions for research

The waveform of currents in phases of traction motor and current in input DC circuit of drive (filter choke current) were scanned and consequently evaluated at the measurings. The currents were scanned by galvanically separated probes (100 kHz). The record and data evaluations are done by a special device with software developed by the Škoda Electric company. The PWM inverter switching frequency is 5 kHz. The majority of the measurings were done on a slow ramp. The ramp was represented by a frequency ramp of a converter for an asynchronous motor (load). The PMSM was operated with a torque feedback control. The analysis of measured waveforms is based on 3D graphs with a time axis, frequency axis of harmonic component and axis of effective values of corresponding harmonic component of measured current.

2.2 The reference measuring

The overall view of the frequency spectrum of PMSM current in phase is shown in Fig. 2. This spectrum map was measured with the load torque (T) of the traction motor at 20 % of nominal values. The fundamental harmonic component of current, whose value is increases following the ramp up to a nominal value 238 Hz. The frequency then decreases once again following the ramp. The representation of frequencies related to the PWM frequency of inverter (5 kHz) is evident from the spectrum map. The frequencies which are represented particularly are given by sum and difference of the PWM frequency and double the frequency of current fundamental harmonic, and further by the sum and difference of PWM frequency and quadruple the frequency of current fundamental harmonic. The current spectrum in this area is obviously related to the method of PWM generation with variable relative time of inverter transistor switching in one period of fundamental harmonic, and with the fact that the currents of phases motor are summated in a shared neutral point. Further the 3^{rd}, 5^{th} and 7^{th} harmonic values are presented in the current spectrum. The high effective values of the subharmonic components are obvious from the spectrum map as well.

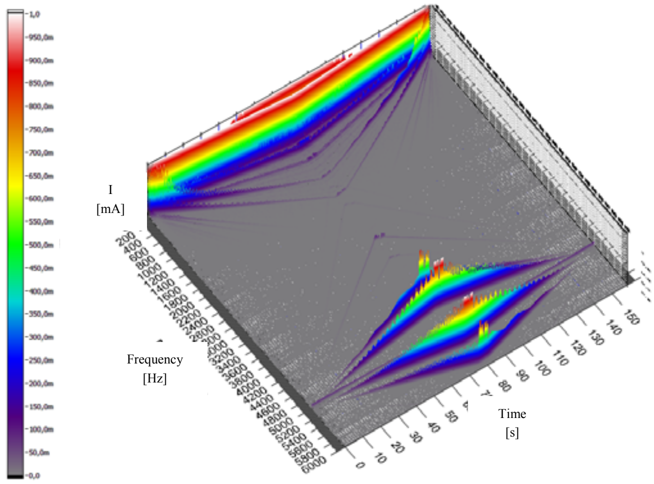

Fig. 2 - The spectrum map of phase current of traction motor for T = 20 % and filter parameters L = 5.7 mH, C = 4.7 mF

The spectrum map of current of inverter input filter contains only components of low frequencies. Any current component with frequency derived from PWM frequency does not pass in front of the filter. The detail of frequency spectrum is in Fig. 3. In this spectrum, the marked presentation of subharmonic components is evident. The frequencies of these subharmonic components correspond at the certain speed of drive with resonant frequency of inverter input filter f_{rez} = 30.7 Hz. For this reason it does not pass by filter operation to their damping but on the other hand to their amplification.

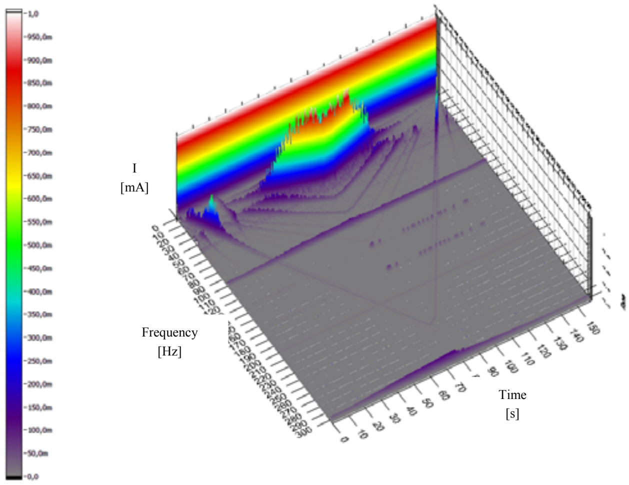

Fig. 3 - The spectrum map of current of inverter input filter choke for T = 20 % and filter parameters L = 5.7 mH, C = 4.7 mF – to 305 Hz

2.3 The research of effects

A lot of measurings have been done at the experimental workplace with the aim to find out effects on harmonic spectrum of drive currents. These effects and properties were verified. The results of these researches will be presented only in short.

2.3.1 The research of current symmetry in motor phases

- During this research it was found, that the asymmetry is the most significant, only at selected multiples of subharmonic components with frequency slightly overcrossing the 1st harmonic value. The asymmetry is not significant and it does not even reach 10 % at the most unfavorable cases.

2.3.2 The research of the effect of motor load on harmonic spectrums

- During this research it was found, that as well as increasing of magnitude of the 1st harmonic, there exists significant increasing of the 3th harmonic in the current of motor phase as well. The increasing of motor load by magnitude increase of components with frequency 300 Hz and by magnitude increase of subharmonic components in proximity to the filter resonant frequency, finds expression in filter choke current at input inverter. The component with frequency 300 Hz is given by the effect of input three-phase diode rectifier from which the inverter is fed.

2.3.3 The research of the effect of a front-end resistor inclusion on current spectrum of filter choke

- During this research it was found, that there is a significant attenuation of harmonic components. The effect is visible from a comparison of spectrums in Fig. 3. From this, it is evident that the harmonic spectrum of input current, which a vehicle takes from DC network, will be dependent on the quality of this network.

2.3.4 The research of the effect of motor/generator mode

- During this research it was found, that the mode has effect neither on the motor current spectrum nor on input filter choke current. The findings of the effect of inverter blanking time on the harmonic spectrum of drive currents, led to the safety time being extended from 4 μs to 8 μs. This extension of blanking time found expression in phase current of the motor by frequent increasing of the 5th and the 7th harmonic. The extension of inverter blanking time did not occur in the spectrum of input filter choke.

2.3.5 The research of the effect of inverter input filter parameters on current harmonic spectrums of input filter choke

- During this research, the capacity and inductivity of the filter was changed. Experiments with three values of resonant frequency were done. The results of these experiments were in accordance to the theory - the filter with lower resonant frequency eliminated better harmonic components of currents of choke. Futher, in proximity to filter resonant frequency, the magnitude of subharmonic components increased in particular.

2.4 The problems of drive current subharmonic components

For the most significant effect found out in the above mentioned experiments, it is necessary to consider the origin of significant subharmonic components in current spectrums of motor phase. These subharmonic components are transmitted also to the harmonic spectrum of drive DC input currents (through inverter and inverter input filter). It was found out that these subharmonic components originate independently from the magnitude of motor load torque and from drive mode. Near to resonant frequency of inverter input LC filter, these components are significantly increased and the magnitudes of their effective values are not the same in individual phases of the motor.

The research proceeded to another step whose aim was to map out in more details the causes of origin and effect of subharmonic components in currents of traction drive with low-speed PMSM. The finding of frequency values of significant components in motor currents and in choke currents of inverter input filter was the first step. These frequency values are possible to determine from the following Fig. 4 which presents the detail of the frequency spectrum of motor phase current in an area of low frequencies.

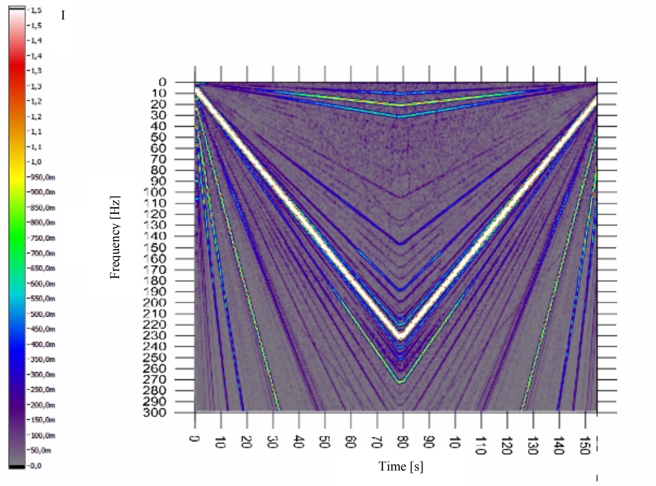

Fig. 4 - The frequency spectrum of motor phase current (at in input filter of converter) for T =70 % and filter parameters L = 1.0 mH, C = 4.7 mF , detail up to 300 Hz

If we focus on time in Fig. 4, when the motor runs at the highest speed (the frequency of the 1[st] harmonic of motor phase - 230 Hz), it is obvious that the subharmonic component with the lowest frequency has, in this time, a frequency of 10 Hz. The experiments were done on the motor with 44 poles (22 pairs). If the frequency value of the 1[st] harmonic is divided by pole pairs, we receive frequency 10.45 Hz. That the frequency value of the lowest subharmonic component is equal to the frequency of the motor mechanical turns. From Fig. 4 it is obvious that the subharmonic component with the highest effective value has double frequency compared with the frequency of the motor mechanical turns (it is generated by effect which is repeated twice per mechanical turn). The findings are unfavorable for this reason, that if low-speed PMSMs are constructed as multipoles and if these drives generate subharmonic components with frequencies from the frequency value of mechanical turns, the harmonic component will have very low frequencies. If the components with these frequencies are present in input current of drive, their elimination by inverter input filter from the viewpoint of its higher resonant frequency, will probably be very difficult. The frequency detail of the current spectrum map of the inverter input filter choke is shown in Fig. 5.

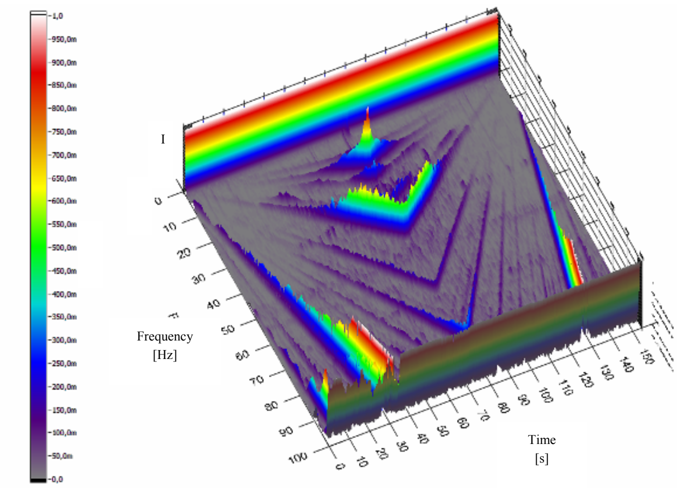

Fig. 5 - The spectrum map of current in input filter of inverter for T =70 % and filter parameters L = 1.0 mH, C = 4.7 mF , detail up to 100 Hz

From comparison of Fig. 4 and Fig. 5 it is evident, that the frequencies of current subharmonic components of motor phase and current of input filter choke are not totally the same by effect of the inverter operation; however they have negligible values. For the purpose of authentication the experiments were done (at which the harmonic analysis of induced voltage were done), such that the subharmonic components of drive currents are generated by the effect of fluctuation of voltage effective value.

During these research, two phase-to-phase induced voltages of stator of traction PMSM were scanned. The phase-to-neutral voltages were not possible to measure because the motor has no central external terminal. The experiment was done so that PMSM was switched off from feeding and its measured induced voltages were terminal voltages at this free-current state. The curve of induced voltage at free idle running of the motor in its revving state, when the effect of pulse torques occurring in the mechanical or electrical part of the experimental workplace were eliminated, was recorded. The findings of this experiment are crucial for close localization of the origin of drive current subharmonic components. The spectrum map of induced voltage at free idle running of a traction motor is in Fig. 6.

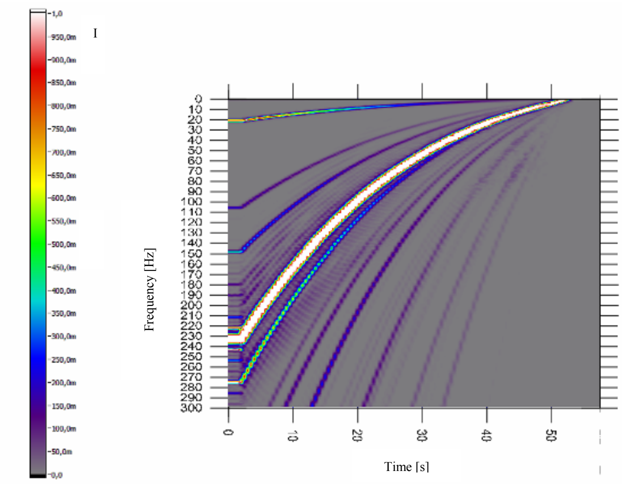

Fig. 6 - The spectrum map of phase-to-phase inducted voltage at free run out of motor

The findings of this experiment are crucial for close localization of the origin of the drive current subharmonic components. The spectrum map of induced voltage at free idle running of a traction motor is in Fig. 6. It is obvious, that the subharmonic components (whose frequencies in large scale correspond with the frequencies of drive current subharmonic components) are also significantly interpreted in induced voltages. The subharmonic component with the highest effective values and also with the lowest frequency is a component whose frequency is equal to double the frequency of mechanical turns. The component with this frequency has the highest effective value even in spectrum of phase currents. The other significantly presented subharmonic components are components with frequencies given by frequency multiples of the highest subharmonic component.

The variation of induced voltage is very slow. However, the effect of this variation to motor currents and also to the drive DC input current is significant from the viewpoint of their harmonic spectrum in the context of the legislative requirements to parameters of currents taken by railway vehicles.

The crucial elimination of determined subharmonic components, which are external to the motor in the electrical part of drive, is very difficult. However finished works indicate that it is necessary to choose resonant frequency of inverter input filter suitably so that it was out of the frequencÿ area of the most marked subharmonic components in the whole field of drive speed. This fact moves the resonant frequency of the filter to higher values. For example: the area of resonant frequencies is approximately from 90 up to 120 Hz at the testing drive. This designed filter allows a wider spectrum of harmonic components however the filter resonance with significant subharmonic components would be very adverse.

3. CONCLUSION

The detection of the existence of unwanted subharmonic components with appreciable effective values of currents at the drive (with low-speed traction PMSM), and the conditions which influence the characteristics of harmonic spectrums of drive currents and the qualification of the possible cause range of the origin of these subharmonics, are results of described researches. The existence of unwanted subharmonic components can bring serious effects for traction drive operation. They are not possible to filter by the input filter converter from the viewpoint of low frequency of subharmonic components.

The existence of observed subharmonic components in input current of traction drive would represent a high risk of incompatibility of traction drive operation with traction infrastructure, in particular with interlocking devices. The frequencies of significant subharmonic components and their multiples change depending on vehicle speed and reach values from tens to hundreds of Hz. The critical fact is that the traction interlocking devices also use this area of frequencies. Also the measurings of the spectrum of currents and inducted voltages at traction drive of the tram 15T within the research of described problems was done in co-operation with the Škoda Electric company. The harmonic spectrums measured at drives of tram 15T had more favorable structure in comparison with experimental drive in the laboratory of the University of Pardubice. The detailed results of these measurings are not possible to publish due to the reasons of company know-how.

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