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# APPLICATION OF SUGENO FLC TO THE STATOR FIELD ORIENTED DOUBLE FED INDUCTION MOTOR DRIVE (DFIM)

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This study deals with the application of the fuzzy control theory to wound rotor induction motor with both its stator and rotor fed by two PWM voltage source inverters in which the system operates in stator field oriented control. Thus, after determining the model of the machine, two types of fuzzy controllers — Mamdani and Sugeno controllers are presented. The training of the latter is carried out starting from the former. Simulation study based on idealized motor and inverter models is conducted to show the effectiveness of the proposed method.

Keywords: Induction motor, Vector control, fuzzy logic.

## 1 INTRODUCTION

The difficulty to control the doubly fed induction motor is related to the fact that the mathematical model in Park configuration is non-linear and highly coupled. Due to the development of power electronics and microprocessors, the DFIM control is possible by applying stator field oriented techniques [1–4]. These techniques provide the de- coupling stator and rotor machine frames that allow to obtain a dynamical model similar to that of a DC machine. Nevertheless, a discontinuous behaviour is imposed by the switching devices of the inverters that supply the DFIM, and yields to a complex mathematical model. Therefore, it is suitable to look for some techniques, which are appropriate to discontinuous operation of the switching devices.

A conventional PI controller used for the speed regulation does not ensure rapid responses during the load torque variations and parametric drifts of the machine resulting in a deterioration of the control quality.

The use of Mamdani controllers allows to obtain better performances. However, it should be noted that a high number of fuzzy sets requires an excessive number of inference rules, so that the processing time is considerably increased. To decrease the control computing time, it is necessary to optimize the size of the knowledge base. This problem can be overcome by choosing the Sugeno type of controllers.

This paper presents the application of Sugeno fuzzy logic control for the DFIM. The parameters of the premises and those of the consequences are given by recopying the data input-output obtained by synthesizing the Mamdani fuzzy controllers [9, 10]. The recopy is obtained by training using the approach of the Kalman filter [5, 9, 12]. This method allows high performance of the control and especially robustness with regard to parameter changing and external disturbances.

## 2 SYSTEM DESCRIPTION AND MACHINE MODELING

The controlled system is a wound rotor induction motor fed at both its stator and rotor sides by two PWM voltage source inverters: one at the stator side and the other at the rotor side where each inverter is supplied by a bridge rectifier via a low-pass filter. The output voltages of each one are controlled by a PWM technique which allows simultaneous adjustment of the frequency and the output voltage of the inverter.

Using the frequently adopted assumptions, thus by assuming sinusoidally distributed air-gap flux density distribution and linear magnetic conditions and considering the stator voltages $(V_{sd}, V_{sq})$ and rotor voltages $(V_{rd}, V_{rq})$ as control inputs, the stator current $(i_{sd}, i_{sq})$ and the rotor current $(i_{rd}, i_{rq})$ and the speed $(\omega_m)$ as state variable. In the referential axis linked to rotating field, the following electrical equations are deduced [1]:

$$v_{sd} = r_s\, i_{sd} + \frac{\mathrm{d}\psi_{sd}}{\mathrm{d}t} - \omega_s\, \psi_{sq} \tag{1}$$

$$v_{sq} = r_s\, i_{sq} + \frac{\mathrm{d}\psi_{sq}}{\mathrm{d}t} + \omega_s\, \psi_{sd} \tag{2}$$

$$v_{rd} = r_r\, i_{rd} + \frac{\mathrm{d}\psi_{rd}}{\mathrm{d}t} - (\omega_s - \omega_m)\psi_{rq} \tag{3}$$

$$v_{rq} = r_r\, i_{rq} + \frac{\mathrm{d}\psi_{rq}}{\mathrm{d}t} + (\omega_s - \omega_m)\psi_{rd} \tag{4}$$

$$\psi_{sd} = l_s\, i_{sd} + m\, i_{rd} = \psi_s \tag{5}$$

$$\psi_{sq} = l_s\, i_{sq} + m\, i_{rq} = 0 \tag{6}$$

$$\psi_{rd} = l_r\, i_{rd} + m\, i_{sd} \tag{7}$$

$$\psi_{rq} = l_r\, i_{rq} + m\, i_{sq} \tag{8}$$

$$C = \psi_{sd}\, i_{sq} \tag{9}$$

$$C - Cr = J\, \mathrm{d}\Omega_m / \mathrm{d}t \tag{10}$$

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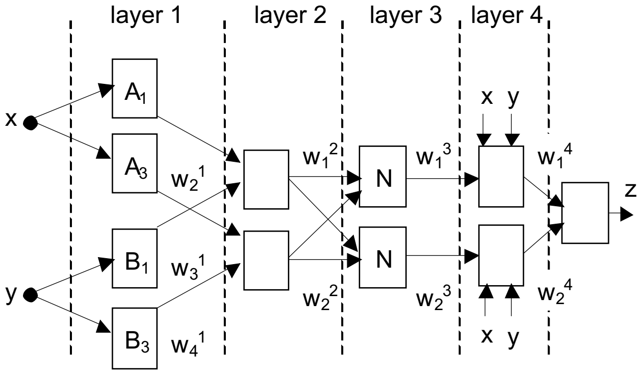

**Fig. 1.** Network based on the Sugeno fuzzy model.

The power factor and stator flux $\psi_s$ are dependent on the direct component of both stator and rotor currents. From equations (1) and (5) it follows that unity power factor at stator side, *ie* alignment of voltage and current vectors, will be obtained in steady state by imposing the references:

$$\begin{cases} i^*_{sd} &= 0 \\ i^*_{rd} &= \psi_s/m \end{cases} \tag{11}$$

In the case of rotor flux oriented vector control of a cage induction motor, it is known that the rotor flux follows the $d$-component of the stator current only with a large (rotor) time constant. For high dynamic drives the flux has thus to be kept high even at no load. In a DFIM, the flux is directly related to the $d$-component of the rotor current and the flux level can be quickly adapted. This allows, if necessary, a flux reduction during no load (economy mode) without too much degrading the torque response.

The controllers for $i_{sd}$ and $i_{rd}$ are decoupled by introducing the control variables $V_{isd}$ and $V_{ird}$ given by:

$$\begin{aligned} V_{isd} &= V_{sd} - m\,V_{rd}/l_r \\ V_{ird} &= V_{rd} - m\,V_{sd}/l_s \end{aligned} \tag{12}$$

After elimination of the flux (with $\psi_{sq} = 0$, $\psi_{sd} = \psi_s$) and of the rotor quadrature current, eqs. (1) and (3) are transformed into:

$$\begin{aligned} V_{isd} &= r_s\,i_{sd} + \sigma l_s\,\mathrm{d}i_{sd}/\mathrm{d}t \\ &\qquad + \big(-r_r m\,i_{rd}/l_r - (\omega_s - \omega_m)\sigma l_s i_{sq}\big) \end{aligned} \tag{13}$$

$$\begin{aligned} V_{ird} &= r_r\,i_{rd} + \sigma l_r\,\mathrm{d}i_{rd}/\mathrm{d}t \\ &\qquad + \big(-r_s m\,i_{sd}/l_s + (\omega_s - \omega_m)\sigma l_s l_r\,i_{sq}/m\big) \end{aligned} \tag{14}$$

with $\sigma = 1 - m^2/(l_s l_r)$ being the total leakage coefficient.

Two $d$-current controllers generate the reference values for the control variables. The reference values for the direct components of stator and rotor voltages are then computed by:

$$V^*_{sd} = \big(V^*_{isd} + m\,V^*_{ird}/l_r\big)/\sigma\,, \tag{15}$$

$$V^*_{rd} = \big(V^*_{ird} + m\,V^*_{isd}/l_r\big)/\sigma\,. \tag{16}$$

The torque reference $C^*$ is transformed into a reference for the $q$-component of the stator current:

$$i^*_{sq} = C^*/\psi_s\,. \tag{17}$$

The torque control is achieved by the $i_{sq}$ component control. It follows from (4), (6), (7) and (8):

$$\begin{aligned} V^*_{rq} &= -r_r l_s\,i_{sq}/m - \big(\sigma l_s l_r/m\big)\,\mathrm{d}i_{sq}/\mathrm{d}t \\ &\qquad + (\omega_s - \omega_m)(l_r\,i_{rd} + m\,i_{sd})\,. \end{aligned} \tag{18}$$

The torque controller generates the reference value for the quadrature component of rotor voltage $V^*_{rq}$.

Finally, the slip or rotor frequency reference is transformed in a reference for the quadrature component of stator voltage (eq. 2):

$$V^*_{sq} = r_s\,i_{sq} + (\omega_m + \omega_r)\psi_s\,. \tag{19}$$

## 2 FUZZY LOGIC CONTROL

The Sugeno controllers are defined in such a way that their outputs are polynomials of one order according to their inputs. The parameters of the premises and those of the consequences are given by recopying the data input-output obtained by synthesizing the Mamdani fuzzy controllers. For the latter, the linguistic input variables $e$ and $\Delta e$ and of output $\Delta u$ are described by seven fuzzy sets. The recopy is obtained by training using the approach of the Kalman filter.

There are several approaches to carry out a fuzzy inference system. Each approach has its image in the representation by the corresponding networks.

To simplify, one considers a fuzzy system having only two inputs and an output [6, 7, 11, 12]. The first order Sugeno fuzzy controller having two rules can be represented as follows:

$$\begin{aligned} &\text{if } ((x \text{ is } A_1) \text{ and } (y \text{ is } B_1) \text{ then } (Z = p_1 x + q_1 y + r_1)) \\ &\text{if } ((x \text{ is } A_2) \text{ and } (y \text{ is } B_2) \text{ then } (Z = p_2 x + q_2 y + r_2)) \end{aligned} \tag{20}$$

where $\{p_i\,, q_i\,, r_i\}$ are the parameter sets associated with the consequences. The corresponding network is shown in Fig. 1, where the nodes which belong to the same layer have the same function.

Let us notice by $W_i^j$ the output of the node $i$ of the layer $j$:

– each node of the first layer has adjustable parameters. The function of the node is identical to the fuzzy set membership function of the discourse universe of the input

$$\begin{aligned} W_i^1 &= \mu_{A_i}(x)\,; &&\text{for } i = 1, 2 \\ W_i^1 &= \mu_{B_{i-2}}(y)\,; &&\text{for } i = 3, 4 \end{aligned} \tag{21}$$

where $x$ and $y$ are inputs of the $i$ node; $A_I$ and $B_{I-2}$

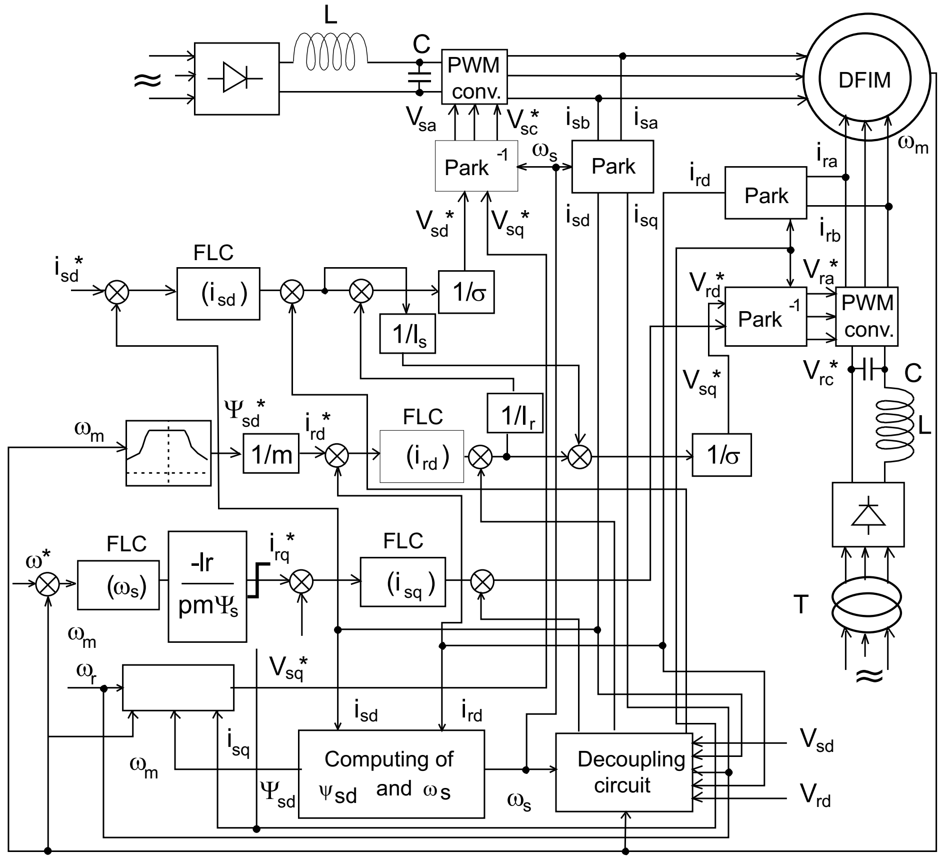

**Fig. 2.** Vector control block diagram of the DFIM.

**Table 1.** Fuzzy Rules.

| $\Delta e/e$ | Ng | Ez | Pg |
|---|---|---|---|
| Ng | $f_1$ | $f_4$ | $f_7$ |
| Ez | $f_2$ | $f_5$ | $f_8$ |
| Pg | $f_3$ | $f_6$ | $f_9$ |

are fuzzy sets associated to this node. The outputs of this layer are the membership functions values of the premise. The membership functions can be chosen as functions with adjustable parameters.

– the nodes of the second layer are fixed. The output of each node is

$$W_i^2 = \mu_{A_i}(x)\,\mu_{B_i}(y)\,; \quad i = 1,2\,. \tag{22}$$

The output of each node of this layer realize the “AND” of each rule.

– the nodes of the third layer are fixed. The output of each node is given by the relation:

$$W_i^3 = \frac{W_i^2}{W_1^2 + W_2^2}\,; \quad i = 1,2\,. \tag{23}$$

– each node of the fourth layer is adjustable, and its function is

$$W_i^4 = W_i^3(p_i\,x + q_i\,y + r_i)\,; \quad i = 1,2\,. \tag{24}$$

– the node of the output layer realizes a fixed function which carries out the sum of the input signals. The output of this node is expressed by:

$$Z = \frac{\sum_{i=1}^{2} W_i^3(p_i\,x + q_i\,y + r_i)}{\sum_{i=1}^{2} W_i^3}\,. \tag{25}$$

The construction of the network based on the Sugeno fuzzy model is now possible (Fig. 1). The inputs of the obtained network are the error and its variation. These inputs are characterized by the fuzzy sets of Gaussian type: $Ng$, $Pg$ and $Ez$, defined by the following relation:

$$\mu(x) = \exp\Big(-0.5\big(\nu_i(x - c_i)\big)^2\Big)\,. \tag{26}$$

where $c_i$ and $v_i$ represent, respectively, the average and the inverse of the variance. The fuzzy control rules are shown in Tab. 1, where $f_1 = p_i e + q_i \Delta e + r_i$.

For the determination of the Sugeno fuzzy controller parameters (parameters of the premises and consequences) a training algorithm based on the Kalman filter is used.

Given the input-output data set $\big(x(k), d(k)\big)$, let us consider a Sugeno fuzzy controller characterized by a vector of parameter $\theta$. The objective is to find the values of the vector $\theta$ so that the output of the fuzzy controller converges to the desired output $d(k)$; *ie* to have

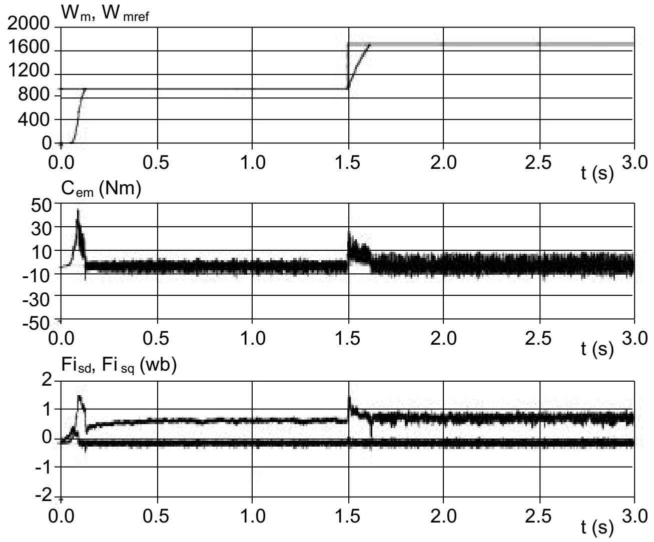

**Fig. 3.** Starting and reference speed changing.

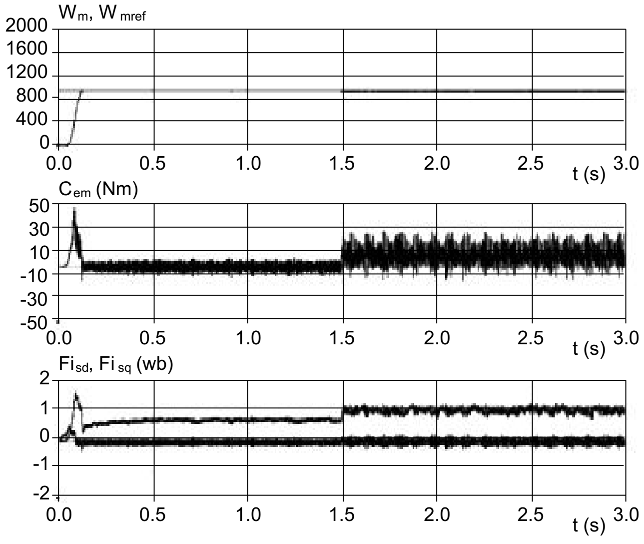

**Fig. 4.** Load torque application.

$\Delta u(x(k);\theta) = d(k)$. The approach of Kalman filter consists in linearizing at any time the output $\Delta u$ around the vector $\hat{\theta}$. This is expressed by

$$\begin{aligned} d(k) &= \Delta u\big(x(k);\hat{\theta}(k-1)\big) + \leq \Psi^t(k)\big(\theta - \hat{\theta}(k-1)\big) \\ \Psi(k) &= \frac{\partial \Delta u\big(x(k);\theta\big)}{\partial \theta} \Big/ \hat{\theta}(k-1) \end{aligned} \tag{27}$$

the solution of which is:

$$\begin{aligned} \hat{\theta}(k) &= \hat{\theta}(k-1) + p(k)\,\Psi(k)\,e(k) \\ e(k) &= d(k) - \Delta u\big(x(k);\hat{\theta}(k-1)\big) \end{aligned} \tag{28}$$

where $p(k)$ represents the gain of the estimation algorithm. In the conjugated gradient method, the gain $p(k)$ is chosen variable. This one is given by the following relation:

$$p(k) = \frac{\alpha_1 I}{\alpha_2 + \Psi^t(k)\,\Psi(k)}\,. \tag{29}$$

The gradient $\Psi = \partial\Delta u/\partial\theta$ is calculated by the retro-propagation method used in the neural networks. In this case, the vector of the parameters is $\theta = [c\ v\ r\ p\ q]^t$. Consequently, it is possible to write

$$\frac{\partial \Delta u}{\partial \theta} = \Big[\frac{\partial \Delta u}{\partial c}\ \ \frac{\partial \Delta u}{\partial \nu}\ \ \frac{\partial \Delta u}{\partial r}\ \ \frac{\partial \Delta u}{\partial p}\ \ \frac{\partial \Delta u}{\partial q}\Big]^t \tag{30}$$

where

$$\begin{aligned} \frac{\partial \Delta u}{\partial c_i} &= \frac{\nu_i^2(x_i - c_i)\sum_{k\in J}\mu_k(f_k - \Delta u)}{\sum_{l=1}^{M}\mu_l} \\ \frac{\partial \Delta u}{\partial \nu_i} &= \frac{\nu_i(x_i - c_i)^2\sum_{k\in J}\mu_k(f_k - \Delta u)}{\sum_{l=1}^{M}\mu_l} \\ \frac{\partial \Delta u}{\partial r_i} &= \frac{\mu_i}{\sum_{l=1}^{M}\mu_l}\,;\ \frac{\partial \Delta u}{\partial p_i} = \frac{\mu_i e}{\sum_{l=1}^{M}\mu_l}\,;\ \frac{\partial \Delta u}{\partial q_i} = \frac{\mu_i \Delta e}{\sum_{l=1}^{M}\mu_l} \end{aligned} \tag{31}$$

where $x_i \in \{e, \Delta e\}$ and $J$ represents the indices set of the fuzzy rules in which parameter $c_i$ or $v_i$ appears.

Figure 2 presents the vector control block diagram of the DFIM.

## 4 RESULTS AND DISCUSSIONS

The speed regulation is obtained using a Sugeno controller in spite of the presence of disturbances such as reference speed variation and step changing of the load torque. Figure 3 shows the starting and the reference speed changing of the DFIM. A rapid response is obtained. Besides, it is very close to the desired reference. It is clearly shown for stator flux responses that decoupling is realized since the direct component of the stator flux converges to the reference $(\psi_{sd})_{ref}$, and its quadrature component to zero.

The dynamic responses of the speed and the electromagnetic torque, when step speed reference is introduced, are represented in Fig. 4. A load torque perturbation has also been imposed in the system at $t = 1.5$ s. It is shown from the results that the input reference is perfectly tracked by the speed and the introduced perturbation is immediately rejected by the control system.

A starting operation followed-up by a step changing of the load torque is illustrated in Fig. 5. The dynamic behaviour of the speed is shown with 75 % rise of $(r_r, r_s)$, and 25 % of ($l_r$, $l_s$ and $m$) relative to the identified model parameters. It is important to notice that the changing parameters are introduced only in the model of the machine. The controller is not involved by these variations. The robustness quality of the fuzzy controllers appears clearly in the test results by changing machine parameters and load torque variation.

## 5 CONCLUSION

The fuzzy control of the stator field oriented double fed induction motor is proposed. To highlight the effectiveness and performances of the developed control scheme, a simulation study is carried out. The proposed

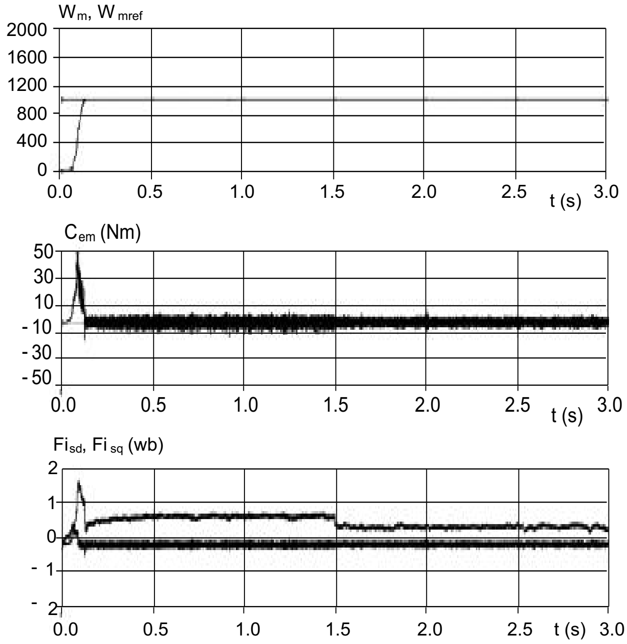

**Fig. 5.** Parameter changing effect.

controller robustness clearly appears in the test results by changing machine parameters and especially the load torque variation. As far as the controller performance is concerned, Sugeno controller provides better dynamic responses. These results are confirmed by the experimental works of Y. Tang [5]. Further study, taking into account inverter switching losses and DFIM magnetic saturation, deserve to be performed in order to definitely validate the proposed control strategy.

## Appendix A — list of principal symbols

$r_s$, $r_r$: stator, rotor resistance,
$l_s$, $l_r$: stator, rotor inductance,
$m$: magnetising inductance,
$V_{sd}$, $V_{sq}$: stator voltage $d–q$ axis components,
$V_{rd}$, $V_{rq}$: rotor voltage $d–q$ axis components,
$i_{sd}$, $i_{sq}$: stator current $d–q$ axis components,
$i_{rd}$, $i_{rq}$: rotor current $d–q$ axis components,
$\Psi_{sd}$, $\Psi_{sq}$: rotor flux $d–q$ axis components,
$\omega_s$: stator angular frequency,
$\omega_r$: rotor angular frequency,
$\omega_m$: rotor speed,
$\theta_s$: angular position,
$\sigma$: total leakage coefficient,
$J$: total inertia,
$f$: coefficient of friction,
$C_r$: load torque,
$p$: number of pole pairs.

## Appendix B — machine parameters

Machine of 1.5 kW, 220 V, 12 V.
$r_s = 4.85\,\Omega$, $r_r = 3.805\,\Omega$,
$l_s = 0.274$ H, $l_r = 0.274$ H,
$m = 0.258$ H, $J = 0.031\,\mathrm{kg\,m^2}$, $f = 0.008\,\mathrm{N\,m\,s/rad}$.

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