A Model-Based Fuzzy Control of an Induction Motor

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Abstract. *The paper presents a method of obtaining a simplified fuzzy model of an induction motor from measured data, without the necessity of preliminary knowledge of its internal structure and parameters. With the aim of avoiding a heuristic search for linguistic control rules, the paper presents one of the possibilities of the application of this method for an inverse fuzzy model based control. The proposed simplified fuzzy model of an induction motor was applied in the control of the desired torque of the drive with induction motor. Obtained results were first verified by simulation in programme Matlab and finally experimentally validated by measurements on an IC inverter–induction motor system. Simulation results and experimental measurements confirmed the correctness of the proposed fuzzy modelling and control method and its applicability also to other nonlinear dynamic systems.*

Keywords

Fuzzy logic control, fuzzy modelling, induction motor, inverse fuzzy model.

1. Introduction

The fuzzy approach in the description and control of dynamic systems has recently undergone considerable development. One of the most successful fuzzy system applications is fuzzy logic control (FLC), which has become an alternative to the use of conventional control techniques in control systems that are often impossible to describe analytically. A very widely used FLC type is control based on fuzzy modelling methods that offer an alternative approach to describing complex nonlinear systems [1], [2], [3], [4] and also reduce the number of rules in modelling higher order nonlinear systems [5]. Fuzzy dynamic models [6], [7], also provide a basis for thr development of systematic approaches to fuzzy controller design in view of powerful conventional control theory and techniques [8]. Fuzzy model based control methods have many modifications that depend on the particular application [9], [10], [11], [12], [13] and [14], while the quality of the fuzzy model of the controlled system is also of significant importance. This may often be a non-linear system without availability of prior knowledge of its structure and parameters. The problem in the development of fuzzy models of these systems lies in obtaining their qualitative properties on the basis of measured experimental data, which, having no prior knowledge on the parameters and structure of these systems, often results in an inconsistent database, in problems with covering the entire possible space of the fuzzy system inputs, etc. The fuzzy model obtained in this way then often shows unusable in practice, although, when a different method of data collection is used, or a suitable selection of qualitative data from the database is made, it is possible to construct a corresponding fuzzy model of the unknown non-linear dynamic system.

The philosophy of systems description on basis of their qualitative parameters enables the finding of relatively simple and practically applicable models even in cases of complex non-linear systems, of course, at the cost of a certain degree of inaccuracy in their description [15]. A typical representative of such a strongly non-linear system in the area of electric drives is the three-phase induction motor, whose analytical description, subject to certain simplifying presumptions, is represented by a set of five non-linear differential equations with three inputs. Modern artificial intelligence methods (fuzzy approach, neural networks) enable the finding of its substantially more simple and practically applicable models based on the description of its significant qualitative properties [16], [17], [18], [19] and [20].

The paper deals with the method of designing a simplified fuzzy model of an induction motor only on basis of external information (i.e. measured relations between inputs and outputs). Obtained results are ap-

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix} i_{1x} \\ i_{1y} \\ \psi_{2x} \\ \psi_{2y} \end{bmatrix} = \begin{bmatrix} -\omega_0 & \omega_1 & -\mathrm{K}_{12}\cdot\omega_g & -\mathrm{K}_{12}\cdot n_p\cdot\omega_m \\ -\omega_1 & -\omega_0 & \mathrm{K}_{12}\cdot n_p\cdot\omega_m & -\mathrm{K}_{12}\cdot\omega_g \\ M_n\cdot\omega_g & 0 & -\omega_g & \omega_2 \\ 0 & M_n\cdot\omega_g & -\omega_2 & -\omega_g \end{bmatrix}\cdot\begin{bmatrix} i_{1x} \\ i_{1y} \\ \psi_{2x} \\ \psi_{2y} \end{bmatrix} + \begin{bmatrix} \mathrm{K}_{11} & 0 \\ 0 & \mathrm{K}_{11} \\ 0 & 0 \\ 0 & 0 \end{bmatrix}\cdot\begin{bmatrix} u_{1x} \\ u_{1y} \\ 0 \\ 0 \end{bmatrix}. \tag{1}$$

$$n_p = \frac{M_n}{L_2}\left(\psi_{2x}\cdot i_{1y} - \psi_{2y}\cdot i_{1x}\right) - M_z = J\frac{\mathrm{d}\,\omega_m}{\mathrm{d}t}. \tag{2}$$

plied in the torque control of the drive with induction motor and experimentally validated by measurements on an IM inverter–induction motor system. In this case, the amount of a model based fuzzy control methods is extended.

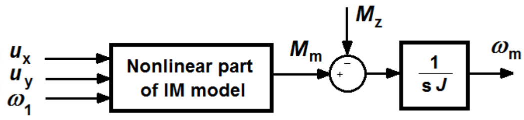

Fig. 1: Structure of the system with induction motor.

2. Method of Determination of an Induction Motor Simplified Fuzzy Model

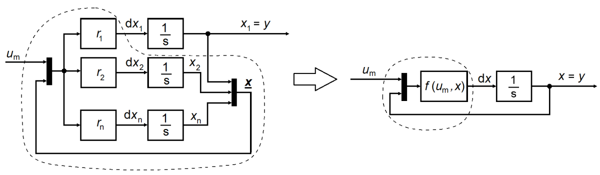

Fig. 2: Procedure of substituting a nonlinear higher order dynamic system by a first order dynamic system.

The induction motor (IM) represents a fifth-order nonlinear system described by state equations in the form Eq. 1, Eq. 2,[21], [22].

It is a current-flux induction motor model with structure as shown in Fig. 1, where u_x, u_y are components of stator voltage vector U_1 in a rotating coordinate system x, y and $\omega = 2\cdot\pi\cdot f_1$ is its angular frequency. The parameters of the model correspond to the parameters of the real motor used in experimental measurements and are specified in the Appendix.

The nonlinear part of the IM represents a fourth-order system for which we need to design a fuzzy model applying the method based on fuzzy linearization of non-linear dynamic system.

In general we want to substitute a nonlinear higher order dynamic system:

$$\mathrm{d}\vec{x} = \mathbf{R}\left(u_m, x\right), \tag{3}$$

$$y = x_1, \tag{4}$$

$$\mathbf{R} = \left[r_1, r_2, \ldots, r_n\right]^{\mathrm{T}}, \tag{5}$$

where function $\mathbf{R} = \left[r_1, r_2, \ldots, r_n\right]^{\mathrm{T}}$ is an unknown nonlinear continuous function, $\vec{x}$ is a state vector and n is the system order (the measured output variable of the system is the first state variable, i.e. $y = x_1$) by a simplified dynamic first-order system in the form:

$$\mathrm{d}x = f\left(u_m, x\right), \tag{6}$$

$$y = x, \tag{7}$$

in which $f\left(u_m, x\right)$ is an unknown nonlinear function obtained from suitable measurements in the system Eq. 3. The best possible similarity to responses of systems Eq. 3 and Eq. 6 for identical input variables um is the criterion for substitution. The procedure is illustrated in Fig. 2.

The basic premise for the identification of system Eq. 3 is that it is stable and at constant input u_m its output settles, after fading of the transient performances, at a constant value y. This means that the transition of some measured system Eq. 3 from one steady state A to another steady state B at constant input u_m determines one relation among the relevant three values $[u_m, x, \mathrm{d}x]$, i.e. one point of function f where $y = x$.

The course of the IM torque for the desired speed step from 0 to 100 % is shown in Fig. 3. When substituting the fourth-order system by a first-order system, the undergoing fast electromagnetic processes in the motor are ignored, which means that the IM torque course is simplified and is presented as a curve representing its medium value as is shown in Fig. 3.

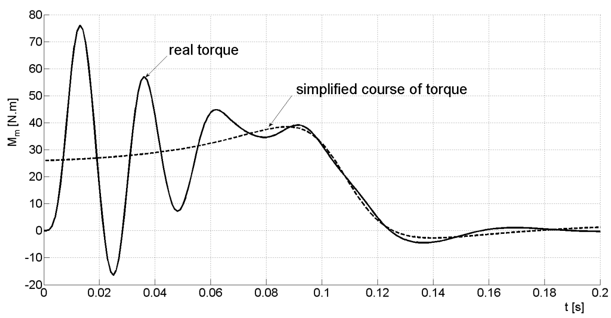

Fig. 3: IM real torque course and its simplified course.

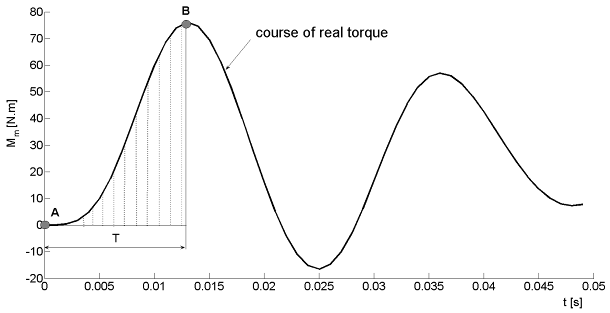

Fig. 4: Determination of starting point.

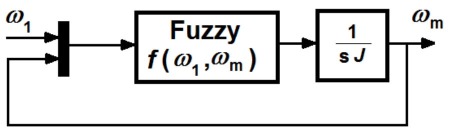

Fig. 5: Fuzzy model structure of the drive with induction motor.

For the purpose of identification of function f in Eq. 6 we need to determine the starting value dx (starting point) for each pair of inputs $[u_m, x]$, which is the initial value of the simplified course of its torque. It can be calculated e.g. as the medium value of the real torque course in the range from zero to the first maximum, as illustrated in Fig. 4.

The mathematical representation is:

$$M_{\text{start}} = \frac{1}{T} \int_A^B M_m \mathrm{d}t. \tag{8}$$

The database of measured data for identification of function f should cover the whole work space of pairs $[u_m, x]$, i.e. it is necessary to measure the desired transitions between the steady states in this space. If we split the input space um and thus also the relevant space of steady outputs Eq. 3 into n parts, then the number of desired measured responses is equal to the number of variations of n elements in groups of 2, i.e.:

$$V_2(n) = \frac{n!}{(n-2)!}. \tag{9}$$

For creating the complete fuzzy model of IM, that structure is shown in Fig. 5, we divided the work space into 6 regular levels. In this case in accordance with relation Eq. 9 it is necessary to measure 30 transitions between steady states and from these to define the identification points for function f. The result of the transition processes between each of the levels is one starting point identified according to the relation Eq. 9. The complete database of starting points for IM fuzzy model generation is shown in Tab. 1. Points on the diagonal represent complemented values of the system steady states.

Tab. 1: Identified points of function f.

$\frac{\omega_1}{\omega_m}$	**0 %**	**20 %**	**40 %**	**60 %**	**80 %**	**100 %**
0 %	0	−18	−34	−44	−50	−54
20 %	7.4	0	−20	−37	−48	−53
40 %	15	25	0	−24	−46	−55
60 %	27	27	28	0	−26	−50
80 %	27	29	34	32	0	−27
100 %	25	23	29	35	39	0

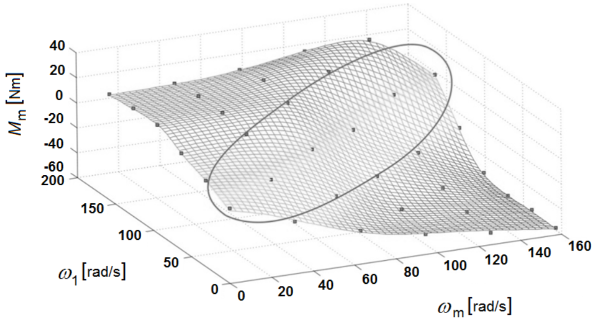

Fig. 6: Characteristic surface of induction motor fuzzy substitute.

This table is the basis for constructing a fuzzy description (model) of function f obtained by Anfisedit tool of the MATLAB programme package. The method used for the fuzzy system generation was the subclustering method, having the following parameters:

- *Range of influence* = 0.5,
- *Squash factor* = 1.25,
- *Accept ratio* = 0.5,
- *Reject ratio* = 0.15.

Function f is represented by Sugeno type fuzzy system with 7 rules, the characteristic surface of which is shown in Fig. 6.

It has to be pointed out that this is a simplified fuzzy model of an induction motor where we substituted a fifth order system by a first order system.

3. Inverse Fuzzy Model Based Torque Control of an Induction Motor

The described method of obtaining a simplified fuzzy model of an induction motor based in general on fuzzy linearization of a nonlinear dynamic system can be used for the control of such systems using a control structure based on an inverse fuzzy model, the basic idea of which is demonstrated in Fig. 7. Nonlinearity of the fuzzy

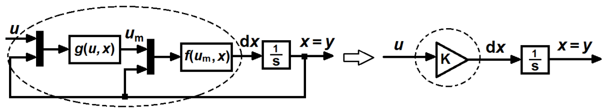

Fig. 7: A control structure based on an inverse fuzzy model.

system $f(u_m, x)$ is compensated by an inverse function $g(u, x)$ that satisfies the following condition:

$$\mathrm{d}y = f(g(u, x)\, x) = \mathrm{K} \cdot u, \tag{10}$$

where K is a constant representing the resulting linearized system (Fig. 7).

3.1. Example

Consider a simple first-order nonlinear dynamic system in the form:

$$\dot{x} = u_m - sin(x). \tag{11}$$

In this case it is obvious that $r_1 = f = (u_m - sin(x))$. When choosing function g in the form $g = \mathrm{K} \cdot u + sin(x)$, it applies that:

$$\begin{aligned} \dot{x} = g(u, x) - sin(x) = \\ \mathrm{K} \cdot u + sin(x) - sin(x) = \mathrm{K} \cdot u, \end{aligned} \tag{12}$$

which obviously accurately satisfies condition Eq. 10. In this simple example we are dealing with linearization of a first-order system, the problem can be solved analytically and linearization is complete.

The role of inverse function g is to adapt input um to the nonlinear system in such a way that the first derivative of the output value corresponds, as much as possible, to the control input u. In the preceding chapter we illustrated the procedure of obtaining a fuzzy description of the function $\mathrm{d}x = f(u_m, x)$ on the basis of experimental measurements. From this relation it is then possible to determine for each particular desired value $\mathrm{d}x$ and for given system output $y = x$ the corresponding value of u_m. For linearization of system Eq. 3 the desired $\mathrm{d}x$ values are determined by equation Eq. 10, in which the amplification K is usually chosen such that it regulates the range of real $\mathrm{d}x$ values to the range of the control signal u.

Described idea was used for the control of the desired torque of an induction motor (M_{mref}) in the control structure based on an inverse fuzzy model, as shown in Fig. 8.

Function g is the function inverse to function f. When creating an inverse function, it is necessary to define correctly the work space for which all the points of the inverse function g are uniquely determined [23], [24] and [25].

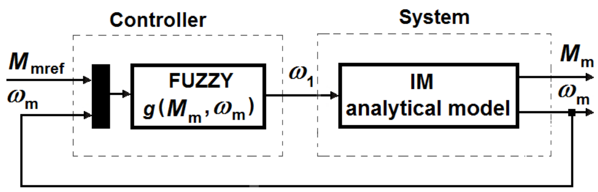

Fig. 8: Control structure based on inverse fuzzy model.

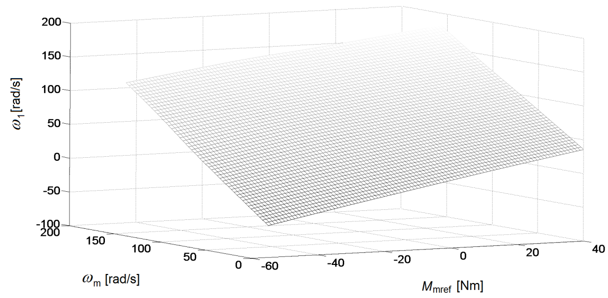

Fig. 9: Characteristic surface of inverse function g used in the control structure.

It is known from the torque characteristic that the IM behaves in operational space as a quasi linear system. In Fig. 6 the black line defines the operational space in the vicinity of zero torque, which represents the transition of the IM from motor to generator mode. From this it follows that if we want to control the IM by means of an inverse model, this model has to be generated only from the database of points that correspond to this operational space. The remaining spaces do not need to be considered, as the controller will not be entering these spaces. The range of M_m will then be $\langle -60, 40 \rangle$ and the range of ω_m can be assumed as being $\langle 0, 200 \rangle$. The matrix of corresponding points for the delimited operational space will be used for generation of the fuzzy description of function g by means of the Anfisedit tool and the subclustering method with standardly pre-set parameters. Function g is represented by a Sugeno type fuzzy system with 8 rules. Its characteristic surface is shown in Fig. 9.

The properties of the control structure based on the inverse fuzzy model (Fig. 8) were validated by simulation for various steps of the desired torque Mmref (Fig. 10). Because of the unexcited motor, it is not possible to achieve the desired torque value at the start of the simulation. With rotations of approximately 30 to 40 rad/s the motor is already excited and the motor torque reaches the desired value. At the time of approx. 2, 3 seconds we can see that the desired torque Mmref is at the value of 20 Nm, but the real torque has already fallen to zero. This is because mechanical angular velocity has reached the nominal value.

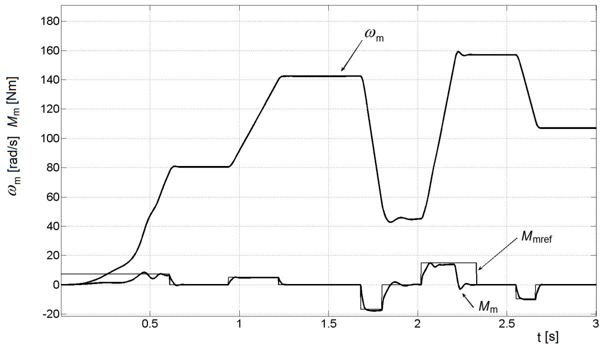

Fig. 10: Properties of control structure based on inverse fuzzy model for various steps of desired torque.

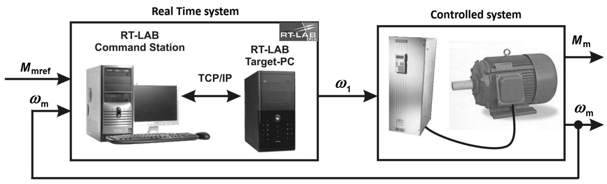

Fig. 11: Layout of the implementation workplace.

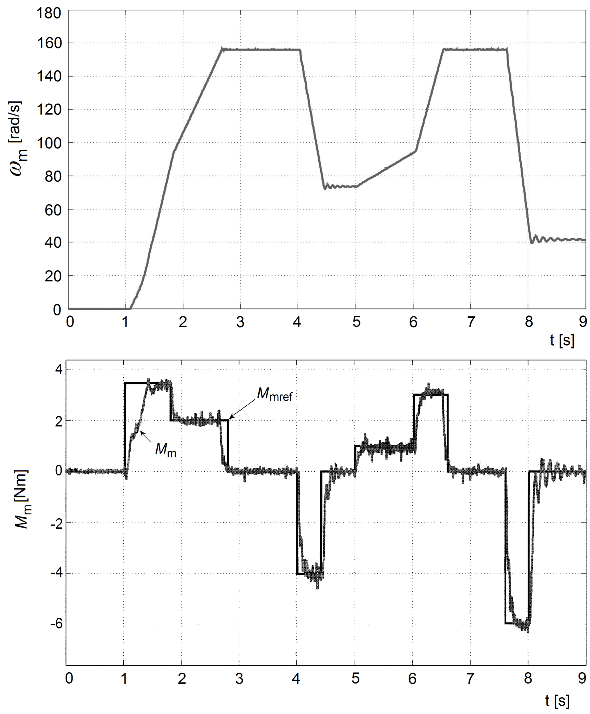

Fig. 12: Measured control responses of angular speed and torque of IM.

4. Experimental Results

Control based on an inverse fuzzy model was applied to a system consisting of a scalar control AC inverter without revolutions control and a three-phase asynchronous motor with parameters as specified in the Appendix.

The procedure of designing the fuzzy model of the controlled system (function f) was identical to the one described in Chapter 2. Identification measurements for the generation of the database of points (see Tab. 1) for the purpose of generating the controlled systems fuzzy model were carried out by means of the *Drive Monitor* software tool. The aim of the identification was to obtain the motors torque course and to subsequently use this for determining starting point values. We used the Drive Monitor tool to record transition actions of mechanical angular velocity. Motor torque was determined indirectly from the equation of motion:

$$M_m - M_z = J\frac{\mathrm{d}\,\omega}{\mathrm{d}\,t} \tag{13}$$

ignoring load torque M_z which is generated by the resistance of the motor bearings and fan and is negligible compared to the motor torque.

The resulting fuzzy systems describing functions f and g were identical with the results obtained by simulation in Chapter 3.

The inverse model based control was implemented by means of the Real Time system OPAL RT – LAB. This real time system makes it possible to convert a model created in Simulink into a simulation running in real time. The layout of the implementation workplace is shown in Fig. 11.

The typical measured control responses of angular speed and torque are shown in Fig. 12. The smaller dynamics of the real torque course to the first step in its reference value is caused by the non-excited status of the motor. The resulting quality of control strongly depends upon the quality of the fuzzy model of the system, where, due to the application of the described procedure, the fifth-order system becomes a first-order fuzzy system, which in IM causes neglect of fast electromagnetic activities. The most important issue with respect to the design of the fuzzy model of the system is the correct identification of the smoothed course of its torque, as illustrated in Fig. 3 and Fig. 4.

5. Conclusion

The paper deals with the setup of a simplified fuzzy model of an induction motor using method based on fuzzy linearization of non-linear dynamic system. For the setup of this model it is necessary to carry out several standard measurements of step responses on the motor, and no prior knowledge of the motor parameters is required.

Simulation results and experimental measurements have confirmed that the fuzzy model obtained by the described method can be exploited also for relatively good control of complex nonlinear systems, such as e.g. that of a drive with induction motor with as little previous knowledge as possible and with no the heuristic search for a rule-based controller, while the quality of the control structure based on an inverse fuzzy model is strongly dependent on good-quality identification of induction motor properties necessary for the construction of its fuzzy model and the correct definition of the operational space.

Comparing fuzzy to conventional modelling and control it must be stressed that in some cases the achieved results are better and in other cases they are not. It depends on the system or a problem to be solved which methods fits best. In this spirit the proposed method of obtaining a simple fuzzy model of a nonlinear dynamic system for which only external information is available (i.e. the measured dependencies between the inputs and outputs) and its exploitation for an inverse fuzzy model based control has to be understood as an enhancement of the wide range of fuzzy modelling and control methods. Because the article deals with fuzzy IM torque control based on the simplified fuzzy model, the resulting dynamics of the controlled system cannot be compared with the much more precise and complex vector control.

In the future the method described could also be applied to other types of nonlinear systems with similar properties that render their identification and control using conventional methods difficult, if not even impossible.

Appendix A AC Drive Parameters

- $P_N = 3$ kW
- $U_{1N} = 220$ V
- $I_{1N} = 6.4$ A
- $n_N = 1420$ rev/min
- $M_N = 20$ Nm
- $J = 0.022$ kg·m^2
- Stator phase resistance: $r_1 = 1.83\ \Omega$
- Rotor phase resistance: $r_2 = 2.26\ \Omega$
- Main inductance: $L_h = 0.216$ H
- Mutual inductance: $M = (3/2)L_h = 0.324$ H
- Leakage inductance $L_{S1} = L_{S2} = 12.036$ mH
- $R_1 = (2/3)r_1 = 1.22\ \Omega$
- $R_2 = (2/3)r_2 = 1.506\ \Omega$
- $L_2 = 2/3(L_{S2} + L_h) = 152.31$ mH
- $K_{11} = 3/2(L_{S1} + (L_{S2}L_h/(L_h + L_{S2}))^{-1} = 63.999\ H^{-1}$
- $K_{12} = -3/2(L_{S1} + L_{S1}L_{S2}^2/L_h)^{-1} = \check{}60.627\ H^{-1}$
- Slip angular speed $\omega_2 = \omega_1 - n_p\omega_m$
- $\omega_0 = K_{11}(R_1 + (M_2/L_2)\omega_g) = 164.723\ s^{-1}$
- $\omega_g = R_2/L_2 = 9.902\ s^{-1}$
- Mechanical angular speed of the motor: ω_m
- Angular frequency of the stator voltage: $\omega_1 = 2 \cdot \pi \cdot f_1 = 314\ s^{-1}$
- Number of pole pairs: $n_p = 2$

Acknowledgment

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