

AN IMPROVED SPEED AND FLUX-LINKAGE ESTIMATION STRUCTURE FOR INDUCTION MACHINES' SENSORLESS CONTROL SYSTEMS

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Abstract – This paper provides an improved method for speed and flux-linkage estimation within sensorless control systems for induction machines. This method is based on the induction machine's voltage equation set referred both to the stationary coordinate system d-q and for the rotating coordinate system $d\lambda r$ -q λr referred to the rotor flux linkage. The main advantage of this method is avoiding problems drift and "pure" integrator problems through a first order basic element usage. The configuration leads to precise estimations of flux linkage and speed (even at low speed values) and may be applied both to field oriented control systems (FOC) and to the direct torque control systems (DTC).

Keywords: induction machine, sensorless control system, speed and flux linkage estimation.

1. INTRODUCTION

Advanced field-oriented electric drives and directtorque-control electric drives are now used to achieve high-dynamic speed accuracy. If sensor-less control is to be used, special estimation-techniques for position and flux-linkage are requested, to enhance the dynamic accuracy of the drive. In high-dynamic electric drives, the drive system must provide accurate control of speed from zero to the maximum despite saturation or other machine's parameter deviations. A suitable speed control structure may be obtained if avoiding integrators.

2. SPEED AND FLUX-LINKAGE ESTIMATION

Various speed and flux-linkage estimators are described in the literature, [1] - [3]. Stator currents and voltages are usually monitored; sometimes, stator voltages are computed from voltage at the DC-inner circuitry terminals and the inverter's switching status. Subsequently, we assume space-vectors of currents and voltages to be two of the control system's inputs; the third input is the imposed (predicted) magnitude of the flux-linkage space-vector $\left|\underline{\Psi}_{r}^{*}\right|$; this input is previosly given in a rotor-flux oriented control, for instance. Rotor speed may be determined by the following relation:

$$\omega_r = \omega_{\lambda_r} - \omega_2 \,, \tag{1}$$



Fig. 1. Vector diagram for the rotor flux-linkage field oriented system.

where: ω_{λ_r} is the rotor flux-linkage speed with respect to the stator, $d\lambda_r/dt$, fig. 1, and ω_2 is the slip frequency. Otherwise ω_2 is the angular frequency of rotor's flux-linkage space-vector with respect to the rotor.

It is possible to build stator or rotor flux-linkage estimators within the drift and "pure" integrator problems are avoided. This may be achieved through limited bandwidth integration of high frequency components and by eliminating imprecise flux linkage estimation (for frequencies less than 1/T), with its imposed value corresponding to a slight transition. In this purpose, the stator voltage equation referred to a two-phase, d - q, coordinate system related to the stator is used, (Fig. 1) as follows:

$$\underline{u}_s = R_s \cdot \underline{i}_s + \frac{d\underline{\Psi}_s}{dt} \,. \tag{2}$$

The stator flux linkage space vector, referred to the d – q coordinate system, is, [7], [9]:

$$\underline{\Psi}_s = L_s \cdot \underline{i}_s + L_m \cdot \underline{i}_{r\theta_r} \cdot e^{j \cdot \theta_r} .$$
(3)

where:

$$L_{s} = L_{s} - M_{s}$$
 is the total three- phased
inductance of the stator;
$$\overline{L}_{s}$$
 is the self-inductance of a
phase winding of the stator;
is the mutual inductance
between the stator windings;
$$L_{m} = \frac{3}{2} \cdot \overline{M}_{sr}$$
 is the magnetization three-
phased inductance;
is the peak value of the
mutual inductance between

stator and rotor.

The rotor flux linkage space vector referred to the $d\theta_r$ - $q\theta_r$ coordinate system, (Fig. 1) is:

$$\underline{\Psi}_{r\theta_r} = L_r \cdot \underline{i}_{r\theta_r} + L_m \cdot \underline{i}_s \cdot e^{-j \cdot \theta_r}$$

The rotor flux linkage space vector referred to the stationary coordinate system d - q may be written as follows:

$$\underline{\Psi}_{r}^{'} = \underline{\Psi}_{r\theta_{r}} \cdot e^{j \cdot \theta_{r}} =$$

$$= L_{r} \cdot \underline{i}_{r\theta_{r}} \cdot e^{j \cdot \theta_{r}} + L_{m} \cdot \underline{i}_{s} = .$$

$$= L_{r} \cdot \underline{i}_{r}^{'} + L_{m} \cdot \underline{i}_{s}$$

$$(4)$$

where:

 $\underline{i}'_{r} = \underline{i}_{r\theta_{r}} \cdot e^{j \cdot \theta_{r}} .$

Follows, from equation (3):

$$\underline{\Psi}_{s} = L_{s} \cdot \underline{i}_{s} + L_{m} \cdot \underline{i}_{r}^{'}.$$
⁽⁵⁾

If we replace $\underline{i'_r}$ given by the relation (5) into relation (4) results:

$$\underline{\Psi}_{r}^{'} = \frac{L_{r}}{L_{m}} \cdot \left(\underline{\Psi}_{s} - L_{s}^{'} \cdot \underline{i}_{s} \right), \tag{6}$$

where:

$$L'_{s} = L_{s} - \frac{L_{m}^{2}}{L_{r}}$$
 is the transient inductance of the stator.

From relation (6) results:

$$\underline{\Psi}_{s} = \frac{L_{m}}{L_{r}} \cdot \underline{\Psi}_{r}^{'} + L_{s}^{'} \cdot \underline{i}_{s} .$$
⁽⁷⁾

Follows, from relations (2) and (7):

$$\underline{u}_{s} - R_{s} \cdot \underline{i}_{s} - L_{s}^{'} \cdot \frac{d\underline{i}_{s}}{dt} = \frac{L_{m}}{L_{r}} \cdot \frac{d\underline{\Psi}_{r}}{dt}, \qquad (8)$$

or,

$$T \cdot \left(\underline{u}_{s} - R_{s} \cdot \underline{i}_{s} - L'_{s} \cdot \frac{d\underline{i}_{s}}{dt}\right) = T_{I} \cdot \frac{d\underline{\Psi}'_{r}}{dt}, \qquad (9)$$

where:

$$T_1 = T \cdot L_m / L_r$$

Now, we may implement a slip frequency estimator, ω_2 , considering the stator voltage equation in the d λ r-q λ r coordinate system (referred to the rotor flux) [4], [9] as follows:

$$0 = R_r \cdot \underline{i}_{r\lambda_r} + \frac{d\Psi_{r\lambda_r}}{dt} + j \cdot \left(\omega_{\lambda_r} - \omega_r\right) \cdot \underline{\Psi}_{r\lambda_r}, \quad (10)$$

where:

$$\left|\underline{\Psi}_{r\lambda_r}\right| = \left|\underline{\Psi}_r\right| = \underline{\Psi}_r$$

and

$$\underline{\Psi}_{r\lambda_r} = L_r \cdot \underline{i}_{r\lambda_r} + L_m \cdot \underline{i}_{s\lambda_r} =$$

$$= L_m \cdot \underline{i}_m + L_{\sigma r} \cdot \underline{i}_{r\lambda_r} \quad .$$
(11)

From definition of the magnetization current corresponding to the rotor flux linkage \underline{i}_{mr} , [4], [9] results:

$$\underline{\Psi}_{r\lambda_r} = L_m \cdot \left| \underline{i}_{mr} \right|. \tag{12}$$

The replacement of equation (11) into equation (10) leads to:

$$0 = R_r \cdot \underline{i}_{r\lambda_r} + L_m \cdot \frac{d|\underline{i}_{mr}|}{dt} + j \cdot (\omega_{\lambda_r} - \omega_r) \cdot L_m \cdot |\underline{i}_{mr}|$$
(13)

From equations (11) and (12), and considering that:

$$\underline{i}_{m\lambda_r} = \underline{i}_{s\lambda_r} + \underline{i}_{r\lambda_r}$$

we obtain:

$$\underline{i}_{r\lambda_r} = \frac{|\underline{i}_{mr}| - \underline{i}_{s\lambda_r}}{l + \sigma_r}, \qquad (14)$$

where:

$$\sigma_r = L_{\sigma r} / L_m$$
 is the leakage coefficient of the rotor.



Fig. 2.Improved structure-diagram for speed and flux-linkage estimation

Through substitution of equation (14) into equation (13) and division of the resulting equation by the factor R_r an equation may be derived. This equation can be transformed into the equation of a first order element as follows:

$$T_r \cdot \frac{d|\underline{i}_{mr}|}{dt} + |\underline{i}_{mr}| = \underline{i}_{s\lambda_r} - j \cdot \left(\omega_{\lambda_r} - \omega_r\right) \cdot T_r \cdot |\underline{i}_{mr}|, (15)$$

where:

$$T_r = L_r/R_r$$
 is the time constant of the rotor.

Splitting into components onto the real- and the imaginary-axis leads to very simple equations describing the flux linkage model in the coordinate system referred to the rotor flux linkage:

$$T_r \cdot \frac{d|i_{mr}|}{dt} + |i_{mr}| = i_{sd\lambda_r}, \qquad (16)$$

and

$$\omega_{\lambda_r} = \omega_r + \frac{i_{sq\lambda_r}}{T_r \cdot |i_{mr}|}.$$
 (17)

According to relation (1) the estimated value is:

$$\hat{\omega}_2 = \frac{i_{sq\lambda_r}}{T_r \cdot |\underline{i}_{mr}|} = \frac{L_m}{T_r} \cdot \frac{i_{sq\lambda_r}}{|\underline{\Psi}_{r\lambda_r}|} \,. \tag{18}$$

The component of the stator's current $i_{sq\lambda_r}$ that produces the electromagnetic torque may be determined by means of actual (measured) stator's currents and the estimate rotor flux-linkage $\underline{\Psi}'_r$, [7], [9]:

$$i_{sq\lambda_{r}} = \frac{\underline{\hat{\Psi}}_{r}^{'} \times \underline{i}_{s}}{\left|\underline{\hat{\Psi}}_{r}^{'}\right|} = \frac{\underline{\hat{\Psi}}_{rd} \cdot i_{sq} - \underline{\hat{\Psi}}_{rq} \cdot i_{sd}}{\left(\underline{\hat{\Psi}}_{rd}^{'2} + \underline{\hat{\Psi}}_{rq}^{'2}\right)^{l/2}}$$
(19)

where: $\underline{\hat{\Psi}}_{r}^{'}$ is $\underline{\hat{\Psi}}_{r} \cdot e^{j \cdot \lambda_{r}}$.

From equations (1), (9), (18) and (19) and a cartesian-polar converter, the speed and flux-linkage estimator diagram is obtained (Fig. 2).

This approach has the following advantages: it is simple to build, and provides precise flux-linkage estimations even at very low frequencies. It also provides accurate estimations for the electromagnetic torque:

 $[m_e = (3/2p) \cdot (L_m/L_r) \cdot (\hat{\Psi}_{rd}i_{sq} - \hat{\Psi}_{rq}i_{sd}), \text{ or, whether}$ directly expressed with respect to the slip frequency $m_e = (3 \cdot p/2 \cdot R_r) \cdot \Psi_r^2 \cdot \omega_2].$

The structure diagram may be used both in vector control and also in direct torque control techniques. For improved results it is very important to choose the appropriate value for the time constant T_1 . The greatest and the lowest values for the time constant should be avoided.

3. CONCLUSIONS

The enhanced structure presented into the paper avoids the drift and "pure" integrators problems that occur in sensorless induction machine drive systems with speed and flux-linkage estimation. These problems are solved by means of a first-order element. The following parameters of the machine are used to build the structure: R_s , L'_s , $k = L_m/L_r$ and T_r . The use of the structure provides precise fluxlinkage estimations even at very low speed and hence precise estimations of the electromagnetic torque. The structure may be used in the induction machine's either vector-control or direct-toque-control.

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