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Improved Method for Position Estimation Using a Two-Dimensional Scheduling Array

The paper presents results of studies on the position estimation for the permanent magnet synchronous motor (PMSM) drive using gain scheduling technique for tuning the observer's parameters. It allows a good estimation accuracy in wide range of working point change. Such observer with multi integral correction function improves the performance, but need to modify its parameters according to its speed and load.

Novelty is the use of a two-dimensional gain scheduling technique and the use in the sensorless drive, where traditional solution is simple one-input scheduling variable - mainly on drives with position sensors. The look-up table output is processed using bilinear interpolation. Position observer is based on back EMF estimation. It uses predefined reference matrices of parameters, which are interpolated and depend on drive's operating point.

Key words: Observers, PMSM, Scheduling, Sensorless control, Variable speed drives

Unaprijeđena metoda estimacije položaja zasnovana na upotrebi dvodimenzionalnog polja za ažuriranje parametara. U radu su predstavljeni rezultati studija vezanih za estimaciju položaja sinkronog motora s permanentnim magnetima (PMSM) uz korištenje regulatora s podesivim pojačanjem za adaptaciju parametara estimatora. Metoda pokazuje dobru točnost estimacije u širokom rasponu radnog područja. Ovakav estimator s više integracijskih korekcijskih funkcija poboljšava performanse, ali i zahtijeva adaptaciju parametara ovisno o brzini i teretu.

Novost predstavlja korištenje dvodimenzionalnog podešavanja pojačanja regulatora te primjena u bezsenzorskom upravljanju elektromotornim pogonom, gdje se tradicionalno koristi jednostavno ažuriranje jedne varijable - prije svega kod elektromotornih pogona sa senzorom za poziciju. Pregledna tablica izlaza koristi se uz bilinearnu interpolaciju. Estimator položaja zasnovan je na estimaciji protuelektromotorne sile. Estimator koristi unaprijed određene referentne matrice parametara koje se interpoliraju te ovise o radnoj točki.

Ključne riječi: Estimatori, PMSM, ažuriranje parametara, bezsenzorsko upravljanje, elektromotorni pogon promjenjive brzine

1 INTRODUCTION

The Permanent Magnet Synchronous Motor (PMSM) is very often used type of motor in industrial applications. Its the most significant advantages are high power density, high torque-to-inertia ratio and small torque ripples. Such drive gives possibility to precise speed and position control at low speed range, a torque control at zero speed and has compact size. A typical control structure of PMSM drive bases on vector control method. It allows to get a good dynamics, effective performance especially during transient processes and prevents overload of the motor by controlling the torque. However, a motor shaft position sensor is required to enable the effective control of the drive. Reliable operation without sensor is still a subject of investigations. The actual investigations are mainly focused on: zero speed range [1–4], high dynamic performance [5,6], motor supplied through choke or LC filter [7–9] and supplied by matrix converter [1, 10]. Various approaches to the sensorless control are applied: using signal injections (typical application is zero speed range), based on back EMF estimation - including continuous observer of the kind which is presented in the paper and sliding mode based observers [11], based on Kalman filter [12, 13], an adaptive interconnected observer [14] and the use of the artificial neural networks [15, 16]. An additional modification that improves the sensorless performance, may be the motor parameter online identification [17] which may improve sensorless performance for low speed range. The other modification is the gain scheduling technique. It is used to expand the range of proper performance, both in sensor and sensorless drives - used to modify parameters of observers or controllers. In a case of the sensor drive, gain scheduling technique is often compared with robust control algorithm [18]. On the other hand, in a case of

sensorless drives, the robust or adaptive implementation is more common, usually using the sliding mode based observers [19, 20]. However, the gain scheduling usage for tunning the observer, depending on the working point, has some advantages. There is no delay as is in adaptive systems, and its implementation contains only traditional controller or observer and the look-up table. Although gain scheduling improves the drive performance, still it is reported as a function of one argument [21–23].

In this paper, the concept and the results of the performance of two inputs gain scheduling module for the sensorless drive are presented. The estimation algorithm utilizes the gain scheduling as a function of two variables - absolute value of the estimated speed and current. The observer estimates the back EMFs and calculates sine and cosine of the rotor shaft position. Then a speed is recalculated. Used structure bases on Luenberger observer [24], modified with multi-integrator correction function [22]. Such structure makes observer extremely robust on inaccurate motor parameter estimation. To ensure a proper estimation error level in whole range of operation, such simple structure of the observer requires the possibility to modify its parameters due to working point. Used the *gain scheduling* technique for observer parameter change is presented. The correctness of the presented concept has been proved using experimental PMSM drive.

2 PMSM MODEL

Assuming ordinary simplified assumptions (there is no windings in rotor, eddy currents and the effect of temperature is neglected, the flux produced by the rotor is constant [25]), the general form of the electrical part of the PMSM model in dq coordinates system rotating with the rotor can be expressed as follows:

$$u_d = R_s \cdot i_d + L_d \cdot \frac{di_d}{dt} - p \cdot \Psi_q \cdot \omega, \qquad (1)$$

$$u_q = R_s \cdot i_q + L_q \cdot \frac{di_q}{dt} + p \cdot \Psi_d \cdot \omega, \qquad (2)$$

$$\Psi_d = L_d \cdot i_d + \Psi_f, \qquad (3)$$

$$\Psi_q = L_q \cdot i_q, \qquad (4)$$

$$T_e = p \cdot \frac{3}{2} \left[\Psi_d \cdot i_q - \Psi_q \cdot i_d \right], \qquad (5)$$

$$J \cdot \frac{d\omega}{dt} = T_e - T_L, \qquad (6)$$

where u_d, u_q means the components of input voltage, i_d, i_q, L_d, L_q means currents and inductance of the motor in the dq axis respectively, Ψ_d, Ψ_q, Ψ_f, means flux in the dq axis respectively and flux excited by permanent magnet. The electromagnetic torque is represented by a symbol T_e and load torque by symbol T_L, ω is the mechanical speed,

and p is number of the pole pairs. The R_S means the windings resistance, and J is the total moment of inertia. The parameters of the motor used in experiments are:

- rated power - $1.23\,\text{kW}$

- nominal speed - $3000\,\text{rpm}$

- rated torque - $3.9\,\text{N·m}$

- number of poles - 6

- measured resistance - $2\,\Omega$

- measured inductance - $5.7\,\text{mH}$

- total moment of inertia - $24.96\,\text{kg·cm}^2$

3 OBSERVER STRUCTURE

Motor model in rotating co-ordinates dq described by equations (1-6) is very convenient for motor operation analysis especially with vector control of stator current but is not recommended for using in observer structure. The reason for it is that transformation of state variable to these co-ordinates requires knowledge of rotor position angle, which is estimated by observer, what can cumulate observation error. Much better observer performance is achieved by applying motor model written in stationary $\alpha\beta$ co-ordinates system, for direct conversion by means of Clarke transformation [26] from three phase abc measured co-ordinates system to observer co-ordinates system, without usage of the estimated position. So, the motor model for observer has the following form:

$$\frac{di_\alpha}{dt} = -\frac{R_s}{L_s} \cdot i_\alpha - \frac{1}{L_s} \cdot e_\alpha + \frac{1}{L_s} \cdot v_\alpha, \qquad (7)$$

$$\frac{di_\beta}{dt} = -\frac{R_s}{L_s} \cdot i_\beta - \frac{1}{L_s} \cdot e_\beta + \frac{1}{L_s} \cdot v_\beta, \qquad (8)$$

$$\frac{d\omega}{dt} = \frac{1}{J} \cdot \left(\Psi_\beta \cdot i_\alpha - \Psi_\alpha \cdot i_\beta - T_L \right), \qquad (9)$$

$$\frac{d\Theta}{dt} = \omega, \qquad (10)$$

where v_α, v_β, means the components of input voltage, i_α, i_β, the components of input currents, Ψ_α, Ψ_β, e_α and e_β, means flux and back EMF in the $\alpha\beta$ axis respectively. The motor model with state variables i_α, i_β, ω and Θ is nonlinear. All state variables are measurable but in a concept without mechanical sensor ω and Θ should be estimated. According to the method presented in [27] it is convenient to use only first two electrical equations (7-8), in which the back EMF components are considered as disturbances. In such a case we can prepare an extended state formula, which can be described as:

$$\dot{\mathbf{x}}_E = \mathbf{A}_E \cdot \mathbf{x}_E + \mathbf{B}_E \cdot \mathbf{u}, \qquad (11)$$

$$\mathbf{y}_E = \mathbf{C}_E \cdot \mathbf{x}_E, \qquad (12)$$

$$\dot{\mathbf{x}}_E = \begin{bmatrix} i_\alpha \\ i_\beta \\ e_\alpha \\ e_\beta \end{bmatrix}, \quad \mathbf{y}_E = \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}, \quad \mathbf{u} = \begin{bmatrix} v_\alpha, v_\beta \end{bmatrix}.$$

$$(13)$$

The E index means *extended*. For such system it is possible to use ordinary Luenberger observer. In typical realization, the correction is based on error between measured and calculated currents value. Assuming that derivative of disturbances is equal zero, one can write the observer equations as (14-17). Located in the observer's equations (16) (17) and then (23) (24) the correction components, cause that observer calculates the proper value although estimated EMF initial values are equal to zero. The other concept, where derivative of disturbances were not zero, were also taken into account [22]. Provided investigation proved that observer with assumed derivative of EMF equal zero operates with comparable accuracy. To achieve smooth observed values, a reference voltage can be used instead of measured ones. In a case the derivative disturbances is equal zero, the observer equations have the following form:

$$\frac{d\hat{i}_\alpha}{dt} = -\frac{R_s}{L_s}\hat{i}_\alpha - \frac{1}{L_s}\hat{e}_\alpha + \frac{1}{L_s}v_{\alpha\,ref} + K_{i\alpha}\left(\hat{i}_\alpha - i_\alpha\right),$$

$$(14)$$

$$\frac{d\hat{i}_\beta}{dt} = -\frac{R_s}{L_s}\hat{i}_\beta - \frac{1}{L_s}\hat{e}_\beta + \frac{1}{L_s}v_{\beta\,ref} + K_{i\beta}\left(\hat{i}_\beta - i_\beta\right),$$

$$(15)$$

$$\frac{d\hat{e}_\alpha}{dt} = K_{e\alpha}\left(\hat{i}_\alpha - i_\alpha\right),$$

$$(16)$$

$$\frac{d\hat{e}_\beta}{dt} = K_{e\beta}\left(\hat{i}_\beta - i_\beta\right),$$

$$(17)$$

where $K_{i\alpha}$ and $K_{i\beta}$ are the estimated currents gains, $K_{e\alpha}$ and $K_{e\beta}$ are the estimated back EMF gains and $v_{\alpha\,ref}$, $v_{\beta\,ref}$, means the components of reference voltage. The parameters in axis α and β should be equal.

This set of equations (14-17) may be presented in matrix form:

$$\dot{\hat{\mathbf{x}}}_E = \mathbf{A}_E \cdot \hat{\mathbf{x}}_E + \mathbf{B}_E \cdot \mathbf{u}_{ref} + \mathbf{K}\left[\Delta\mathbf{i}\right], \qquad (18)$$

where $\mathbf{K}$ is an array of the correction gains. Observer described by formulas (14-17) has weak performance in a case of big calculation step or high speed range and moreover gives significant error of observation when fast changes of EMF appear. The last observer feature is caused by proportional corrector structure in (18). However, there is possibility to achieve much better performance using more complex correction function. Substituting corrector matrix $\mathbf{K}[\Delta\mathbf{i}]$ by corrector function $\mathbf{F}[\Delta\mathbf{i}]$, as in (19):

$$\dot{\hat{\mathbf{x}}}_E = \mathbf{A}_E \cdot \hat{\mathbf{x}}_E + \mathbf{B}_E \cdot \mathbf{u}_{ref} + \mathbf{F}\left[\Delta\mathbf{i}\right], \qquad (19)$$

which contains not only error of current observation but moreover integral of current observation error and its double integral, leads to improvement of observer operation. The modified corrector function is given by formula:

$$\mathbf{F}[\Delta\mathbf{i}] = \mathbf{K}_p[\Delta\mathbf{i}] + \mathbf{K}_i \int [\Delta\mathbf{i}] dt + \mathbf{K}_{ii} \int \left[\int [\Delta\mathbf{i}] dt \right] dt,$$

$$(20)$$

which can be called PII^2.

Finally, the observer structure equation set has the following form:

$$\frac{d\hat{i}_\alpha}{dt} = -\frac{R_s}{L_s}\hat{i}_\alpha - \frac{1}{L_s}\hat{e}_\alpha + \frac{1}{L_s}v_{\alpha\,ref} + \mathbf{F}_{i\alpha}\left(\hat{i}_\alpha - i_\alpha\right),$$

$$(21)$$

$$\frac{d\hat{i}_\beta}{dt} = -\frac{R_s}{L_s}\hat{i}_\beta - \frac{1}{L_s}\hat{e}_\beta + \frac{1}{L_s}v_{\beta\,ref} + \mathbf{F}_{i\beta}\left(\hat{i}_\beta - i_\beta\right),$$

$$(22)$$

$$\frac{d\hat{e}_\alpha}{dt} = \mathbf{F}_{e\alpha}\left(\hat{i}_\alpha - i_\alpha\right),$$

$$(23)$$

$$\frac{d\hat{e}_\beta}{dt} = \mathbf{F}_{e\beta}\left(\hat{i}_\beta - i_\beta\right),$$

$$(24)$$

where $\mathbf{F}_{xy}$ is correction function of the current estimation error, included corrector coefficients (x means index for current estimation loop "i" or back EMF estimation loop "e", y means index for co-ordinates axis α or β). Assumption that in matrices $\mathbf{K}_p$, $\mathbf{K}_i$ and $\mathbf{K}_{ii}$ in (20) only diagonal elements are not equal zero and moreover that due to symmetry of motor stator windings elements, what is visible in (14) and (15), the elements of matrices for axes α and β are equal.

$$K_p = \begin{bmatrix} K_{p11} & 0 \\ 0 & K_{p22} \\ K_{p31} & 0 \\ 0 & K_{p42} \end{bmatrix} \qquad K_i = \begin{bmatrix} K_{i11} & 0 \\ 0 & K_{i22} \\ K_{i31} & 0 \\ 0 & K_{i42} \end{bmatrix}$$

$$K_{ii} = \begin{bmatrix} K_{ii11} & 0 \\ 0 & K_{ii22} \\ K_{ii31} & 0 \\ 0 & K_{ii42} \end{bmatrix} \qquad (25)$$

The gains K_{p11} (K_{i11},K_{ii11}) and K_{p22} (K_{i22},K_{ii22}) are used for current correction calculation (respectively for α and β axis). Because of symmetry of axis α and β, $K_{p11} = K_{p22}$, $K_{i11} = K_{i22}$, $K_{ii11} = K_{ii22}$. So, there are 3 independent gains for current estimation. The gains K_{p31} (K_{i31},K_{ii31}) and K_{p42} (K_{i42},K_{ii42}) are used for EMF correction calculation (respectively for α and β axis). Because of symmetry of axis α and β, $K_{p31} = K_{p42}$, $K_{i31} = K_{i42}$, $K_{ii31} = K_{ii42}$. So, there are next 3 independent gains for EMF estimation. It reduces the number of independent corrector coefficients (elements of matrices) to six.

The advantage of introducing integral and double integral components of the observer corrector is that they ensure the minimization of the observation error even during the transient speed process, in which fast changes of speed and reference currents occur – when the back EMFs waveforms are not in sinusoidal shape. In addition such structure increases the accuracy of observation in a case of the high-step calculations.
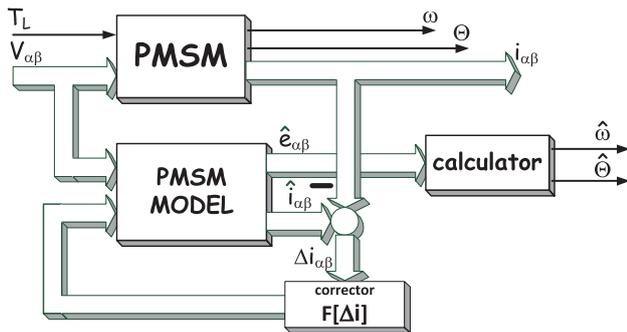
Fig. 1. General structure of observer

As is presented in Fig. 1, the observer generates back EMF values in the stationary coordinate system $\alpha\beta$. Then the position determination is made on the basis of reconstructed back EMF - the sine and cosine of the estimated position are calculated:

$$\sin\left(\hat{\Theta}\right) = -\frac{\hat{e}_\alpha}{|\hat{e}|}, \tag{26}$$

$$\cos\left(\hat{\Theta}\right) = \frac{\hat{e}_\beta}{|\hat{e}|} \tag{27}$$

and

$$|\hat{e}| = \sqrt{\hat{e}_\alpha^2 + \hat{e}_\beta^2}. \tag{28}$$

Because of the rough character of the estimated position waveform, the best performance of the drive (e.g. smooth speed waveform at steady state) are achieved, where speed is calculated without derivative in calculations. If the calculations are based on the estimated position derivative, it forces the use of filters. The result is usually an additional delay in the speed control loop. To avoid this, the speed is calculated using the following equation:

$$|\hat{\omega}| = \frac{|\hat{e}|}{k_e(|\hat{e}|)} \tag{29}$$

and $k_e(|\hat{e}|)$ is the scaling factor depend on EMF. It has been determined "off-line" for different points of operation using presented in the paper parameter optimization technique for steady states. An interpolator, based on fuzzy logic, is used for selecting a proper value of $k_e(|\hat{e}|)$. The

membership input functions are determined in the whole range of speed control. At each step of the calculations, an optimal value of the k_e is determined by means of the fuzzy procedure, which uses the Mamdani implication method and defuzzification by the height method. Determination of the degrees of membership enables to calculate the interpolated value of coefficient using the height defuzzification method. The input signal for the interpolator is the value of speed estimated at the preceding step of the calculation. In that speed calculation method, the drawback is lack of speed sign information.

4   THE GAIN SCHEDULING

Such observer, based on some number of integrators, is very simple in implementation by programming language and quick in calculating by microprocessor system. The cost for that simplicity is the necessity of the change of the observer's corrector parameters settings due to operating point (usage the *gain scheduling*). Modifying the observer's parameters as a function of speed only is not sufficient in a case where the load could change in a wide range. In a low speed range, the corrector parameters may be constant. Otherwise a scheduling mechanism should be used. Presented sensorless control algorithm consists of two independent scheduling system. First, based on fuzzy logic implementation, is used to correct speed estimated value $k_e(|\hat{e}|)$ in (29) as was presented in [22].

```
float MAC0[sizey][sizex]=
{
{0.0  ,5.0 ,50.0,60.0,70.0,80.0},
{0.2  ,5.16,45.0,33.0,25.0,17.0},
{0.4  ,20.0,50.0,40.0,25.0,17.0},
{2.0  ,30.0,60.0,45.0,30.0,19.0},
};
```

Fig. 2. The example 2D matrix code in C language for the observer parameter index 0 (parameter P0)

The second one, using bilinear interpolation technique in 2D space, is used to modify observer coefficients. The inputs of the gain scheduler are absolute value of actual current $|i_q|$ and signal of the estimated speed $\hat{\omega}$. During investigations turned out that a filter of speed signal must be introduced to prevent stimulation of this signal oscillation. The observer's parameters are changed with limited dynamics, especially in transients, to avoid loss of the stability of the sensorless speed control loop. Stability at steady states is preserved by use by scheduler the previously prepared sets of observer's parameters for different operation points (as is presented in Fig. 2). The output is an actual value calculated for the all six observer parameters

for the operating point identified by ω and i_q. The example $2D$ matrix for one of the (six) observer parameters has the form presented in Fig. 2. The first row is the speed values $(5.0 - 80.0 \left[\frac{rad}{s}\right])$ and the first column $(0.2 - 2.0 \, [A])$ is the i_q current values for which was prepared this array. The other values of the matrix have been obtained experimentally, e.g. using special algorithm implemented as a part of the control program (Fig. 6, 7 in section 6). Each of the six observer's parameters has its corresponding array. The actual value of the all parameters is calculated using the bilinear interpolation algorithm, which is one of the simplest methods for interpolation in $2D$. The implementation based on [28] takes the form:

$$OUT(X, Y) = P_{00} + (P_{10} - P_{00}) \cdot \frac{X - X_0}{X_1 - X_0} +$$
$$+ (P_{01} - P_{00}) \cdot \frac{Y - Y_0}{Y_1 - Y_0} + \quad (30)$$
$$+ (P_{11} - P_{01} - P_{10} + P_{00}) \cdot \frac{X - X_0}{X_1 - X_0} \cdot \frac{Y - Y_0}{Y_1 - Y_0},$$

where
$$\begin{aligned} P_{00} &= \mathbf{MAC}_n(X_0, Y_0), \\ P_{01} &= \mathbf{MAC}_n(X_0, Y_1), \\ P_{10} &= \mathbf{MAC}_n(X_1, Y_0), \\ P_{11} &= \mathbf{MAC}_n(X_1, Y_1). \end{aligned} \quad (31)$$

The variables X_0, X, X_1, Y_0, Y, Y_1 are the values corresponding to the Fig. 3, n is the index of the observer parameter matrix ($\mathbf{MAC_0}$-$\mathbf{MAC_5}$), P_{00}-P_{11} are the key values of the cells, whose contents are closest to the input values X and Y (marked as "A" dots at Fig. 3). The concept of that interpolation is first to calculate the Z axis values for X input value for Y_0 and Y_1 baselines (the result are "B" dots on Fig. 3), and then the Z axis between "B" dots for Y input value (result: dot "C").

It should be noted that the used implementation of the interpolation procedure, as an output, for inputs outside the range of parameter array, returns the boundary value.

5 STABILITY ANALYSIS

To check the stability of the system in a case when the observer parameters are changing, the observer module was converted from C language into a MATLAB-Simulink model form and linearized. Deployment of the poles dependent on variable parameters were calculated. Pole-zero map is calculated in whole range of parameter change, to prevent situation where system is stable for key values of the lookup table but in a case the interpolated values usage - does not. Figure 4 presents deployment of the poles and zeros on the s-plane. In whole range of parameter change (for matrix modifying the parameters of the estimator: $P0 = (5.16, 60.0)$, as is presented in look-up table
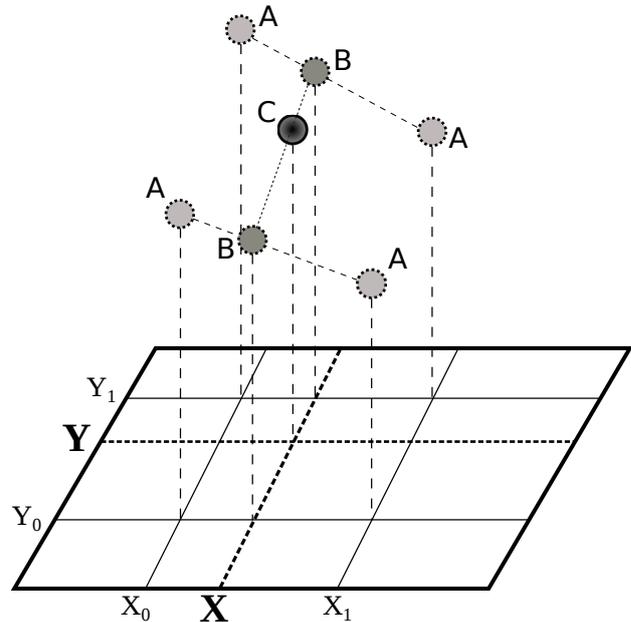
Fig. 3. Bilinear interpolation principles

at Fig. 2), poles are on the left side of the s-plane. Magnified part in the origin area for Fig. 4 is presented on Fig. 5. To get the legible view, only one parameter - $P0$, from the all available observer parameters $P0 - P5$ was changed.
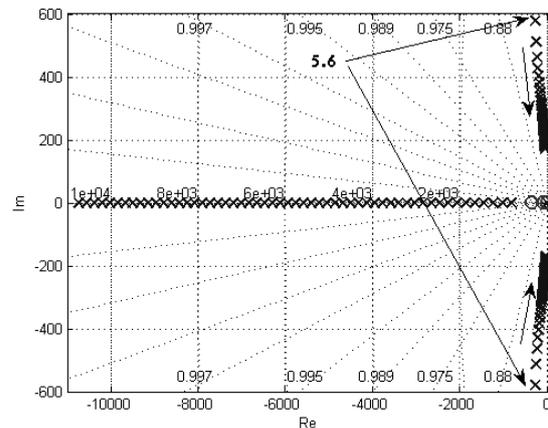
Fig. 4. Poles x and zeros o of linearized observer model as parameter $P0$ is varied in a range $5.16 - 60.0$

6 OBSERVER PARAMETER SETTING

The choice of observer parameters is an important task and should take into account dynamics in closed loop system as well as good accuracy of observation. Because
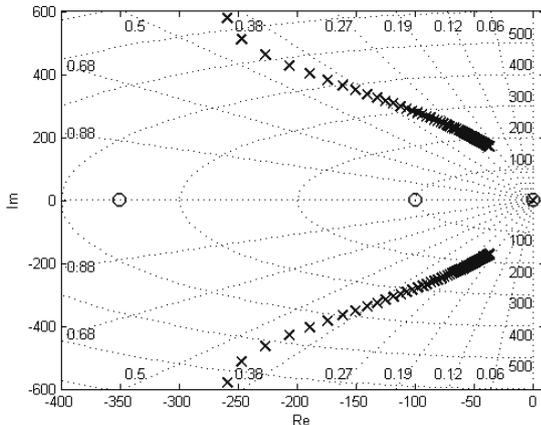
Fig. 5. Poles x and zeros o of linearized observer model as in Fig. 4 - zoomed the origin area

of the motor non-linearity, discontinuity caused by the inverter structure and discrete structure of the control loop, it makes difficult to calculate the parameters of the observer. In order to determine the observer parameters an automatic procedure was prepared. Based on *Monte Carlo* stochastic techniques, presented on Fig. 6 algorithm was prepared [22]. Such algorithm (named "full") chooses (draws) all the coefficients (i.e. scale factor $k_e(\omega)$ and the corresponding component "P", "I" and "I^2" independently in both estimation loops, both current and back EMF) of the observer at the same time. Although that algorithm demonstrates its effectiveness, but the studies led to the conclusion, that the algorithm should be modified. There is some other concept of observer synthesis. One can start with the simplest observer structure of P type (without I and I^2 component) and check if this structure ensures satisfying operation. If does not, the integral components are sequentially added in two stages. In second stage the structure PI is tested and in case of still unsatisfying operation, in the next stage full observer structure (PI extended by I^2 to the PII^2) is evaluated (Fig. 7). The searching process may be performed using the quality index. Used in experiments quality function is formulated as:

$$Q = K_1 \int\limits_{t_1}^{t_1+\tau} \left(e_{sin}^2(t) + e_{cos}^2(t) \right) dt + K_2 \Delta e_\Theta(\tau), \quad (32)$$

where e_{sin} and e_{cos} are sine and cosine function of the estimation error of the shaft position, Δe_Θ is the range of the error value changes of the estimated position during the transient process in time range τ. The time boundaries of the integral calculation are marked as t_1 and $t_1 + \tau$, where K_1, K_2 are the weight factors to normalize obtained in-

dex values. Such quality index combines desired low estimation error value (e_{sin}, e_{cos}) and penalty for oscillations (Δe_Θ). So far, studies indicate that more important for stable drive performance is to achieve smooth position error waveform than small its constant component. To achieve this, it is important, to set a K_2 big enough to ensure the adequate impact of smooth requirement on whole quality index calculation.

7 EXPERIMENTAL RESULTS

Used in investigations test bench includes PMSM supplied by laboratory inverter, which is controlled by means of microprocessor system and a second similar PMSM, supplied by industrial AC drive. The second machine working as a controlled load source. The evaluation board is based on the floating point DSP from SHARC family. Inverter's carrier frequency is equal to $10\,\text{kHz}$. The observer and *gain scheduling* algorithms as well as control algorithm were implemented on DSP processor system. All that programs are executed every $100\,\mu\text{s}$. The measurement algorithms are implemented in additional FPGA evaluation board. All the waveforms except shown in Fig. 8 were obtained in closed loop mode, where estimated speed $\hat{\omega}$ and sine and cosine of the estimated position $\hat{\Theta}$ were used in control chain. A confirmation of the concept of the observer parameters changing method is presented here. On the following pictures selected results are shown. The zero level on the scale for the recorded waveforms for channel 1 and 2 is marked by channel pointer. Figure 8 presents drive performance in case where the *gain scheduling* is turned off. Speed reference is changing its value in steps in sequence $60 \rightarrow 70 \rightarrow 80\,\frac{\text{rad}}{\text{s}}$. The observer parameter set is constant and prepared for $\omega = 70\,\frac{\text{rad}}{\text{s}}$ and current $i_q = 0.2\,\text{A}$. The measured speed ω is shown on channel 3. Position error waveform is presented on channel 1. It is noticeable that the position estimation error reached too high values. As an effect, the drive in such case is not able to work in the sensorless mode. Motor current i_q is presented in channel 2. Its steady state value is about $0.5\,\text{A}$.

Next, the sensorless mode and *gain scheduling* were enabled and results for the operation of the unloaded motor under the same test conditions were presented on Fig. 9. There is a big improvement of the position estimation error values, especially at steady state, although only parameter $P0$ was modified in this test. It is important, that the parameters of the controllers , both currents and speed, were unchanged, despite the change in the mode of operation is sensor or sensorless. The active current waveform is smooth as well as the measured speed. A drive operation in a case of loaded motor is shown on Fig. 10. Motor is loaded with current about $i_q = 1.0\,\text{A}$. Proper operation of
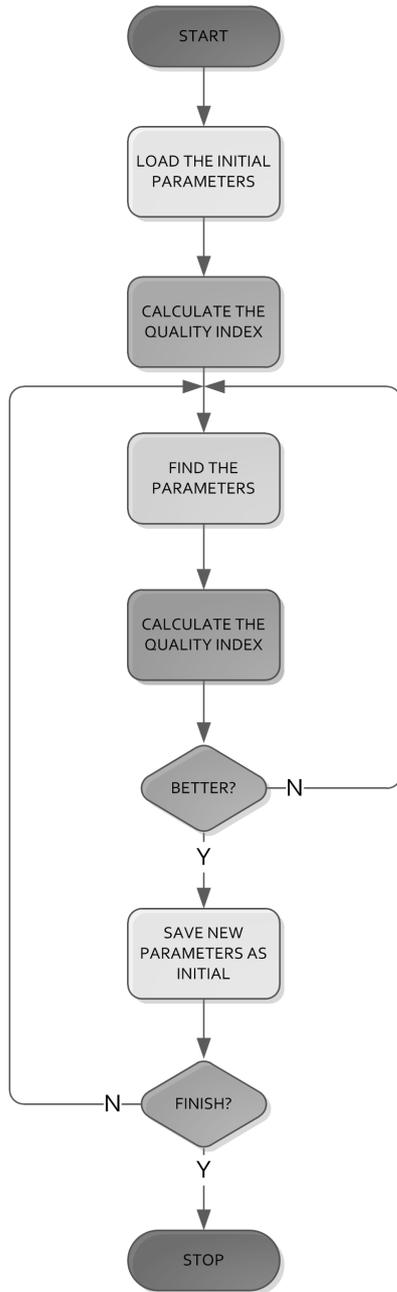
Fig. 6. Parameter selection MC algorithm of the observer - mode "full"
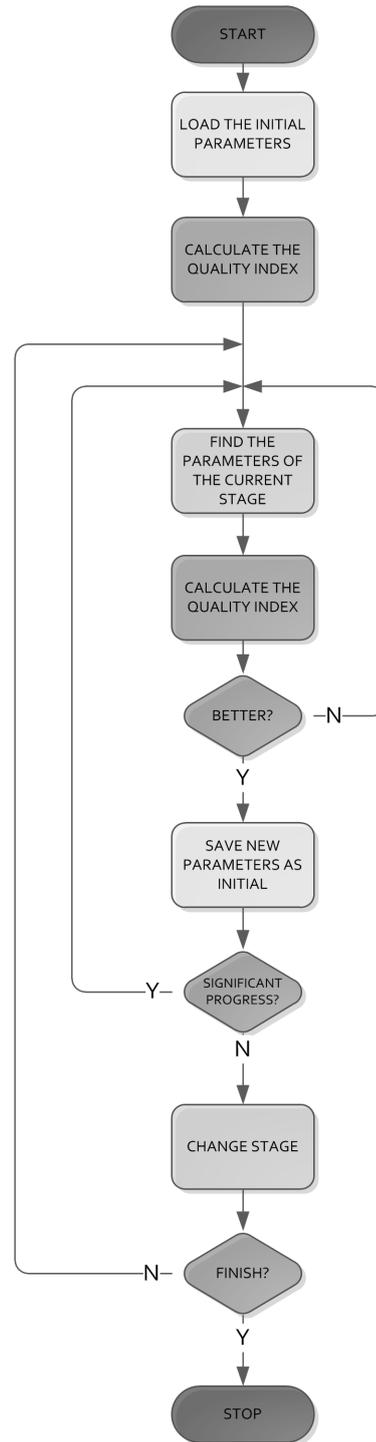
Fig. 7. Parameter selection MC algorithm of the observer - mode "staging"

the drive is visible also in this case. It can be noted, that in the transients of position error (loaded and unloaded motor), the peak error value does not depend on speed change sign. Finally, the direct comparison of the estimated and measured shaft position is presented in Fig. 11 (channel 1 and 2). In addition, that figure proves robustness on inaccurate motor parameter estimation: used in observer motor

resistance is at this case equal $8\,\Omega$, while the measured is about $2\,\Omega$. Drive with estimated speed (channel 4) as a
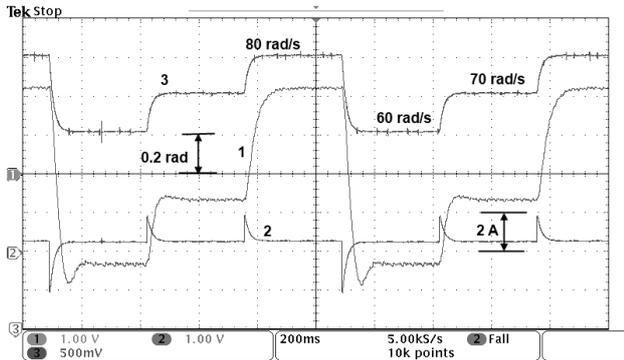
Fig. 8. *Sensor mode, motor unloaded, constant parameters for* $\omega = 70 \frac{rad}{s}$, $i_q = 0.2$ A, *step reference speed sequence:* $60 \rightarrow 70 \rightarrow 80 \frac{rad}{s}$, *CH1: position estimation error, CH2:* i_q *axis current, CH3: measured speed*
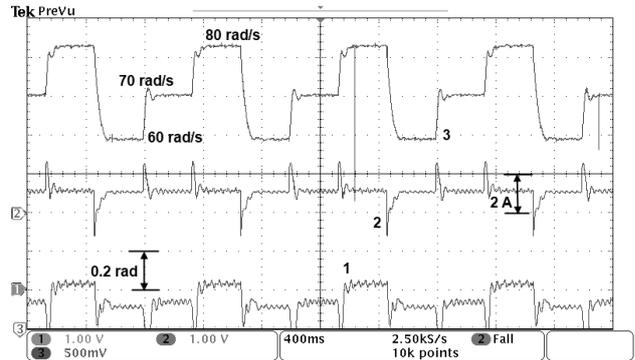
Fig. 10. *Sensorless mode, motor loaded* $i_q = 1.0$ A, *variable parameters, step reference speed sequence:* $60 \rightarrow 70 \rightarrow 80 \frac{rad}{s}$, *CH1: position estimation error, CH2:* i_q *axis current, CH3: measured speed*
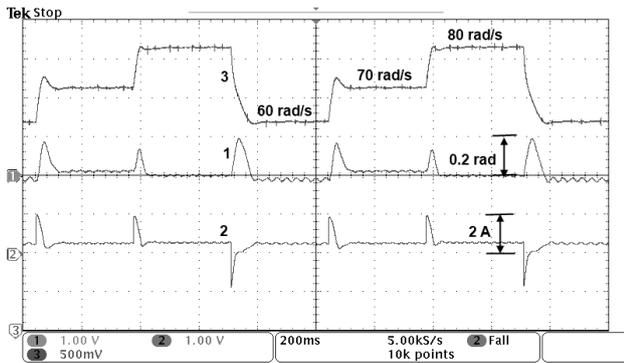
Fig. 9. *Sensorless mode, motor unloaded, variable parameters, step reference speed sequence:* $60 \rightarrow 70 \rightarrow 80 \frac{rad}{s}$, *CH1: position estimation error, CH2:* i_q *axis current, CH3: measured speed*
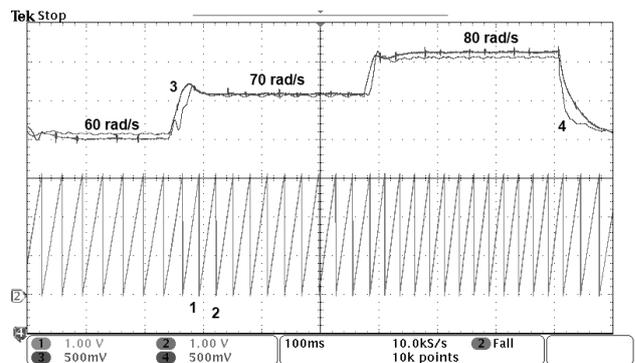
Fig. 11. *Sensorless mode, motor unloaded, variable parameters,* $R_{obs} = 4.0 \cdot R_S$, *step reference speed sequence:* $60 \rightarrow 70 \rightarrow 80 \frac{rad}{s}$, *CH1: measured position, CH2: estimated position, CH3: measured speed, CH4: estimated speed*

feedback operates well (waveform of the measured speed is still smooth - channel 3). Presented observer structure is highly robust against inaccurate motor parameters estimation. Performed tests confirmed, that sensorless drive has possibility to proper operate, if the motor parameters estimation varies in the range:

$$R_{obs} = (0.4 \div 4.0) R_S, \qquad L_{obs} = (0.9 \div 1.1) L_{d/q}, \tag{33}$$

where R_{obs}, L_{obs} are the parameters saved in observer.

8   CONCLUSION

In this paper the observer parameters modification technique is presented. A simple structure and robustness against inaccurate motor parameter identification encourages the widespread use of such control structure in drive applications. The position estimation error, caused by difference between nonlinear object (motor) and its linear observer, can be reduced by supplementing the gain scheduling mechanism for instant modification of the observer's parameter set due to working point change. Bilinear interpolation technique was implemented and verified its usefulness. Test confirms that at the steady state is possible to minimize the constant component of the estimation error. It is the matter of accuracy of mapping an arrays of the observer parameters. Minimize of the position error in transients (although they are relatively small) is the next objective to achieve.

Due to estimation method, based on estimation back EMF, that observer is not recommended to work in very

small speed range - the drive works stable at speeds exceeding $15\,\frac{\text{rad}}{\text{s}}$, with and without torque load.

The simplicity of the observer gives the opportunity to use cheap microcontrollers to perform sensorless control - – the laboratory stand uses system with set calculation step of $100\,\mu\text{s}$.

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