Simple Technique of Initial Speed Identification for Speed-Sensorless Predictive Controlled Induction Motor Drive

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Abstract: This article presents a simple technique of identifying the initial speed that allows for restarting a sensorless induction motor (IM) drive controlled by a model predictive flux control (MPFC). Initial speed identification is required because, according to the research, the applied current-model reference adaptive system (C-MRAS) can restart the IM after failure only if the error of the initial speed set in the estimator is <25%. The proposed technique is based on short periods of flux generation for the certain initial speed and observation of the estimated torque respond. The direction of the estimated torque determines whether the real speed is higher or lower than the initial one set in the estimator. In two steps, the algorithm identifies the initial speed with an accuracy of 25%. This allows for a quick restart of the IM from any speed, eliminating the disadvantage of the sensorless drive control system with the C-MRAS speed estimator. The experimental results measured on a 50 kW drive which illustrates the operation and performances of the system are presented.

Keywords: induction motor • sensorless control • model predictive control • MRAS estimators • initial speed identification • restarting IM

1. Introduction

Sensorless speed control methods allow to eliminate the mechanical motion sensor (tachogenerator, resolver), which improves the reliability and reduces complexity and costs of hardware and maintenance, so they are widely used in industrial and transportation drives (Holtz, 2002, 2005; Orlowska-Kowalska and Dybkowski, 2011; Abu-Rub et al., 2013; Boldea and Nasar, 2017).

In almost all practical applications, the induction motor (IM) should be immediately restarted after turning off the inverter due to over-current or over-voltage errors, without stopping the rotating drive. Of course, it is necessary that the control system should be able to restart smoothly and speed-up the free running IM. If there is a mechanical speed sensor, there is no problem with magnetizing the motor again. However, the problem arises when the actual speed in the sensorless drive is unknown and large inrush current may occur as a result of differences between the frequency of the inverter and the angular frequency of the rotating IM. Therefore, for restarting sensorless IM drive, estimation of both the initial speed and the rotational direction is required. To solve this problem, various methods have been proposed and investigated for IM drives. These methods can be categorized in the following groups: frequency searching methods, electromotive force (EMF) based, DC current injection based, adaptive full order observer (AFO). In the frequency searching methods, the initial value of the stator frequency is adjusted by the frequency controller to find the minimum input power or stator current, and these methods are more suitable for speed open-loop V/Hz control (Pan et al., 1997; Lee et al., 2017). The EMF-based methods deteriorate in the low-speed range because of the low value of EMF and the effects of stator resistance variations (Tajima et al., 1996; Kondo, 2015; Kobayashi et al., 2016). The DC current injection methods use proportional integral (PI) current...
controllers and are convenient for vector control systems but not for direct torque or predictive torque control (Iura et al., 2011; Kikuchi et al., 2018; Yin et al., 2020). The group of AFO-based method is promising and can be used with a combination of predictive torque and flux control; however, it requires a complicated design (Wang et al., 2015; Yang et al., 2017).

In this paper, a simple technique of initial speed identification based on model reference adaptive system (MRAS) sensorless control with predictive torque and flux control system is presented. The proposed technique uses MRAS estimator, generates a sequence of short flux reference pulses and observes the estimated torque response to infer the direction and level of the rotor speed. The experimental results measured on the 50 kW IM drive illustrate the operation of the developed method.

1.1. Block scheme of speed-sensorless predictive stator flux and torque control

The considered speed-sensorless stator model predictive flux control (MPFC) system is presented in Figure 1. Among several approaches to finite control set model predictive control FCS-MPC of three-level inverter-fed drives (Habibullah et al., 2017; Donoso et al., 2018; Zhang et al., 2019), in this work the class of optimal switching sequence (OSS) has been chosen (Vazquez et al., 2017) because it guarantees constant switching frequency of the power inverter. Another important selection was the MPFC scheme because it allows to design the IM predictive model and minimization of the cost function without necessity for labour-intensive weights values selection procedure using the “trial and error” method. This is because the IM torque is expressed in terms of stator flux (Zhang and Yang, 2016).

The detailed design and description of the developed and constructed OSS-MPFC drives are described in Stando (2018) and Stando and Kazmierkowski (2020).

2. Speed Estimation with C-MRAS

In this study, for IM stator flux and speed estimation, the compensated current-model reference adaptive system (C-MRAS) version is used (Figure 2; Orlowska-Kowalska and Dybkowski, 2010). It employs the real IM as the reference model and the full voltage-speed (V – Ω_m) model of the IM (Depenbrock, 1988; Kazmierkowski and Tunia, 1994) as the adaptive model. The C-MRAS, like other variants of MRAS estimators, is parameter dependent; however, it is more robust thanks to real-time correction with measured stator currents (Wang et al., 2014).

The adaptive (V – Ω_m) model (Figure 3) is described by the following equations:

\[
\frac{d\hat{\Psi}_a}{dt} = V_a - R_i \hat{I}_a \\
\frac{d\hat{\Psi}_\beta}{dt} = V_\beta - R_i \hat{I}_\beta
\]
\[ \dot{\Psi}_{ra} = \frac{1}{\sigma L_s L_r} \left( \frac{1}{\sigma} - 1 \right) \dot{\Psi}_{sa} - \frac{1}{\sigma L_r} \dot{\Psi}_{ra} - p_\beta \dot{\Omega}_m \dot{\Psi}_{r\beta} \]  

\[ \dot{\Psi}_{r\beta} = \frac{1}{\sigma L_s L_r} \left( \frac{1}{\sigma} - 1 \right) \dot{\Psi}_{s\beta} - \frac{1}{\sigma L_r} \dot{\Psi}_{r\beta} - p_\beta \dot{\Omega}_m \dot{\Psi}_{ra} \]  

\[ \dot{i}_{sa} = \frac{L_r \dot{\Psi}_{sa} - L_M \dot{\Psi}_{ra}}{\sigma L_s L_r} \] 

Fig. 2. Block diagram of speed estimation using compensated C-MRAS

Fig. 3. Voltage-speed flux IM model used as an adaptive system in C-MRAS
where \( V_s = (V_{sa} \cdot V_{sb}) \), \( I_s = (I_{sa} \cdot I_{sb}) \) and \( \Psi_s = (\psi_{sa} \cdot \psi_{sb}) \) are the stator voltage vector, the stator current vector and stator flux vector, respectively; \( I_I = (I_{ia} \cdot I_{ib}) \) and \( \Psi_I = (\psi_{ia} \cdot \psi_{ib}) \) are the rotor current vector and rotor flux vector, respectively; \( \Omega_m \) denotes the rotor electrical angular speed; \( R_s, R_r, L_s, L_r \) and \( L_M \) are the stator resistance, rotor resistance, stator inductance, rotor inductance and main inductance, respectively; and finally, \( p \) denotes the number of poles, \( J \) is the moment of inertia, \( \Psi' \) is conjugate stator flux vector, \( T_L \) is the load torque, \( \sigma \) is the total leakage factor and symbol \(-\) denotes the estimated values.

Both models are supplied by the same reference voltage \( V_s \) (Figure 2). The adaptive system is additionally tuned by two closed loops. The first one considers error between measured current \( I_s \) and calculated form (3), while the second one the adaptively estimated speed (5). The first closed loop is responsible for offsets compensation introduced mainly from current sensors. The mechanism of offset compensation is realized by two PI controllers, one for each of the \( \alpha \) and \( \beta \) components. Inputs of these controllers are the current errors \( (I_s - \hat{I}_s) \) while the outputs are the offset compensation signals added to the right-hand side of Eq. (1). For proper compensation in the whole range of the IM rotor speed, the controller time constant is tuned proportionally to the speed value. Furthermore, the controllers operate very slowly for two reasons: to ensure lack of influence for the estimation in transients because they integrate errors from sinusoidal signals. The second closed loop delivers the mechanical speed \( \hat{\Omega}_m \) which is estimated based on the error between measured \( I_s \) and estimated \( \hat{I}_s \) current multiplied by the estimated stator flux vector \( \Psi_s \) according to (4):

\[
e_{\Omega} = \text{Im}\left(\hat{\Psi}_s \Delta \hat{I}_s\right) = \hat{\Psi}_{s\beta}(I_{ssa} - \hat{I}_{s\beta}) - \hat{\Psi}_{s\alpha}(I_{sb} - \hat{I}_{s\beta})
\]

\[
\hat{\Omega}_m = K_p e_{\Omega} + \frac{K_p}{T_I} \int e_{\Omega} dt
\]
does not cause undesirable behaviour of the drive. The first step is to determine the direction of shaft rotation. For this purpose, the initial speed $\Omega^*_{m0}$ commanded to the estimator is set to zero. In the second step, the initial speed is set to half the nominal one with the sign corresponding to the estimated sign of torque. The second torque impulse gives information about whether the real speed is below or above half the nominal one. After the test, the initial speed for start-up is set as $\pm 25\% \Omega_{mN}$ or $\pm 75\% \Omega_{mN}$. The time diagram of the speed division during initial speed identification is shown in Figure 5, and the dependence of the torque sign from set speed and real one is summarized in Table 1.

![Block diagram of the initial speed identification algorithm](image1)

**Fig. 4.** Block diagram of the initial speed identification algorithm

![Time diagram of the speed division during initial speed identification](image2)

**Fig. 5.** Time diagram of the speed division during initial speed identification

<table>
<thead>
<tr>
<th>Step 1</th>
<th>Step 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega^<em>_{m0}$ $\Omega^</em><em>{m1}$ $\Omega^*</em>{m2}$</td>
<td>$\Omega^<em>_{m0}$ $\Omega^</em><em>{m1}$ $\Omega^*</em>{m2}$</td>
</tr>
<tr>
<td>$0.0$ ($+$ $&gt; -50% \Omega_{mN}$)</td>
<td>$+ &lt; -75% \Omega_{mN}$ $- &gt; -25% \Omega_{mN}$</td>
</tr>
<tr>
<td>$0.0$ $- &lt; +50% \Omega_{mN}$</td>
<td>$+ &lt; +75% \Omega_{mN}$ $- &gt; +25% \Omega_{mN}$</td>
</tr>
</tbody>
</table>
4. Experimental Results

The selected experimental results for the identification of the initial speed are presented in Figures 6–8. In Figure 6, the step-by-step identification process of the initial speed is shown. Before the first step, the speed commanded to MRAS estimator $\Omega_{\text{MRAS}}$ is set to 0 rpm. After the first stator flux impulse ($t_1 - t_2$), the direction of the rotation is determined from the torque sign. Then, before the second stage, the estimator speed $\Omega_{\text{MRAS}}$ is set to $-50\% \Omega_{\text{mN}}$.

The second stage starts after 250 ms (this period ($t_2 - t_3$) is selected to ensure the accuracy of the estimation over the entire speed range) and determines the speed range of the motor shaft rotation between 0% $\Omega_{\text{mN}}$ and $-25\% \Omega_{\text{mN}}$. When the identification is completed, in time $t_5$ begins the start-up of the motor. After 80 ms, the speed estimator identifies the initial speed, which is $-150$ rpm.

A similar starting process can be observed in the other two figures, where the starting speed was identified, respectively: $-1,700$ rpm in Figure 7 and 700 rpm in Figure 8.

Fig. 6. Start-up with $-150$ rpm, after initial speed identification, where $|\hat{\Psi}_s|$ is the estimated stator flux, $\hat{T}_e$ is the estimated torque, $\hat{\Omega}_m$ is the estimated mechanical speed and $I_a$ is the phase current.

Fig. 7. Start-up with $-1,700$ rpm, after initial speed identification, where $|\hat{\Psi}_s|$ is the estimated stator flux, $\hat{T}_e$ is the estimated torque, $\hat{\Omega}_m$ is the estimated mechanical speed and $I_a$ is the phase current.
5. Conclusions

A novel technique of initial speed identification in sensorless IM drive with predictive flux and torque control and C-MRAS estimator has been presented in this paper. The proposed solution is characterised by the following features:

- It is implemented in the drive C-MRAS estimator of torque and stator flux;
- It generates the stator flux pulse reference and observes the sign of the estimated torque;
- The procedure is simple and is performed in two steps. So, the executing time is <0.5 s;
- It is verified by experimental tests.

References


Appendix A

A.1. Motor and Inverter data

**Table A1. Parameters of 3L-NPC inverter**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S_n )</td>
<td>200 kV A</td>
</tr>
<tr>
<td>( I_n )</td>
<td>300 A</td>
</tr>
<tr>
<td>( V_n )</td>
<td>( 3 \times 400 ) V</td>
</tr>
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</table>

**Table A2. Parameters of IM (STDA 200L4)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_n )</td>
<td>50 kW</td>
</tr>
<tr>
<td>( I_n )</td>
<td>88 A</td>
</tr>
<tr>
<td>( V_n )</td>
<td>380 V</td>
</tr>
<tr>
<td>( f_n )</td>
<td>65 Hz</td>
</tr>
<tr>
<td>( p_b )</td>
<td>2</td>
</tr>
<tr>
<td>( \Omega_{m} )</td>
<td>1,917 rpm</td>
</tr>
<tr>
<td>( T_{m} )</td>
<td>250 Nm</td>
</tr>
<tr>
<td>( R_s )</td>
<td>0.067 ( \Omega )</td>
</tr>
<tr>
<td>( R_l )</td>
<td>0.046 ( \Omega )</td>
</tr>
<tr>
<td>( L_s )</td>
<td>0.02346 H</td>
</tr>
<tr>
<td>( L_l )</td>
<td>0.02346 H</td>
</tr>
<tr>
<td>( L_m )</td>
<td>0.023 H</td>
</tr>
</tbody>
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