

Experimental Research of Harmonic Spectrum of Currents at Traction Drive with PMSM

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Abstract. *The paper deals with the significant results of the experimental research of current harmonic spectrum of traction drive with permanent magnet synchronous motor. The experiments were done on a special workplace with a real traction drive for wheel vehicles. Current harmonic spectrum was analyzed by a specialized device on the base of central measuring station. The knowledge of current marked subharmonic components of stator winding is the most significant finding of experiments. The frequencies of these components are given by multiples of frequency of mechanical speeds. The subharmonic components also pass to input DC current of drive. This fact is important in particular from the point of view of legislative requirements to electromagnetic compatibility of drive with railway interlocking devices.*

Keywords

Permanent magnet synchronous motor (PMSM), traction drive, spectrum, harmonic component, converter, inverter, analysis.

1. Introduction

Engineering development of power semi-conductor converters has brought new conceptions of electric traction drives providing to drive systems high quality from point of view of traction, dynamic and also energy site. Concurrently the problems of side noise effects of power semi-conductor converters have been opened due to this development. These effects are interrelated with high dv/dt and di/dt of power semi-conductor elements used in these converters. The magnitude and type of drive noise effects depend on a lot of effects. It concerns in particular the whole conception of vehicle traction circuits, power converter construction, assembly of electro-equipment of vehicles, traction circuit parameters (R, L, C), distribution of traction circuit parameters, switching properties of semi-conductor elements, PWM frequency, algorithm of PWM generation and magnitudes of blanking times of converters, converter input filter parameters, motor construction, instantaneous speed, mode and torque of motor. The input

current harmonic spectrums of driving wheel vehicles are analyzed for the reason of possibility of parasitic effect of railway interlocking devices by operation of traction circuits. Particularly the harmonic components with frequencies used in interlocking devices are necessary to reduce in input current of vehicle during operation of traction circuits. Under conditions in the Czech Republic it is in particular frequencies 50 Hz, 75 Hz and 275 Hz. The standards specify the limits of effective values of harmonic components at the defined frequencies. The value limits of magnitudes of harmonic components at traction circuit input are in range up tens to hundreds mA [1 - 6]. The valid legislation is topical in particular for railway operation. The detail comparison has not any sense in this case because the results quantitatively different are expected for vehicle for heavy railway operation. The potential sources of technical problems at future power traction slow-speed drives with permanent magnet synchronous motor (PMSM) are shown in particular qualitatively in this paper. The other detailed information sources about problems of power converter and their electromagnetic compatibility (EMC) are in [7 - 15].

The problems of interference effects of traction drives are intensely monitored by manufacturer of rail engineering. The Jan Perner Transport Faculty co-operates with ŠKODA group in this field. In recent time, the first rail vehicle with low-speed traction PMSM (tram 15T), which was manufactured and operated in the Czech Republic, was put into service by this company. The manufacturer is not monitoring the problems of interference effects only from point of view of urban mass transportation vehicles but also particularly from point of view of perspectives of usage of these drives at power railway vehicles where the problems of interference effects are monitored more strictly.

2. Traction Drive with PMSM

Traction drives with PMSM are utilized most often for an individual drive of wheels or axels of rail vehicle. The three-phase bridge inverter with six power switched elements (in most cases IGBT) and six reverse diodes are used in majority of applications for motor feeding. The

inverter input circuit has voltage character and is created by LC-network. These days at the Department of Electrical and Electronic Engineering and Signalling in Transport in the Jan Perner Transport Faculty (JPTF), University of Pardubice the experimental researches of special characteristics of traction drives with PMSM from point of view of interference effects in low-frequency area are performed. Some of selected significant results of these works are presented in following parts of this paper. For experimental research of traction drives with PMSM, the JPTF is equipped with the special workplace with traction PMSM: nominal power of 58 kW, nominal speed of 650 rpm, nominal torque of 852 Nm, nominal phase current of 122 A, system of 3x368 V, nominal frequency of 238 Hz, number of poles 44, the other data is in [16].

The main circuit diagram of this workplace is shown in Fig. 1. During the research works many measurements were done. Their aim was to map out harmonic spectrum of stator phase currents and currents in inverter input filter choke at traction motor with PMSM, further 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 and effect of rotation direction. The traction drive located on experimental workplace of the JPTF was fed through diode rectifier from network 3x400V, see Fig. 1. It represents the input voltage of traction inverter (560 V DC). Traction network of real operations of urban mass transportation has nominal voltage of 600 V DC (at new operations 750 V DC). Traction network is always very soft, that is why the authenticity of measurements is not affected by feeding circuit solution on the experimental workplace in the laboratory of the JPTF.

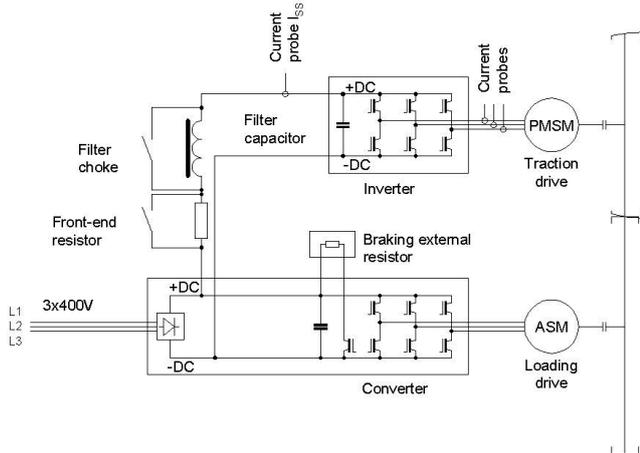


Fig. 1. The power circuit diagram of the experimental workplace.

3. The Results of the Experiments

The waveform currents in phases of traction motor and the current in input DC circuit of drive i.e. filter choke

current were scanned and consequently evaluated during the measuring. The currents were scanned by galvanically separated probes (100 kHz) working on the principle of Hall Effect. The record and data evaluation are done by a special device with software developed by Škoda Electric. All measurements were done and evaluated by a specific device developed on the base of central measuring station (Compact RIO by National Instruments). This measuring device is utilized at measurements of rail vehicles of urban mass transportation and railway. The PWM inverter switching frequencies are 5 kHz. The majority of the measurements were done on a slow ramp. The ramp was represented by a frequency ramp of converter of a load asynchronous motor. The PMSM was operating with torque feedback control. The analysis of measured waveform is based on 3D graphs with time axis, frequency axis of harmonic component and axis of effective values of corresponding harmonic component of current in mA, respectively in A.

Except of 3D spectrum maps it is possible to obtain the results in other forms (e.g. frequency spectrums for sampling window) from measuring device. The 3D spectrum maps always provide very comprehensive image of the whole situation and it is possible to study them deeply by usage of relevant software. Unfortunately during conversion of spectrum maps from special software to standard software of MS Office the partial loss of resolution arises. From the reason of whole comprehensiveness of description of the problem we decided to present the results of measurements just in form of 3D spectrum maps even if the accuracy was lost partly.

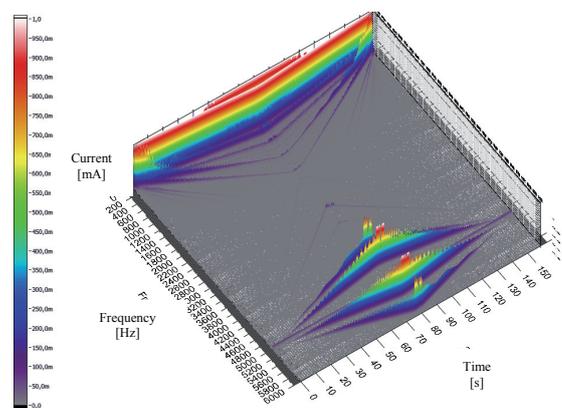


Fig. 2. The spectrum map of phase current of traction motor for T = 20 % and filter parameters L = 5.7 mH, C = 4.7 mF

The overall view of frequency spectrum of current in phase of PMSM is shown in Fig. 2. The spectrum map, Fig. 2, was measured with the load torque (T) of the traction motor 20 % of nominal values. The fundamental harmonic component of current, whose value is increasing on the ramp up to nominal value (238 Hz), is the most noticeable in Fig. 2 and then the frequency is again decreasing on the ramp. The representation of frequencies related to the PWM frequency of inverter (5 kHz) is evident from the spectrum map. The frequencies given by the sum and dif-

ference of PWM frequency 5 kHz and double of frequency of fundamental harmonic of current and further by sum and difference of frequency 5 kHz and quadruple of value of frequency of fundamental harmonic are represented particularly. The current spectrum in this area is obviously related to the method of PWM generation with variable relative time of switch of inverter transistors in one period of fundamental harmonic.

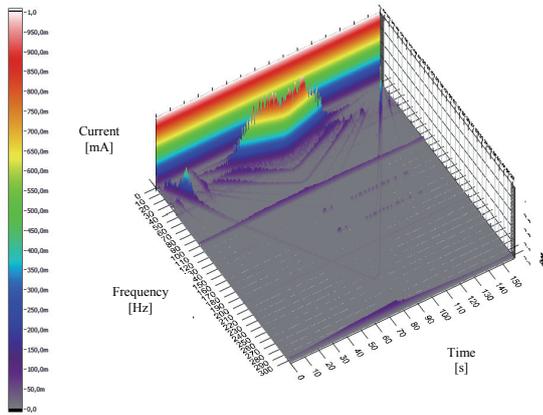


Fig. 3. The spectrum map of current of inverter input filter choke for $T = 20\%$ and filter parameters $L = 5.7\text{ mH}$, $C = 4.7\text{ mF}$ – detail to 305 Hz.

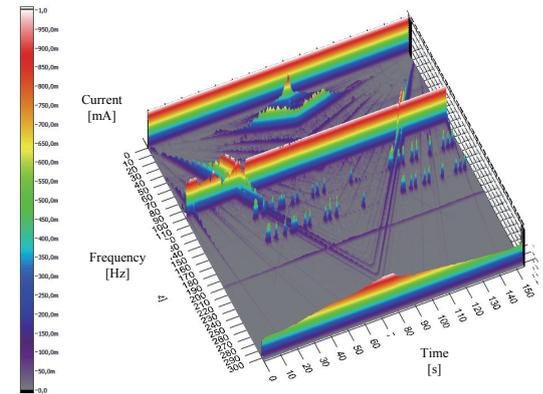


Fig. 4. The spectrum map of current of inverter input filter choke for $T = 70\%$ and filter parameters $L = 1\text{ mH}$, $C = 4.7\text{ mF}$ – detail to 305 Hz.

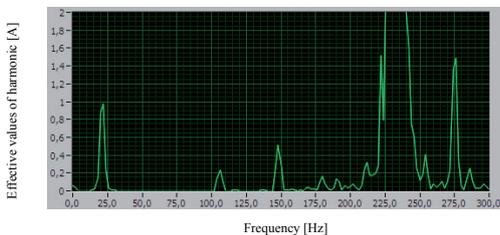


Fig. 5. The spectrum of harmonics of inductive voltage at the beginning running out of motor

Further the 3rd, 5th and 7th harmonic values are presented in the current spectrum. The high effective values of the subharmonic components are also obvious from the spectrum map.

The spectrum maps, which are in Fig. 3 and Fig. 2, were received at the same experiment. The detail for components with frequencies up to 305 Hz is shown in Fig. 3. From Fig. 3 it is evident that the component with frequency given by the phase fundamental harmonic of motor passes to input current in minimal range with exception of surroundings of filter resonance frequency approx. 30 Hz. The subharmonic components, whose effective values are again emphasized in vicinity of filter resonance frequency, are marked. The current spectrum map of input filter choke measured at low inductance of filter choke of 1 mH is in Fig. 4. Further the motor load was increased to nominal torque of 70 %. It is obvious that the subharmonic components are not increased any more by filter resonance frequency, which has value of 73.5 Hz now, but they still assume significant effective values. The existence of harmonic components with frequency of 100 Hz and 300 Hz is given by operation of input diode rectifier, Fig. 1. It is obvious from comparison of Fig. 3 and Fig. 4 that the filter with higher inductivity (Fig. 3) reduces harmonic components generated by inverter and operation of input diode rectifier. The components with frequency higher than value of resonant frequency of filter are reduced significantly. At the mentioned comparison it is necessary to respect that Fig. 4 was measured at higher motor load.

4. Conclusion

Nowadays the PMSM motors are used in rail vehicles in particular for urban mass transportation systems. The very real assumptions to PMSM motor usage at railway vehicles, where the very strict legislation focused on EMC of vehicles and interlocking devices is valid, exist in consideration of their favorable properties. The presentation of existence of current significant subharmonics components in context with prospects of traction gearless drives with multi-poles PMSM is the aim of this presented paper. The subharmonic components of input currents are not possible to eliminate practically by input inverter filter because they have very low frequencies (tens of Hz), which are moreover variable depending on vehicle speed. The detail of harmonic spectrum of inductive voltage of traction motor, which was measured at free running out, at practically constant frequency (235 Hz) and at speed in monitored interval, is in Fig. 5. The frequencies of significant harmonic components of inductive voltage correspond with frequencies of current subharmonic components were found out by analysis of measured waveforms. It shows that the cause of generation of current subharmonic components is probably by disturbing components of motor magnetic flux. The elimination of problem in this case is related to the problems of traction motor construction.

The problem of current subharmonic components at drives with high-speed motors with gearboxes was not studied explicitly at the JPTF. According to available data it is possible to state that the situation at usage of low-speed drives from point of view of interference effects is

less favorable. In the case of problem solution by analytical way, the results of experiments indicate that this solution by available means would be very difficult task. Except experiments done at the JPTF, which are presented in this paper, the staff of the JPTF had possibility to participate the similar measurings at tram 15T in Prague tram system. The construction of motors and power part of converters is very similar to devices in the laboratory of the JPTF. The results of experiments are to a large extent different although the analytical description of both drives is analogical. However it is not allowed to publish the results of measurings in real vehicle at real service.

The other researches in this area both on experimental level and on drive mathematical model level, which is being finished at these days, will proceed at the JPTF.

Acknowledgements

The research is supported by the Czech Science Foundation under the grant “Permanent magnets synchronous motor traction drives electromagnetic compatibility to supply network and possibilities of its improvement”, No. 102/09/P253. The authors thank to GAČR for financial support. The authors are thankful to the reviewers whose suggestions helped in improving the article.

References

- [1] *Standard ČSN 34 2613* Railway Signalling Equipment - Track circuits and the outer conditions for their function (in Czech).
- [2] *Standard EN 50121-1* Railway applications - Electromagnetic compatibility, Part 1: General.
- [3] *Standard EN 50121-2* - Railway applications - Electromagnetic compatibility, Part 2: Emission of the whole railway system to the outside world.
- [4] *Standard EN 50121-3-1* Railway applications - Electromagnetic compatibility, Part 3-1: Rolling stock - Train and complete vehicle.
- [5] CHALOUPKA, F. Electromagnetic compatibility, description of problems and ways to solution of EMC at traction vehicles. In *Workshop on Disturbing Effects of Traction Devices and Their Elimination and Electromagnetic Compatibility*. University of Pardubice, Jan Perner Transport Faculty, Pardubice 2010, ISBN 978-80-7395-255-6 (in Czech).
- [6] VURM, J. Authorization of modern traction vehicles in Czech Republic. In *Workshop on Disturbing Effects of Traction Devices and Their Elimination and Electromagnetic Compatibility*. University of Pardubice, Jan Perner Transport Faculty, Pardubice 2010, ISBN 978-80-7395-255-6 (in Czech).
- [7] NOVÁK, J., ŠIMÁNEK, J., ČERNÝ, O., DOLEČEK, R. EMC of frequency controlled electric drives. *Radioengineering*, 2008, vol. 17, no. 4, p. 101 – 105.
- [8] LETTL, J., FLÍGL, S. Electromagnetic compatibility of matrix converter system. *Radioengineering*, 2006, vol.15, no. 4, p. 58–64.
- [9] KAISER, L. K. *Electromagnetic Compatibility Handbook*. CRC Press, USA, 2005, ISBN 0-8493-2087-9.
- [10] SHEPHERD, W., ZHANG, L. *Power Converter Circuits*. New York: Taylor and Francis, 2004, ISBN 0-8247-5054-3.
- [11] DOLEČEK, R., ČERNÝ, O., NĚMEC, Z. EMC of traction drive with permanent magnet synchronous motor. In *Proc. of International Conference on Electromagnetics in Advanced Applications (ICEAA 09)*, Torino (Italy), September 2009.
- [12] QIANTAH, Z., XIAOFEI, L. Permanent magnetic synchronous motor and drives applied on a mid-size hybrid electric car. In *Proc. of Vehicle Power and Propulsion Conference (VPPC'08)*. Harbin, September 2008, p.1-5, ISBN 978-1-4244-1848-0.
- [13] MUGUR, P., ROUDET, CREBIER, J. Power electronic converter EMC analysis through state variable approach techniques. *IEEE Trans. Electromagnetic Compatibility*, 2001, vol. 43, no. 2, p. 229-238.
- [14] LETTL, J., DOLEČEK, R. EMC increasing of PWM rectifier in comparison with classical rectifier. *Radioengineering*, 2008, vol. 17, no. 4, p. 93-100.
- [15] NOVÁK, J. Analysis of disturbance effects of traction drives with permanent magnet synchronous motor. In *Workshop on Disturbing Effects of Traction Devices and Their Elimination and Electromagnetic Compatibility*. University of Pardubice, Jan Perner Transport Faculty, Pardubice 2010, ISBN 978-80-7395-255-6 (in Czech).
- [16] DOLEČEK, R., NOVÁK, J., ČERNÝ, O. Traction permanent magnet synchronous motor torque control with flux weakening. *Radioengineering*, 2009, vol. 18, no. 4, p. 601 – 605.

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