Traction Drive with PMSM: Frequency Characteristics Measurement

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***Abstract* — This paper describes a new method for measurement of frequency characteristics of ac traction drives. It helps to find dangerous resonant frequencies of the traction drive supplied from a dc electrification system and it allows finding danger oscillations of the dc-link LC filter. The presented method has verified a drive with a surface mounted PMSM controlled by DTC. The results prove that the drive amplifies LC filter oscillations under constant taken power. We have proposed an improvement of the drive control in order to protect the drive against this phenomenon. The behaviour of the improved DTC has been analyzed by experiments made on the laboratory model of the traction drive of the rated power of 10 kW.**

Keywords— traction, measurement, permanent magnet motors

I. Introduction

This research has been motivated by the fact that a part of a traction drive fed from a dc electrification system is an input trolley-wire LC filter which can cause dangerous dc-link voltage oscillations. The existence of these oscillations in traction drives and their dangerous impacts are well-known from the past [1], [2] and has been solved until nowadays. These oscillations can be excited e.g. by an unsuitable control command from the control system at a given output frequency of the drive where the positive feedback can appear, see e.g. [3], [4]. There can be destroyed either an electrical part or a mechanical part of the vehicle propulsion unit [5]. The problem with oscillations of input LC filter is one of the most serious topics in modern traction drives. There do not exist up to now any generally accepted techniques making possible to mitigate this phenomenon as can be seen from different approaches in the literature, e.g. [6], [7].

A frequency analysis is an important part of the stability analysis of electric drives. The aim of this paper is to propose a new measurement method allowing to find dangerous resonant frequencies of the trolley-wire LC filter and hence, to design corresponding solutions for mitigation of its possible oscillations and the instability at given frequencies (i.e. drive control algorithm correction or adaptation). The proposed technique for measurement of the drive frequency characteristics is verified by both simulations and experiments made on a developed laboratory traction drive prototype with permanent magnet synchronous motor (PMSM) employing direct torque control strategy.

The presented paper is structured as follows: In the first part of the paper, there is described the proposed measurement method for the frequency analysis of the drive. In the next part, there is briefly described the used direct torque control method for the traction PMSM drive and several experimental results verifying the proper function of the system are presented. In the last part, measured frequency characteristics of the traction PMSM drive controlled by the direct torque control are introduced and in detail analyzed.

The configuration of the measurement system including the power circuit (so called injected current generator) is shown in Figure 1. The voltage at the current generator capacitor is controlled to the value corresponding to $2\times V_c$, where V_c is the dc-link voltage of the measured drive. The power circuit works as a boost (step-up) converter in the voltage charger mode or as step-down converter in the injected current generator mode. Because of the three-phase connection, it is possible to use the converter with shifted control which enables to increase the switching frequency of the output signal (lower injected current ripple).

A. *The new measurement method principle*

The measuring principle is as follows: The current generated by the injected current generator is injected in the main dc-link circuit composed of an LC filter. The injected current is injected with known frequencies which are slowly changed in time and the excited current is then measured for all frequencies.

Measurement is performed in three steps:

1) The calibration data for the Rogowski coil, which is used for the further excited current $i_{excited}$ measurement, have to be found. The injected current $i_{injected}$ is in the first step measured by both the Rogowski coil and the current sensor at the same time and from those data the frequency spectrum using FFT is determined. The magnitudes and phase shift between both signals are used to calibrate the

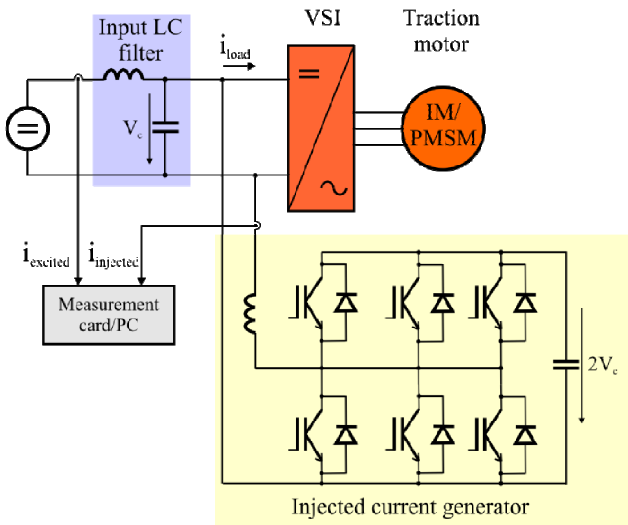

Figure 1. Proposed method for the ac traction drives frequency characteristic measurement: Configuration of both power circuit and measurement chain.

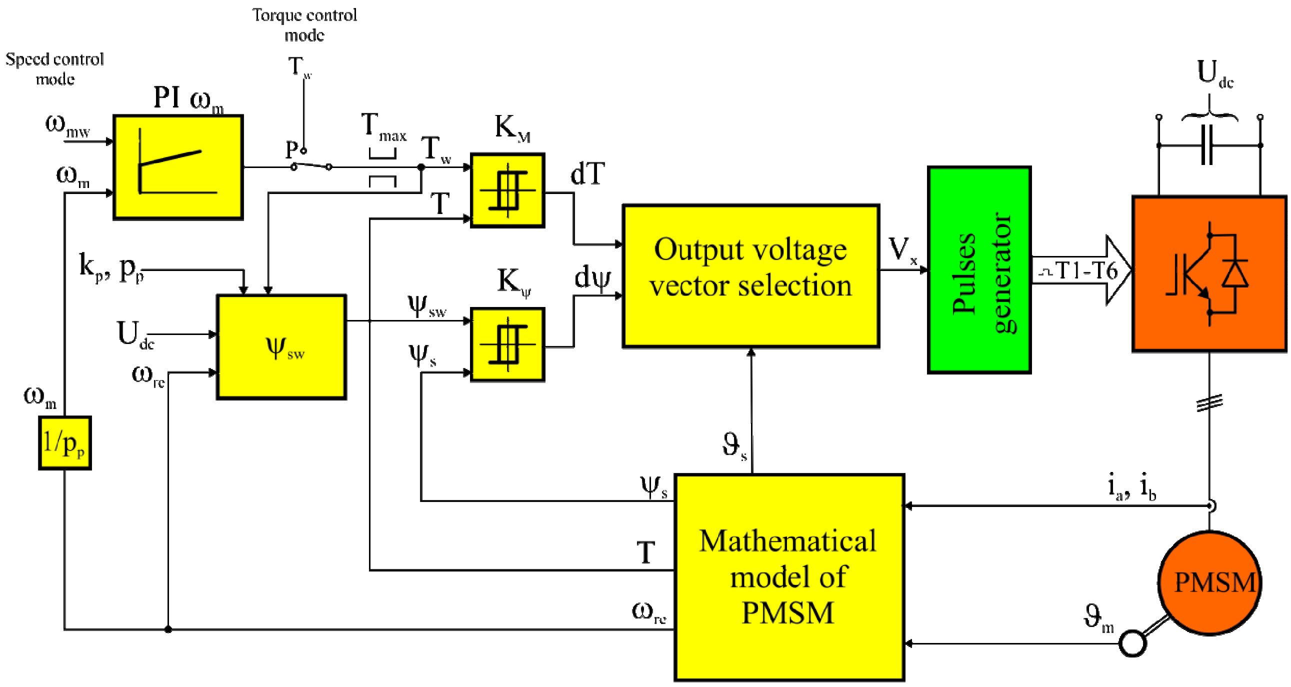

Figure 2. Designed control system for the PMSM drive controlled by DTC.

Rogowski coil which is used for further measurement of the ac component of the excited current in the dc-link circuit.

2) In the second step, the frequency characteristic of the alone LC filter is measured; the traction drive is no-loaded or in stand-by mode ($i_{load} = 0$). The frequency of the injected current $f_{injected}$ is changed in suitable range with given step $\Delta f_{injected}$ (the frequency range and the step of measurement depends on the assumed LC filter resonant frequency and the duration of the measurement). The first measurement could be performed e.g. in the range from $f_{injected}$ = 100 Hz to zero to find the resonant frequency of the circuit and to verify that the magnitude of the injected current does not cause dangerous voltage oscillations (see next paragraph) and thereafter; the behaviour of the circuit can be observed in a narrower frequency range for more detailed analysis.

3) In the last step, the measurement is completed for a predefined set of stator frequencies of the controlled traction drive. The stator frequency is changed from zero to the given maximum stator frequency with given step and selected range of the injected current frequencies.

The measurement loop consists of the next points:

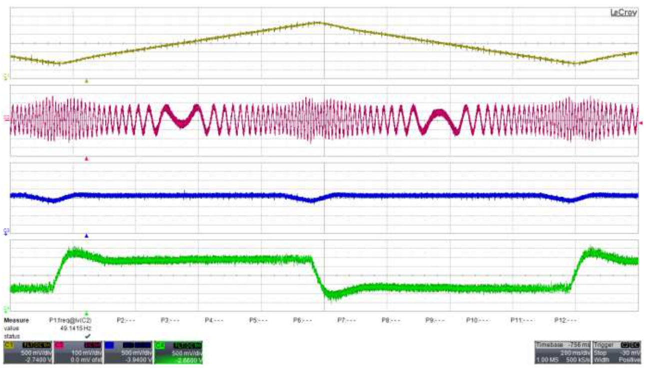

Figure 3. Speed control mode, speed reversal, triangular speed profile, f_{remax}= 100 Hz. Ch1: rotor speed (40 Hz/div), ch2: motor phase current (10 A/div), ch3: stator flux magnitude (0,027 Wb/div), ch4: torque (5 Nm/div).

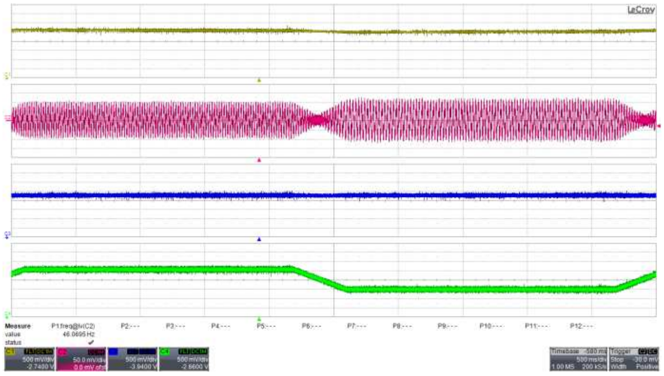

Figure 4. Torque control mode, slow change of commanded torque from +5 Nm to -5 Nm (traction/break mode): V_{dc} = 200V, f_{re} = 50 Hz. Ch1: rotor speed (40 Hz/div), ch2: motor phase current (5 A/div), ch3: stator flux magnitude (0,027 Wb/div), ch4: torque (5 Nm/div).

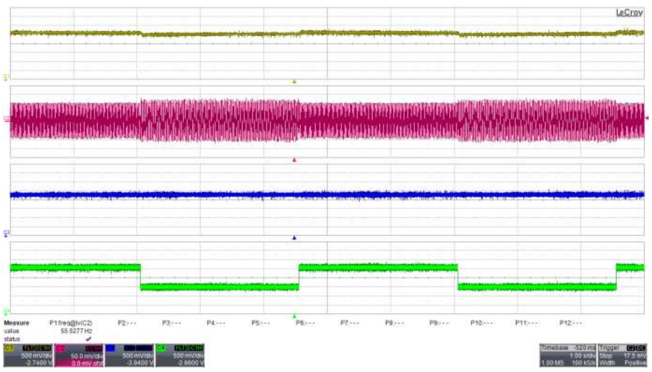

Figure 5. Torque control mode, step changes of commanded torque from +5 Nm to -5 Nm (traction/break mode): V_{dc}= 200 V, f_{re}=50 Hz. Ch1: rotor speed (40 Hz/div), ch2: motor phase current (5 A/div), ch3: stator flux magnitude (0,027 Wb/div), ch4: torque (5 Nm/div).

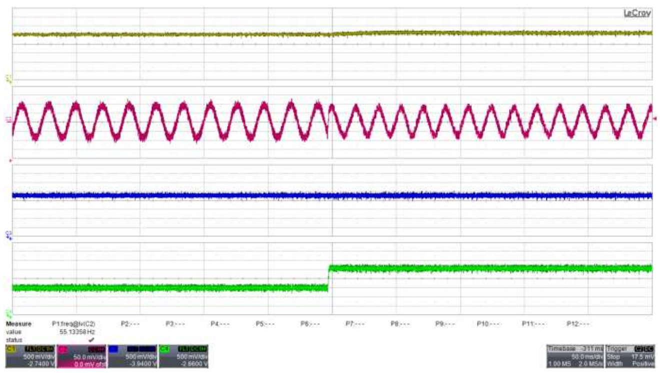

Figure 6. Torque control mode, step change of commanded torque from -5 Nm to 5 Nm in detail: V_{dc} = 200V, f_{re} = 50 Hz. Ch1: rotor speed (40 Hz/div), ch2: motor phase current (5 A/div), ch3: stator flux magnitude (0,027 Wb/div), ch4: torque (5 Nm/div).

(i) to set the demanded stator frequency and keep it constant e.g. with using an appropriate load,

(ii) to set the $f_{injected}$ and slow decrease in the defined range by a defined step. The speed of $f_{injected}$ changing depends on the demanded FFT time window,

(iii) to measure the excited current and perform the FFT on this current,

(iv) back to point (i).

An important task is to get the demanded magnitude of the injected current. It is obvious that if the injected current magnitude is very high, there could appear a dangerous voltage oscillation in the dc-link and on the other hand, if the current magnitude is very low, it is very hard to measure the excited current. Therefore, the magnitude of the injected current must be chosen as a compromise between a high value which causes dangerous oscillations and a low value which is the last possible to measure (sufficient ratio signal/noise). The magnitude has to be determined empirically by a set of performed experiments.

II. TRACTION PMSM DRIVE WITH THE DIRECT TORQUE CONTROL

One of tested traction drive configurations for frequency analysis we have performed has been a traction drive with PMSM controlled by a direct torque control method. The configuration of the drive is shown in Fig 2. The control enables to control the drive in so called speed control mode or in the torque control mode. The modes can be changed by the switch P. In the speed control mode, the demanded speed and measured (calculated) speed are led to the speed PI controller $PI\omega_m$. The output of the controller is the demanded torque T_w and it is led to the torque comparator where it is compared with the calculated torque of the controlled machine. The torque and stator flux feedbacks are calculated by the block "Mathematical model of PMSM" which can be written as follows:

$$\begin{gathered} \psi_{sd} = \psi_{PM} + L_{sd} . i_{sd} , \\ \psi_{sq} = L_{s} . i_{sq} , \end{gathered} \tag{1}$$

where Ψ_{sd} and Ψ_{sq} are stator flux components in the electrical rotor speed rotation reference frame, Ψ_{PM} is permanent magnet flux, L_{sd} and L_{sq} are stator inductances in axes d, q (for surface mounted PMSM $L_{sd} = L_{sq}$). i_{sd} and i_{sq} are components of stator current vector in rotating reference frame. Further, the stator flux position ϑ_s can be calculated from (2):

$$\vartheta_s = \vartheta_{re} + \text{atan}\frac{\psi_{sd}}{\psi_{sq}}, \quad (2)$$

where ϑ_{re} is the rotor flux position (in this case measured by an absolute position encoder) and it is used for the rotor speed ω_{re} calculation as well. In dependence on the output of the comparators and on the stator flux position ϑ_s the optimum output voltage vector V_x is selected and it is used as the control demand for the voltage source inverter. If the torque control mode is enabled the speed PI controller is not applied in the control system of the drive. The torque control mode has been used for the frequency characteristic measurement and the PMSM has been loaded by the induction motor drive emulating a high moment of inertia of a traction drive. Detailed description of the DTC algorithm can be found e.g. in [8].

III. Developed PMSM Traction Drive with DTC: Experimental Tests

Next figures show behaviour of the PMSM drive with the designed DTC algorithm under different transient and steady- state conditions. The control algorithms have been implemented in fixed-point format in the digital signal processor TMS320F2812, the dc-link voltage has been set to $V_c = 200$ V.

Figure 3 shows the behaviour of the drive in the speed control mode under speed reversal, where the maximum rotor frequency has been set to f_{remax} = 100 Hz for both rotation directions. Figure 4 presents behaviour of the drive in the torque control mode where the demanded torque changes from the traction force mode to the break mode and vice versa are relatively slow. Figure 5 shows the drive behaviour under the step change of the demanded torque. This figure shows high dynamic response of the designed drive. Figure 6 shows the transition from break mode to the traction force mode in detail.

IV. Analysis of Frequency Characteristics of the Investigated Traction Drives

Figures 10 and 11 show dependence of the ratio $\Delta I_{excited}/\Delta I_{injected}$ on the stator frequency of the drive and on the injected current frequency, where $\Delta I_{excited}$ and $\Delta I_{injected}$ are the current alternate components peak to peak values of $i_{excited}$ and $i_{injected}$ respectively. The ratio represents quality of resonance in the LC filter circuit. There can be seen dangerous states of combination of stator frequencies with the resonant frequency of the LC filter from the graphs and its moving in the area of stator frequencies.

A. *Uncompensated torque control of the PMSM drive with DTC*

Figure 10 shows the frequency characteristic and the phase characteristic of the drive with PMSM controlled by direct torque control algorithm described in the previous paragraph. For the measurement the PMSM drive with rated power of 10 kW has been controlled in the torque control mode with the demanded torque $T_w = 10$ Nm. The dc-link voltage has been set to 200 V. The load has been created using an induction motor drive with the closed loop scalar control. The stator frequency of the tested drive has been controlled and changed with step of 3.3 Hz every 5.5 minutes. The rotor speed of the tested PMSM drive has been controlled by a loading induction motor drive. In each of those intervals, there has been set the injected current frequency $f_{injected}$ from 15 Hz up to 39 Hz with step 0.5 Hz and 5 seconds time window. In the time windows, frequency $f_{injected}$ has been halted constant for the FFT analysis of the measured currents.

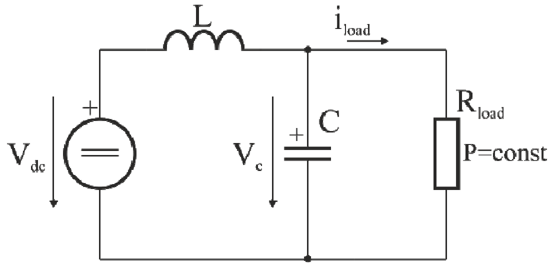

Figure 7. The LC filter for detailed analysis of the compensation method.

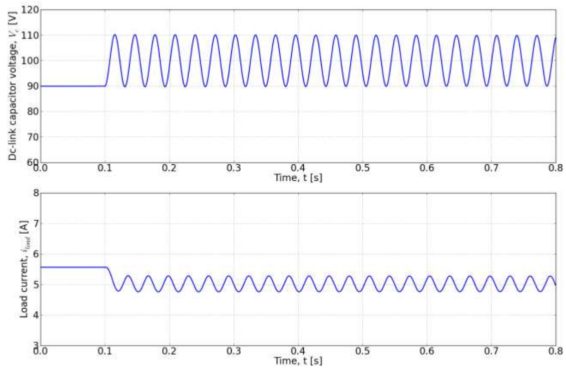

Figure 8. Behaviour of the LC filter with uncompensated current demand and constant taken power.

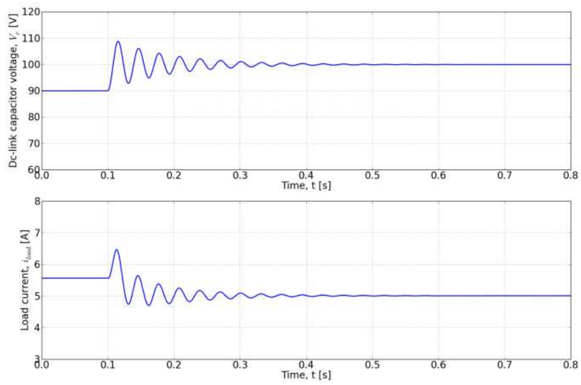

Figure. 9. Behaviour of the LC filter with corrected current demand and constant taken power.

It can be seen from Figure 10 that with increasing stator frequencies the effect of the resonance raises (ratio $\Delta I_{excited}/\Delta I_{injected}$ raises with the stator frequency). This phenomenon can be evaluated as a positive feedback and it could lead to uncontrolled voltage oscillations at the input of the inverter and that phenomenon must be suppressed.

B. Compensated torque control of the PMSM drive with DTC

As has been shown in the previous paragraph, uncompensated torque control of the drive can lead to dangerous voltage oscillations and instability of the dc-link LC filter and hence of the whole drive. Therefore, we proposed a compensated torque control for the PMSM traction drive with the DTC which should mitigate the LC filter oscillations. This proposal involves adjustment of the demanded torque in dependence on the dc-link capacitor voltage (3):

$$T_{w_{corr}} = T_w \cdot \left(\frac{V_{cf1}}{V_{cf2}}\right)^2 \quad , \qquad (3)$$

where T_{w_corr} is the corrected demanded torque, T_w is the original demanded torque without any corrections (the demand from the control system in Figure 3), V_{cf1} and V_{cf2} are filtered dc-link voltages, whereas V_{cf1} is filtered by a filter with much shorter time constant than the filter of V_{cf2}. This correction causes that the torque demand is raised with the square of the ratio of the filtered voltages and the power taken from the capacitor is higher if voltage V_{cf1} is higher than V_{cf2} (that means the voltage increases). That causes decreasing of the capacitor voltage – its stabilization (negative feedback). The stabilization effect can be seen from the measured magnitude characteristics, ratio $\Delta I_{excited}/\Delta I_{injected}$ decreases with the stator frequency of the PMSM drive, as can be seen in Figure 11.

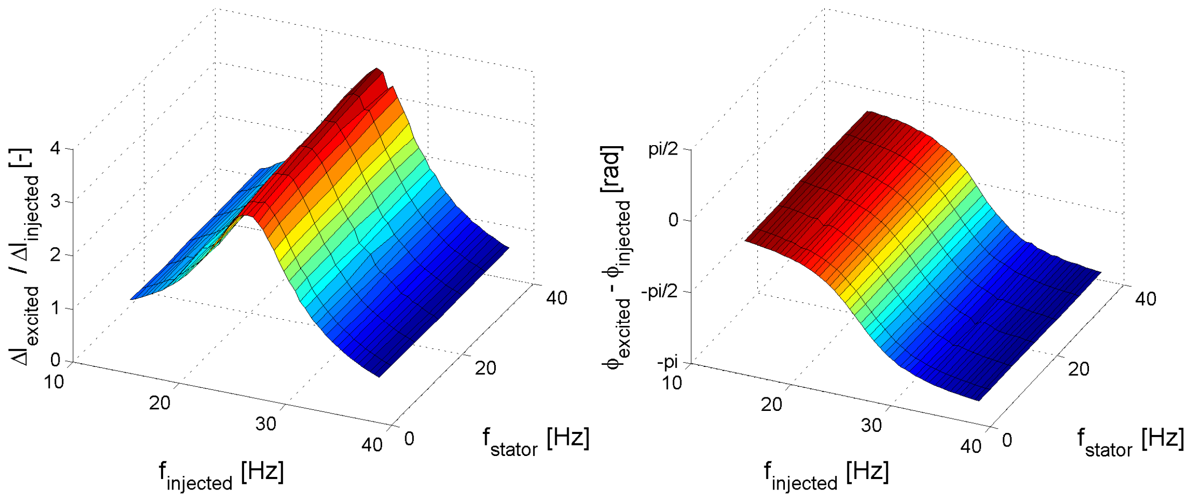

Figure 10. Magnitude and phase characteristics of the PMSM drive controlled by uncompensated DTC: T_w = 10 Nm, V_c = 200 V, f_{stator} = 0 –70 Hz, $f_{injected}$ = 15–39 Hz, ΔT = 1.2 Nm, Δψ = 0.009 Wb.

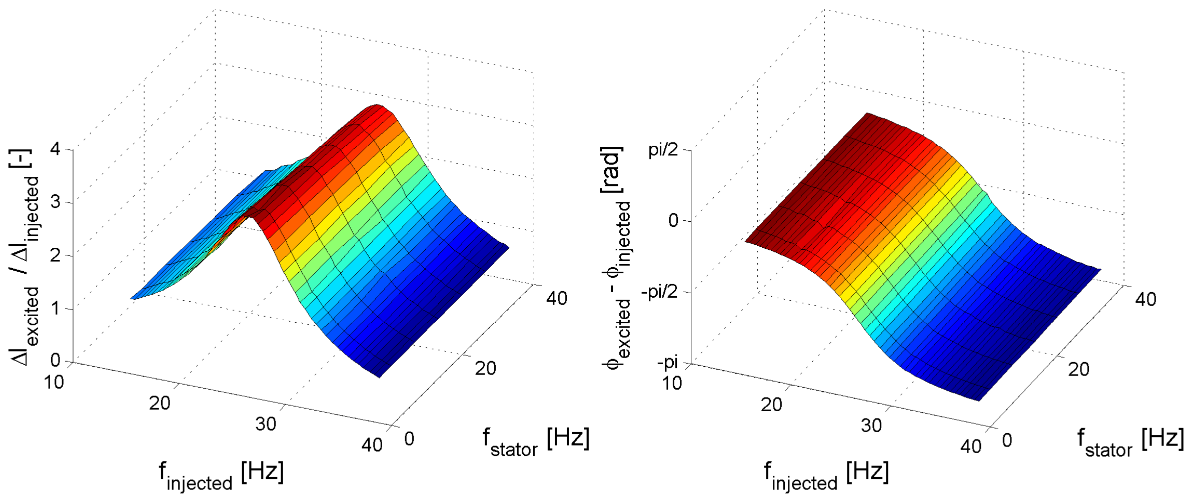

Figure 11. Magnitude and phase characteristics of the PMSM drive controlled by compensated DTC: T_w = 10 Nm, V_c = 200 V, f_{stator} = 0 –70 Hz, $f_{injected}$ = 15- 39 Hz, ΔT = 1.2 Nm, Δψ = 0.009 Wb.

For detailed explanation of this proposed compensation method it can be used the system in Figure 7 which is composed of the LC filter and a load taking constant power. Figure 8 presents idealized behaviour of the dc-link circuit in an uncompensated system with the taken constant power of 500 W. The torque demand is substituted by a demand of the load current i_{load} in this idealized example. In time of 0.1 s, voltage V_{dc} changes from 90 V to 100 V which causes oscillations of the voltage V_c. These oscillations are transferred to the load current i_{load} and are not dumped (or weakly dumped depending e.g. on the resistance of the filter inductance). Figure 9 shows behaviour of the system with the corrected current demand analogically to the corrected torque control (3). It can be seen that the oscillation of the capacitor voltage V_c are dumped well.

V. CONCLUSIONS

There has been introduced a new method for measurement of frequency characteristics of ac traction drives in this paper. The knowledge of the drive frequency characteristic which is linked with danger oscillations of the input trolley-wire LC filter is a key factor for a proper design of the traction drive control. The described method consists of harmonic current injection to the traction drive dc-link circuit which includes an input trolley-wire LC filter. The response of the drive to the injected current in the form of the excited current which is an ac component of the trolley-wire current is then measured and the current spectrum is analyzed by the Fast Fourier Transform. Resonant frequencies of the traction drive can be found by this method.

Based on the known resonant frequencies it is possible to adjust the traction drive control algorithm which can actively damp dangerous oscillations at exactly given frequencies.

The presented method of measurement of the traction drive frequency characteristics has been verified by simulations and laboratory prototype of the traction PMSM drive with the rated power of 10 kW controlled by a DTC algorithm.

It has been discovered that the developed PMSM drive with the DTC begins to be instable with increasing stator frequencies; therefore the compensation for the demanded torque has been proposed. Thereafter, the traction drive is stable and the danger of resonance of the dc-link LC filter decreases using our modification of DTC, as can be seen from the measurement results.

ACKNOWLEDGMENT

This research has been funded by Regional Innovation Centre of Electrical Engineering under project CZ.1.05/2.1.00/ 03.0094 and by Czech Science Foundation under project GA ČR P102/11/0437.

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