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COMMUNICATIONS

DIRECT TORQUE AND FLUX CONTROL OF INDUCTION MACHINE AND FUZZY CONTROLLER

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In this paper we describe the control of an induction machine (IM) using the principle of direct torque and flux control (DTFC). This method is designed by means of fuzzy logic with three inputs and three outputs and contains 180 rules. For improvement of this method a fuzzy duty ratio controller is added. This controller prepares an optimum voltage vector (output from fuzzy DTFC control). In this control the selected inverter switching state is applied for a portion of the switching period, defined as duty ratio δ, and the zero switching state is applied for the rest of the period. The duty ratio is chosen to give an average voltage vector for a change of torque with decreasing ripples. The control is verified by simulation.

K e y w o r d s: induction machine, servo system, direct torque and flux control, fuzzy controller, speed control

1 INTRODUCTION

DTFC (direct torque and flux control) is characterized, as deduced from the name, by directly controlled torque and flux and indirectly controlled stator current and voltage [1]. It is an alternative dynamic control for vector control. The big interest in DTFC is caused by some advantages in comparison with the conventional vector-controlled drives, like:

- The control is without using current loops.
- The drive does not require coordinate transformation between the stationary frame and synchronous frame.
- A pulse-width modulation (PWM) modulator is not required.

Conventional DTFC has also some disadvantages:

- Possible problems during starting and low speed operation.
- High requirements upon flux and torque estimation.
- Variable switching frequency.

These are disadvantages that we want to remove by using and implementing modern resources of artificial intelligence like neural networks, fuzzy logic, genetic algorithms *etc.* [3]. In the following, we will describe the application of fuzzy logic in DTFC control.

2 FUZZY LOGIC DTFC

To obtain improved performance of the DTFC drive during changes in the reference torque, it is possible to use a fuzzy-logic-based switching vector selection process [1]. For this purpose a Mamdani-type fuzzy logic system will be used. The different output voltage states (active and zero states) are selected by using three inputs: flux e_ψ and torque e_m errors and also the position of the stator flux linkage space vector $\boldsymbol{u}_s$ (Fig. 1).

For this purpose it is assumed that the stator flux linkage space vector can be located in any of twelve sectors, each spanning over a 60° wide region. For every sector there are 15 rules. The stator flux error $\left(e_\psi = \Psi_s^* - \widetilde{\Psi}_s\right)$ has three fuzzy sets: stator error can be positive P, zero ZE, and negative N. For the torque error, there are five fuzzy sets: the torque error $e_m = M_m^* - \widetilde{M}_s$ can be positive large PL, positive small PS, zero ZE, negative small NS and negative large NL (Fig. 2). Since there are 12 sectors, for each sector 15 rules, the total number of rules is 180.

Example.
Rule 1: if e_ψ is P and e_m is PL and $\boldsymbol{u}$ is S1 then n is 1
Rule 2: if e_ψ is P and e_m is PS and $\boldsymbol{u}$ is S2 then n is 1
Rule 3: if e_ψ is P and e_m is ZE and $\boldsymbol{u}$ is S3 then n is 0
Where S1, S2 and S3 are fuzzy labels (*eg* S1 is the label for those stator flux angles which correspond to stator fluxes in sector 1, *etc*).
i-th rule: If e_ψ is A_i and e_m is B_i and $\boldsymbol{u}_s$ is C_i then n is N_i

Thus by using the minimum operation for the fuzzy AND operation, the firing strength of the rule (where $i = 1, 2, \dots, 180$), α_i can be obtained by considering

$$\alpha_i = \min\lfloor \mu_{Ai}(e_\psi), \mu_{Bi}(e_m), \mu_{Ci}(\boldsymbol{u}_s)\rfloor$$

where $\mu_{Ai}(e_\psi)$, $\mu_{Bi}(e_m)$, $\mu_{Ci}(\boldsymbol{u}_s)$ are the membership functions of the fuzzy sets A_i, B_i and C_i of the flux error, torque error and flux position and n is the switching state. The output from the i-th rule is then obtained using

$$\mu_{N_i'}(n) = \min\left[\alpha_i, \mu_{N_i}(n)\right]$$

where $\mu_{N_i}(n)$ is the membership function of fuzzy set N_i of variable n.

The outputs from the fuzzy system are crisp numbers (switching state n), and for defuzzyfication the maximum criterion is used:

$$\mu_N(n) = \max\left[\mu_{N_i^*}(n)\right] \dots i = 1, 2, \dots, 180\,.$$

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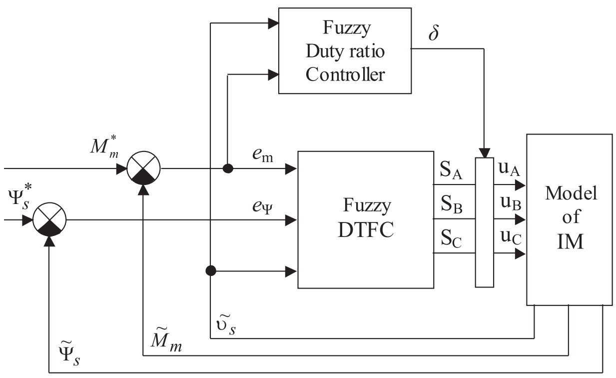

Fig. 1. Fuzzy DTFC AM and fuzzy duty ratio controller.

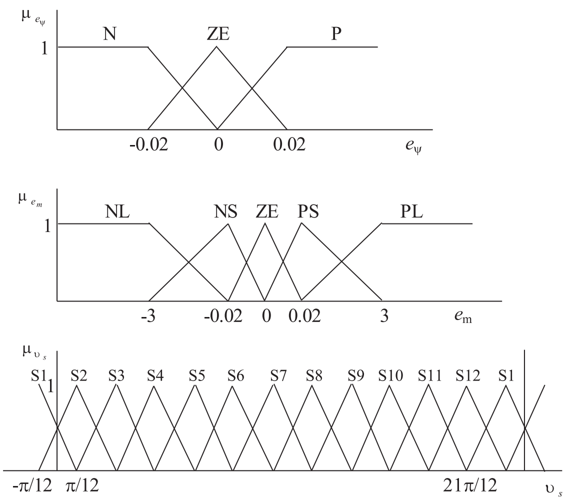

Fig. 2. Membership functions for fuzzy DTFC.

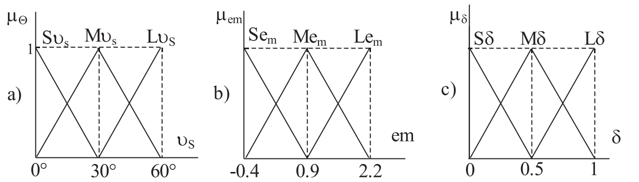

Fig. 3. Membership function for a) stator flux error b) torque error c) for fuzzy duty ratio controller.

3 FUZZY DUTY RATIO CONTROLLER

The voltage vectors selected from the fuzzy DTFC are not optimal in some region of stator flux vector positions. These disadvantages are improved by the fuzzy controller called a duty ratio controller [1]. In this control the selected inverter switching state is applied for a portion of the sample period, defined as a duty ratio δ [3], and the zero switching state is applied for the rest of the period. The duty ratio is chosen to give an average voltage vector, which causes torque change with ripple reduction. Fuzzy controller includes two inputs (torque error e_m and the position of the stator flux linkage $\boldsymbol{u}_s$ according on sector) and one output (duty ratio δ). Figure 3 describes membership function inputs and outputs. The fuzzy logic controller is a Mamdani type and contains a rule base. This base comprises two groups of rules, each of which contains nine rules. The first group is used when the stator flux linkage modulus is smaller than its reference value (Tab. 1 a), and the second group of rules is used when it is greater than its reference value (Tab. 1 b). There are together 18 simple rules and only three fuzzy sets.

Table 1. Fuzzy rules for duty ratio control

a)

$e_m\backslash\boldsymbol{u}_S$	$S_{\boldsymbol{u}_S}$	$M_{\boldsymbol{u}_S}$	$L_{\boldsymbol{u}_S}$
Se_m	$M\delta$	$S\delta$	$S\delta$
Me_m	$M\delta$	$M\delta$	$M\delta$
Le_m	$L\delta$	$L\delta$	$L\delta$

b)

$e_m\backslash\boldsymbol{u}_S$	$S_{\boldsymbol{u}_S}$	$M_{\boldsymbol{u}_S}$	$L_{\boldsymbol{u}_S}$
Se_m	$S\delta$	$S\delta$	$M\delta$
Me_m	$M\delta$	$M\delta$	$L\delta$
Le_m	$M\delta$	$L\delta$	$L\delta$

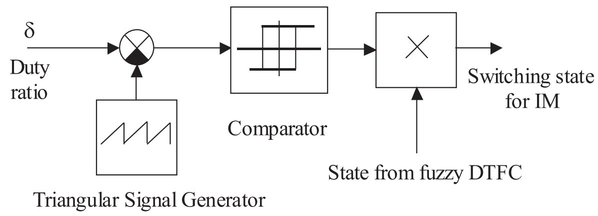

Fig. 4. Implementation of duty controller in switching state.

For implication of rules $\alpha_i = \mu_{mj}(e_m)\cdot\mu_{uk}(\boldsymbol{u}_s)$ is used, and membership function μ_δ for control is calculated as $\max_{i=1}^{9}\big(\sup(\alpha_i, \mu_\delta(\delta))\big)$. For defuzzyfication the method of the centre of gravity is used.

Implementation of duty ratio controller δ

The duty ratio controller prepares an optimal voltage vector for optimization outputs, which generate fuzzy DTFC. So, the fuzzy controller generates a number between 0 and 1, it is a filling of signal in one period (0 to 100 %). Figure 4 presents this realization, the frequency of a triangular signal generator has the same value as the signal frequency from fuzzy DTFC (switching state frequency) and the value of amplitude is 1. The comparator compares two signals and generates the duty ratio, which is a product with the fuzzy DTFC state. The triangular signal generator was used for pulse width modulation of outputs signal.

4 EXPERIMENTS

Simulations in Simulink/Matlab 6.5.1 verify the control. With a speed controller on the torque generator (Fig. 1.) we get speed fuzzy DTFC control of the induction machine. For verification of the control we do not need the speed, torque and flux estimators (for sensorless control). These state values are the feedback from the model of the induction machine.

5 DISCUSSION AND CONCLUSIONS

The sample time of simulation is 0.1 ms, so the voltage vector states are switched on with a frequency of 10 kHz. The simulation frequency is like a clock frequency of DSP processor available for the control of the induction machine.

By these simulations we have verified the control of zero speed operation, where the control is more sensitive than elsewhere. Figure 7 presents the curves of the switching state, for example only S_a. There is an evident interference of the duty ratio control. Figures 7 and 8 present that the new method brings a decrease of the torque and stator flux ripples. So, we conclude that the fuzzy duty ratio controller brings improvements in fuzzy DTFC and in DTFC generally.

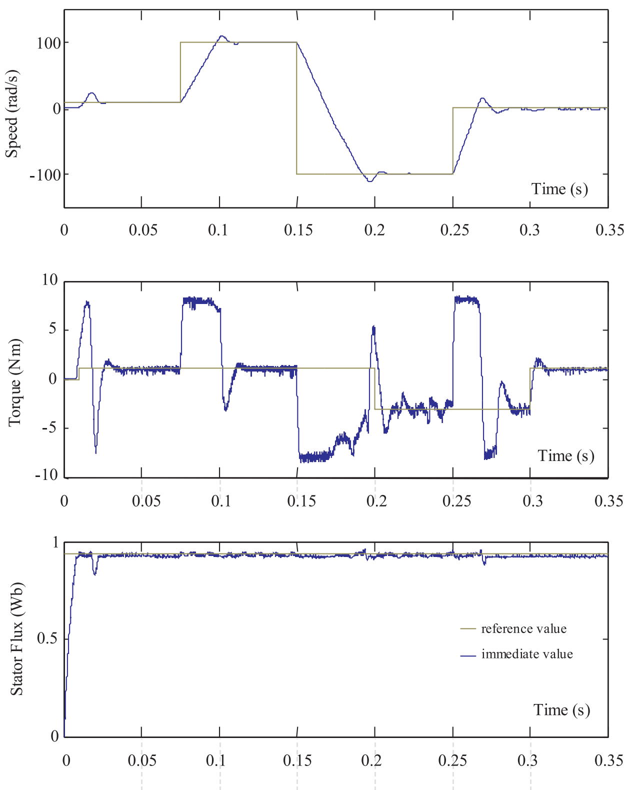

Fig. 5. Control overrun, speed, torque and flux in 0.35 sec.

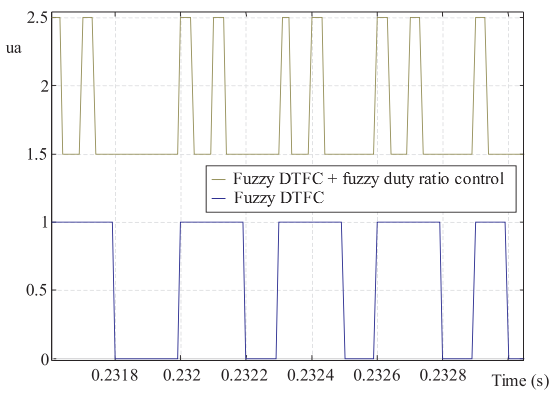

Fig. 6. Comparison curves of switching state S_a, sample period is $T_{vz} = 0.1$ ms.

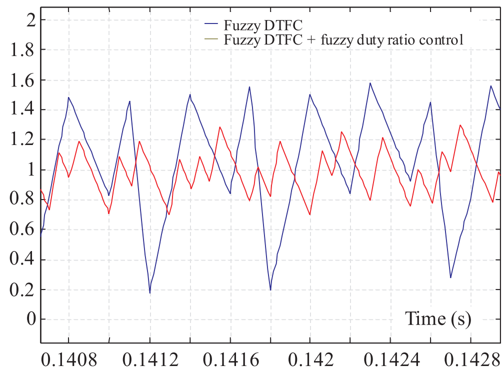

Fig. 7. Comparison torque curves (zero speed).

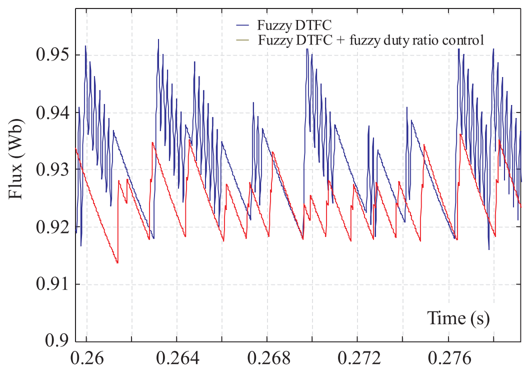

Fig. 8. Comparison stator flux curves (zero speed).

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