An Algorithm for Induction Motor Stator Flux Estimation

Djordje M. STOJIC
Electrical Institute "Nikola Tesla", University of Belgrade
Koste Glavinica 8a, 11000 Belgrade, Serbia
djordje.stojic@ieent.org

***Abstract*—A new method for the induction motor stator flux estimation used in the sensorless IM drive applications is presented in this paper. Proposed algorithm advantageously solves problems associated with the pure integration, commonly used for the stator flux estimation. An observer-based structure is proposed based on the stator flux vector stationary state, in order to eliminate the undesired DC offset component present in the integrator based stator flux estimates. By using a set of simulation runs it is shown that the proposed algorithm enables the DC-offset free stator flux estimated for both low and high stator frequency induction motor operation.**

***Index Terms*—digital control, induction motors, motor drives, numerical models, sensorless control.**

I. Introduction

The development of the speed sensorless induction motor (IM) control algorithms [1]-[3] relies on the precise estimation of the IM stator flux. The flux estimation is based on two different approaches: the current model, and voltage model of induction motor. The current model based flux estimation method [1], [2], [3], [6], [10] relies on the IM model which incorporates stator and rotor variables, including rotor speed. Dissimilarly, the voltage model based flux estimation method [4]-[5], [8]-[9], [11] relies on the estimation of the stator flux by using only the stator variables.

The first approach for the stator and rotor flux estimation is based on the set of equations representing the current model of induction motor [1]-[3], [6], [10]. The precise operation of the estimation scheme requires the on-line calculation of the IM model stator and rotor variables. This estimation is realized by using the IM model observers, which in some cases include the adaptive parameter calculation. The problem associated with the full-order observer based stator flux estimation resides in the unstable drive operation in the torque reversal operation, i.e. during the regeneration mode of the IM operation.

In the estimation scheme based on the voltage IM model [4]-[5], [8]-[9], [11] the stator flux vector is calculated by integrating the IM back electromotive force (EMF). In this approach, the accuracy of stator flux estimation depends on the precise knowledge of one parameter, the IM stator resistance. The problem associated with the voltage model estimation schemes resides in the presence of DC offset in the stator flux estimates. The presence of a DC offset is in pure integrator based estimators inevitable and, if not compensated, it can degrade the accuracy of stator flux estimation, and produce the instability of the superimposed control algorithm.

This paper presents a novel algorithm for the stator flux estimation based on the voltage IM model, where the proposed estimation scheme can be implemented in the IM control algorithms with known stator frequency (e.g., a field oriented control algorithm, or DTC with the constant switching frequency). It enables the compensation of DC offsets in the stator flux estimates for a wide range of stator frequencies, including the values approaching zero. The DC offset compensation is accomplished by using the back-emf observer based structure, which reduces the steady-state estimation error, i.e., it eliminates the DC offset present in the stator flux estimates due to pure integration.

The proposed integration algorithm is based on the stationary state value of the stator flux vector derived from the stator variables and stator frequency. This technique differs from the voltage model based methods [4]-[5], [8]-[9], [11] used to the rejection of the DC offset, in the following ways. Namely, the first method [4], [8]-[9], [11] uses the low pass filters instead of the pure integrator for the stator flux estimation. The drawback of this solution is the presence of stator flux estimation error in the stator frequency range below the filter cutoff frequency, i.e., for the frequency range approaching zero. Although, in [9] and [11] the magnitude and phase error in the stator flux estimates is compensated in the wide range of operating frequencies, the proposed flux phase and magnitude compensation fails in the frequency range around zero. Contrary to this, in this paper the stator flux estimation algorithm enables the error free stator flux estimation in the low frequency range, together with the successful operation in the high frequencies. In the second stator flux estimation scheme [5], the saturated feedback integrator is used. This solution requires a relatively long time for the DC offset compensation, especially for low IM stator frequencies. However, the stator flux estimation technique proposed in this paper doesn't introduce the estimation error in any frequency region as in [4], while operating with adjustable estimation time, set by the values of the estimator parameters. The estimation dynamic can consequently be adjusted to enable the lower estimation time when compared to [5]. In [24], an improved low pass filter solution is proposed that includes the steady-state flux estimation error compensation, but with the shortcoming that it requires the division by a near-zero value of the low frequency mode of IM drive operation.

Digital Object Identifier 10.4316/AECE.2012.03007

In the following sections, the proposed flux estimation scheme is analyzed in more details and verified through a set of simulation runs. Section 2 presents the structure of the proposed stator flux estimator. In Section 3, the stator flux estimation results are investigated and verified through a set of simulation runs, over a wide range of the stator frequencies.

II. The Flux Estimation Algorithm

The proposed estimation algorithm is based on the set of equations (1)-(8), representing the model of IM in the stationary $\alpha\beta$ reference frame.

$$V_{\alpha s} = R_s i_{\alpha s} + \frac{d}{dt}\psi_{\alpha s} \tag{1}$$

$$V_{\beta s} = R_s i_{\beta s} + \frac{d}{dt}\psi_{\beta s} \tag{2}$$

$$0 = R_r i_{\alpha r} + \frac{d}{dt}\psi_{\alpha r} - \omega_r \psi_{\beta r} \tag{3}$$

$$0 = R_r i_{\beta r} + \frac{d}{dt}\psi_{\beta r} + \omega_r \psi_{\alpha r} \tag{4}$$

$$\psi_{\alpha s} = L_s i_{\alpha s} + L_m i_{\alpha r} \tag{5}$$

$$\psi_{\beta s} = L_s i_{\beta s} + L_m i_{\beta r} \tag{6}$$

$$\psi_{\alpha r} = L_r i_{\alpha r} + L_m i_{\alpha s} \tag{7}$$

$$\psi_{\beta r} = L_r i_{\beta r} + L_m i_{\beta s} \tag{8}$$

where $V_{\alpha s}$ represents stator voltage α component, $V_{\beta s}$ stator voltage β component, $i_{\alpha s}$ stator current α component, $i_{\beta s}$ stator current β component, $\psi_{\alpha s}$ stator flux α component, $\psi_{\beta s}$ stator flux β component, $i_{\alpha r}$ rotor current α component, $i_{\beta r}$ rotor current β component, $\psi_{\alpha r}$ rotor flux α component, $\psi_{\beta r}$ rotor flux β component, R_s stator resistance, R_r rotor resistance, L_s stator inductance, L_r rotor inductance, L_m mutual inductance, and ω_r rotor speed.

The stator and rotor flux values can be estimated by using the following equations

$$\psi_{\alpha s} = \int \left(V_{\alpha s} - R_s i_{\alpha s}\right) dt \tag{9}$$

$$\psi_{\beta s} = \int \left(V_{\beta s} - R_s i_{\beta s}\right) dt \tag{10}$$

$$\psi_{\alpha r} = \frac{L_r}{L_m}\psi_{\alpha s} - \frac{L_s L_r - L_m^2}{L_m} i_{\alpha s} \tag{11}$$

$$\psi_{\beta r} = \frac{L_r}{L_m}\psi_{\beta s} - \frac{L_s L_r - L_m^2}{L_m} i_{\beta s} \tag{12}$$

derived from (1)-(8).

Equations (9)-(10) show that the stationary flux vector can be estimated by integrating the IM back-emf. Equations (11)-(12) show that the rotor flux vector can be derived by using the estimate of the stationary flux vector and measured values of stator currents.

As previously mentioned in the introductory section, integration of the back-emf signals (9)-(10) causes the DC biased stator flux estimation. In this paper, the novel integration method is introduced, which enables the compensation of integrator DC offset signal by using the back-emf observer. The back-emf observer is based on the stationary state value of the back-emf integrates, derived from stator IM variables and stator frequency value. Namely, the integration of the sinusoidal signal with the angular frequency ω introduces the phase lag of $\pi/2$ and amplitude attenuation $1/\omega$. Consequently, the stationary state of the integral $\psi^s_{\alpha\beta s}$ of back-emf vector $e_{\alpha\beta s}$, rotating with angular frequency ω in the stationary $\alpha\beta$ frame, can be calculated as

$$\begin{aligned}\psi^s_{\alpha\beta s} &= \psi^s_{\alpha s} + j\psi^s_{\beta s} = \frac{1}{j\omega}\left(V_{\alpha\beta s} - R_s I_{\alpha\beta s}\right) \\ &= \frac{1}{j\omega} e_{\alpha\beta s} = \frac{1}{\omega}\left(e_{\beta s} - j e_{\alpha s}\right)\end{aligned} \tag{13}$$

Consequently, from (13) the stationary state values of stator flux vector components in $\alpha\beta$ frame is derived from

$$\psi^s_{\alpha s} = \frac{1}{\omega} e_{\beta s} = \frac{1}{\omega}\left(V_{\beta s} - R_s I_{\beta s}\right) \tag{14}$$

$$\psi^s_{\beta s} = -\frac{1}{\omega} e_{\alpha s} = -\frac{1}{\omega}\left(V_{\alpha s} - R_s I_{\alpha s}\right). \tag{15}$$

The problem associated with the calculation of the stationary value of stator flux vector, given in (14) and (15), is linked with the algorithm operation for the low stator frequency values. Namely, the division by ω makes (14) and (15) impractical in the low frequency range.

However, the known stationary value of the stator flux can be used to reduce the DC offset in the stator flux estimate obtained by the means of pure integration, given in (16).

$$\psi_{\alpha\beta s} = \int e_{\alpha\beta s} dt = \int \left(V_{\alpha\beta s} - R_s I_{\alpha\beta s}\right) dt \,. \tag{16}$$

The discrete equivalent of (16) is represented by

$$\psi_{\alpha\beta s}(k) = \psi_{\alpha\beta s}(k-1) + T_s e_{\alpha\beta s}(k) \,. \tag{17}$$

The DC offset in (17) can be reduced by incorporating the steady-state value of the stator flux (13) in (17), in the following manner

$$\begin{aligned}&\psi_{\alpha\beta s}(k) = \psi_{\alpha\beta s}(k-1) + \\ &T_s \left\{ e_{\alpha\beta s}(k) - C\left[\psi_{\alpha\beta s}(k-1) - \psi^s_{\alpha\beta s}(k-1)\right]\right\}\end{aligned} \tag{18}$$

In order to prevent the division by ω in (13) and (18), the following value for C is adopted

$$C = k_1 \frac{\omega}{\omega + k_2} \tag{19}$$

The diagram of the proposed stator flux estimation scheme is given in Fig. 1.

Consequently, the following stator flux estimator expression is obtained by substituting (13) and (19) into (18)

$$\psi_{\alpha\beta s}(k) = \psi_{\alpha\beta s}(k-1)\left(1 - \frac{T_s k_1 \omega}{\omega + k_2}\right) + T_s e_{\alpha\beta s}(k) - j\frac{T_s k_1}{\omega + k_2} e_{\alpha\beta s}(k-1) \tag{20}$$

where T_s represents the flux estimator sampling period of 300 μs.

The components of the stator flux estimate (20), which include the back-emf vector components given in (14) and (15), are given in the following equations.

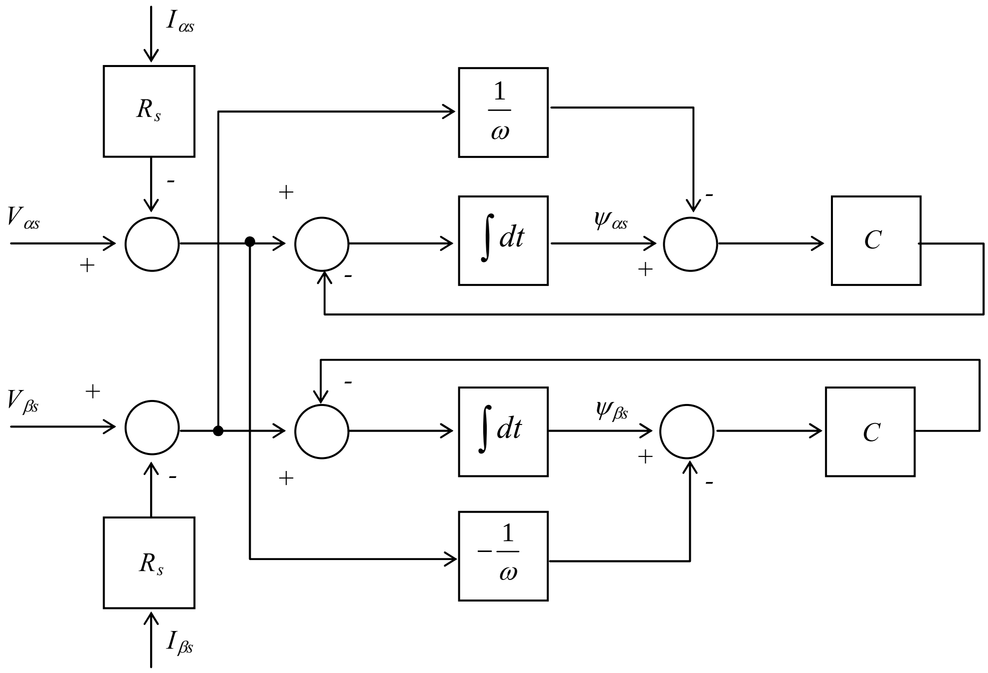

Figure 1. The schematic diagram of the proposed stator flux estimator

$$\psi_{\alpha s}(k) = \psi_{\alpha s}(k-1)\left(1 - \frac{T_s k_1 \omega}{\omega + k_2}\right) + T_s e_{\alpha s}(k) + \frac{T_s k_1}{\omega + k_2} e_{\beta s}(k-1) \tag{21}$$

$$\psi_{\beta s}(k) = \psi_{\beta s}(k-1)\left(1 - \frac{T_s k_1 \omega}{\omega + k_2}\right) + T_s e_{\beta s}(k) - \frac{T_s k_1}{\omega + k_2} e_{\alpha s}(k-1) \tag{22}$$

Parameters k_1 and k_2, together with the value of frequency ω, determine the speed of stator flux estimation, i.e., they define the placement of the estimator discrete transfer function (23) poles, derived from (20)

$$G_{est}(z) = \frac{\psi_{\alpha\beta s}(z)}{e_{\alpha\beta s}(z)} = \frac{zT_s - j\dfrac{T_s k_1}{\omega + k_2}}{z - \left(1 - \dfrac{T_s k_1 \omega}{\omega + k_2}\right)}. \tag{23}$$

Thus, the pole σ of the discrete transfer function (23), equal to $\sigma = 1 - T_s\, k_1\, \omega / (\omega + k_2)$, determines the speed of stator flux estimation, and therefore it should be set to the value that enables a stable and fast estimator operation in the entire range of stator frequencies. In Fig 2, the analysis of the pole placement of the transfer function (23) is performed in the low frequency range, for the parameters k_1 and k_2 set to values 1000 and 0.01, respectively.

Namely, in Fig. 2 the pole values of the stator flux estimator are shown in relation to the stator voltage angular frequency ω. It is shown that for the frequencies above 0.01 rad/s (k_2 value) the estimator transfer function pole resides within the range between 0.5 and 0.75, which guarantees the fast extraction of the DC offset signal present in the stator flux estimates. For the frequencies below 0.01 rad/s, the estimator transfer function pole values converge to 1.

Consequently, the choice of the value of parameter k_2 determines the lower frequency margin for the DC offset free stator flux estimation, while k_1 defines the range of the transfer function (23) pole values for stator frequencies above k_2. For the frequencies bellow k_2 the speed of DC offset diminution decreases, and, for the zero stator frequency the proposed stator flux estimation algorithm performs as a common integrator.

The practical implementation of the stator flux estimation algorithm given in (23) should not impose any out of ordinary obstacles, due to the fact the motor control oriented microcontrollers with the floating-point based arithmetic [26] are extensively being introduced in IM motor drive control electronics.

In the next section, the results of simulation runs are presented, in order to verify the performance of the proposed stator flux estimation scheme.

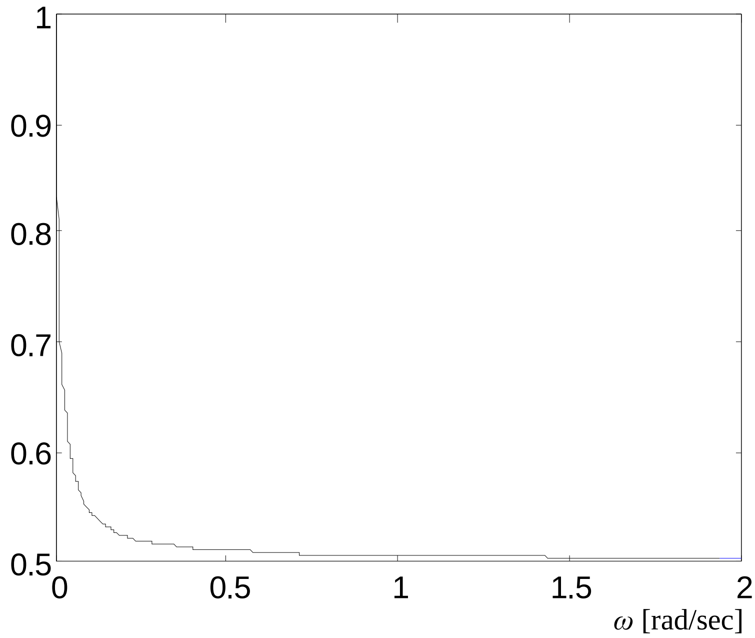

Figure 2. The estimator pole placement in relation to the stator frequency value

III. Simulation Results

The operation of the proposed stator flux estimation scheme is tested through the set of simulation runs, based on the induction motor modes of operation for the three different stator frequencies.

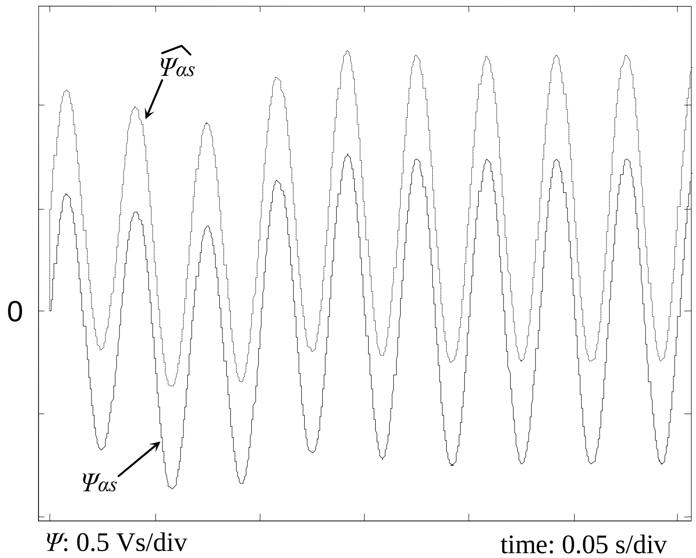

Figure 3. Stator flux estimation with a pure integrator, for the stator frequency 30 Hz

Figure 3 shows the simulation results for the induction motor operating with 30 Hz stator frequency value, with the common integration scheme used for the stator flux estimation. Due to the initial integrator condition error, the DC offset in the stator flux estimate (dashed plot) is present, when compared to the actual stator flux value (filled plot).

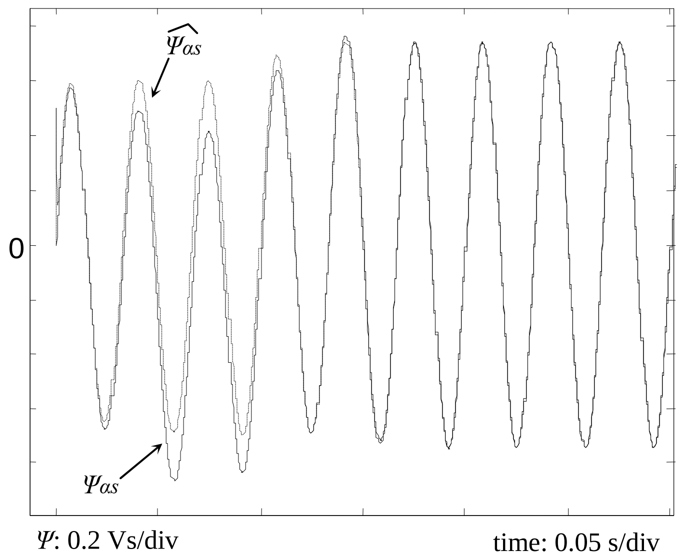

Figure 4. Stator flux estimation with the proposed integrator, for the stator frequency 30 Hz

In Fig. 4, the results of the stator flux estimation scheme in Fig. 1 are presented. The result of simulation runs show that the observer based estimation enables the DC-offset-free operation. Also, the fast DC offset extraction is achieved, in accordance with the flux estimator pole placement plot given in Fig. 2.

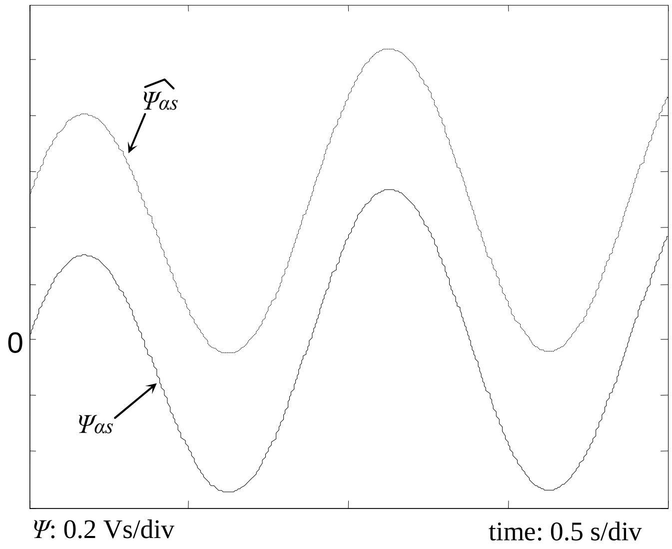

Figure 5. Stator flux estimation with a pure integrator, for the stator frequency 1 Hz

For the next simulation run the stator frequency is set to 1 Hz, in order to examine the estimation performance within a low frequency range. Similar to the high frequency estimator operation, for the common integrator estimation scheme the stator flux estimate with DC offset is produced, as illustrated by the simulation traces given in Fig. 5.

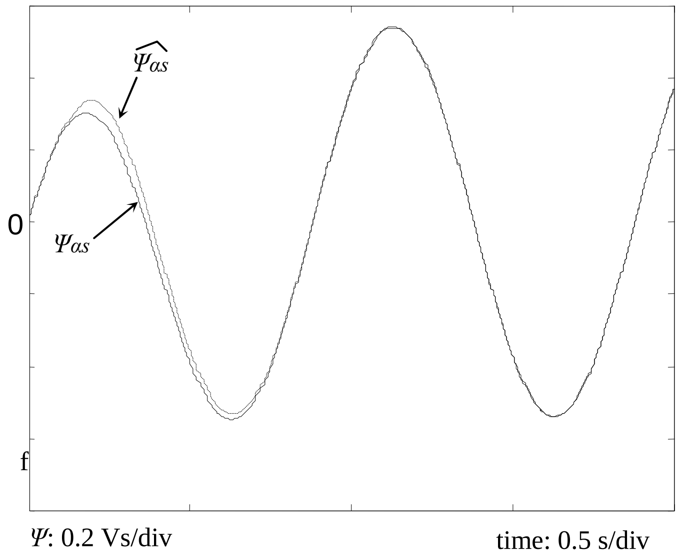

Figure 6. Stator flux estimation with the proposed integrator, for the stator frequency 1 Hz

However, the observer-based stator flux estimator produces offset-free estimates, given in Fig. 6. Also, the simulation traces in Fig. 6 show that for the low frequency range the proposed estimator enables a fast extraction of the DC bias from the stator flux estimates.

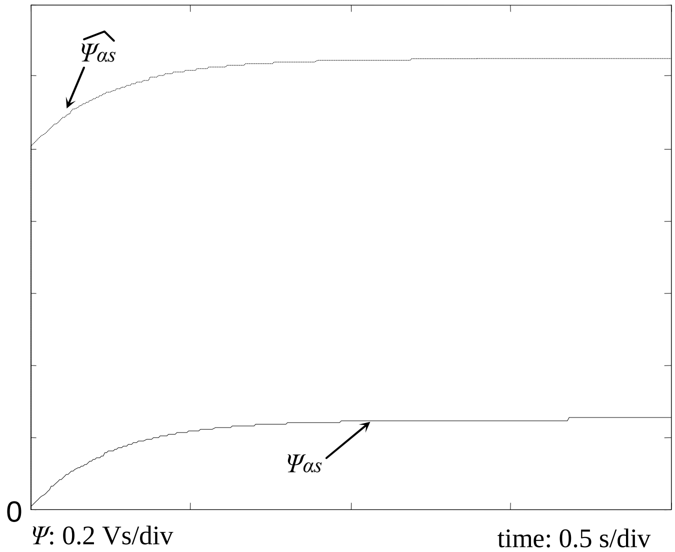

Figure 7. Stator flux estimation with a pure integrator, for the stator frequency 0.01 Hz

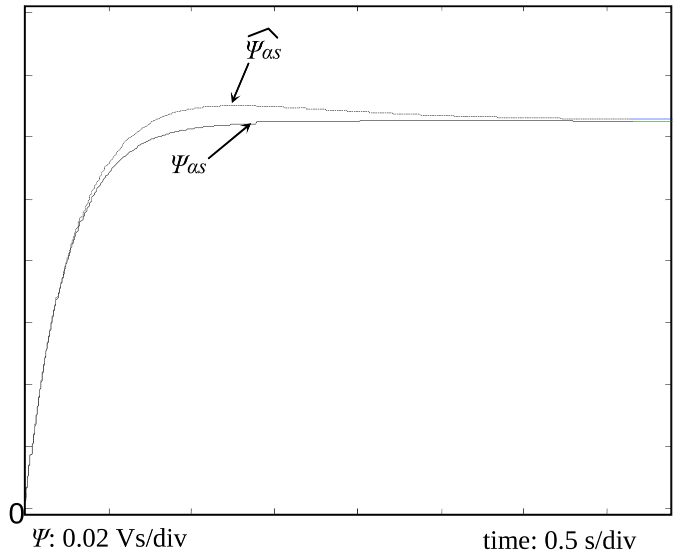

Figure 8. Stator flux estimation with the proposed integrator, for the stator frequency 0.01 Hz

Figures 7 and 8 present the simulation results for near zero stator frequency operation of the flux estimator. For the stator frequency 0.01 Hz common integrator scheme produces biased estimation (Fig. 7), while the observer-based scheme enables the bias-free estimator operation (Fig. 8). Simulation runs given in Fig. 8 prove that, when compared to [4]-[5], [8]-[9], [11] stator flux integration scheme proposed in this paper extends the low frequency value margin within which the DC offset free extraction is achieved. Consequently, by choosing a sufficiently low value of the parameter k_2, the lower frequency margin for the successful stator flux estimation can be further extended.

Nevertheless, by comparing the simulation results in Figs. 3-8 it can be concluded that the stator flux settling time varies with the stator frequency value, i.e. it increases as the stator frequencies decrease. This effect is illustrated by the plot in Fig. 2 that presents the pole distribution of the estimator characteristic polynomial. As the stator frequencies decrease, the estimator poles approach to 1, meaning the estimation time increases. The estimation time in the low frequency region can further be decreased by increasing the value of parameter *k1*.

IV. CONCLUSIONS

In this paper, the new algorithm for the estimation of IM stator flux has been presented. It enables the fast flux estimation, free of DC offset bias in the estimated stator flux value. The proposed estimation scheme is realized by using the numerical algorithm, which uses the stationary stator flux vector value to compensate the DC offset from the stator flux estimates. The algorithm includes the modified integration scheme based on the back-emf observer. The estimator performance, including the estimation time, can be adjusted by the means of two parameters *k1* and *k2*. While the first parameter serves for the closed loop estimator pole placement, the second parameter determines the estimator dynamic for the zero frequency operation. The presented IM flux estimation can advantageously be implemented in the speed sensorless IM drives with known stator frequency value. The efficiency of the proposed algorithm is verified through the set of simulation runs. Presented simulation results show that the estimator successfully operates in high, low frequency region, and in the frequency range around zero.

ACKNOWLEDGEMENT

This work was supported by the Ministry of Education and Science of the Republic of Serbia under the project TR33020 "The power efficiency improvement of the hydro and power plants in the Electric Power Industry of Serbia using the development of the power electronics technologies and devices for the control and automation".

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