Precision Low Cost Electric Motor Flux and Torque Measurement Method

Abstract

Torque and flux measurements in ac motor are often a complicated matter.

For flux measurement, a coil or a field sensor must be inserted inside stator windings causing relevant costs especially for big machines. Anyway, measurement has not great accuracy since calibration is not easy. For torque measurement, a telemetry system can be installed on rotor axle but, especially for notable accuracy, this system has high costs. Sometimes is not possible to install a telemetry directly on rotor axle and a gear box must be interposed, losing every chance to obtain a precise measurement. Cost and measurement uncertainties increase with machine size so that, for high power (more than 500 kW), this is about an insoluble matter.

In this paper, a method based on a state observer is proposed, that overcomes all disadvantages of other methods because only voltages and current measurement is needed. For more accuracy, only rotor speed measurement is needed in addition.

Introduction

Nowadays, new technologies applied in the field of power electronics, computer science and control systems have produced great performance improvements in electric drives. In fact new high speed power devices are today available, microprocessor computational capability has considerably increased and new control approaches have been introduced. All these, applied on electric drives, caused a notable progress so that field oriented electric drives with very compact weight and size, excellent fatigue characteristics and fast dynamic response are commercially available today. Although drive regulation schemes have relevantly changed with respect to the past, variables to be regulated remained essentially the same: flux and torque.

Since flux and torque are the regulated quantities, an estimate of the performances of an electric drive needs an accurate examination of flux and torque waveforms. Unfortunately flux and torque measurements, as will be explained, are not an easy matter.

Flux measurement can be done inserting a certain number of coils inside the stator windings and taking the resulting voltage. This practice is yet afflicted by the following counterparts:

- Mechanical access difficulty, especially on small size machines and in already installed big machines.
- Air gap measurement only.

Torque measurement is normally performed employing a sensor, that is often a strain gauge telemetry system, directly mounted on the rotor axle. This practice has yet the following counterparts:

- High noise level due to rotating part coupling.
- Calibration difficulties especially for high power machines.
- Presence of gear box that introduces hysteresis and low pass characteristics.
High costs.

For this reason, flux and torque measurements don’t give today sufficiently accurate results and great efforts are directed towards the research of new methods.

In this paper a precision low cost flux and torque measurement method is described, based on the technique of the state observer. As it is well known, in an electric motor, torque is a function of rotor and stator flux. The proposed method consists in estimating rotor and stator flux of an induction motor and then calculating the torque as the result of these estimations.

State observer

Considering a $dq$ fixed stator reference frame, the induction motor model can be expressed with the following matrix equations.

$$
\dot{\phi} = A_{d} \cdot \phi + V
$$
$$
i_{s} = C \cdot \phi
$$

where,

$$\phi = \begin{bmatrix} \psi_{ds} & \psi_{qs} & \psi_{dr} & \psi_{qr} \end{bmatrix}^{T}, V = \begin{bmatrix} V_{ds} & V_{qs} & 0 & 0 \end{bmatrix}^{T}, i_{s} = \begin{bmatrix} i_{ds} & i_{qr} \end{bmatrix}^{T}$$

$$A_{d} = \frac{1}{L_{r}L_{s} - L_{m}^{2}} \begin{bmatrix} -R_{s}L_{r} & 0 & R_{s}L_{m} & 0 \\ 0 & -R_{s}L_{r} & 0 & R_{s}L_{m} \\ R_{r}L_{m} & 0 & -R_{r}L_{s} & -\omega_{r}(L_{s}L_{r} - L_{m}^{2}) \\ 0 & R_{r}L_{m} & 0 & -R_{r}L_{s} \end{bmatrix}$$

$$C = \frac{1}{L_{r}L_{s} - L_{m}^{2}} \begin{bmatrix} L_{r} & 0 & -L_{m} & 0 \\ 0 & L_{r} & 0 & -L_{m} \end{bmatrix}$$

$$L_{s} = L_{ls} + L_{m}$$

$$L_{r} = L_{lr} + L_{m}$$

In equations (1) to (6) $L_{ls}$ and $L_{lr}$ are respectively the stator and the rotor stray inductances, $L_{m}$ is the magnetisation inductance, $V$ is the input voltage vector, $\phi$ is the stator and rotor flux vector, $i_{s}$ is the stator current vector and $\omega_{r}$ is the rotor electrical speed.

When a measurement of the state of a process is needed, but not directly measurable, a software model can be implemented in order to reproduce it. As shown in fig. 1, process input is measured and given as input to the model. In this way, if input data are supplied continuously to the model, integrating eq. (1), estimated state process (i.e. the estimated flux vector $\hat{\phi}$) will be available. This is the simplest version of what in control systems literature is called state observer.
The observer shown in fig. 1 is unfortunately afflicted by numerous drawbacks. Induction motor parameter uncertainty reduces the estimation accuracy, stator and rotor resistances vary relevantly with temperature and frequency, machine inductances are frequency dependent. In order to obtain better accuracy, induction machine stator currents can be measured and used as a correction term for eq. (1).

In this way, the proposed observer matrix equation becomes:

\[ \dot{\hat{x}} = A\hat{x} + V + K(i_s - \hat{i}_s) \text{,} \]

(7)

where the symbol “ \( ^\hat{\text{^\_\_} \text{\_\_}} \) ” indicates estimated quantities. The related block diagram is shown in fig. 2.

![Block diagram of the proposed observer](image)

Fig. 2: Process and proposed state observer

With an appropriate choice of matrix \( K \), observer closed loop eigenvalues can be assigned and a specified observer dynamics can be selected. For many applications, especially in real time measurements, where calculation time is a topic matter, speed dependent terms in matrix \( A \) can be neglected obtaining:

\[
A = \frac{1}{L_r L_s - L_m^2} \begin{bmatrix} -R_s L_r & 0 & R_s L_m & 0 \\ 0 & -R_r L_r & 0 & R_r L_m \\ R_s L_m & 0 & -R_s L_s & 0 \\ 0 & R_r L_m & 0 & -R_r L_s \end{bmatrix} \text{.} \]

(8)

Further advantage of the use of a constant matrix is that the state observer is not afflicted by instability with respect to \( \omega \) variations.
Comparative torque measurement.

To evaluate the precision of the proposed method, torque must be measured also in a different way. In railways applications, torque is obtained indirectly by measurement of the loco’s traction effort $F_t$.

One way to execute this measurement is illustrated in fig. 3.

Recalling the conventions adopted in fig. 3, motion equation, for the loco, can be written as:

$$F = R_m + m \cdot a + F_t$$  \hspace{1cm} (9)

In eq. (9), $R_m$ is the motion resistance due to the slope of the path, the curvature of the track and to the air resistance, $m \cdot a$ is the inertial resistance of the loco and $F_t$ is the force exchanged between the loco and the train.

$R_m$ is a function of line parameters as slope, curve radius and speed, and is practically calculated by means of tabulated values. The effective traction force $F_t$ is measured with a strain gauge system installed on the traction hook, between the loco under test and the train. The acceleration is obtained by differentiation of the speed measurement signal, coming from a phonic wheel, so that the inertia resistance can be calculated, provided that mass $m$ is known.

At this point, the total force $F$ can be derived from eq. (9) and, from the knowledge of the wheel radius and the gear box ratio, it is easy to obtain the axle torque:

$$T = \frac{F \cdot r}{n \cdot K_r}$$  \hspace{1cm} (10)

where $n$ represents the number of motors in the loco, $r$ is the wheel radius and $K_r$ is the gear box reduction ratio.

Experimental results

The method described in the previous paragraphs has been applied to the measurement of the traction effort for the Italian Railways’ E412 loco. As illustrated in fig. 4, the E412 loco is moved by four double star asynchronous motors. For each motor, parameters of a single star are reported in table 1.

For the E412 the gear box ratio is $K_r = 3.65$ and the wheel radius is $r = 0.55m$. 

\[Fig. \, 3: \, \text{Traditional traction effort method for torque measurement}\]
Table I: E412 induction motor parameters (single star)

<table>
<thead>
<tr>
<th>$P_n$ (kW)</th>
<th>$T_n$ (Nm)</th>
<th>$f_n$ (rad/s)</th>
<th>$V_n$ (V)</th>
<th>$R_s$ ($\Omega$)</th>
<th>$L_{ds}$ (mH)</th>
<th>$L_{dm}$ (mH)</th>
<th>$L_{dr}$ (mH)</th>
<th>$R_r$ ($\Omega$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1400</td>
<td>9000</td>
<td>50</td>
<td>155.5</td>
<td>1304</td>
<td>0.0578</td>
<td>0.75</td>
<td>23.2</td>
<td>0.75</td>
</tr>
</tbody>
</table>

Data have been acquired and saved to a PC with the aid of a Virtual Instrument and a 12 bit acquisition board. Sampling frequency has been set at the value of $f_s = 20kHz$.

Acquired voltages and currents, together with the speed, are fed as input to the software implemented observer. Different analysis have been carried out, at the speed of 18 km/h (low speed), 68 km/h (medium speed) and 150 km/h (high speed).

To ensure the stability and a satisfactory dynamic of the observer, according to the speed, different poles have been selected, as reported in table II. Observer initial conditions (stator and rotor flux) have been always set to zero.

Table II: Observer eigenvalues choice, related to the loco’s speed

<table>
<thead>
<tr>
<th>Speed (km/h)</th>
<th>18</th>
<th>68</th>
<th>150</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eigenvalues</td>
<td>[-100 -100 -1 -1]</td>
<td>[-500 -450 -1 -1]</td>
<td>[-1000 -450 -1 -1]</td>
</tr>
</tbody>
</table>

In fig. 5 (a), fig. 6 (a) and fig. 7 (a), respectively for the speed of 18 km/h, 68 km/h and 150 km/h, the estimated torque is reported, in comparison with the measurement obtained by the traditional method. The transitory overshoot, due to the null initial conditions set for the observer, settles down very quickly and ensures small permanent measurement error.

In fig. 5 (b), fig. 6 (b) and fig. 7 (b) a closer look at the estimated torque waveform is presented, respectively for the speed of 18 km/h, 68 km/h and 150 km/h.

In fig. 5 (c), fig. 6 (c) and fig. 7 (c), respectively for the speed of 18 km/h, 68 km/h and 150 km/h, the paths followed by the estimated stator and rotor flux are represented.

Fig. 4: E412 Traction circuit

![Fig. 4](image-url)
Fig. 5: Observer measurements at the speed of 18 km/h

Fig. 6: Observer measurements at the speed of 68 km/h

Fig. 7: Observer measurements at the speed of 150 km/h

Fig. 8, instead, shows the comparison between the traditional and the proposed method, during a torque transient at the speed of 150 km/h.
Conclusions

In this paper, a method for high dynamics torque measurement, based on a flux observer, has been presented. Compared with the traditional method, that is widely adopted in railways applications, torque measurement made with the observer method shows higher resolution and allows to investigate also the behaviour of the traction drive in terms of torque ripple. Besides, the observer method produces also estimates of stator and rotor flux, that can be used in order to achieve a deep sight inside flux and torque control strategies that are employed in the specific drive.

References


