An Evaluation of Sensorless Induction Motor Drives for Low Speed Operation

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***Abstract* – In this paper some sensorless strategies for induction motor drives are reviewed and analyzed. A method for accurately obtaining the PWM stator voltage is used to minimize the problem of estimating stator flux from the stator voltage equation in low speeds. A Gopinath style stator flux observer is presented and its capability to compensate for stator voltage errors is discussed.**

Keywords: Sensorless induction motor drives, flux observer, voltage measurement in PWM circuits.

I. INTRODUCTION

Induction motor drives have been thoroughly studied in the past few decades and many vector control strategies have been proposed, ranging from low cost to high performance applications.

In order to increase the reliability and reduce the cost of the drive, a great effort has been made to eliminate the shaft speed or position sensor in most high performance induction motor drive applications [1]-[3].

Generally, using the induction motor state equations, the flux and speed can be calculated from the stator voltage and current values [4]-[7], [11], [12]. The flux is estimated or observed from the stator voltage equation and the speed is obtained using the estimated flux and the rotor equation.

A model reference adaptive system (MRAS) [5], [6] is also used as an alternative method for sensorless induction motor drive strategy. In this case, the rotor flux is estimated from the induction motor stator equation (considered to be the reference model, once it does not depend on the speed) and also using the rotor equation (adaptive model). The speed is then obtained by the use of an adaptive law having the cross product of the two flux estimates as input.

In another proposed scheme [7], the flux is obtained by a full order Luenberger observer, taking the difference between measured and estimated stator currents to improve the observer dynamic response. In this case, the adaptation law to estimate the speed uses the cross product of the current error vector and the observed flux vector as input.

The methods above perform well except in very low speeds, near zero stator frequency. It can be shown [2] that at zero stator frequency the stator quantities are not affected by the rotor speed and, therefore, the speed cannot be observed from measured stator voltages and currents. Further, the stator voltage provided by the inverter is difficult to measure and sometimes is assumed to be equal to the reference voltage or calculated from the DC link voltage and inverter switches conditions. The errors caused by these assumptions are often negligible in high speeds. However, they can be relatively high in low speeds, since the voltages are reduced to maintain the reference flux and the errors due to the voltage drops and dead times in the switching devices become more prominent in lower output voltage range.

Other approaches have been recently proposed [8]-[10]. However, they need a high computational effort to be implemented and in some of them, a kind of intervention in the machine is necessary (e.g., high frequency signal injection and modifications on the rotor slots).

Despite the many attempts to obtain accurate flux and speed estimation for wide speed range induction motor drives proposed recently, it seems that the solutions do not meet simultaneously the simplicity, accuracy and reliability requisites to be largely accepted and used in the industries.

The main objective of this paper is to present some sensorless induction motor drives and the problems that arise in low speed operation. It will be shown how an accurate measurement of the stator voltage can improve sensorless drives and enable their use in lower speeds.

II. INDUCTION MOTOR MODEL

In an arbitrary reference frame, the induction motor model is described by the equations below:

$$\vec{v}_s = R_s \vec{i}_s + \dot{\vec{\lambda}}_s + j\omega_e \vec{\lambda}_s \quad (1)$$

$$\vec{0} = R_r \vec{i}_r + \dot{\vec{\lambda}}_r + j(\omega_e - \omega_r)\vec{\lambda}_r \quad (2)$$

$$\vec{\lambda}_s = L_s \vec{i}_s + L_m \vec{i}_r \quad (3)$$

$$\vec{\lambda}_r = L_m \vec{i}_s + L_r \vec{i}_r \quad (4)$$

where

$\vec{v}_s$	Stator voltage vector (V)
$\vec{i}_s$, $\vec{i}_r$	Stator and rotor current vectors (A)
$\vec{\lambda}_s$, $\vec{\lambda}_r$	Stator and rotor flux vectors
L_s, L_r, L_m	Stator, rotor and mutual inductances (H)
R_s, R_r	Stator and rotor resistances (Ω)
ω_e, ω_r	Reference frame and rotor speeds (elect. rad/s)

III. REVIEW OF SENSORLESS STRATEGIES

In this section, some of the methods based on the *dq* model for speed estimation in sensorless induction motor drives will be presented and discussed.

A. *Speed Calculation from State-Space Equations*

Two of these methods will be presented.

In the first one [4], the rotor flux vector is first estimated. In order to make the flux computation independent from the speed, the stator voltage equation (*voltage model*) in a stator fixed reference frame is usually preferred:

$$\vec{\lambda}_r = \frac{L_r}{L_m}\left[\int\left(\vec{v}_s - R_s\vec{i}_s\right)dt - \sigma L_s\vec{i}_s\right] \tag{5}$$

where σ is the leakage coefficient.

Rotor equation (2) can then be used to obtain rotor speed.

$$\omega_r = \begin{cases} -\dfrac{\dfrac{\lambda_{rd}}{\tau_r} - \dfrac{L_m}{\tau_r}i_{sd} + \dot{\lambda}_{rd}}{\lambda_{rq}} \\[2ex] \dfrac{\dfrac{\lambda_{rq}}{\tau_r} - \dfrac{L_m}{\tau_r}i_{sq} + \dot{\lambda}_{rq}}{\lambda_{rd}} \end{cases} \tag{6}$$

The author [4] proposed the use of the first equation only to estimate the speed. It should be noted however that the *d* and *q* axis flux components will be generally sinusoidal quantities. Thus, in order to avoid dividing by zero, we suggest using the second equation whenever $|\lambda_{rd}| > |\lambda_{rq}|$.

For low speed operation, when the frequency is also low, the integral in Eqn. (5) is difficult to implement due to offsets and drifts. A filter is often implemented to allow the strategy to be used in moderate and high speeds. A good measuring scheme, such as the one presented in the next section can be used to reduce the minimum speed for which the method can be applied.

Fig. 1 shows simulation results in low and high-speed operation of a sensorless drive with this strategy. No offsets or drifts in the measured signals were considered. The stator voltage was considered to be measured by using the scheme described in the next section. The good results show that it is ideally possible to implement a sensorless induction motor drive for zero speed operation, since the offsets and drift problems are solved for the integral in Eqn. (5) to be stable.

Another alternative to calculate flux and speed from the induction motor equations can be derived from the stator flux vector speed [11] and slip speed [12] expressions:

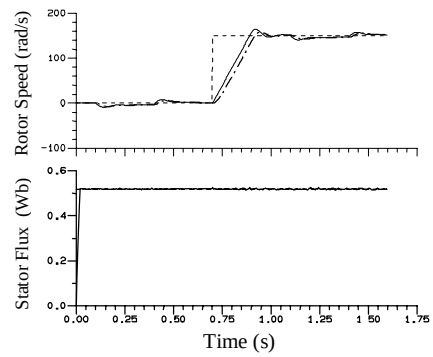


Fig. 1 Simulation results. Sensorless strategy according to Rajashekara [4].

$$\omega_e = \frac{\lambda_{sd}\dot{\lambda}_{sq} - \lambda_{sq}\dot{\lambda}_{sd}}{\lambda_{sd}^2 + \lambda_{sq}^2} \tag{7}$$

$$\omega_s = \frac{L_m}{\tau_r}\frac{\lambda_{sd}i_{sq} - \lambda_{sq}i_{sd}}{\lambda_{sd}^2 + \lambda_{sq}^2} \tag{8}$$

Rotor speed is obtained by subtracting Eqn. (8) from Eqn. (7).

The same problems associated to the low frequency integration necessary to compute the stator flux vector arise here. Simulation results without considering dc errors in the measuring signals are presented in Fig. 2. The results show again that the flux and speed calculation scheme would suffice, even for low speed operation, if no dc measurement errors were present. For high-speed operation the velocity became oscillatory and a digital filter was used.

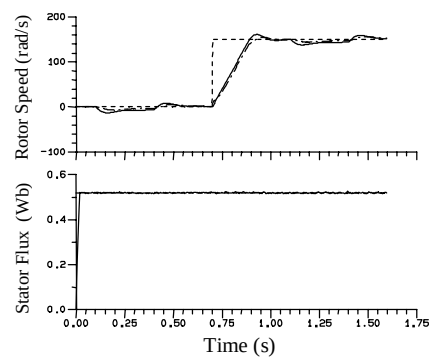


Fig. 2 Simulation results. Sensorless strategy using Eqs (7) and (8).

B. *Speed Estimation Using MRAS Techniques*

Model Reference Adaptive Systems (MRAS) techniques were applied in [5] and [6] in order to estimate rotor speed. Schauder [5] used the induction motor voltage model as in Eqn. (5), and the current model, derived from the rotor equation, to obtain two estimates for the rotor flux. The voltage model was considered to be the reference, once it does not depend on the speed. Then, from the two rotor flux estimates, an adaptive mechanism to generate the rotor speed to be used in the current model was developed. The current model and the adaptive mechanism are described by Eqns. (9) and (10) below.

$$\dot{\vec{\lambda}}_r = -\left(\frac{1}{\tau_r} - j\omega_r\right)\vec{\lambda}_r + \frac{L_m}{\tau_r}\vec{i}_s \qquad (9)$$

$$\hat{\omega}_r = k_p\left(\hat{\vec{\lambda}}_r^v \times \hat{\vec{\lambda}}_r^i\right) + k_i\int\left(\hat{\vec{\lambda}}_r^v \times \hat{\vec{\lambda}}_r^i\right)dt \qquad (10)$$

Simulation results using this speed estimation technique are shown in Fig. 3.

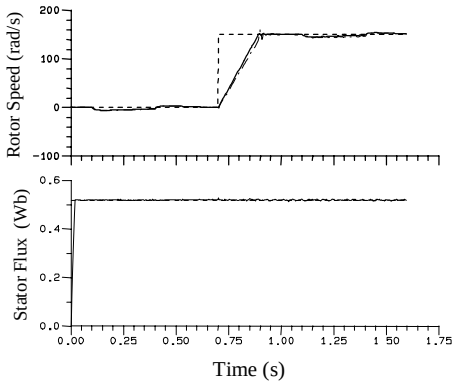


Fig. 3 Simulation results. Sensorless strategy according to Schauder [5].

All the alternatives presented make use of the voltage model in some way for the speed estimation and have problems for low speed operation.

Other techniques for speed estimation have been proposed recently. Rotor position and velocity can be estimated by injecting a high frequency signal in the machine terminals and tracking the rotor magnetic saliencies [8].

In a wye connected machine, the sum of the three stator voltages is dominated by the third harmonic component and a high frequency rotor slot ripple. Assuming a balanced operation, it can be shown [9], [10] that the amplitude and position of the air gap flux can be obtained from the third harmonic air gap voltage. In low speed operation, however, the signal/noise relation is very low and the third harmonic voltage is difficult to be precisely measured.

IV. Stator Voltage Measurement

When a shaft position or speed sensor is available, the use of a flux observer and the assumption of the stator voltage to be equal to the inverter reference voltage generally leads to good dynamical responses, even at zero speed. However, if the flux is obtained by the use of the voltage model, this assumption makes the flux estimation to fail in low speeds. In order to obtain a better estimation of the stator voltage, it is usual to determine the stator voltage from the inverter switches states and the measured DC link voltage.

Sensorless induction motor drives have their use limited to speeds down to about 1% of rated value [13]. In order to extend this speed range, problems caused by the inaccuracy of stator voltage measurement and problems due to offsets and drifts must be solved.

The inverter instantaneous output voltage measurement is difficult to implement, once it requires A/D conversion in a very high sampling rate. Some methods to calculate precisely the stator voltage from the DC link voltage and the states of the inverter switches have been recently proposed [13]-[16]. Generally, a compensation scheme for A/D conversion offsets, dead time of the inverter and forward voltage drops in the switches is used.

Another alternative was presented in [17]. The voltage to be measured is integrated each switching period. At the end of each period, the integration is stopped and the output is held during an interval necessary for its digital detection. The average voltage is obtained by dividing the detected value by the switching period. Then, the integrator is reset to zero until the next operation. Two groups of circuit are necessary for alternating the measurement. This *instantaneous average voltage-measuring* scheme was used to obtain the results in this paper. The scheme is simple and inexpensive and was physically implemented. The two integrators must use accurate components to give identical results for identical inputs. Otherwise some voltage fluctuation will appear in the output and this may deteriorate the flux calculation. The circuit must be carefully built in order to ensure its linearity and accuracy.

V. Control Strategy

A Deadbeat Direct Torque and Flux Control (DTFC) strategy recently proposed was used [18]. The voltage vector necessary to eliminate the flux and torque errors in one switching period is determined in a stator flux reference frame. This calculated voltage vector serves as a reference to a space vector PWM scheme.

The flux and torque controllers are described below.

A. Flux Control

In a stator flux reference frame, the *q* axis flux component is zero and the flux dynamics can be imposed only by the *d* axis stator voltage component.

$$v_{sd} = R_s i_{sd} + \dot{\lambda}_{sd} \qquad (11)$$

Considering *T* as the sampling period and *k* as the sampling instant, Eqn. (11) can be written as a discrete forward difference equation:

$$\lambda_{sd}(k+1) = \lambda_{sd}(k) + [v_{sd}(k) - R_s i_{sd}(k)]T \qquad (12)$$

In order to impose a deadbeat flux control, it should be considered that $\lambda_{sd}(k+1) = \lambda_s^*$. Then

$$v_{sd}(k) = \frac{\lambda_s^* - \hat{\lambda}_{sd}(k)}{T} + R_s i_{sd}(k) \qquad (13)$$

where the symbols * and ^ denote the commanded value and the estimated or observed value, respectively.

B. Torque Control

The electromagnetic torque in the stator flux reference frame is

$$T_e = \frac{3}{2}\frac{P}{2}\lambda_{sd} i_{sq} \qquad (14)$$

where P is the pole number.

Considering that the flux is conveniently controlled, the torque depends only on the q axis current. This current is strongly related to the stator flux vector speed as it can be seen from the quadrature component of Eqn. (2), rewritten in terms of stator flux and current components in a stator flux reference frame:

$$\omega_e = \omega_r + \frac{\frac{L_s}{\tau_r} i_{sq} + \sigma L_s \dot{i}_{sq}}{\lambda_{sd} - \sigma L_s i_{sd}} \tag{15}$$

where τ_r is the rotor time constant and σ is the leakage coefficient.

By the use of a sufficiently small sampling period, the current derivative in (15) can be written as a forward difference equation:

$$\dot{i}_{sq} = \frac{i_{sq}(k+1) - i_{sq}(k)}{T} \tag{16}$$

and, imposing the electromagnetic torque to be equal to the commanded value in the next sampling instant results in

$$i_{sq}(k+1) = \frac{T_e^*}{\frac{3}{2}\frac{P}{2}\hat{\lambda}_{sd}(k)} \tag{17}$$

Combining (15), (16) and (17) gives

$$\omega_s^* = \omega_r(k) + \frac{\frac{L_s}{\tau_r} i_{sq}(k) + \left(\frac{T_e^*}{\frac{3}{2}\frac{P}{2}\hat{\lambda}_{sd}(k)} - i_{sq}(k) \right)}{\hat{\lambda}_{sd}(k) - \sigma L_s i_{sd}(k)} \tag{18}$$

In order to impose w^*_s the q axis component of Eqn. (1) can be used, taking v_{sq} as input:

$$v_{sq}(k) = R_s i_{sq}(k) + \omega_s^* \lambda_{sd}(k) \tag{19}$$

Fig. 4 shows the block diagram of the prototype implemented to obtain the experimental results.

VI. Flux and Speed Estimation

In order to evaluate the effect of the voltage measuring scheme and whether a flux observer is able or not to compensate for the voltage errors, a reduced order Gopinath stator flux observer was implemented. A feedback term based on the derivative of the stator current error was added to the stator voltage equation in a stator reference frame to improve the observer dynamic response.

$$\begin{cases} \dot{\vec{\lambda}}_s = \vec{v}_s - R_s \vec{i}_s \\ \dot{\hat{\vec{\lambda}}}_s = \vec{v}_s - R_s \vec{i}_s - \boldsymbol{L}(\dot{\vec{i}}_s - \dot{\hat{\vec{i}}}_s) \end{cases} \tag{20}$$

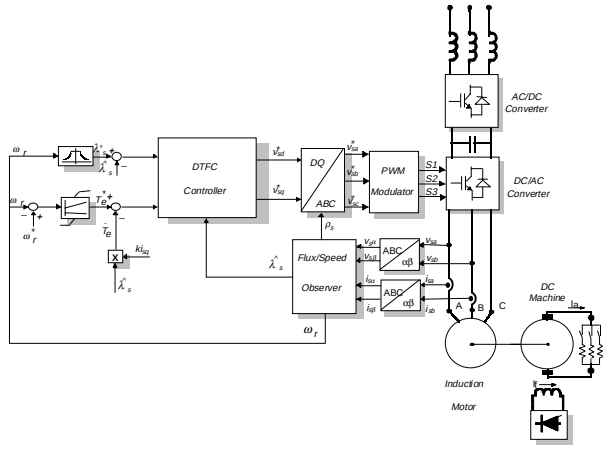


Fig. 4. Induction Motor Drive Station

The stator current derivative in Eqn. (20) is calculated from stator voltage, stator current and stator flux, using the induction motor state model:

$$\begin{cases} \dot{\vec{i}}_s = \frac{1}{\sigma L_s}\left[\vec{v}_s - R_s' \vec{i}_s + \left(\frac{R_r}{L_r} - jw_r \right) \vec{\lambda}_s - \left(\frac{R_r}{L_r} - jw_r \right) \sigma L_s \vec{i}_s \right] \\ \dot{\hat{\vec{i}}}_s = \frac{1}{\sigma L_s}\left[\vec{v}_s - R_s' \vec{i}_s + \left(\frac{R_r}{L_r} - jw_r \right) \hat{\vec{\lambda}}_s - \left(\frac{R_r}{L_r} - jw_r \right) \sigma L_s \vec{i}_s \right] \end{cases} \tag{21}$$

where

$$R_s' = R_s + R_r \frac{L_m^2}{L_r^2}.$$

The stator flux error is then governed by

$$\dot{\vec{\varepsilon}} = \dot{\vec{\lambda}}_s - \dot{\hat{\vec{\lambda}}}_s = \boldsymbol{L} \frac{1}{\sigma L_s} \left(\frac{1}{\tau_r} - j\omega_r \right) \vec{\varepsilon} \tag{22}$$

or, considering

$$\boldsymbol{L} = \begin{bmatrix} l_1 & -l_2 \\ l_2 & l_1 \end{bmatrix}$$

$$\dot{\vec{\varepsilon}} = \frac{1}{\sigma L_s} \begin{bmatrix} \frac{l_1}{\tau_r} - l_2\omega_r & l_1\omega_r - \frac{l_2}{\tau_r} \\ -\left(l_1\omega_r - \frac{l_2}{\tau_r} \right) & \frac{l_1}{\tau_r} - l_2\omega_r \end{bmatrix} \vec{\varepsilon} = \begin{bmatrix} \alpha & -\beta \\ \beta & \alpha \end{bmatrix} \vec{\varepsilon} \tag{23}$$

Any observer dynamics can be easily imposed by an adequate choice of l_1 and l_2. However, in order to make the real part of the eigenvalues to be independent from the speed, l_2 will be chosen equal to zero. The observer poles are then

$$s_{1,2} = \frac{1}{\sigma L_s} \left(\frac{l_1}{\tau_r} \pm j\omega_r l_1 \right) \tag{24}$$

As it can be seen, ω_r influences only the imaginary part of the eigenvalues. However, l_1 cannot be arbitrarily chosen for the discrete time flux computation requires a limited sampling rate.

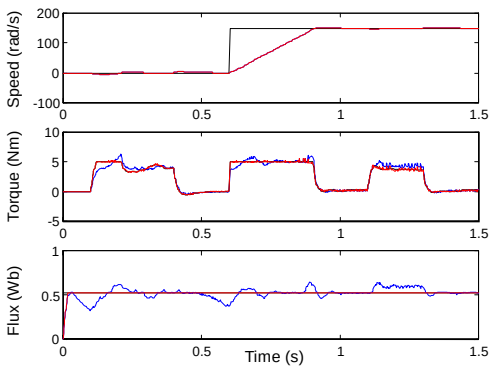
VII. Flux Observer and Voltage Measurement Effects

Some simulation results are presented to emphasize the flux observer capability to compensate for the stator voltage errors on estimated flux and therefore on the speed accuracy.

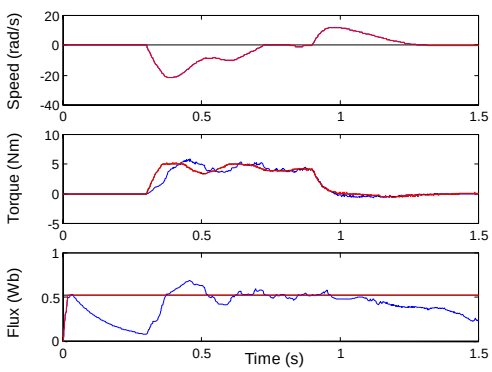
The flux, torque and speed responses to steps in the load torque and commanded speed are analyzed at standstill and 150 electrical radians per second. Reference, observed and real values are shown in the graphs.

The sensorless results were here obtained by the use of the strategy proposed in [4], and presented in section 3.

The results considering no voltage measuring scheme (for the flux estimation, the stator voltage was assumed to be equal to the inverter reference voltage), a flux estimation based on induction motor equations without any feedback and the existence of an ideal speed sensor is presented in Fig.5. As shown, the stator flux can be estimated, although with high errors, except in low speeds. The inverter does not ideally produce stator voltage reference. The flux is estimated integrating the stator voltage equation and considering the stator voltage to be equal to the reference voltage was the main cause for flux and torque errors. At zero speed the flux estimation fails for the relation between voltage error and stator voltage is much bigger.



(a)



(b)

Fig. 5 Results assuming no voltage measurement, flux estimated using voltage model and ideal speed measurement. (a) Zero and 150 rad/sec responses. (b) Zero speed response.

The inclusion of the described Gopinath observer to the scheme above enables the flux to be accurately determined, even at zero speed, as shown in Fig. 6. Using the observer means that additional information is given by the current model, reducing the effect of the voltage errors in the flux estimate.

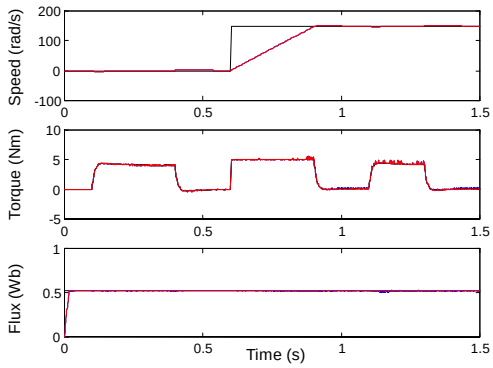


Fig. 6 Results with no voltage measurement, presence of flux observer and ideal speed measurement.

In a sensorless drive, however the flux observer was no longer capable of compensating for the stator voltage errors and unstable results were obtained. The speed estimation errors made the current model inaccurate to be used for correcting the voltage model flux estimate.

In Figs. 7 and 8, the instantaneous average stator voltage measurement was used. No speed sensors were considered and the flux was obtained simply by the use of the induction motor stator voltage equation.

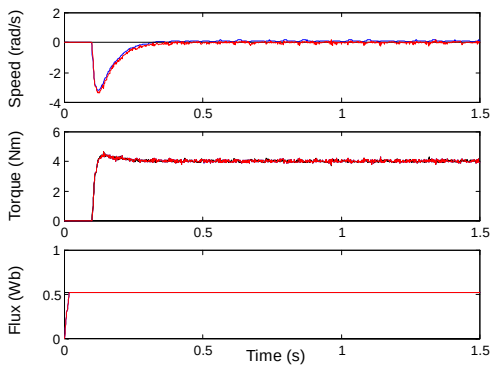


Fig. 7 Zero speed results with average voltage measurement, flux estimated using voltage model and no speed sensor.

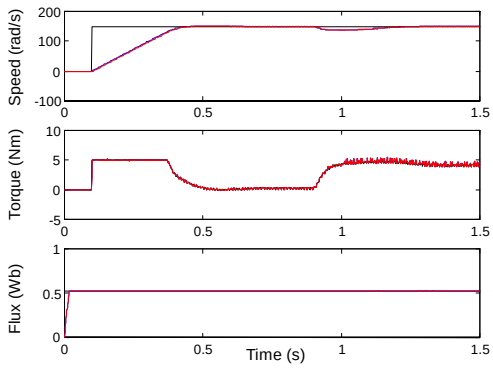


Fig. 8 150 rad/sec results with average voltage measurement, flux estimated using voltage model and no speed sensor.

As indicated in the results, the stator voltage measurement enables the use of the sensorless induction motor drive at standstill, with or without load torque applied. It should be noted that when operating at zero speed without load torque applied the stator frequency is

zero and the speed is not observable from terminal quantities. There will be an error in the flux and torque estimates and some torque will be applied. This causes the frequency to increase and the speed to become again observable. The minimum speed for which the drive can operate depends on the measurement errors, specially due to the problems of integrating stator voltage containing a DC offset.

VIII. EXPERIMENTAL RESULTS

Experimental responses to steps in the speed and load torque commands with the use of a speed sensor, considering the stator voltage to be ideally produced by the PWM inverter and using the proposed reduced order flux observer are presented in [18]. The results obtained are very similar to the simulations.

Sensorless strategy proposed by Rajashekara [4] was used to obtain the results presented in Figs. 9, 10 and 11. Stator voltages were again considered to be equal to the reference values. However, in order to avoid DC errors to make the flux estimation unstable, stator *emf* integration was made by the use of a low pass filter. A programmable time constant was used in the filter to enable its use in a wide speed range. Further, a compensation scheme for the filter to have gain and phase equal to that of a pure integrator in steady state was used.

In Fig. 9 steps in the speed command of 150 electrical rad/d and 40 electrical rad/s are applied, respectively. Good flux, torque and speed responses are observed. However, the system was not able to operate in speeds below 20 electrical rad/s. This means that the low pass filter for the flux estimation was no longer capable of distinguishing the DC errors from the low frequency signal to be integrated in a sufficiently short time.

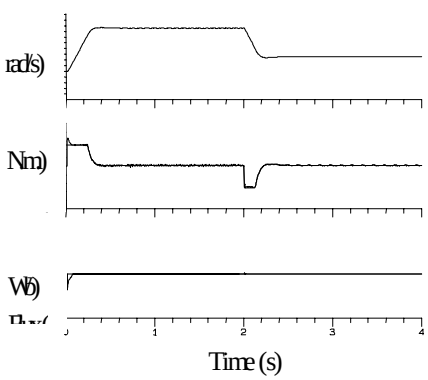


Fig. 9 Responses to steps in the commanded voltage. No voltage or speed measurement. Voltage model used to estimate the stator flux.

The response to a ± 2 N.m. square wave commanded torque in the low speed range is presented in Fig. 10. The corresponding speed versus torque curve is shown in Fig. 11. As shown the estimated torque follows accurately the reference and a corresponding triangular speed curve is obtained.

Unfortunately, the *instantaneous voltage measuring scheme* was implemented with components not accurate enough and the difference in the responses of the two necessary circuits made the measured voltage too oscillatory. For this reason, no experimental results using the technique are presented. The authors are working for the improvement of the voltage measuring circuit.

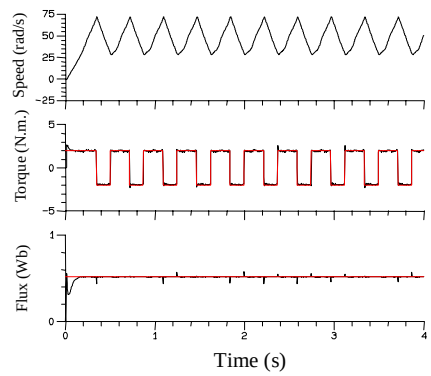


Fig. 10 Responses to a square wave commanded torque. No voltage or speed measurement. Voltage model used to estimate the stator flux.

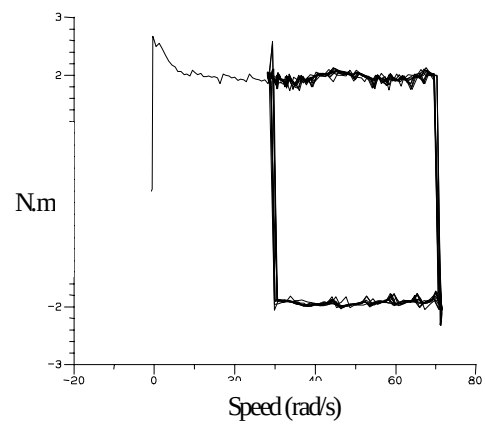


Fig. 11 Speed x Torque response to a square wave commanded torque. No voltage or speed measurement. Voltage model used to estimate the stator flux.

IX. CONCLUSION

Some of the strategies for sensorless induction motor drives were reviewed and the effects of including a flux observer and a PWM *instantaneous average measuring scheme* were analyzed.

When a speed sensor is available, the use of a flux observer showed to be an effective means to enable fast and precise flux estimation without any voltage-measuring scheme. The observer uses both voltage and current models. Since the current model depends on the speed, some additional mechanism must be used to ensure convergence for sensorless drives without some voltage measuring scheme.

The implemented stator voltage-measuring scheme reduces the lower speed limit for induction motor drives with stator flux estimated only by the voltage model to be applied.

X. ACKNOWLEDGEMENT

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