Synergetic synthesis of aggregated discrete regulators for induction motors

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Abstract. The paper presents the method of synergetic synthesis of a nonlinear discrete control system for induction motors. The proposed approach is based on using the methods of the synergetic control theory and nonlinear mathematical models of induction motors. This approach allows to create nonlinear closed-loop piecewise-continuous control systems which guarantee the asymptotic stability of the controlled induction motors, accomplishment of the determined technological and electromagnetic invariants and selective invariance to the unknown external disturbances acting on the system. The invariance of the designed systems is ensured due to the usage of a dynamic discrete regulator which increases the astatism of the synthesized system.

1. Introduction

Induction (or asynchronous) motors (IM) is a very popular and perspective solution for the modern complex technical systems with mechanical energy generation subsystems. IMs are one of the simplest, most reliable and most economically effective motors. They are commonly used in the systems where regulation of the rotation frequency and turning angle over a wide range is not required. However, the design of IMs is associated with some typical difficulties. This type of motors is one of the most complex electromechanical highly dynamic objects from the control point of view. Its exceptional difficulty is due to the fact that the precise mathematical models of IMs are high-dimensional and highly nonlinear. Effective functioning of IMs requires control over several interrelated coordinates — rotation frequency, angular position, torque, flux, current, etc.

That is why, the scalar control methods have become the most widespread solution for IMs. In these methods, one of the essentially independent control channels (e.g. the stator’s voltage amplitude) is assumed to be dependent on another control — the source voltage frequency [1, 2, 3]. Then, the control law is synthesized using simplified linearized models, which don’t reflect the physical processes accurately enough. Moreover, these methods of synthesis are based upon the principles of “compensation” of the model’s nonlinearities (or even completely ignoring them), separation of the control channels, neutralization of cross-connections, etc. Naturally, such methods impose significant restrictions upon such important qualitative characteristics of IMs as the stability region, regulation range, mechanical characteristics, etc. All this eventually leads to the ineffective exploitation of the wide technological capabilities of IMs.

At the modern stage of development of the theory and practical applications of IMs, the further performance improvement is only possible if the nonlinear interconnections in the AC machines are taken into account via using vector control synthesis techniques. The vector control methods [4, 5] allow to achieve a significant improvement in the IMs’ functioning. A big breakthrough in the IM control
systems design occurred with the progress of the sliding mode control methods [6, 7, 8]. It is important to mention that one of the intrinsic problems of vector control systems is the difficulties in gaining accurate information about the instantaneous values of the IM states. This problem led to the development of the methods which use the IM states estimates [9, 10, 11, 12].

The cornerstone problem on the way to improving the IMs performance is the formulation of the full dynamical model of the controlled IM, which would take into account its nonlinear properties. It should also have such a structure which would best reflect the identity of the basic processes of all types of AC machines and at the same time identify specific properties for each of these types. The theory of such synthesis, which would remove any restrictions on the dimensionality and nonlinearity of the controlled object, was developed in the frame of synergetic control theory [13, 14]. Consequently, there appeared opportunities for development and realization of more effective nonlinear vector control laws in the controlled IMs. In [15, 16], the methods of synergetic synthesis of continuous vector control systems for IMs were presented, including the design of sensorless systems [17]. However, considering that modern systems rely on digital tools, we propose to apply the method of Analytical Design of Aggregated Discrete Regulators (ADADDR) [18, 19] to the problem of IM vector nonlinear control systems design.

2. Mathematical model and IM invariants
The IMs are modelled as systems of nonlinear differential equations in one of the following reference frames:
- stator oriented stationary reference frame \(\alpha, \beta\);
- rotor oriented rotationary reference frame \(d, q\);
- rotor flux oriented rotationary reference frame \(x, y\).

The most popular choice for the basis vector of IM control systems is the rotor flux linkage oriented vector, i.e. \(x, y\) reference frame model [5]:

\[
\begin{align*}
J \frac{d\omega_r}{dt} &= \frac{m}{2} pk_r \psi_r l_{sy} - M_c; \\
d\psi_r \frac{dt}{dt} &= r_r k_r l_{sx} - \frac{1}{r_r} \psi_r; \\
di_{sy} \frac{dt}{dt} &= -\frac{1}{L_s} i_{sy} - \omega_p l_{sx} - \frac{pk_r}{L_s} \omega_r \psi_r + \frac{1}{L_s} u_{sy}; \\
di_{sx} \frac{dt}{dt} &= -\frac{1}{L_s} i_{sx} + \omega_p l_{sy} + \frac{k_r}{T_r^*} \psi_r + \frac{1}{L_s^*} u_{sx}.
\end{align*}
\]

where \(u_{sx}, u_{sy}\) are the stator voltage projections to the \(x\) and \(y\) axes of the rotationary reference frame; \(i_{sx}, i_{sy}\) are the stator current projections to the axes; \(\psi_r\) — absolute value of the resulting rotor flux vector; \(\omega_r\) — rotor’s angular velocity; \(\omega_p\) — rotor flux rotation frequency; \(k_r = \frac{l_m}{l_r}\) — rotor’s electromagnetic link coefficient; \(r_s, r_r\) — active resistances of the stator and rotor wirings; \(L_s, L_r\) — full inductances of the stator and rotor wirings; \(L_m\) — mutual inductance between stator and rotor; \(L_s^* = L_s - L_m k_r, r_s^* = r_s + r_r k_r^2\) — transformed inductance and resistance of the stator; \(T_r = \frac{l_r}{r_r}, T_s^* = \frac{l_s^*}{r_s^*}\) — time constants of the stator and rotor; \(p\) is the number of the pole pairs; \(J\) — moment of inertia; \(m\) — the number of the motor phases; \(M_c\) — moment of resistance of the IM’s shaft load. We assume that the variables related to the rotor wiring (such as the power sources’ voltages, currents and fluxes) as well as the rotor wiring parameters are taken with respect to the number of the stator wiring coils. Besides, we add the static equation to the equation (1):

\[
\psi_r (\omega_p - p \omega_r) = k_r r_r l_{sy}.
\]
We consider the model (1), (2) with the following commonplace assumptions:

- the parameters of the rotor and stator wirings are the same, and the system of the phase voltages is symmetric;
- the magnetic cores are not saturated;
- the air gap between the moving parts is uniform;
- the magnetomotive force in the air gap is sinusoidal;
- the effect of the steel wearout as well as the skin effect in IM are neglected;
- both IM parts have identical distributions of the wirings.

To solve the control synthesis problem, we present new applied methods of control design, which are based on the principles of the synergetic control theory. The control criteria (or the design goals) in this theory are expressed as a corresponding system of invariants. These invariants act as control goals, and either the execution of a given control task is insured on the invariants or some given energetic relations (physical, chemical, etc.) are maintained. The synergetic synthesis procedure consists of finding the control laws such that the invariants are fulfilled.

Two main groups of possible IM invariants can be distinguished [15, 16] — technological and electromagnetic. The form of a technological invariant is defined by a given practical task solved by the IM included to some technological process. It characterizes the desired dynamic or static state of the controlled variables — rotation frequency, turning angle or torque. By example, for the task of rotation frequency stabilization, the technological invariant is \( \omega_r = \omega_{r0} \).

A particular interest lies in the invariants related to the constant motor flux — electromagnetic invariants. The idea of stabilization of the IM magnetic state is widespread in the well known frequency control laws for IMs, and it has a significant practical importance. These electromagnetic invariants include:

- \( \psi_s = \text{const} \) — constant stator flux linkage;
- \( \psi_r = \text{const} \) — constant rotor flux linkage;
- \( \Phi = \text{const} \) — constant combined flux linkage.

The choice of the invariant set is an important step in the process of solving the synergetic IM control synthesis problem. This set must correspond to the designer’s goals for the mechanical, electromagnetic and other properties of the IM and to satisfy the requirements of the given task. The number of invariants is defined by the number of control channels. Thus, for the two-channel amplitude-frequency IM control, it is possible to form a set consisting of two invariants.

It is worth noting that in the synthesis of vector control laws with synergetic approach (i.e. using the technological and electromagnetic invariants), it is not even necessary to use the terms of amplitude and frequency of the source currents and voltages, which are customary for the theory of IM frequency control. In order to fully reflect the dynamic and static states of the IM, it is sufficient to define the desired rotation frequency of the shaft as a technological invariant, as well as the value characterizing the state of the IM’s magnetic circuit, e.g. the rotor flux linkage, as an electromagnetic invariant. In this case, the control goal is to maintain the given rotation frequency with the optimal state of the IM’s magnetic circuit. Depending on the invariant set, one can come up with other types of controlled IMs.

3. Synergetic synthesis of discrete vector regulators for IMs

We address the problem of synthesis of a discrete regulator which stabilizes the IM’s shaft rotation frequency and the rotor flux linkage. For that purpose, we formulate an extended model of synergetic synthesis [19] taking into account the technological and electromagnetic invariants:

\[
\begin{align*}
\frac{dv}{dt} &= Qx - Lg; \\
\frac{dx}{dt} &= A(x)x + Bu - Cv,
\end{align*}
\]
where $\mathbf{x} = [\mathbf{\omega}_r, \mathbf{\psi}_r, i_{sx}, i_{xy}]^T$ — vector of the object’s phase coordinates; $\mathbf{v} = [\dot{\mathbf{z}}_1, \dot{\mathbf{z}}_2]^T$ — vector of the regulator’s state coordinates; $\mathbf{u} = [\mathbf{u}_1, \mathbf{u}_2]^T$ — control vector; $\mathbf{g} = [\dot{\omega}_r, \dot{\psi}_r]^T$ — vector of the desired values of the control variables;

$$
\begin{align*}
\mathbf{L} &= \begin{bmatrix}
\eta_1 & 0 \\
0 & \frac{mpk_r}{2T_r} \mathbf{\psi}_r & 0 \\
0 & -\frac{1}{T_s} & 0 & r_r k_r \\
-p_i_{sx} & -\frac{p k_r}{L_s} \mathbf{\omega}_r & -\frac{1}{T_s} & -k_r r_r i_{sx} \\
pi_{sy} & \frac{k_r}{T_s L_s} & k_r r_r i_{sy} & -\frac{1}{T_s}
\end{bmatrix}; \\
\mathbf{A} &= \begin{bmatrix}
0 & 0 & 0 & 0 \\
0 & 0 & \frac{K_C}{L_s} & 0 \\
0 & 0 & 0 & \frac{K_C}{L_s} \\
0 & 0 & 0 & 0
\end{bmatrix}; \\
\mathbf{B} &= \begin{bmatrix}
1 & 0 \\
0 & 1 \\
0 & 0 \\
0 & 0
\end{bmatrix}; \\
\mathbf{Q} &= \begin{bmatrix}
\eta_1 & 0 & 0 & 0 \\
0 & \eta_2 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{bmatrix}; \\
\mathbf{C} &= \begin{bmatrix}
1 & 0 \\
0 & 1 \\
0 & 0 \\
0 & 0
\end{bmatrix}.
\end{align*}
$$

Now, we apply the Euler approximation to the equations (3), which results in the discrete model of synergetic synthesis:

$$
\begin{align*}
\mathbf{v}[k+1] &= \mathbf{Sx}[k] - \mathbf{Wg}[k]; \\
\mathbf{x}[k+1] &= \mathbf{F(x}[k])\mathbf{x}[k] + \mathbf{Du}[k] - \mathbf{Hv}[k],
\end{align*}
$$

where $\mathbf{F} = \mathbf{I}^d + T_0 \mathbf{A}; T_0$ — discretization step in time; $\mathbf{I}^d$ — unit matrix of dimensionality $4 \times 4$; $\mathbf{D} = T_0 \mathbf{B}; \mathbf{H} = T_0 \mathbf{C}; \mathbf{S} = T_0 \mathbf{Q}; \mathbf{W} = T_0 \mathbf{L}$. Following to the next step of the ADADR, we now introduce the first set of macrovariables:

$$
\mathbf{\psi}_1[k] = \mathbf{P} (\mathbf{\bar{z}}[k] + \mathbf{\varphi}_1[k])
$$

where $\mathbf{\psi}_1[k] = [\psi_{1,1}[k], \psi_{1,2}[k], i_{sx}[k], i_{sy}[k]]^T; \mathbf{\varphi}_1[k] = [\varphi_{1,1}[k], \varphi_{1,2}[k]]^T$ — vector of the internal controls;

$\mathbf{P} = \| p_{ij} \|$ — numeric invertible matrix $i, j = 1, 2$.

The parallel set of macrovariables (5) must satisfy the solution $\mathbf{\psi}_1[k] = 0$ of the vector equation:

$$
\mathbf{\psi}_1[k+1] + \mathbf{\Lambda}_1 \mathbf{\psi}_1[k] = 0,
$$

where $\mathbf{\Lambda}_1 = \begin{bmatrix} \lambda_{1,1} & 0 \\ 0 & \lambda_{1,2} \end{bmatrix}$. To assure the asymptotical stability of the solution for the equation(6), the following conditions are necessary:

$$
|\lambda_{1,1}| < 1, |\lambda_{1,2}| < 1.
$$

After the transients $\mathbf{\psi}_1[k] = 0$, for which the process speed is defined as $\lambda_{1,1}$ and $\lambda_{1,2}$, are finished, the dynamic decomposition of the closed-loop system occurs:

$$
\begin{align*}
\mathbf{v}[k+1] &= \mathbf{\dot{S}} \mathbf{\bar{z}}[k] - \mathbf{Wg}[k]; \\
\mathbf{\bar{z}}[k+1] &= \mathbf{\dot{F}} \mathbf{\bar{z}}[k] - \mathbf{D} \mathbf{\varphi}_1[k] - \mathbf{Hv}[k],
\end{align*}
$$
where $\bar{x}[k] = [\omega_r \psi_r]^T$ — the decomposed state vector; $\bar{F} = \begin{bmatrix} 1 & 0 \\ 0 & 1 - \frac{T_0}{r_T} \end{bmatrix}$; $\bar{D} = \begin{bmatrix} 0 & T_0 \frac{mpk_r}{2} \psi_r[k] \\ r_T k_T T_0 & 0 \end{bmatrix}$; $\bar{H} = \begin{bmatrix} T_0 & 0 \\ 0 & T_0 \end{bmatrix}$; $\bar{S} = \begin{bmatrix} T_0 \eta_1 & 0 \\ 0 & T_0 \eta_2 \end{bmatrix}$.

For the decomposed model (8), we introduce the second set of macrovariables

$$\psi_2[k] = \bar{x}[k] + K v[k],$$

(9)

where $\psi_2[k] = \begin{bmatrix} \psi_{2,1}[k] \\ \psi_{2,2}[k] \end{bmatrix}$; $K = \begin{bmatrix} \gamma_1 & 0 \\ 0 & \gamma_2 \end{bmatrix}$.

From the combined solution (9), the functional equation

$$\psi_2[k + 1] + \Lambda_2 \psi_2[k] = 0$$

(10)

and the decomposed model (8), we find the expressions for the internal equations:

$$\varphi_1[k] = (\bar{D})^{-1} \{(\bar{F} + \Lambda_2 + K \bar{S}) \bar{x}[k] + (\Lambda_2 K - \bar{H}) v[k] - K W g[k] \},$$

(11)

where $\Lambda_2 = \begin{bmatrix} \lambda_{2,1} & 0 \\ 0 & \lambda_{2,2} \end{bmatrix}$, $|\lambda_{2,1}| < 1$, $|\lambda_{2,2}| < 1$. We transform the equation (11) as

$$\varphi_1[k] = \tilde{R}(\bar{x}[k]) \bar{x}[k] + \tilde{R}(\bar{x}[k]) v[k] - \tilde{R}(\bar{x}[k]) g[k],$$

(12)

where $\tilde{R} = (\bar{D})^{-1}(\bar{F} + \Lambda_2 + K \bar{S}); \bar{R} = (\bar{D})^{-1}(\Lambda_2 K - \bar{H}); \tilde{R} = (\bar{D})^{-1} K W$.

We find the vector control law for the rotation frequency of the IM’s shaft by solving the combined equations (5), (6) while taking into account the mathematical model of the synthesis (4)

$$u[k] = -(P \bar{D})^{-1} [P \bar{F}(x[k]) x[k] + A_1 P(x[k] + \varphi_1[k]) + P \varphi_1[k + 1]],$$

(13)

where $\bar{D} = \begin{bmatrix} 0 & T_0 \frac{k_T}{L_z} \\ T_0 \frac{k_T}{L_z} & 0 \end{bmatrix}$; $\bar{F} = \begin{bmatrix} -T_0 p_{sy} - \frac{p_{sx}}{l_s} \omega_r & 1 - \frac{\tau_o}{r_T} & -k_T r_T T_0 \frac{i_{sy}}{\psi_r} \\ T_0 p_{sy} \frac{k_T}{r_T} - \frac{k_T}{r_T} \tau_o & k_T r_T T_0 \frac{i_{sy}}{\psi_r} & 1 - \frac{\tau_o}{r_T} \end{bmatrix}.$

We obtain the final solution for the IM’s control law by substituting (12) to (13):

$$v[k + 1] = S x[k] - W g[k];$$

$$u[k] = L(x[k]) x[k] + L(x[k]) v[k] - \tilde{L}(x[k]) g[k],$$

(14)

where $R_1 = \begin{bmatrix} O_2 & : & O_2 \\ \vdots & \ddots & \vdots \\ O_2 & : & O_2 \end{bmatrix}$; $R_2 = \begin{bmatrix} O_2 \end{bmatrix}$; $O^2 = \begin{bmatrix} 0 & 0 \end{bmatrix}$; $L = -(P \bar{D})^{-1} [P \bar{F}(x[k]) + \tilde{R}(x[k]) x[k] + \tilde{R}(x[k]) v[k] + \tilde{L}(x[k]) g[k]]$.

$$R_1 = A_1 P - P \tilde{R}(x[k + 1]) x[k + 1];$$

$$R_2 = \Lambda_1 P \tilde{R}(x[k]) + P \bar{R}(x[k + 1]) x[k + 1];$$

$$\tilde{L} = -(P \bar{D})^{-1} (A_1 P \tilde{R}(x[k]) + P \bar{R}(x[k + 1]) x[k + 1] + P \tilde{R}(x[k + 1]) x[k + 1] + P \bar{R}(x[k + 1]) x[k + 1] + P \tilde{R}(x[k + 1]) x[k + 1] + P \bar{R}(x[k + 1]) x[k + 1]) x[k + 1];$$

$$\bar{L} = -(P \bar{D})^{-1} \tilde{R}(L(x[k]) x[k] + L(x[k]) v[k] + L(x[k]) g[k]).$$
The results of the modelling for the synthesized discrete-continuous control system (1), (2), (14) are shown in the figures 1 and 2. For the modelling, we set the IM’s parameters as follows: \( r_s = 0\,\Omega \), \( r_r = 0.0172\,\Omega \), \( L_m = 0.0154\,H \), \( m = 3 \), \( p = 2 \), \( L_s = L_r = 0.0158\,H \), \( J = 0.968\,kg\,m^2 \) and the regulator parameters: \( p_{11} = 1 \); \( p_{12} = 2 \); \( p_{21} = 3 \); \( p_{22} = 4 \); \( \omega_{r0} = 150\,rad/s \); \( \psi_{r0} = 0.987\,Wb \); \( \eta_1 = \eta_2 = 10 \); \( \gamma_1 = \gamma_2 = 2 \); \( \lambda_{1,1} = \lambda_{2,1} = \lambda_{2,2} = -0.9 \); \( T_0 = 0.00\,s \) and for the case of unknown external disturbance \( M_c = \mu \omega_r - M_{c0} \), where \( \mu = 0.5\,N\cdot m/s/rad \):

\[
M_{c0} = \begin{cases} 
400\,N\cdot m, & \text{for } t < 0.7; \\
1000\,N\cdot m, & \text{for } 0.7 \leq t < 1.5; \\
100\,N\cdot m, & \text{for } t \geq 1.5.
\end{cases}
\]

The figure 3 shows the phase portrait of the system with \( M_c = \mu \omega_r - M_{c0} \), where \( \mu = 0.5\,N\cdot m/s/rad \), \( M_{c0} = 400\,N\cdot m \).

The modelling results of the closed-loop discrete-continuous IM control system (1), (2), (14) demonstrate its high precision in the sustaining of the required values of the output variables. In other words, it satisfies the introduced invariant set \( \omega_r = \omega_{r0} \), \( \psi_r = \psi_{r0} \), it is invariant to unknown external disturbances, and it is asymptotically stable in the whole range of the phase coordinates.
The figures 4 and 5 show the test results for different types of disturbances:

- for the curves I $M_c = \mu \omega_r + M_{c0} \text{sign}[\omega_r]$, $\mu = 0,5$ N·m·s/rad, $M_{c0} = 200$ N·m;
- for the curves II $M_c = \mu \omega_r + \xi \omega_r |\omega_r| + M_{c0}$, $\mu = 0,5$ N·m·s/rad, $M_{c0} = 200$ N·m, $\xi = 0,2$ N·m·s$^2$/rad$^2$;
- for the curves III $M_c = \mu \omega_r + \alpha \omega_r^3 + M_{c0}$, $\mu = 0,5$ N·m·s/rad, $M_{c0} = 200$ N·m, $\alpha = 0,0025$ N·m·s$^3$/rad$^3$.

![Figure 4. Rotation frequency of the shaft in a system with different types of external disturbances](image)

![Figure 5. Rotor flux linkage in a system with different types of external disturbances](image)

The figures (6), (7) demonstrate the modelling results of the closed-loop discrete-continuous IM control system (1), (2), (14) when varying the wiring parameters:

- figure I nominal object parameters;
- figure II — rotor resistance is two times bigger than nominal;
- figure III — rotor resistance is two times smaller than nominal;
- figure IV — stator resistance is two times bigger than nominal;
- figure V — stator resistance is two times smaller than nominal;

![Figure 6. Rotation frequency of the shaft in a system with varying parameters of the IM wirings](image)

![Figure 7. Rotor flux linkage in a system with varying parameters of the IM wirings](image)

The numerical modelling results show that the synthesized discrete regulator (14) makes the closed-loop system invariant to the external disturbances and robust to the parameter changes.
4. Conclusion
We presented the method of synergetic synthesis of discrete-continuous control systems for torque generation in induction motors. The synthesis makes use of the exhaustive mathematical description of the electromechanical energy transformation in IMs. The methodology of synergetic synthesis applied to the design of IM control systems allows to synthesize highly effective control laws which assure such important properties as asymptotic stability in relation to the desired stationary or dynamic equilibrium, invariance to the unknown external disturbances and parametric robustness of transients.
The use of the synergetic control systems for torque generators in complex hierarchical structures allows to maintain precise accomplishment of the tasks from the higher levels, and thus, guarantees effective functioning of the systems and achievement of the global control goals.

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