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OUTPUT CURRENTS OF VSI WITH ECONOMIC DC LINK SUPPLYING INDUCTION MOTOR

This paper deals with spectral analysis of currents of asynchronous motor fed from voltage source inverter with very small capacity in the DC link. It allows the estimation of the torque and speed quality in smart drives using VSI with such economic DC link.
***Keywords**: induction motor, voltage source inverter, current harmonics, economic DC link*

Introduction

Among many other technical solutions of the AC drives with speed control especially often is chosen the solution consisting of voltage source inverter and squirrel-cage asynchronous motor. The electrolytic capacitor in the DC link of such frequency converter has relative great capacity and volume (C > k · 1000 μF). The electrolytic capacitor limits moreover the working life of the whole inverter. Therefore the inverters in so called “smart drives” operate often with extremely small smoothing capacities in the DC link in order to reduce dimensions and weight of these components. The result is an “economic DC link” using small and faster non-electrolytic capacitors (Fig. 1).

The paper deals with the spectral analysis of the motor currents in the above mentioned AC drive supplied from frequency converter with economic DC link. It is obvious that stronger DC link voltage deformation causes additional motor current harmonics which has also influence on torque and speed of the whole smart drive.

Mathematical model

The rough structure of the typical electronic part of investigated smart drive is shown below. The output voltages are formed by a VSI with sinusoidal pulse-width modulation supplied from economic DC link (Fig. 1).

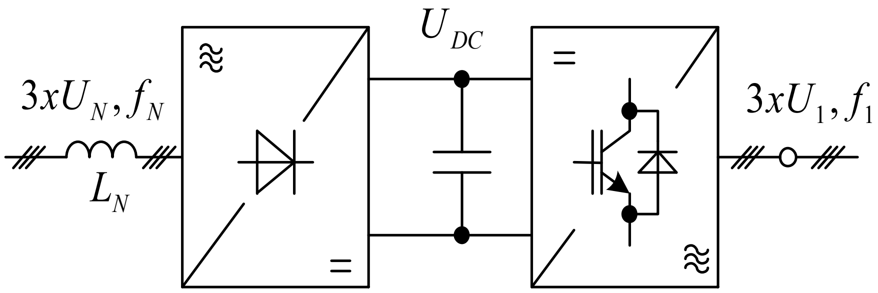

Fig.1. Block diagram of frequency converter with economic DC link

Because of very small smoothing capacity between the net side diode rectifier and the inverter there occur pulsations of the DC link voltage. The modelling using Matlab Simulink showed that for analysis of the DC voltage curve the influence of such small capacitance can be to a first approximation neglected. We assume therefore conditions without any smoothing in the DC link, ideal electronic switches and linear impedances of the fed induction machine.

The output voltage $u_{DC}(t)$ of the 3 phase rectifier bridge without any smoothing in the DC link (Fig. 2) can be expanded in a Fourier series

$$u_{DC}(t) = \hat{U}_0 / 2 + \sum_{k=1}^{\infty} \hat{U}_k \cos(k\Omega t) \qquad (1)$$

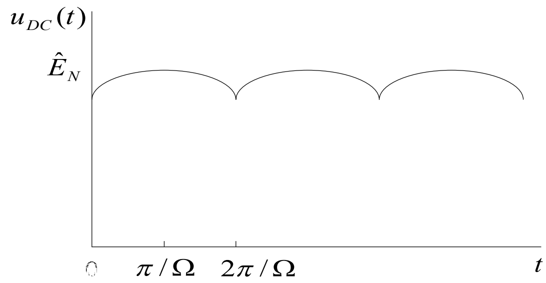

Fig. 2. The output voltage of a three phase diode rectifier without smoothing
(ÊN – amplitude of the phase-to-phase net voltages)

with cosine series components (even function) and Ω as an angular frequency of the voltage $u_{DC}(t)$. The harmonic amplitudes of the DC link voltage are:

$$\hat{U}_0 = \frac{\Omega}{\pi}\int_0^{2\pi/\Omega} u(t)dt,$$

$$\hat{U}_k = \frac{\Omega}{\pi}\int_0^{2\pi/\Omega} u(t)\cos(k\Omega t)dt = \frac{(-1)^{k+1}\hat{E}_N}{\pi}\cdot\frac{6}{(6k)^2-1}. \quad (2)$$

This fast converging Fourier series allows considerations reduced to two dominating harmonic components of the DC link voltage. In related quantities we obtain for the pulsating DC voltage:

$$\gamma(t) = \frac{U_{DC}(t)}{\hat{E}_N} \approx \gamma_0 + \gamma_1\cos[\Omega t], \quad (3)$$

with: $\gamma_0 = \hat{U}_0/(2\hat{E}_N)$, $\gamma_1 = \hat{U}_1/\hat{E}_N$.

Harmonic analysis of output currents of VSI with economic DC link

For the calculation of the output currents of the VSI with economic DC link which feeds an induction motor we use the typical equivalent circuit of an asynchronous motor (Fig. 3).

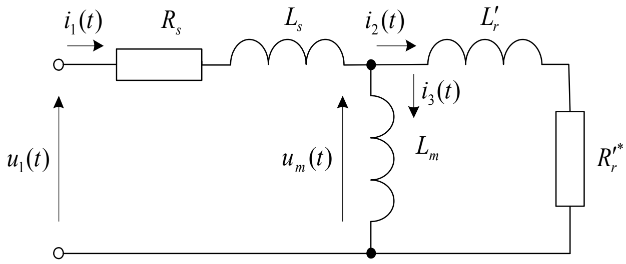

Fig.3. Equivalent circuit of one phase of induction motor

The equations for each phase taking under consideration the pulsations of the DC voltage are:

$$\hat{U}_1\gamma(t)\cos(\omega_1 t) = L_s\frac{di_1(t)}{dt} + R_s i_1(t) + u_m(t),$$

$$u_m(t) = L_m\frac{di_3(t)}{dt}, \qquad u_m(t) = L'_r\frac{di_2(t)}{dt} + R'^*_r i_2(t), \quad (4)$$

$$i_1(t) = i_2(t) + i_3(t)$$

where L_s, L'_r – stator and rotor leakage inductances; R_s, R'_r – stator and rotor resistances; L_m – a main inductance; $\hat{U}_1$ – an amplitude of an inverter output voltage; $\omega_1 = 2\pi/T_1$;
T_1 – period of the inverter output voltage;
$\gamma(t)$ – a modulating function as defined in (3).

Considering the equations (2) and (3) the first term in (4) can be transformed in

$$\hat{U}_1\gamma(t)\cos(\omega_1 t) = \hat{U}_1\gamma_0\cos(\omega_1 t) + \hat{U}_1\gamma_1\cos(\omega_1 t)\cos(\Omega t) \quad (5)$$

where: $\Omega = 6\omega_{1N}$ = const.

The phases of the motor are symmetrical, so it is sufficient to find a current in one phase. The second term in (5) can be expanded for the first phase as follows

$$\hat{U}_1\gamma_1\cos(\omega_1 t)\cos(\Omega t) = \hat{U}_1\gamma_1\cos(\Omega-\omega_1)t/2 + \hat{U}_1\gamma_1\cos(\Omega+\omega_1)t/2\,. \quad (6)$$

Taking into account the solutions for all three voltage terms according to (5) and (6) we obtain the motor current

$$i_1(t) = U_1\gamma_0\cos(\omega_1 t - \chi_{\omega 1})/Z_{\omega 1} + U_1\gamma_1\cos((\Omega-\omega_1)t - \chi_{6-})/(2Z_{6-}) + U_1\gamma_1\cos((\Omega+\omega_1)t - \chi_{6+})/(2Z_{6+}) \quad (7)$$

where: $Z_{\omega 1}, \chi_{\omega 1}$; Z_{6-}, χ_{6-}; Z_{6+}, χ_{6+} are motor impedances for the above mentioned voltage terms and phase shifts of the three current components.

Calculation results for no-load operation of smart drive

The calculations of the steady-state current harmonics have been carried out for the induction motor with P_N = 1,1 kW, U_N = 400 V, I_N = 2,6 A, p = 2, f_N = 50 Hz, n_N = 1405 1/min. and the equivalent circuit parameters: $R_1 = 8\Omega$, $R'_r = 5{,}6\Omega$, $L_s = L'_r = 24\,mH$, $L'_r = 24\,mH$, $L_m = 417\,mH$ supplied in a smart drive with almost negligible DC link capacitance (8 µF / 700 V power film capacitor of Motec 8200 - Fig. 4). For the supplying net (3x400 V, 50 Hz) and three phase diode rectifier we obtain for the DC-link voltage (Fig. 2, (1)–(3)): $\hat{U}_N = 325V$, $\gamma_0 = 0{,}955$, $\gamma_1 = 0{,}055$, $\hat{E}_N = 564V$

Fig. 4. Smart Drives consisting of asynchronous motors and frequency converters with economic DC links: Motec 8200, Lenze Company/ Germany (left) and Grundfoss / Danmark (right)

For the calculations we assume no-load operation of the analysed drive. It leads to working conditions with the highest percentage of the higher current harmonics in relation to the wished first harmonic of the motor current. For clearer equations we use the related frequency value of the first voltage harmonic defined as:

$$\alpha = \frac{f_1}{f_{1N}}. \quad (8)$$

The rotor resistance R'^{*}_r in equivalent circuit of the induction motor (Fig. 3) and therefore the whole impedances in the equation (7) differ strong. The resistance value for the main harmonic ($\omega_1 = 2\pi\cdot f_1$) and its values for the upper harmonics ($\Omega \pm \omega_1 = 6\omega_{1N} \pm \omega_1$, i.e. with related frequency value $6 \pm \alpha$) are:

$$R_{r\alpha}^{'*} = R_r^{'} \frac{\alpha}{\alpha - \alpha_{mech.}}, \qquad R_{r(6\pm\alpha)}^{'*} = R_r^{'} \frac{6 \pm \alpha}{6 \pm \alpha - \alpha_{mech.}} \tag{9}$$

with: $\alpha_{mech} = n / n_{1N}$ as the related motor speed.

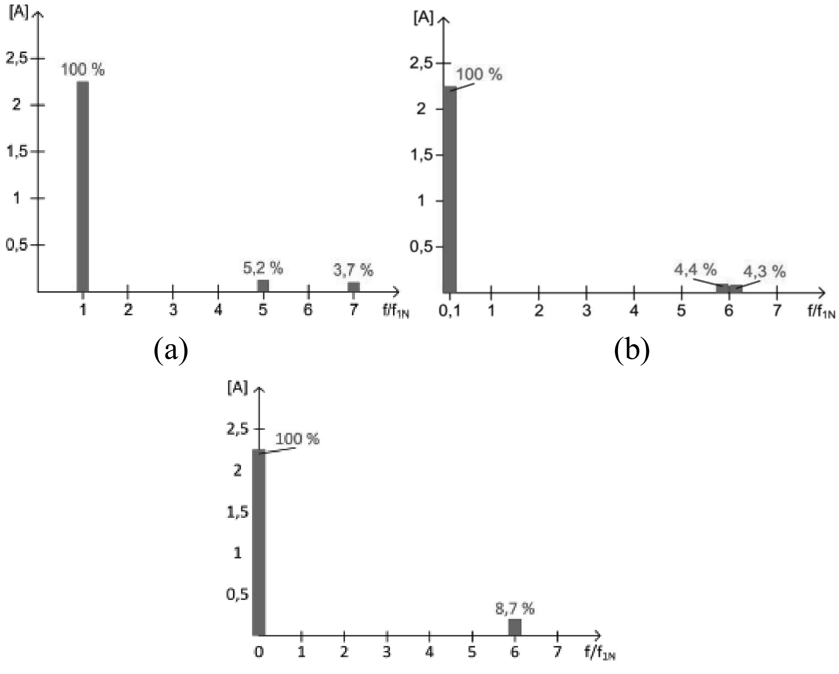

Fig.5. The amplitudes of motor current harmonics for no-load operation and various drive frequencies: f_l = 50 Hz (a), f_l = 5 Hz (b), f_l = 0 Hz (c)

The amplitudes of the three main motor current harmonics for no-load operation (related values in percent of the no-load current by nominal drive frequency) were calculated for the investigated motor on the basis of the described mathematical model. The results for the exemplary frequencies are shown in the Fig. 5.

Conclusions

The analysis of the current harmonics of an induction motor fed from VSI with economic DC link shows, that the currents of the two main upper harmonics reach in the critical no-load operation only ~ 4 % of the first motor harmonic. For operations with higher load this percentage will be even lower. The upper current harmonic with the frequency "$6\omega_{1N} - \omega_1$" increases and the harmonic with the frequency "$6\omega_{1N} + \omega_1$" decreases with the growing of the drive frequency f_l. In the frequency range above nominal frequency the stronger upper harmonic exceeds to ~ 6 % of the first current harmonic. In the case of drive frequency $f_l \approx 0$ both a.m. upper current harmonics unite to one harmonic with frequency 300 Hz and with amplitude of 8,7 % in relation to the first motor harmonic.

The other interesting area is the dynamic of drive system using VSI with economic DC link. The above results should be verified by means of measurements and investigations in the real drive system with economic DC link.

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