Electric Motor Drive with Inverter Output Filter

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Abstract - The paper focuses on some aspects of control and estimation in electric drives with inverter output filters. The filters are used in some industrial drives with pulse width modulated (PWM) inverters. They smoothes the motor supply voltage and current so nearly sinusoidal shapes are obtained. The filters can also limit the bearing current and shaft voltages. Because of the voltage drop and phase shift, the motor voltages and currents differ from the inverter output. This fact can seriously complicate the drive operation due to the problems with the control and estimation process – especially in speed sensorless drives. To solve those problems the filter model should be taken into account in the control and estimation algorithms. In this paper a sensorless solution for induction motor (IM) drives is proposed together with inverter output filter. A short description and discussion of the schemes is given. Simulation and experimental results validate the proposed solution.

I. INTRODUCTION

Voltage inverters are widely used in industrial electric drives with IM. Nowadays the inverters are working with high transistors switching frequency according to the PWM principle. This gives a rectangular modulated motor supply voltage, and, due to motor inductance, a nearly sinusoidal current. The high dv/dt of motor supply voltage gives the disadvantageous consequences: high motor insulation stress, bearing current phenomena, decreased motor efficiency, EMC noises, etc. The problems grow if a long inverter-motor cable is used [1-2].

To prevent these problems, numerous methods are proposed [3-5]. The suggestion is to use filters or/and change the inverter structure, e.g. to use multilevel converters [6], and modify the PWM algorithms [7].

A popular industrial solution is to use passive filter with the a combination of inductors and capacitors. The filter is installed close to the inverter (Fig. 1).

To prevent unwanted PWM effects, good results are obtained if a combination of differential and common mode (CM) filters is used [3]. The differential mode filter gives the motor a sinusoidal voltage and current (Fig. 2), whereas the CM filter reduces the common mode current (Fig. 3).

Analysis of the motor model for CM current flow gives information that the CM filter has no influence on motor torque. Motor torque is dependent only on differential mode variables. So it is obvious that a differential mode filter adds an extra voltage drop and phase shift between voltages and currents on the input and output of the filter. This can influence the control and estimation algorithms if they are without any changes compare to the drive without the filter.

The necessity for the control and estimation algorithms modification has been reported in the [8-10]. An extra multi-loop control has been proposed in [8] and [9]. However, the systems presented in [8] and [9] require additional motor current and voltage sensors. That is not practically feasible because the filter is the outer element the additional wiring system is sensitive to noises. It is also uneconomic.

The drive without additional sensors was proposed in [10], where an extended classical field oriented control (FOC) and modified adaptive flux and speed observer were proposed.
Kubota type observer has been extended with additional filter equations. Finally it was possible to on-line estimate all the required motor variables.

The same concept of sensorless control with the filter was assumed in [11]-[14]. In these papers, other control strategy and estimation method were used: nonlinear control and disturbance observer.

This paper continues the work of [11]-[14]. The speed sensorless drive with nonlinear FOC [15] is presented and a new observer based on an improved motor stator model is used. Both control and estimation procedures have taken into account the inverter output filter.

The following sections presents the model as well control and estimation aspects. The operation of the drive without and with the filter is compared. The robustness of the system is tested as well. Both simulation and experimental results are presented.

II. MODEL OF THE INDUCTION MOTOR AND FILTER

A. Filter model

The filter used in the proposed electric drives has a structure similar to that proposed by Akagi in [3] (Fig 4).

Three chokes $L_1$ and three capacitors $C_1$ are parts of the differential filter for $d/q$ components. Resistor $R_c$ is desirable for transients damping. The common mode filter elements are: coupled choke $M_1$, capacitor $C_0$ and resistor $R_o$. Such a circuit is closed by capacitors in the DC link of the inverter. By contrast with the filter from [3], the second CM choke $M_2$ is used to limit the flow of zero component of current in the external circuit relative to the filter and inverter. The detailed electrical circuit is presented in Fig. 5.

It is assumed that both chokes $M_1$, and $M_2$ as well as inductor $L_1$ are ideal elements – resistances and leakage inductances were omitted. The equations of the filter for the ABC frame and related to the $C_{DC}$ terminal have the following form:

\[
\begin{pmatrix}
    u_{fx} \\
    u_{fy} \\
    u_{fz} \\
\end{pmatrix}
= \frac{d}{dt}
\begin{pmatrix}
    M_1 & M_1 & M_1 \\
    M_1 & M_1 & M_1 \\
    M_1 & M_1 & M_1 \\
\end{pmatrix}
\begin{pmatrix}
    i_{fx} \\
    i_{fy} \\
    i_{fz} \\
\end{pmatrix}
+ L_1 \frac{d}{dt} \begin{pmatrix}
    i_{lx} \\
    i_{ly} \\
    i_{lz} \\
\end{pmatrix}
+ \begin{pmatrix}
    M_2 & M_2 & M_2 \\
    M_2 & M_2 & M_2 \\
    M_2 & M_2 & M_2 \\
\end{pmatrix}
\begin{pmatrix}
    i_{su} \\
    i_{sv} \\
    i_{sw} \\
\end{pmatrix}
+ \begin{pmatrix}
    u_{fa} \\
    u_{fb} \\
    u_{fc} \\
\end{pmatrix}
\] (1)

\[
\begin{pmatrix}
    u_{su} \\
    u_{sv} \\
    u_{sw} \\
\end{pmatrix}
= \frac{d}{dt}
\begin{pmatrix}
    M_2 & M_2 & M_2 \\
    M_2 & M_2 & M_2 \\
    M_2 & M_2 & M_2 \\
\end{pmatrix}
\begin{pmatrix}
    i_{su} \\
    i_{sv} \\
    i_{sw} \\
\end{pmatrix}
+ \begin{pmatrix}
    u_{cs} \\
    u_{cs} \\
    u_{cs} \\
\end{pmatrix}
+ \begin{pmatrix}
    i_{cx} \\
    i_{cy} \\
    i_{cz} \\
\end{pmatrix}
+ \begin{pmatrix}
    i_{cy} \\
    i_{cz} \\
    i_{cz} \\
\end{pmatrix}
+ \begin{pmatrix}
    R_c & 0 & 0 \\
    0 & R_c & 0 \\
    0 & 0 & R_c \\
\end{pmatrix}
\begin{pmatrix}
    i_{cx} \\
    i_{cy} \\
    i_{cz} \\
\end{pmatrix}
- \begin{pmatrix}
    M_2 & M_2 & M_2 \\
    M_2 & M_2 & M_2 \\
    M_2 & M_2 & M_2 \\
\end{pmatrix}
\begin{pmatrix}
    i_{su} \\
    i_{sv} \\
    i_{sw} \\
\end{pmatrix}
\] (2)

Filter model (1)-(6) has been transformed to the $a\beta0$ orthogonal frame of reference:

\[
\begin{pmatrix}
    u_{d0} \\
    u_{a0} \\
    u_{b0} \\
\end{pmatrix}
= \frac{d}{dt}
\begin{pmatrix}
    3M_1 & I_{10} & I_{10} \\
    0 & I_{10} & I_{10} \\
    0 & 0 & I_{10} \\
\end{pmatrix}
\begin{pmatrix}
    i_{d0} \\
    i_{d0} \\
    i_{d0} \\
\end{pmatrix}
+ \begin{pmatrix}
    M_2 & M_2 & M_2 \\
    M_2 & M_2 & M_2 \\
    M_2 & M_2 & M_2 \\
\end{pmatrix}
\begin{pmatrix}
    i_{a0} \\
    i_{a0} \\
    i_{a0} \\
\end{pmatrix}
+ \begin{pmatrix}
    3M_1 & I_{10} & I_{10} \\
    0 & I_{10} & I_{10} \\
    0 & 0 & I_{10} \\
\end{pmatrix}
\begin{pmatrix}
    i_{b0} \\
    i_{b0} \\
    i_{b0} \\
\end{pmatrix}
\] (7)

\[
\begin{pmatrix}
    u_{s0} \\
    u_{sa} \\
    u_{sb} \\
\end{pmatrix}
= \frac{d}{dt}
\begin{pmatrix}
    I_{10} & 0 & 0 \\
    0 & I_{10} & 0 \\
    0 & 0 & I_{10} \\
\end{pmatrix}
\begin{pmatrix}
    i_{s0} \\
    i_{s0} \\
    i_{s0} \\
\end{pmatrix}
+ \begin{pmatrix}
    I_{10} & 0 & 0 \\
    0 & I_{10} & 0 \\
    0 & 0 & I_{10} \\
\end{pmatrix}
\begin{pmatrix}
    i_{sa} \\
    i_{sb} \\
    i_{sb} \\
\end{pmatrix}
+ \begin{pmatrix}
    R_0 & 0 & 0 \\
    0 & R_0 & 0 \\
    0 & 0 & R_0 \\
\end{pmatrix}
\begin{pmatrix}
    i_{s0} \\
    i_{s0} \\
    i_{s0} \\
\end{pmatrix}
- \begin{pmatrix}
    3M_2 & 0 & 0 \\
    0 & 3M_2 & 0 \\
    0 & 0 & 3M_2 \\
\end{pmatrix}
\begin{pmatrix}
    i_{a0} \\
    i_{b0} \\
    i_{b0} \\
\end{pmatrix}
\] (8)

\[
C_1 \frac{d}{dt}
\begin{pmatrix}
    u_{e0} \\
    u_{e0} \\
    u_{e0} \\
\end{pmatrix}
= \begin{pmatrix}
    I_{10} & 0 & 0 \\
    0 & I_{10} & 0 \\
    0 & 0 & I_{10} \\
\end{pmatrix}
\begin{pmatrix}
    i_{e0} \\
    i_{e0} \\
    i_{e0} \\
\end{pmatrix}
+ \begin{pmatrix}
    I_{10} & 0 & 0 \\
    0 & I_{10} & 0 \\
    0 & 0 & I_{10} \\
\end{pmatrix}
\begin{pmatrix}
    i_{ea} \\
    i_{eb} \\
    i_{eb} \\
\end{pmatrix}
\] (9)
where $\tau$ is time per unit, i.e., $\tau = 2\pi f_c t$, and $f_c$ is the electrical grid frequency.

The $\alpha\beta0$ circuits of the filter structure $\alpha\beta0$ are presented in Fig. 6.

One can see that for the $\alpha\beta$ components the parameters of the differential mode filter exist. For the 0 component, only common mode filter elements are present.

B. Motor model

The IM model in the stationary $\alpha\beta0$ frame was used. In the motor model following state variables were used: stator current $i_s$, rotor flux $\psi_r$ and motor mechanical speed $\omega_r$. The model was described in a per unit system (15):

$$
\frac{d}{dt} \begin{bmatrix} i_{s\alpha} \\
\psi_{r\alpha} \\
\psi_{r\beta} \end{bmatrix} = A \begin{bmatrix} i_{s\alpha} \\
\psi_{r\alpha} \\
\psi_{r\beta} \end{bmatrix} + B \begin{bmatrix} u_{s\alpha} \\
0 \\
0 \end{bmatrix}
$$

(12)

$$
\frac{d}{dt} \begin{bmatrix} \psi_{r\alpha} \\
\psi_{r\beta} \end{bmatrix} = a_3 \begin{bmatrix} \psi_{r\alpha} \\
\psi_{r\beta} \end{bmatrix} + a_5 \begin{bmatrix} i_{s\alpha} \\
0 \end{bmatrix} + u_{s\beta} \begin{bmatrix} \psi_{r\alpha} \\
0 \end{bmatrix}
$$

(13)

$$
\frac{d\omega_r}{dt} = \frac{1}{J} \left( L_m \begin{bmatrix} \psi_{r\alpha} i_{s\beta} - \psi_{r\beta} i_{s\alpha} \end{bmatrix} - t_L \right)
$$

(14)

where: $t_L$ is load torque, $J$ is motor inertia, and $a_1 = -\left( R_i L_r^2 + R_r L_m^2 \right)/\left( L_r L_m \right)$, $a_2 = R_r L_m/\left( L_r \right)$, $a_3 = L_m/\omega_r$, $a_4 = L_r/\omega_r$, $a_5 = -R_r/\left( L_r \right)$, $a_6 = R_r L_m/\left( L_r \right)$ and $\omega_r = L_r L_s - L_m^2$.

The $\alpha\beta0$ circuits of the filter structure $\alpha\beta0$ are presented in Fig. 7.

III. CONTROL SYSTEM

The general structure of the system is presented in Fig. 8. The main loops are for the motor control, whereas subordinate loops are for the filter control. For filter control, the multi-loop system presented in [9] was implemented. The motor control principle is similar to the FOC solution but instead of stator current q component loop the motor torque is controlled (Fig. 9).

![Diagram](image)

Fig. 8. General structure of the control system.
The non-linear FOC (NFOC) system was presented in [15] for the drive without the filter. The NFOC idea is to eliminate the coupling between the flux and torque and the non-linearity of the motor model. In NFOC, instead of $i_{sq}$ the $i_e$ is controlled:

$$i_e = i_{sq} \psi_{rd}$$

(15)

where $dq$ are coordinates fixed with the $\psi_r$ vector.

Then the motor model (12)-(14) is as follows:

$$\frac{di_{sd}}{dt} = a_1 i_{sd} + a_2 \psi_{rd} + t_e \frac{\omega_{sy}}{\psi_{rd}} + a_4 u_{sd}$$

(16)

$$\frac{di_e}{dt} = \left( a_2 - \frac{R_s L_r}{\omega_c} \right) i_e + a_6 t_e i_{sd} - \omega_{sy} \psi_{rd} (i_{sd} + a_3 \psi_{rd}) + a_2 \psi_{rd} u_{sq}$$

(17)

$$\frac{d\psi_{rd}}{dt} = \frac{1}{J} \left( \frac{L_m}{L_r} t_e - t_L \right)$$

(18)

where rotor flux pulsation is: $\omega_{sy} = a_i \psi_{sq} / \psi_{rd} + \omega_r$.

If the next control variables $v_1$ and $v_2$ are used:

$$v_1 = a_i \frac{L_m}{L_r} i_{sd} - \omega_{sy} \psi_{rd} (i_{sd} + a_3 \psi_{rd}) + a_4 \psi_{rd} u_{sq}$$

(20)

$$v_2 = \omega_{sy} t_e + a_2 \psi_{rd} + a_4 u_{sd}$$

(21)

the motor model is linear and decoupled:

$$\frac{di_{sd}}{dt} = a_1 i_{sd} + v_2$$

(22)

$$\frac{d\psi_{rd}}{dt} = a_2 \psi_{rd} + a_6 i_{sd}$$

(23)

$$\frac{di_e}{dt} = \left( a_2 - \frac{R_s L_r}{\omega_c} \right) i_e + a_6 i_{sd} + \frac{1}{J} \left( \frac{L_m}{L_r} t_e - t_L \right)$$

(24)

(IV. OBSERVER FOR MOTOR AND FILTER)

As presented in Fig. 8, the observer requires information on inverter output voltages and currents. Because of this, no additional sensors are required in comparison with the drive without the filter, i.e. two sensors of the inverter output currents and one sensor for DC link voltage. Because the PWM with dead time compensation is used, instead of a real inverter output voltage the commanded $u_{stk}^{\text{com}}$ is used. The observer is based on the IM voltage model with a combination of the rotor and stator fluxes. Motor flux $\psi_r$ is calculated using two model simultaneously, i.e. model I ($\psi_s$, $\psi_r$) [16]-[17]:

$$\tau_e \frac{d\psi_{st}}{dt} + \psi_{st} = k_r \psi_{rt} + \tau_e u_{st}$$

(26)

$$\tau_e \frac{d\psi_{sq}}{dt} + \psi_{sq} = k_r \psi_{rq} + \tau_e u_{sq}$$

(27)

and model II ($\psi_s$, $i_t$):

$$\tau_e \frac{d\psi_{st}}{dt} = \frac{u_{st} - R_s i_{st}}{k_r}$$

(28)

$$\tau_e \frac{d\psi_{sq}}{dt} = \frac{u_{sq} - R_s i_{sq}}{k_r}$$

(29)

Stator flux is calculated in model I, whereas rotor flux is taken from model II:

$$\psi_{st} = \psi_{st} - \sigma L_s i_{st}$$

(30)

$$\psi_{sq} = \psi_{sq} - \sigma L_s i_{sq}$$

(31)

In the observer, the motor supply voltage and currents are also required, so the observer is extended with equations from the filter model – in the same way as presented in [10]-[14]. Finally, the following observer structure is used:

$$\frac{d\hat{\psi}_{st}}{dt} = \frac{-\hat{\psi}_{st} + k_r \hat{\psi}_{rt} + \hat{u}_{st} - k_A (i_{ta} - \hat{i}_{ta}) + k_B (i_{tb} - \hat{i}_{tb})}{\tau_s}$$

(32)

$$\frac{d\hat{\psi}_{sq}}{dt} = \frac{-\hat{\psi}_{sq} + k_r \hat{\psi}_{rq} + \hat{u}_{sq} - k_A (i_{ta} - \hat{i}_{ta}) - k_B (i_{tb} - \hat{i}_{tb})}{\tau_s}$$

(33)

$$\frac{d\hat{\psi}_{t}}{dt} = \frac{\hat{u}_{t} - R_s \hat{i}_{t}}{k_r}$$

(34)

$$\frac{d\hat{i}_{ta}}{dt} = \frac{\hat{u}_{ta} - R_s \hat{i}_{ta}}{k_A}$$

(35)

$$\frac{d\hat{i}_{tb}}{dt} = \frac{\hat{u}_{tb} - R_s \hat{i}_{tb}}{k_B}$$

(36)

$$\frac{d\hat{i}_{t}}{dt} = \frac{-\hat{i}_{t} + \hat{i}_{st} - \hat{i}_{sq}}{C_1}$$

(37)

$$\frac{d\hat{i}_{ta}}{dt} = \frac{\hat{u}_{ta} - \hat{i}_{ta} - \hat{i}_{sb}}{L_1}$$

(38)

$$\frac{d\hat{i}_{tb}}{dt} = \frac{\hat{u}_{tb} - \hat{i}_{tb} - \hat{i}_{sb}}{L_1}$$

(39)

where $\psi_{st}$, $\psi_{sq}$, $\psi_{t}$, $i_{ta}$, $i_{tb}$ are stator flux components taken from models I and II respectively.

The stator magnitude, stator and rotor flux angles are:

$$\left| \psi_s \right| = \sqrt{\psi_{st}^2 + \psi_{sq}^2}$$

(42)

$$\hat{\rho}_{\psi_{st}} = \arctan \left( \frac{\psi_{sq}}{\psi_{st}} \right)$$

(43)

$$\hat{\rho}_{\psi_{sq}} = \arctan \left( \frac{\psi_{st}}{\psi_{sq}} \right)$$

(44)

The stator current vector for observer feedback is:

$$\hat{i}_s = \frac{\left( \hat{\psi}_s - k_r \hat{\psi}_r \right)}{\sigma L_s}$$

(45)

The IM mechanical speed is as follows:
\[ \dot{\omega}_2 = \dot{\omega}_{yr} - \dot{\omega}_2 \]  
\[ \dot{\omega}_{yr} = \frac{d\psi_{yr}}{dt} \]  
\[ \dot{\omega}_2 = \frac{\psi_{ru}^1 i_{ru} - \psi_{rb}^1 i_{rb}}{||\psi_r||^2} \]  

where \( \dot{\omega}_2 \) is motor slip pulsation.

The structure of the observer is robust because rotor resistance is not included directly in the observer system (32)-(41). It only appears in the slip calculation (48).

The observer presented in this section is a new solution for the drive with inverter output filter, which has not been presented earlier.

V. Results

The proposed IM sensorless drive with inverter output filter was investigated by simulations and experiments. The data of the IM and the filter are in Table I.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_n )</td>
<td>1.5 kW</td>
<td>nominal power</td>
</tr>
<tr>
<td>( U_n )</td>
<td>400 V</td>
<td>nominal phase to phase voltage</td>
</tr>
<tr>
<td>( I_n )</td>
<td>3.5 A</td>
<td>nominal current</td>
</tr>
<tr>
<td>( n_n )</td>
<td>1410 rpm</td>
<td>nominal mechanical speed</td>
</tr>
<tr>
<td>( p )</td>
<td>2</td>
<td>number of poles pairs</td>
</tr>
<tr>
<td>( f_n )</td>
<td>50 Hz</td>
<td>nominal supply voltage frequency</td>
</tr>
<tr>
<td>( J )</td>
<td>0.0028 kg·m²</td>
<td>inertia</td>
</tr>
<tr>
<td>( R_s )</td>
<td>4.75 Ω</td>
<td>stator resistance</td>
</tr>
<tr>
<td>( R_r )</td>
<td>4.76 Ω</td>
<td>rotor resistance</td>
</tr>
<tr>
<td>( L_{ms}, L_{mr} )</td>
<td>0.3201 H</td>
<td>stator inductance (leakage + mutual)</td>
</tr>
<tr>
<td>( L_m )</td>
<td>0.3032 H</td>
<td>mutual inductance</td>
</tr>
<tr>
<td>( L_f )</td>
<td>6.3 mH</td>
<td>filter inductor</td>
</tr>
<tr>
<td>( C_f )</td>
<td>3.3 μF</td>
<td>filter capacitor</td>
</tr>
<tr>
<td>( R_c )</td>
<td>3 Ω</td>
<td>damping resistance</td>
</tr>
<tr>
<td>( M_1, M_2 )</td>
<td>14 mH</td>
<td>CM choke inductance</td>
</tr>
<tr>
<td>( \Delta U )</td>
<td>3%</td>
<td>filter voltage drop at nominal load</td>
</tr>
<tr>
<td>( f_{rez} )</td>
<td>1.1 kHz</td>
<td>filter resonance frequency</td>
</tr>
</tbody>
</table>

Initial investigations were done for testing the control system. The drive was working without the observer and all variables used in the control process were taken directly from the simulation model of the motor and filter. The results are shown in Fig. 10.

Three tests for commanded speed variations are presented in Fig. 10:
1) test 1: drive without filter,
2) test 2: drive with filter and NFOC without changes,
3) test 3: drive with filter and NFOC with proposed changes.

It is noticeable that the NFOC with the filter has serious problems with torque control and high oscillations appear. This negatively influences the speed dynamics control. The drive properties were greatly improved when the NFOC with filter controllers was applied. The speed control is nearly the same as in the drive without the filter. Only small oscillations of the torque and flux are observed.

Next test were done for the observer (Fig. 11). The observer accuracy was tested during slow motor reverse. The estimated speed coincides with the measured one except for small errors that appear when speed direction is changed. The error appears when machine is working in the regenerative mode which is generally problem for IM drives – as reported, e.g. in [18–20]. That inaccuracy of the observer in low speed
mode operation is more noticeable in flux estimation. The maximal rotor flux magnitude error is close to 12% whereas does not exceed 3% for the higher speed level.

The experimental results were obtained in the laboratory test bench. The DSP processor ADSP21065L and FPGA based board were used to control the drive and to communicate with a personal computer for data acquisition. The drive was working without necessity of the speed sensor, however the speed was measured for monitoring purposes. The results are presented in Fig. 12.

In the experiments the commanded speed was increased first and next the speed direction was changed. The acceleration is fast with small overshoots appearing in the speed transients. In the torque transients small oscillations are visible for low speed. Experimental results are similar to the simulation ones.

VI. CONCLUSIONS

In the electric drives with voltage inverters the output filters are installed to eliminate some disadvantages of the PWM inverter supply. Both differential and common mode filters are used. The differential mode filter parameters can influence closed loop motor control—especially when speed sensorless solutions are applied. To prevent that negative consequences the control and estimation algorithms should be modified taking into account inverter model. With such approach the drive can work properly in spite of the filter use, and without any additional sensors—except the sensors already used in the drive without the filters.

The proposed solution was analyzed and proved by simulation and experiments. The proposed idea contains a structure for motor and filter variables on-line estimation.

REFERENCES