Book Chapter

New Stable Non-Vector Control Structure for Induction Motor Drive

Pavol Fedor, Daniela Perdukova*, Peter Bober and Marek Fedor

Department of Electrical Engineering and Mechatronics, Technical University of Kosice, Slovakia

***Corresponding Author:** Daniela Perdukova, Department of Electrical Engineering and Mechatronics, Technical University of Kosice, Letna 9, 04200 Kosice, Slovakia

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Abstract

The article focuses on a design and experimental verification of continuous nonlinear systems control based on a new control structure based on a linear reference model. An application of the Lyapunov's second method ensures its asymptotic stability conditions. The basic idea in the development of the control structure consists in utilizing an additional information from a newly introduced state variable. The structure is applied for angular speed control of an induction motor (IM) drive representing a higher-order nonlinear system. The developed control algorithm helps to achieve the zero steady-state control deviation of the IM drive angular speed. Simulations and experiments performed in various operating states of the IM drive confirm the advantages of the new control structure. Except of set dynamics the method ensures that the system is stable, invariant to disturbances, and is robust against variations of the parameters. When comparing the obtained control structure of the IM control with the classical vector control, the proposed control structure is simpler. The main advantage over conventional control techniques consists in the fact that the controller design does not require any exact knowledge of ther system parameters and moreover, it does not suffer from system stability problems. The method will find a wide applicability not only in the field of AC controlled drives with IM but also generally in control of industry applications.

Keywords

Control System Synthesis, Induction Motor, Motion Control, Nonlinear Control Systems, Variable Speed Drives, Lyapunov's Second Method

Introduction

Induction motors (IMs) are robust and reliable and due to their low cost and maintenance they find a wide utilization in industrial applications. A problem consists in their control requiring more complex control circuitry due to variable frequency, complex dynamics, and parameter variations [1-3]. The IM itself presents a typical example of a nonlinear and considerably oscillating system with incorporated positive feedback. The accuracy of its speed control is significantly influenced by unknown external disturbances and variable motor parameters.

Several control methods of the IM are known. The simplest one is the scalar speed control method. It has a simple control structure [4,5] due to which is suitable for simpler industrial applications. A better drive performance of the scalar control method requires using on account of a more expensive and less reliable solution.

A precise drive performance is obtained by field oriented control (FOC) employing classical cascade PI controllers [6]. Various modifications of the FOC usually requiring transformation of the IM variables into a rotating reference frame have been developed which enable to control the IM in a similar manner like a separately excited DC motor [7-9]. A drawback of such solution consists in increased complexity of the control scheme and in necessity of using powerful computational means (digital signal processors) for its implementation.

From the point of view of the modeling and control the IM principally presents a nonlinear dynamic system with uncertain parameters. Many design techniques for nonlinear control have already been applied for the control of IM drives providing a better performance than the FOC [10,11].

Various sensorless methods to measure the rotor position of electrical drives with IMs [12-14] have been proposed in order to decrease the hardware complexity and cost and simultaneously to increase higher mechanical robustness and by this a reliability of the drive performance.

From the field of applications of nonlinear control methods to the speed and position control of the IMs a sliding mode control should be mentioned [15-17]. Soft computing methods like fuzzy logic, artificial neural networks, evolutionary algorithms and their combinations have also been applied for the IM drives control [18-23]. But, again, their drawbacks consist in powerful real-time calculation processes and, moreover, they can incline to the stability problems of the system (like it is very often case of fuzzy control theory methods).

An overview of several methods of the IM control at inaccurate determined parameters (the rotor resistance, mains failure and load torque) is given in [24]. It follows that the quality of the IM control depends in principle on the accuracy of the IM model used for all methods. However, the exact model of the drive is not available as at a large volume serial production the exact motor parameters can vary significantly.

Several methods have been proposed to solve the problem of the IM control with an inaccurate model. A disadvantage of an adaptive version of the sliding mode [25-26] is that it guarantees the robustness only within a range of the uncertainties, and it still suffers from a chattering problem. The predictive control [27-29] can be complemented by a parameter observer to estimate the uncertain model parameters, but the stability for such schemes is usually not guaranteed. A backstepping control method [30] that has appeared recently, allows the design of the control law and the estimation of the motor parameters. However, the proposed method is suitable for a limited set of adaptive parameters only.

Summarizing the review, it is clear that the high quality of the IM control should take into account the following criteria: a nonlinear and oscillating character of the IM dynamics, variations of motor parameters, the influence of external disturbances, and a simple implementation of the control algorithm.

In the article a new robust control structure with a reference model is designed to control the angular speed of an IM drive where the system stability is derived on basis of the Lyapunov's second method [31]. Its main advantage consists in the fact that that the design of the control structure does not require any accurate knowledge of values of the IM parameters. The resulting structure yields optimal dynamic properties in terms of the minimum control deviation and minimum input energy [32] criteria, which are normally used for evaluation of the control efficiency.

The proposed method consists in an extension of the control algorithm by an additional information. This is easily obtained from the system output variable which ensures that the steady-state of the output variable is zero. If the control algorithm for the extended system is designed in such a way that the system would be asymptotically stable with the dynamics prescribed by the reference model, it will reach the goal of control both in the steady and in the transition states.

The properties of the proposed control structure have been verified by simulations and experimental measurements on the IM laboratory model. The proposed control structure is considerably simpler than FOC structure. It is stable, linear, robust, and it has identical dynamical properties without any necessity of knowledge of exact mathematical model of the IM. These features will increase the implementation potential of this strategy in industrial applications.

The paper is organized as follows: after Introduction, the design of the linear model reference control structure is presented in Section 2. Section 3 describes the mathematical model of IM, its parameters and properties, which in Section 4 are further used to design control for IM drive angular speed control. The proposed control method is verified by simulation in various IM operating states and by experimental measurements on a laboratory model in Section 5 and Section 7. Section 6 describes a comparison of the proposed control structure with the vector control structure (FOC). Finally, basic characteristics of the novel control structure are presented in Section 8 and Section 9.

Design of the Linear Model Reference Control Structure

The desired system dynamics of a controlled system is very often described by a reference model. When chosen this model as a linear system, it can be optimally designed using standard methods of the optimal control theory. The state-space reference model for the controlled system with n state variables and p inputs is described by the state equation:

$$\frac{\mathrm{d}\mathbf{x}_M}{\mathrm{d}t} = \mathbf{A}_M\mathbf{x}_M + \mathbf{B}_M\mathbf{w} \tag{1}$$

where $\mathbf{x}_M$ (n×1) is the state vector of the reference model, $\mathbf{A}_M$ (n×n) is the state matrix of the reference model, $\mathbf{B}_M$ (n×p) is the input matrix of the model and $\mathbf{w}$ (p×1) is the vector of the desired values.

The controlled system is described in state space as a nonlinear continuous system with parametric and with additive disturbances (or deviations from the reference model) in the form:

$$\frac{\mathrm{d}\mathbf{x}}{\mathrm{d}t} = (\mathbf{A}_M + \Delta\mathbf{A})\mathbf{x} + (\mathbf{B}_M + \Delta\mathbf{B})\mathbf{u} + \mathbf{v} = = \mathbf{A}_M\mathbf{x} + \mathbf{B}_M\mathbf{u} + (\Delta\mathbf{A}\mathbf{x} + \Delta\mathbf{B}\mathbf{u} + \mathbf{v}) \tag{2}$$

where $\mathbf{x}$ (n×1) is the state vector of the controlled structure, $\mathbf{u}$ (p×1) the vector of input variables, $\Delta\mathbf{A}$ (n×n), $\Delta\mathbf{B}$ (n×p) – the matrices of the parametric disturbances and $\mathbf{v}$ (n×1) – the vector of additive disturbances.

In this case the goal of the electric drive control is twofold:

1. to reach the zero state of the state vector $\mathbf{x}$ and
2. to reach the zero state of all deviation of state variables from the desired values.

For this reason, the deviations of the state vector components from the desired values the are suitable to choose as the state variables of the controlled system. The system stability is investigated with regard to these deviations.

Let us calculate the deviation between the reference model and controlled system:

$$\mathbf{e} = \mathbf{x}_M - \mathbf{x} \tag{3}$$

where $\mathbf{e}$ (n×1) is the vector of deviations between the state variables of the model $\mathbf{x}_M$ according to (1) and of the system $\mathbf{x}$, defined in equation (2). By differentiating this vector of deviations one gets:

$$\frac{\mathrm{d}\mathbf{e}}{\mathrm{d}t} = \frac{\mathrm{d}\mathbf{x}_M}{\mathrm{d}t} - \frac{\mathrm{d}\mathbf{x}}{\mathrm{d}t} \tag{4}$$

After inserting equations (1) and (2), the expanded system is:

$$\frac{\mathrm{d}\mathbf{e}}{\mathrm{d}t} = \mathbf{A}_M(\mathbf{x}_\boldsymbol{M} - \mathbf{x}) + \mathbf{B}_M\mathbf{w} - \mathbf{B}_M\mathbf{u} - \Delta\mathbf{A}\mathbf{x} - \Delta\mathbf{B}\mathbf{u} - \mathbf{v} \tag{5}$$

$$\frac{\mathrm{d}\mathbf{e}}{\mathrm{d}t} = \mathbf{A}_M\mathbf{e} - \mathbf{B}_M\mathbf{u} + \mathbf{f} \tag{6}$$

where the vector $\mathbf{f}$ (n×1) presents a generalized disturbance vector comprising all parametrical and additive disturbances affecting the system with regard to its reference model:

$$\mathbf{f} = -\Delta\mathbf{A}\mathbf{x} - \Delta\mathbf{B}\mathbf{u} - \mathbf{v} + \mathbf{B}_M\mathbf{w} \tag{7}$$

The goal of the controller design is to find such mathematical formulation for determining the input vector $\mathbf{u}$ for which the zero solution of the system (6) is asymptotically stable, i.e. $\lim_{t\to\infty} \mathbf{e} = \mathbf{0}$. In order to investigate the asymptotic stability of the system (6) according to the Lyapunov criterium, the positive definite Lyapunov function is chosen in the weighted quadratic form of the system states:

$$V = \mathbf{e}^T\mathbf{P}\mathbf{e} \tag{8}$$

The derivation of the Lyapunov function (8) after inserting (1), (2), (3), (6) and performing simple modifications is:

$$\frac{\mathrm{d}V}{\mathrm{d}t} = \mathbf{e}^T(\mathbf{A}_M^T\mathbf{P} + \mathbf{P}\mathbf{A}_M)\mathbf{e} + 2[\mathbf{f}^T\mathbf{z} - (\mathbf{B}_M\mathbf{u})^T\mathbf{z}] = \mathbf{e}^T\mathbf{Q}\mathbf{e} + 2[\mathbf{f}^T\mathbf{z} - (\mathbf{B}_M\mathbf{u})^T\mathbf{z}] \quad (9)$$

where the vector **z** (n×1) is the weighted state deviation vector:

$$\mathbf{z} = \mathbf{P}\mathbf{e} \quad (10)$$

In (8), (9), (10) the matrix **P** (n×n) is a symmetric positively definite matrix which satisfies the Lyapunov matrix equation:

$$\mathbf{A}_M^T\mathbf{P} + \mathbf{P}\mathbf{A}_M = -\mathbf{Q} \quad (11)$$

where **Q** (n×n) is also a symmetric positive definite matrix.

Choosing the reference model according to (1) one can avoid solving (11). If the state matrix of the reference model is in the controllability form, then based on the optimal control theory [32] it is possible to determine the elements of the matrix **P** analytically as follows:

$$\mathbf{Q} = -\alpha\mathbf{P} \quad (12)$$

where the parameter α allows to set an optimal dynamics of the controlled variable satisfying the criteria of the minimum control deviation and of the minimum input energy. The model dynamics is inversely proportional to the value of the parameter α.

The system (6) is asymptotically stable if the derivation of Lyapunov function (9) is a negative definite function. Based on (10), (11), (12), the derivation of the Lyapunov function is:

$$\frac{\mathrm{d}V}{\mathrm{d}t} = -\alpha\mathbf{e}^T\mathbf{P}\mathbf{e} + 2[\mathbf{f}^T\mathbf{z} - (\mathbf{B}_M\mathbf{u})^T\mathbf{z}] \quad (13)$$

$$\frac{\mathrm{d}V}{\mathrm{d}t} = -\alpha\mathbf{e}^T\mathbf{z} + 2[\mathbf{f}^T\mathbf{z} - (\mathbf{B}_M\mathbf{u})^T\mathbf{z}] \tag{14}$$

Here the expression $\mathbf{e}^T\mathbf{z} = \mathbf{e}^T\mathbf{P}\mathbf{e}$ (where $\mathbf{z} = \mathbf{P}\mathbf{e}$) is always positive and as a result, the term $-\alpha\mathbf{e}^T\mathbf{z}$ in (14) is negative. Then the system (6) will be asymptotically stable, i.e., its derivation will be negative, if for the input **u** it holds that:

$$\mathbf{u} = \mathbf{K}\mathbf{z} \tag{15}$$

where **K** ($n\times n$) is an optional constant matrix of positive parameters. The matrix $\mathbf{B}_M$ is a constant matrix and its influence can be generally included in the values of the optional elements of the matrix **K**, when modifying equation (14) with respect to equation (15). Then the second expression on the right side in (14) will be negative if for each component of the vector **f** the following inequality is met:

$$\left|\mathbf{k}_i^T\mathbf{z}\right| \geq |f_i| \quad \text{pre } i = 1 \dots n \tag{16}$$

where $\mathbf{k}_i^T$ is the i-th row of the matrix **K**. Let's note that for a single-input system instead of the matrix **K** the row vector $\mathbf{k}^T$ is used. The inequality (16) is ensured if the optional positive parameters in the matrix **K** will have sufficiently large values.
In order to achieve the zero control deviation, i.e. the difference between the output variables of the reference model and the controlled system $(y_M - y)$ in steady-state, the first component of the vector **e** will be chosen as an integral of this difference:

$$x_{ext} = \int (y_M - y)\,\mathrm{d}t \tag{17}$$

By introducing this integral, the reference model (1) is extended by the new state variable x_{ext}. Now, the extended deviation vector (3) $\mathbf{e}^*$ will be:

$$\mathbf{e}^* = \begin{bmatrix} x_{\text{ext}} \\ \mathbf{e} \end{bmatrix} \tag{18}$$

The reference model extension does not affect the stability of the designed control structure provided that the conditions in the equations (10), (11) and (12) are valid also for the extended system.

Maximum values of the disturbance vector components |**f**| usually are physically limited. The limitation can be ensured by a relevant increase of the values of the optional parameters in the matrix **K** – the condition (16).

The block diagram of the designed controlled system with the extended reference model derived according to the above theory is shown in Figure 1.

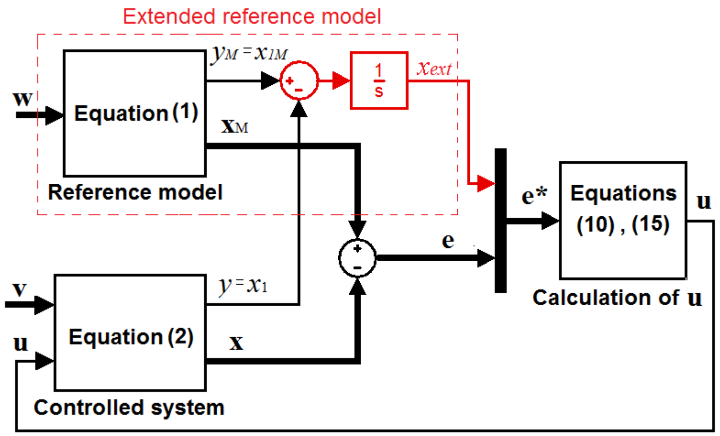


Figure 1: The structure of the designed controlled system.

The following basic features result from the control structure design:

- The control structure design and controller parameters does not depend on accurate values of the nonlinear system parameters. Thus, they do not depend on an exact description and the values of the nonlinear controlled system parameters;
- The controlled system dynamics is prescribed by the reference model (1), where both the reference model and the controlled system are of the same order. The linear reference model can be designed using standard methods of the linear

control theory in order to set an optimal motion dynamics of the controlled system;
- The reference model dynamics can be set using a single parameter α. By its introduction, the matrix **P** satisfies the Lyapunov matrix equation (11) and according to [32] it does not have to be solved;
- The stability of the control is ensured by the condition (16), in which the positive elements (gains) of the matrix **K** present the optional parameters at the controller design.
- The values of the of the disturbance vector **f** components in technical systems usually are physically limited. It means that at a sufficient large values of the matrix **K** elements the control deviation of the output (controlled) variable always converges to zero in steady-state.

Mathematical Model of Induction Motor

The current-flux model of the IM presents the 3rd order system. Its current-flux model [8] is described in the $\{x, y\}$ reference system by components of the stator currents and rotor fluxes:

$$\frac{\mathrm{d}\psi_{2x}}{\mathrm{d}t} = -\omega_g\psi_{2x} + L_m\omega_g i_{1x} + (\omega_1 - \omega)\psi_{2y} \tag{19}$$

$$\frac{\mathrm{d}\psi_{2y}}{\mathrm{d}t} = -\omega_g\psi_{2y} + L_m\omega_g i_{1y} - (\omega_1 - \omega)\psi_{2x} \tag{20}$$

$$T_{mech} = L_m\frac{p}{L_1}\left(\psi_{2x}i_{1y} - \psi_{2y}i_{1x}\right) \tag{21}$$

$$\frac{J}{p}\frac{\mathrm{d}\omega_m}{\mathrm{d}t} = T_{mech} - T_L \tag{22}$$

where the notation of the parameters and variables is as follows:

i_{1x}, i_{1y}	components of stator current space vector $\mathbf{i}_1$
ω_m	mechanical angular speed of the rotor
ω_1	angular frequency of the stator voltage
ω_2	slip angular speed $\omega_2 = \omega_1 - \omega_m$
R_2	rotor phase resistance
Ψ_{2x}, Ψ_{2y}	stator and rotor magnetic flux components

L_m	main inductance
L_1, L_2	leakage inductances
ω_g	constant $\omega_g = R_2/L_2$
T_{mech}	mechanical motor torque
T_D	dynamic motor torque
p	number of pole pairs
J	moment of inertia
T_L	load torque

From equations (19) – (22) it is obvious that the IM presents a strongly nonlinear higher-order controlled system having oscillating character.

The values of the motor parameters used for simulation are specified in Tab. 1.

Table 1: Induction motor parameters for modeling and experimentation.

P_N = 3 kW	U_{1N} = 220 V	I_{1N} = 6.9 A
J = 0.1 kgm^2	r_1 = 1.8 Ω	R_1 = 2/3 r_1 = 1.2 Ω
n_N = 1430 rev./min	r_2 = 1.85 Ω	R_2 = 2/3 r_2 = 1.23 Ω
p = 2	$L_1 = L_2$ = 0.2106 H	$\omega_g = R_2/L_2$ = 5.84 s^{-1}
T_N = 20 Nm		

The characteristics in Figure 2 show the motor model torque and angular speed responses at the step change on the motor inputs when the motor is supplied from a current converter in which the current loop time constant already is compensated. Let's note that according to (19) – (22) in this case the values of the current vector components of the IM model used for simulation are i_{1x} = 0 A, i_{1y} = 15 A. At this supply the angular speed reaches the value of ω_1 = 200 rad/s.

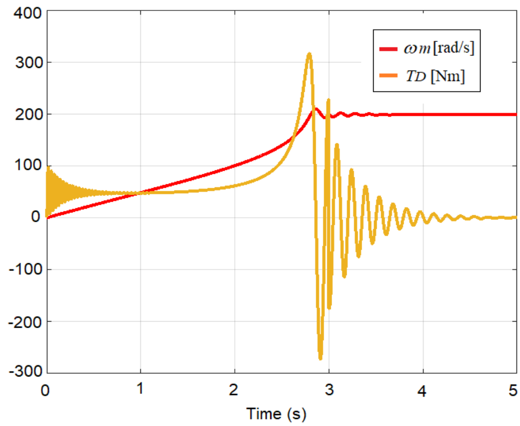


Figure 2: Time courses of the IM model torque and speed at motor starting when supplied by the current vector.

Design of the IM Drive Control

The objective of the IM drive control consists in control of its angular speed where the motor dynamics is prescribed by a linear reference model to be designed. For the control structure design according to Section 2 it is not necessary to know an exact model of the controlled system. The simplified model of the IM presents a nonlinear dynamic system of the 2nd order as shown in Figure 3.

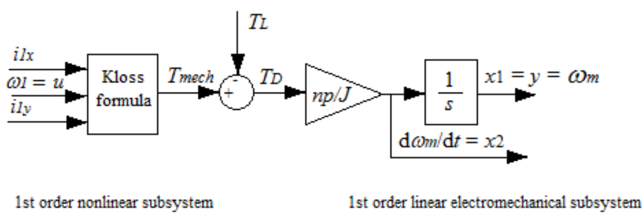


Figure 3: Simplified model of the IM presenting a 2nd order nonlinear system.

The static nonlinearity in generating the mechanical torque of the T_{mech} motor is usually described by the Kloss formula with the 1st order dynamics and the electromagnetic linear subsystem is described by the equation of the torque equilibrium on the drive shaft.

Let's select the state variables of the IM as shown in Figure 3: $x_1 = y = \omega_m$ (the rotor angular speed) and $x_2 = \mathrm{d}x_1/\mathrm{d}t = \mathrm{d}\omega_m/\mathrm{d}t$ (the rotor acceleration corresponding to its motor dynamic torque T_D).

As the IM is considered as a nonlinear 2nd order system, according to [32] its required dynamics is prescribed by the 2nd order linear reference model:

$$\begin{bmatrix} \dot{x}_{1M} \\ \dot{x}_{2M} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\frac{\alpha^2}{2} & -\alpha \end{bmatrix} \begin{bmatrix} x_{1M} \\ x_{2M} \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{\alpha^2}{2} \end{bmatrix} w \qquad (23)$$

where the state variables x_{1M} and x_{2M} prescribe the dynamic behavior of the corresponding state variables of the controlled system, i.e.: $x_{1M} = y_M = \omega_{mM}$ and $x_{2m} = \mathrm{d}x_{1M}/\mathrm{d}t = \mathrm{d}\omega_{mM}/\mathrm{d}t$.

The optimal dynamics of the controlled variable can be set by the optional positive parameter α in the reference model (23).

To ensure the zero control deviation of the angular speed of the controlled system and the reference model at steady-state, the reference model is extended by a new state variable x_{ext}.

To create a deviation between the state variable of the reference model and the system according to (17), the following relation is used:

$$x_{ext} = \int (x_{1M} - x_1)\mathrm{d}t = \int (\mathrm{y}_M - \mathrm{y})\mathrm{d}t \qquad (24)$$

Now the extended vector of the deviation will be in the form:

$$\mathbf{e}^* = \begin{bmatrix} x_{ext} \\ e_1 \\ e_2 \end{bmatrix} \qquad (25)$$

This means, the extended reference model of the IM drive presents the 3rd order system. According to the optimization theory [32], its state matrices are in the form:

$$\mathbf{P} = \begin{bmatrix} \frac{\alpha^5}{2} & \alpha^4 & \frac{\alpha^3}{2} \\ \alpha^4 & \frac{5\alpha^3}{2} & \frac{3\alpha^2}{2} \\ \frac{\alpha^3}{2} & \frac{3\alpha^2}{2} & \frac{3\alpha}{2} \end{bmatrix}; \ \mathbf{Q} = -\alpha\mathbf{P} \quad (27)$$

$$\mathbf{A}_M = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -\frac{\alpha^3}{2} & -\frac{3\alpha^2}{2} & -\frac{3\alpha}{2} \end{bmatrix}; \quad \mathbf{b}_M = \begin{bmatrix} 0 \\ 0 \\ \frac{\alpha^2}{2} \end{bmatrix} \quad (26)$$

where $\mathbf{b}_M$ is the input vector in case of the one-input model.

The optimal matrices **P** and **Q** conforming the Lyapunov matrix equation (11) are:

The IM as a controlled system will follow the extended reference model with $\lim_{t\to\infty} \mathbf{e}^* = \mathbf{0}$, i.e. the controlled system will be asymptotically stable, if the input u is calculated using (15):

$$u = [k_1 \quad k_2 \quad k_3] \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix} \quad (28)$$

According to (16) the elements for the vector $\mathbf{k}^T$ presenting gains must be positive and large enough to ensure the asymptotic stability of the controlled system. On the other hand, the value of the parameters in the vector $\mathbf{k}^T$ is limited by physical constraints in the controlled system. In case of an electric drive it is the electric motor current, the dynamics of real power converter, etc. According to (10) the components of the vector **z** are:

$$z_1 = p_{11}x_{\text{ext}} + p_{12}e_1 + p_{13}e_2 \quad (29)$$

$$z_2 = p_{21}x_{ext} + p_{22}e_1 + p_{23}e_2 \quad (30)$$

$$z_3 = p_{31}x_{ext} + p_{32}e_1 + p_{33}e_2 \qquad (31)$$

The elements of the matrix **P** are known from evaluating the equation (27).

The resulting control scheme for controlling the angular speed of the IM drive in accordance with the derived control structure presented in Figure 1 is shown in Figure 4.

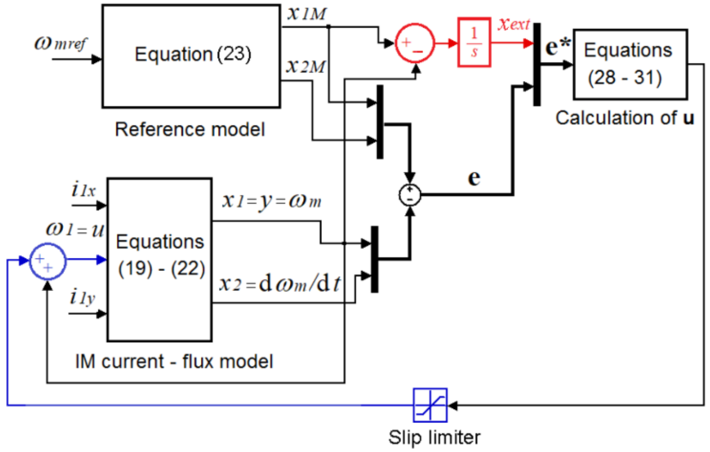


Figure 4: IM drive block diagram.

In order that the IM would operate in a stable part of its torque characteristic, the block diagram in Figure 4 has been completed by a conversion of the action variable to slip that is completed by its limitation (like it is case in a real motor). The slip limiter, however, does not change the validity of the structure shown in Figure 1. The limitation of the state variables of the drive system (the current and torque) can be realized inside the reference model without any affecting the control loop stability. This is due to the fact that the reference model is linear and the limitations do not influence position of the linear system poles.

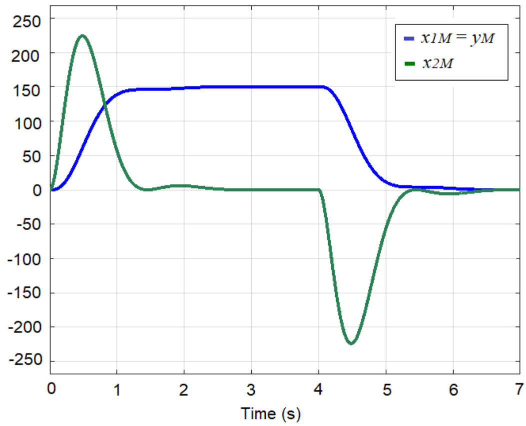
Simulation of the IM Drive in Basic Operation States

The verification of the control structure properties was carried out by simulation in MATLAB with the motor parameters specified in Table 1. The desired value of the mechanical angular speed of the IM was set in the reference model to $\omega_{mref} = 150$ rad/s and the stator current vector were $i_{1x} = 0$ A, $i_{1y} = 20$ A.

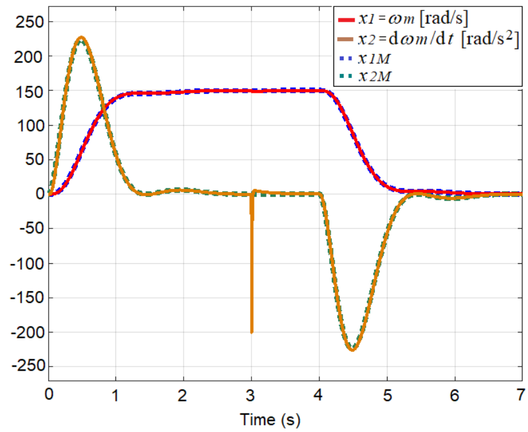
The controller gain, which is represented by optional components of the vector $\mathbf{k}^T$ in (28) has been set to the value $\mathbf{k}^T = [0.0031\ \ 0.0019\ \ 0.00038]$. The dynamics of the reference model setting (using the parameter α) must take into account the physical properties of the drive, which in our case are presented by the current (torque) overloading of the IM. The dynamic properties of the IM are described by unit step characteristics shown in Figure 2. The value of the parameter α is inversely proportional to the model dynamics. This means that based on the Shannon–Kotelnik theorem for stabilizing the angular speed of the IM within the time of 2 seconds, the value of the optional parameter is chosen $\alpha = 5$.

The operation cycle of the IM drive consists of three phases: the starting the IM drive, its running at constant speed and stopping (Figure 5a). An external (additive) disturbance of the IM drive – the load torque $T_L = T_N = 20$ Nm was also introduced in time $t = 3$ s.

The time course of the angular speed ω_m (the output variable) for the considered operation cycle is shown in Figure 5. It is obvious that the angular speed of the IM drive practically tracks the reference angular speed prescribed by the reference model (Figure 5a) during the entire operation cycle, even during the step disturbance T_L as is shown in Figure 5b. This is also observed on changes of the variable $d\omega_m/dt \approx T_D$ (corresponding to the acceleration) in Figure 5b, where the considered disturbance torque T_L is settled with a high dynamics. This experiment verifies that the proposed control structure is invariant against the additive disturbances.



(a)



(b)

Figure 5: Time courses of the IM control during the operation cycle: a) prescribed by the reference model, b) achieved by the motor at its starting and loading.

The robustness of the proposed control structure has been verified at the change of two most important parameters of the controlled system significantly affecting its properties. In case of IM they are: the rotor resistance R_2 and the moment of inertia J.

In majority of the control systems for IM the precise speed control depends on knowledge of the rotor resistance value that usually is identified by various types of observers. Figure 6 shows time response when the rotor resistance R_2 was increased to the double of its original value. The dynamics of the controlled system is almost identical to the dynamics of the reference model during the entire operation cycle (Figure 5b). The time courses of the variables in Figure 6 confirm the controlled system invariancy at the considered change of the parameter R_2.

Another parameter that considerably influences the motor dynamics is the moment of inertia J applied to the motor shaft. Its value can vary during the operation cycle what is case of many industrial applications of the IM drives (e.g. winding machines, robotic and transportation systems). As it follows up from the time courses in Figure 7a and Figure 7b, the increase of the moment of an additional inertia to a half/or double of the motor nominal moment of inertia does not influence the motor dynamics. This fact presents a very significant advantage in control of nonlinear systems having an oscillating character. The effect of the load torque T_L is again compensated with high dynamics also at a significant change of the motor inertia, which confirms the high invariance against the parameter variations in the proposed control structure.

The simulations have confirmed that the proposed controller ensures a high quality angular speed control of the IM drive during the entire operation cycle according to the prescribed dynamics.

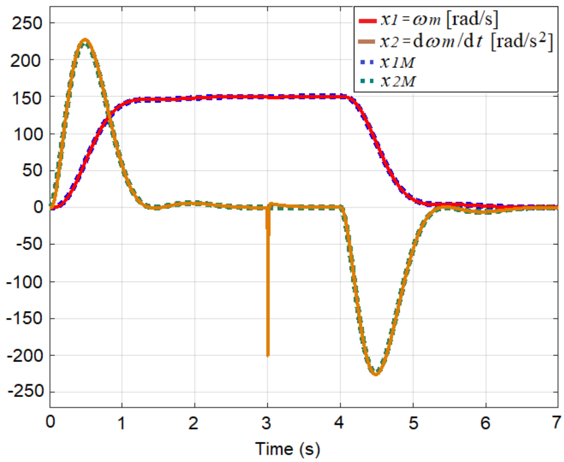
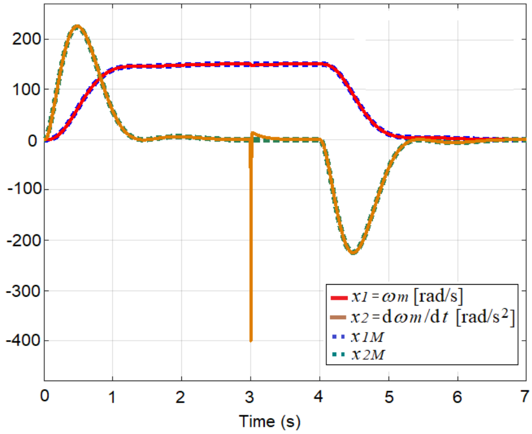


Figure 6: The effect of change of rotor resistance R_2=2 R_{2N} on control dynamics at motor starting and loading.



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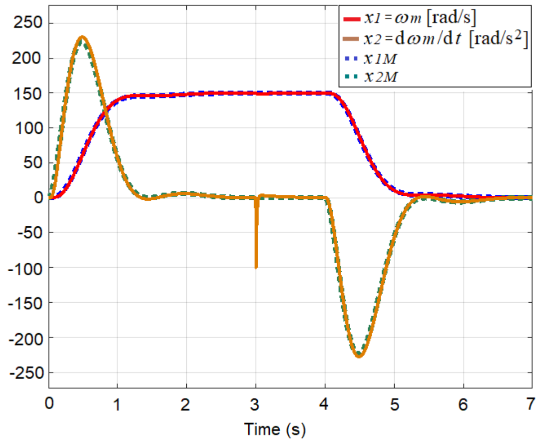

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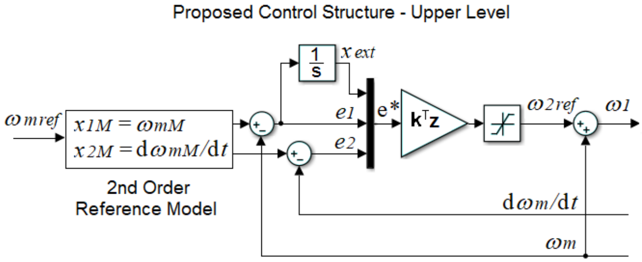
Figure 7: The effect of change of additional moment of inertia to the value: (a) $J = 0.5\ J_N$; (b) $J = 2\ J_N$ on control dynamics at motor starting and loading.

Moreover, the controller satisfies all basic control objectives: the drive is invariant against the disturbances (the load torque) and robust against changes of the motor parameters (the rotor resistance and additional moment of inertia connected to the rotor shaft).

Comparison of the Proposed Control Structure with the Vector Control Structure

The vector drive control of the IM presents one of the most common control methods in the technical practice today. Its specific dynamic properties depend on the used modification and are described by a large number of the references, e.g. [6,10]. In the next, the proposed control properties will be compared with those of the vector control on the basis of a comparison of their structures. The basic structures of both control methods are shown in Figure 8 – 10. In both structures, the upper control level controls the desired mechanical speed ω_m of the drive, eventually it sets the excitation flow magnitude of the motor through its current components in the rectangular rotating reference frame $\{x,y\}$ rotating at the angular speed ω_1.



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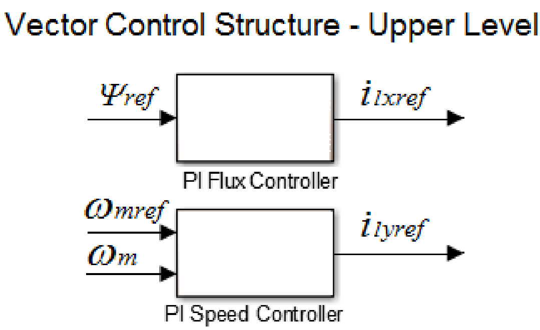


(**b**)

Figure 8: The upper control level: (a) of the designed control structure; (b) of the vector control structure.

At the upper control level (Figure 8a, b), there are seen two basic differences:

1. The first difference relates the control structures: both structures are linear. They differ in their internal interconnection and by the control structure order;
2. The second difference consists in the type of the output action variable. In the vector control they are variable setpoints of the stator current components i_{1x}, i_{1y}. In the proposed control structure the angular speed of the stator current vector presents the action variable and, in principle, the components i_{1x}, i_{1y} are kept constant.

The lower control level (Figure 9) contains the controllers of the stator current components i_{1x}, i_{1y} and the transformations between the stator system {*a*,*b*,*c*} and the reference frame {*x*,*y*}. At the lower control level, the two structures being compared are practically identical.

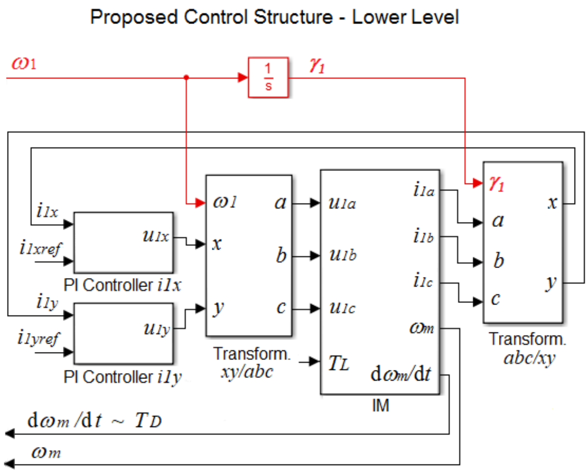


Figure 9: The lower control level of the proposed control structure, where γ_1 is the instantaneous position of the stator voltage vector and u_{1x}, u_{1y} are the components of the stator voltage space vector $\mathbf{u}_x$.

A significant difference consists in the stator currents transformations into the reference frame {*x*,*y*}. While in the vector control, this system is the most often tied to the position of the rotor flux vector γ, in the proposed control structure it is firmly tied to the position of the stator current vector $\mathbf{i}_1$ (which in the fact presents an integral from the angular speed ω_1). In the case of the vector control (Figure 10), the problems arise when using the Park transformation. It requires the measurability of the rotor flux position, the dependence of this position estimation on the unknown and variable value of the rotor resistance, problems at low mechanical angular speeds, etc. These uncertainties can significantly affect quality of the control.

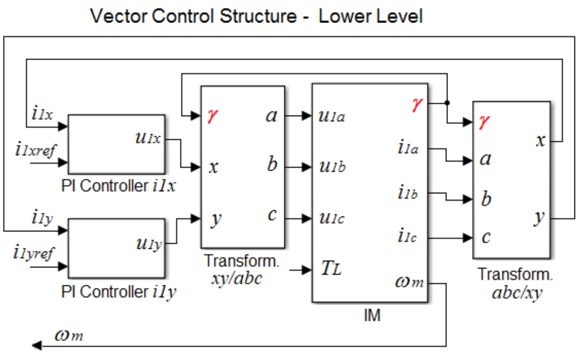


Figure 10: The lower level of the vector control structure, where γ is the actual position of the rotor flux vector.

In the proposed control structure, the value of the stator angular velocity ω_1 inputs from the higher control level. Its value is always precisely known which guarantees the accuracy of this transformation and its independence from the current states or other parameters of the IM.

Experimental Verification of the IM Drive Speed Control on a Laboratory Model

The linear model reference control structure is verified on the three-phase induction motor TYPE 1AV3104B (400 V, 2.2 kW, 1465 RPM, 14.3 Nm) driven by the VQFREM 400 004 – 4MA power converter (400 V, 11 A), manufactured by VONSCH Co, Slovakia. The structure of the experimental setup is shown in Figure 11.

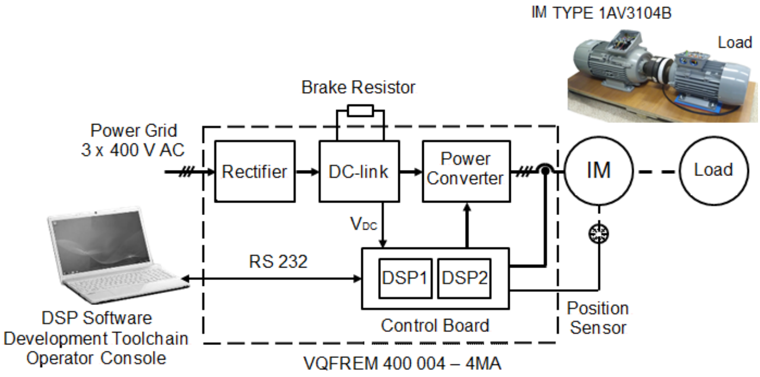


Figure 11: The structure of the experimental setup with VQFREM 400 004 – 4MA power converter.

The control board of the power converter has two processors DSP TMS320F2406. The first DSP processes signals from the current, DC-link, and position sensors. It also performs the Clarke and Park transformations and uses PI type controllers with a sample time of 50 µs to controls the stator currents i_{1x} and i_{1y} in the $\{x,y\}$ reference frame. The second DSP implements the speed control and communicates with a higher-level controller and operator console. The speed control sample time is 1 ms. The fast current control loop is written in assembler language and the rest of the code is written in C language. The Texas Instruments software development toolchain is used for programming DSPs. The setup with the input choke, power converter, and brake resistors is shown in Figure 12.

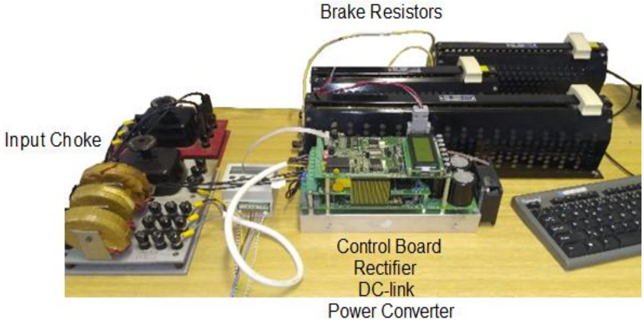
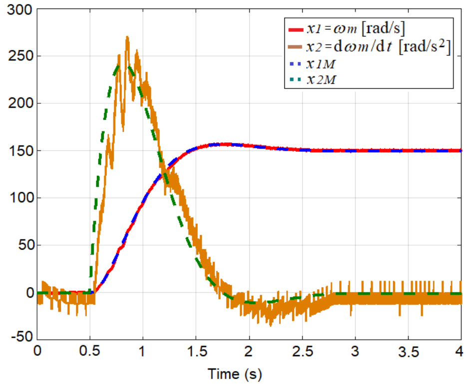
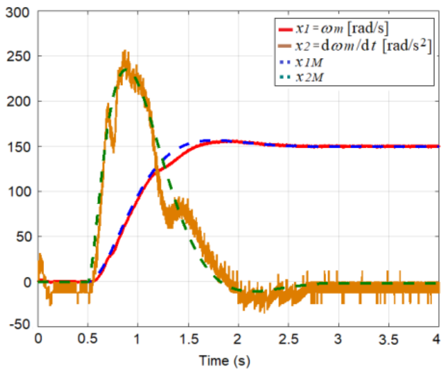


Figure 12: The experimental setup with VQFREM 400 004 – 4MA converter.

To verify experimentally the proposed control structure from Figure 4, measurements were performed on a laboratory model with IM at its starting up to its rated speed ω_m = 150 rad/s. An influence of the optional positive parameter in the reference model α was investigated on the motor dynamics. For example, Figure 13a shows the control dynamics for the parameter α = 5 (eq. 23) and the values of the optional vector $\mathbf{k}^T$ elements $\mathbf{k}^T$ = [0.0031 0.0019 0.00038].



(a)



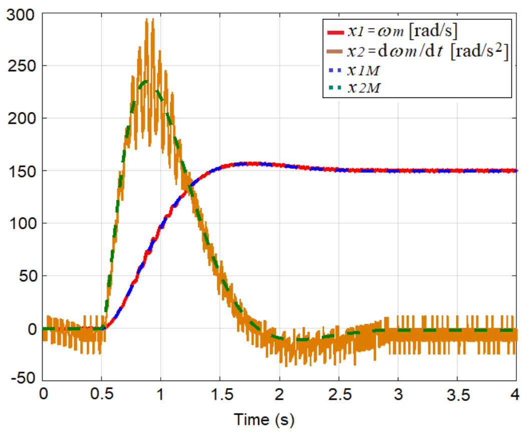
(b)

Figure 13: Motor starting at: (a) α = 5 and $\mathbf{k}^T$ = [0.0031 0.0019 0.00038]; (b) α = 5 and $\mathbf{k}^T$ = 0.25 [0.0031 0.0019 0.00038].

In the graphs the time courses of the model state variables x_{1M}, x_{2M}, prescribing the required dynamics for the motor angular speed and acceleration are compared with their measured values. The time courses of the measured quantities show a very good agreement with the reference model.

Figure 13b shows time similar courses when decreasing the optional gain of the elements of the vector $\mathbf{k}^T$ to 25 % of their original value. It is obvious that the introduced change influences the time course of variables in dynamic states (e.g. here the state variable x_2 oscillates less, but it has a larger absolute deviation from the reference model). It is important that again a substantial agreement between the measured quantities and the reference model outputs has been reached.

The time courses in Figure 14a show the dynamics of the IM drive starting at 300 % change of the controller optional gain $\mathbf{k}^T$ against its original value. Due to the substantial increase of the gain in the control circuit, the state variable x_2 (presenting the acceleration proportional to the motor dynamic torque) is visibly more oscillating, while the output variable x_1 (IM speed) practically follows the reference model.



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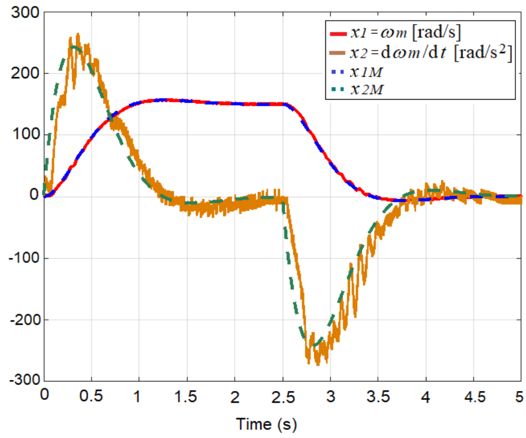

(**b**)

Figure 14: Motor starting at: (a) α = 5 and $\mathbf{k}^T$ = 3 [0.0031 0.0019 0.00038]; (b) α = 5 and $\mathbf{k}^T$ = [0.0031 0.0019 0.00038].

The starting of the motor from the non-energized state and its stopping for the values of the control parameters valid for Figure 13a are shown in Figure 14b. Here it can be observed that the motor follows the reference model both during starting and stopping, i.e., it behaves as a linear system according to the reference model (23). Therefore, the proposed control structure is able to ensure the quality of the angular speed IM control within the whole control range.

The experimental measurements confirm that the controlled drive behaves with a high accuracy as its reference model, where for this case an optimal 2nd order linear system was chosen. The reference model dynamics is determined by the optional parameter α and the gain vector $\mathbf{k}^T$.

Discussion

Based on the simulation and experimental results and on comparison of the designed control structure with the vector control structure, the proposed new control structure with the reference model is characterized by the following properties:

- No accurate values of the controlled system parameters are required. For the reference model design only a simplified IM model presenting a nonlinear 2nd order system (Figure 3) is used;
- The parameters settings is performed through two constant parameters (the gains). The first parameter (i.e. the parameter α in the description of the reference model (23) determines the overall control dynamics and the remaining optional parameters in the vector $\mathbf{k}^T$ ensure the transient phenomena and stability. They must comply the condition (16). The setting of the mentioned parameters can be realized without any exact knowledge of the controlled nonlinear system parameters. They are tuned by gradual increase of their values on the basis of the measured standardized responses of the controlled system (e.g. based on unit step characteristics);
- Comparing with the speed vector control structure, the proposed control structure is a simpler one what concerns the interconnection and lower order of the control structure). The use of the necessary Park transform in the proposed control structure is independent from the exact knowledge of the IM parameters which increases the quality of control (as shown in Section VI);
- From view of the superior control, the novel structure exhibits dynamic properties of an optimal linear dynamic system satisfying the criteria of minimum control deviation and minimum input energy [32]. Thus the drive properties are practically identical to the properties of a high quality vector control of the IM drive;
- In the proposed control structure the controlled nonlinear system is complemented by linear subsystems only (Figure 8a). For this reason, it can be implemented by a cheap conventional hardware;
- The stability of the proposed control structure is ensured by calculating the parameters (the elements of the positive definite matrix **P**) by means of the Lyapunov matrix equation (11);
- The proposed control structure is robust against considerable variations changes not only of the important parameters of IM (e.g. of the moment of inertia – Figure 7a and Figure 7b),

but also to inaccurate known parameters of the nonlinear controlled system. Here, the control system follows with high accuracy the reference model output which is confirmed by the measurements in Figure 13, 14;
- The proposed control structure is invariant against the external disturbances (e.g. of the load torque equal to the nominal torque: Figure 5 – Figure 7) where the dynamics of the disturbance is very fast);
- The proposed control of the IM angular speed solves also the problems occurring at low speed. The controlled drive follows its reference model with high accuracy also in the range of low speeds up to the zero speed.

Conclusions

The designed new stable control method can be applied generally for any continuous nonlinear system. In the article a controlled AC drive with induction motor was chosen for verification of its properties, where the IM represents a highly oscillating nonlinear system and its parameters (e.g. the rotor resistance and moment of inertia) can vary during the motor operation.

Both simulation results and experimental measurements performed for basic operating states of the IM drive have confirmed advantages of the proposed controller concerning simplicity at the design and implementation and the excellent performance of the controlled system. Application of the new control method considerably contributes to improving dynamic properties and simultaneously ensures the drive stability, invariance against disturbances and robustness against the motor parameters variations. Compared to the control structures of the vector control of IM, the new control structure is significantly simpler; it exhibits features of an optimal linear system and simultaneously it achieves almost identical control performance.

The main advantage of the novel control structure consists in the fact that it does not require any knowledge of controlled system parameters. On the other side, the precise control at majority of the used control methods strongly depends on precise knowledge of system parameters. The control quality is also guaranteed by independence of the Park transformation calculation from the exact knowledge of the IM parameters. The control structure ensures high quality of the IM speed control within the whole control range, up to zero speeds.

The proposed control structure is suitable for control of continuous nonlinear systems with unknown and time-varying parameters. The controller is suitable specially for any drive system including control of robotic systems control having a precise hierarchical control structure. Therefore, its broad utilization in industrial applications can be assumed.

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