Abstract—In this paper, a sensorless induction motor (IM) drive using speed observer system is presented. The system includes load torque computation for gear fault detection. Nonlinear control method is adopted for controlling the motor over a wide speed range. An LC filter for smoothing current and voltage waveforms is used at the output of the voltage inverter. The use of filter imposes more building of the used observer to avoid using additional current and voltage sensors. An analysis of the motor load torque makes it possible to detect existing problems in the load. The developed algorithm was verified by simulation and experiments for a 1.5 kW induction motor drive system.

INTRODUCTION

Currently, most variable speed drives use induction motors. In such systems, advanced control strategies that make it possible to utilize motor capabilities over a wide speed range are frequently used [1]. In more recent motor drive systems, it is common to eliminate the speed sensors. A few references show different methods for speed computation - particularly using adaptive state observers [2], [3].

The widely used PWM voltage source inverters with fast transistors switching frequencies are reasons for existing different unfavorable phenomena, e.g. accelerating the degradation of motor bearing and insulation [4]. Limiting these unwanted effects is possible using passive filters at the inverters output [5]. On the other hand, using LC filters complicate motor control because of creating additional voltage drop and phase shift of voltages and currents at the input and output of the filter [6]. Therefore, it is essential to consider the filter parameters in the observer as well in the whole control system [7]-[11]. It is particularly important in the case of speed sensorless drives [7], [12-13].

Transmitting mechanical torque from the motor to the load is done through a mechanical system with different degrees of complexity. Inaccurate manufacturing, defects in assembling, or even typical characteristics of mechanical components may be the reasons for unwanted vibrations, which may lead to system damage or failure [14]. So the diagnostic of the mechanical system condition is very crucial. The diagnostic methods can be based on vibration measurements or on measured electrical signals and their sophisticated analysis [15]-[23]. For example, by detecting the motor load torque signal it is possible to detect the condition of mechanical system [24]-[26].

In this paper, a voltage source inverter fed motor drive system with control of current, flux, torque and speed with a possibility for fault detection of mechanical part is presented. In this system, the inverter output LC filter for filtering current and voltage is used. The parameters of this filter are taken into account during variables estimation and in the control scheme. Although a filter was added, however it was decided to use only preexisting sensors in the inverter. For mechanical components faults detection, a different load torque observer is used. In this paper, the simulations of the developed theory followed by experiments are presented.

MODEL OF INDUCTION MOTOR

Induction motor model in the stationary $\alpha\beta$ reference frame are given by [26-27].

\[
\frac{d\alpha_s}{dt} = a_1\alpha_s + a_2\psi_r - a_3\psi_r + a_4u_s , \quad (1)
\]

\[
\frac{d\psi_s}{dt} = a_3\alpha_s + a_2\psi_r + j\omega_s\psi_r , \quad (2)
\]

\[
\frac{d\omega_s}{dt} = J_\text{M}^{-1}(u_{m}/L_s) \text{Im} \left(\frac{\psi_r^*}{L_r} - T_L\right) , \quad (3)
\]

\[
i_s = \begin{bmatrix} i_{sa} \\ i_{sb} \end{bmatrix}^T , \quad \psi_s = \begin{bmatrix} \psi_{ra} \\ \psi_{rb} \end{bmatrix}^T , \quad u_s = \begin{bmatrix} u_{sa} \\ u_{sb} \end{bmatrix}^T , \quad (4)
\]

where $u_s$, $i_s$, $\psi_s$ denote the stator voltage, stator current and rotor flux vectors, $T_L$ – motor load torque, $J_M$ – motor inertia and $L_m$, $L_s$, $a_1$...$a_6$ are the motor parameters and coefficients [25].

INVERTER OUTPUT LC FILTER

In the presented system, the inverter output LC filter shown Fig. 1 is used. The aim of the filter is to insure sinusoidal stator current and voltage waveforms illustrated in Fig. 2.

Fig. 1. AC drive with inverter and LC filter
The output voltage ripples in Fig. 2 are electronic noises. The equations of the filter are follows [29]:

\[ \frac{du_c}{d\tau} = \frac{i_c}{C_1}, \quad (5) \]
\[ \frac{di_f}{d\tau} = \left( u_{if} - R_s i_c - u_c \right)/L_1, \quad (6) \]
\[ i_c = i_{if} - i_s, \quad (7) \]
\[ u_s = R_s \left( i_{if} - i_s \right) + u_c, \quad (8) \]

where: \( u_{if}, i_{if}, u_c, i_c \) are the filter input and output voltages and currents, respectively.

Selection of the LC parameters including the resonance and switching frequencies consideration were presented in [6].

**CONTROL SYSTEM**

The control system consists of two parts. The main part is used for controlling the motor state variables whereas the secondary (additional) part is used for LC filter control as shown in Fig. 3.

For the motor control, the multi-scalar model-based method (MMB) was used [27]. In MMB, the natural motor variables are controlled:

\[ x_{11} = \omega_s \]
\[ x_{12} = \psi_{r1} i_{r1} - \psi_{r\beta} i_{r\beta} \]
\[ x_{21} = \psi_{r1}^2 + \psi_{r\beta}^2 \]
\[ x_{22} = \psi_{r1} i_{r1} + \psi_{r\beta} i_{r\beta} \]

In MMB, the motor nonlinearities are compensated by,

\[ u_1 = w_q x_{11} \]
\[ u_2 = w_q \left( -x_{11} x_{22} + a_3 x_{21} + m_1 \right)/L_r \]

where \( m_1, m_2 \) are the MMB internal control signals, \( w_q \) is motor parameters dependent [25], and \( u_1, u_2 \) are the auxiliary variables used for evaluating the motor commanded voltage \( u_s^{com} \):

\[ u_s^{com} = \frac{\psi_{r1} u_2 - \psi_{r\beta} u_1}{\psi_r^2}, \quad (15) \]
\[ u_s^{com} = \frac{\psi_{r1} u_1 - \psi_{r\beta} u_2}{\psi_r^2}. \quad (16) \]

With (9)-(16) the induction motor model is decoupled and converted into two separate linear subsystems: mechanical and electromagnetic. Details are in [27]-[29].

For subordinated LC filter control a multi-loop feedback controller with disturbance compensation was used [10], [11]. The filter state variables are controlled in the rotating \( dq \) reference frame aligned with the position of \( u_s \) vector. Further details on the solution could be found in [29].
SPEED OBSERVER

For controlling of motor natural variables (9)-(12) the calculation of speed, and flux should be done correctly. For this purpose, the speed observer from [28] was implemented in the presented drive system. In contrary to [28], the closed-loop components of the observer were modified to improve the observer performance. Additionally, the component related to the motor speed derivative was omitted assuming that for enough small step of observer calculation this component is close to zero.

To assure proper operation of observer including the LC filter, the initial observer equations from [28] were extended to include the model of the filter given by (5)-(8). These are given by,

$$\begin{align*}
\frac{d\hat{x}_1}{dt} &= a_1\hat{i}_s + a_2\hat{\psi}_r - ja_3\hat{\psi}_s + a_4\hat{u}_s + k_i(\hat{i}_s - i_s) \\
\frac{d\hat{\psi}_r}{dt} &= a_5\hat{x}_1 + a_6\hat{\psi}_r + j\omega_0\hat{x}_1 + j\omega_0\hat{\psi}_s + jk_2\hat{\psi}_s \cdot (\hat{i}_s - i_s) \\
\frac{d\hat{\psi}_s}{dt} &= a_7\hat{x}_1 + a_8\hat{\psi}_r + a_9\hat{\psi}_s + \omega_0\hat{\psi}_s + jk_2\hat{\psi}_r \\
\frac{dS_{of}}{dt} &= k_{\psi}(S_h-S_{of}) \\
\frac{d\hat{a}_x}{dt} &= (\hat{i}_s-i_s)/C_i \\
\frac{d\hat{i}_d}{dt} &= (\hat{u}_d^{com} - \hat{u}_d)L_d + (\hat{\psi}_r^{com} - \hat{\psi}_r^i) + k_\psi\hat{\psi}_r \cdot (\hat{i}_s - i_s) \\
\hat{a}_x &= \hat{x}_1 + (\hat{i}_s-i_s)R_i \\
\hat{e}_y &= [k_2S_\psi\hat{\psi}_r + k_\psi\hat{\psi}_r^i + S_h-S_{of}] \\
\hat{\xi} &= \omega_0\hat{\psi}_r
\end{align*}$$

where: $\xi$ is the motor electromotive force (EMF), $i_s$, $\psi_r$, $\psi_s$, $k_i$, $k_\psi$, $S_h$, $S_{of}$ are the observer gains, $S_h$ is the observer internal stabilizing component, $S_{of}$ is $S_h$ is the filtered value and $k_\psi$ is the inverse of $S_h$ - filter time constant.

The motor speed is estimated as follows:

$$\hat{\omega}_r = \frac{(\hat{\xi}_{\psi r} + \hat{\xi}_{\psi r^i})}{\hat{\xi}_{\psi 21}}$$

Using (17)-(26), the motor and LC filter state variables are estimated simultaneously. Further details on initial observer system theory, tuning and stability were presented without LC filter in [28] and with the filter in [29].

LOAD TORQUE ESTIMATION

Load torque signal is an important variable for proper fault detection of the load. Frequency analysis of this signal lends itself to possibility of detecting natural frequencies related to different fault types of mechanical system. Widely used methods are based on measurements using accelerometers [14], [15], [30], [31]. Measurement based methods are not practical for industrial applications. Therefore, there is a demand for seeking sensorless solutions based on a computation of motor torque using easily measured signals such as current, voltage or speed [17]-[19], [23].

In this solution, the observer used is based on Gopinath’s theory [20], [24]:

$$\begin{align*}
\frac{dz}{dt} &= \begin{bmatrix} 0 & -k_{1z} \\ 1 & -k_{2z} \end{bmatrix} z + \begin{bmatrix} k_{1z}k_{2z}hJ_M \\ k_{2z}^2 - k_{1z} \end{bmatrix} \hat{\theta}_r + \begin{bmatrix} k_{1z} \\ k_{2z} \end{bmatrix} T_e \\
\hat{T}_L &= z_2 - k_2J_M\hat{\omega}_r
\end{align*}$$

where: $z = [z_1 \ z_2]^T$ is the load torque observer internal state variable, $T_e$ is the calculated motor electromagnetic torque, $\hat{T}_L$ is the calculated motor load torque and $k_i$, $k_\psi$ are the observer coefficients.

The motor electromagnetic torque is calculated as follows:

$$T_e = \psi_{ra}\dot{i}_d - \psi_{rd}\dot{i}_s$$

In (27)-(28), the motor speed calculated by (26) is used.

The solution presented in this paper was implemented in earlier work for high speed trains’ traction drives without LC filters [25].

SIMULATION INVESTIGATIONS

Example of simulations results for a speed sensorless ac drive with inverter and LC filter are shown in Fig. 4.

Fig. 4 presents the motor response to speed command change including reversing and response to load torque variation. The whole system operation is stable and controllable. The motor flux presented as its square value $\hat{x}_{21}$ is kept constant except the small oscillations in transients. Such oscillations appear if saturation is reached on the speed controller output. It is noticeable that $\hat{x}_{12}$ variable which is proportional to the motor electromagnetic torque is limited during transients. This may be achieved by keeping the motor current within its safe value, $I_{max}$ based on,

$$x_{12\lim} = \sqrt{I_{max}^2 - x_{21}^2}$$

where $x_{12\lim}$ is the output speed controller variable limit shown in Fig. 5. Condition (27) is indispensable in the control principle because the motor stator current variable does not exist directly in the MMB control system.

Fig. 5. Speed controller variable limitation performed to limit the motor current.

An example of the load torque observer calculations is presented in Fig. 6.

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In Fig. 6, the motor load torque step change was applied, while the motor commanded speed was kept constant. The estimated load torque $\hat{T}_L$ is very close to the real torque $T_L$. The highest error is up to 5% in transients when large load torque was applied. The nominal motor torque is equal to 0.65 pu.

**EXPERIMENTAL RESULTS**

The presented drive system was tested experimentally. Experimental setup consists of a test bench with 1.5 kW induction motor coupled with dc machine as a load. Induction motor is fed by voltage source inverter with IGBT. A dc generator supplied by a chopper represents a variable load. An LC circuit was used at the inverter output for filtering purposes and ensuring that the THD is lower than 5%. Additionally, two common mode current chokes were used for limiting the motor common mode current. In the experimental setup mechanical speed sensor, voltage sensor in the inverter DC bus, two current sensors at the inverter output, and two current sensors at the filter output were used. The speed sensor and filter output voltage and current sensors have not been used for control but only for monitoring and comparison purposes. The experimental setup is shown in Fig. 7, while the system data are given in Table I.

An example of the experimental results for the speed reversal in sensorless control is presented in Fig. 8. Two speed signals, estimated and measured, are shown for comparison purposes. Only the estimated speed value was used in the control process. The speed observer uses only the voltage measured in the DC bus and the current measured at the input of LC filter. The whole system works correctly. The reverse is slower than in simulation because the maximal motor torque is limited to protect mechanical coupling. Interesting paper. More results of the sensorless system were presented in [13].

In the test bench the mechanical vibrations are generated in two ways:
- Two machines were fixed with artificial angular misalignment by installing metal washers under the feet of loading machine shown in Fig. 9,
- Creating an artificial unbalance in the drive unit by installing a metal weight on the encoder side of the motor shaft as illustrated in Fig. 10 (weight no 1 and 2).

<table>
<thead>
<tr>
<th>TABLE I</th>
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<tbody>
<tr>
<td>TEST BENCH DATA</td>
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<tr>
<td>Asynchronous motor</td>
</tr>
<tr>
<td>Power $P_n$</td>
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<tr>
<td>Voltage $U_n$</td>
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<tr>
<td>Current $I_n$</td>
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<td>Speed $n_e$</td>
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<tr>
<td>Frequency $f$</td>
</tr>
<tr>
<td>Inertia $J$</td>
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<tr>
<td>Stator resistance $R_s$</td>
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<td>Rotor resistance $R_r$</td>
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<td>Stator inductance $L_s$</td>
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<tr>
<td>Rotor inductance $L_r$</td>
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<tr>
<td>Mutual inductance $L_m$</td>
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</table>

| Voltage inverter | |
| Switching frequency | 3.3 kHz |
| Dead time | 4.5 μs (compensated) |
| Pulse width modulation | Space vector |

| LC filter | |
| Inductance $L_1$ | 5.6 mH |
| Resistance $R_1$ | 0.05 Ω |
| Capacitance $C_1$ | 3 µF |
| Resistance $R_C$ | 1 Ω |
| Voltage drop $ΔU$ | 4.8 % |
| Voltage THD | ≤5 % |
| Resonance frequency | 1.2 kHz |

| Control system | |
| Calculation sampling | 150 μs (synchronized with PWM) |
| DSP program calculation time | 80 μs |

Fig. 6. Simulation results of the load torque observer calculation – comparison of the real load torque $T_L$ with estimated torque $\hat{T}_L$.

Fig. 7. Complete test bench - speed sensorless ac drive with voltage source inverter, LC filter and control data acquisition DSP and FPGA system.

Fig. 8. Experimental results of speed sensorless control system during speed and load torque variations.
Fig. 9. Artificial angular misalignment in the drive unit – the metal washers were installed under the generator feet.

The load torque signal computed in the observer was analyzed using Fast Fourier Transformation (FFT). Because of the specific characteristic of realized artificial faults the required bandwidth was limited to lower frequencies up to 125 Hz.

The results obtained are shown in Fig. (11-14). The same scaling in two figures were applied.

Fig. 11 presents the harmonic amplitudes for the healthy drive system. The drive system was free of any fault symptoms over a wide operating range and without any vibrations. The harmonics obtained were taken as the basis for comparison. The changes in amplitudes of particular frequencies were searched for in the faulty systems.

Fig. 12 presents the load torque harmonics amplitudes of the drive with an artificial angular misalignment. Increases in the magnitudes of frequencies related to motor rotational frequencies are evident.

Fig. 13 and 14 present amplitudes of the harmonics for the drive with artificial unbalance. The provided unbalance caused the vibrations of the whole motor-load system. This is evident in the increase of the amplitudes for the verified frequency range. An increase in the metal weight caused further amplitudes increase as shown in Fig. 14.

CONCLUSIONS

The presented induction motor drive with voltage source inverter works properly at different operating points. Although LC filter was used at the inverter output, it is possible to perform speed control over a wide range. The proposed system detects load torque oscillations, which are caused by different defects in the mechanical load of the motor drive. Based on the load torque analysis, it is possible to diagnose the condition of the drive mechanical part.

A corrective action of the drive was possible after including a model of the LC filter in the observer structure and in the control scheme. The proposed idea avoids using
speed sensor and filter output voltage and current sensors. In the proposed solution, the same measurement procedure was used as in the standard voltage source inverter without an LC filter.

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