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DIRECT TORQUE CONTROL OF INDUCTION MOTOR WITH FUZZY MINIMIZATION TORQUE RIPPLE

Fatiha Zidani [*] **— Rachid Naït Saïd** [**]

This paper presents an improved direct torque control based on fuzzy logic technique. The major problem that is usually associated with DTC drive is the high torque ripple. To overcome this problem a torque hysteresis band with variable amplitude is proposed based on fuzzy logic. The fuzzy proposed controller is shown to be able to reducing the torque and flux ripples and to improve performance DTC especially at low speed.

K e y w o r d s: direct torque control, induction motor, fuzzy logic, torque ripple minimization

1 INTRODUCTION

Direct torque control (DTC) is receiving wide attention in the recent literature [1, 2]. DTC minimizes the use of machine parameters [3, 4]. This type of control is essentially a sliding mode stator flux-oriented control. The DTC uses the hysteresis band to directly control the flux and torque of the machine. When the stator flux falls outside the hysteresis band, the inverter switching stator is changed so that the flux takes an optimal path toward the desired value [3, 4].

The name direct torque control is derived from the fact that on the basis of the errors between the reference and the estimated values of torque and flux it is possible to directly control the inverter states in order to reduce the torque and flux errors within the prefixed band limits [5, 6].

The main advantages of DTC are robust and fast torque response, no requirements for coordinate transformation no requirements for PWM pulse generation and current regulators [7]. The major disadvantage of the DTC drive is the steady state ripples in torque and flux. The pulsations in flux and torque affect the accuracy of speed estimation. It also results in higher acoustical noise and in harmonic losses [8].

Generally there are two methods to reduce the torque and flux ripple for the DTC drives. One is multi level inverter [9 ,10], the other is space vector modulation (SVM) [11]. In the first method, the cost and the complexity will be increased, in the second method, the torque ripple and flux ripple can be reduced, however the switch frequency still changes [12].

In DTC, open loop and close loop speed and position estimators are widely analysed in literature [13]. The improved voltage-current model speed observers based on a MRAS structure is used in this paper to estimate rotor speed. A fuzzy controller is introduced to allow the performance of DTC scheme in terms of flux and torque ripple to be improved.

2 BASIC DTC PRINCIPLES

The DTC scheme is given in Fig. 1, the ε_ϕ and ε_Γ signals are delivered to two hysteresis comparators. The corresponding digitized output variables: change of magnetic flux Δ_ϕ, of mechanical torque Δ_{Γ_e} and the stator flux position sector s_N created a digital word, which selects the appropriate voltage vector from the switching table. The selection table generates pulses S_a, S_b, S_c, to control the power switches in the inverter.

Three-level torque and two level flux hysteresis controllers are used according to the outputs of the torque controller and the sector information (S_ϕ) of ϕ_s, appropriate voltage vectors for both the inverters are selected from a switching table as it is shown in Table 1.

Table 1. Classical DTC switching table

Flux	Torque	Sector S_ϕ					
Δ_ϕ	Δ_{Γ_e}	$S_{\phi 1}$	$S_{\phi 2}$	$S_{\phi 3}$	$S_{\phi 4}$	$S_{\phi 5}$	$S_{\phi 6}$
1	1	V_2	V_3	V_4	V_5	V_6	V_1
1	0	V_7	V_0	V_7	V_0	V_7	V_0
1	−1	V_3	V_1	V_2	V_3	V_4	V_5
−1	1	V_3	V_4	V_5	V_6	V_1	V_2
−1	0	V_0	V_7	V_0	V_7	V_0	V_7
−1	−1	V_5	V_6	V_1	V_2	V_3	V_4

Figure 2 shows the voltage vectors which are usually employed in DTC scheme when the stator flux vector is lying in sector I. The selection of a voltage vector at each cycle period is made in order to maintain the torque and the stator flux within the limits of two hysteresis bands [14]. This simple approach allows a quick torque response to be achieved, but the steady state performance is characterized by undesirable ripple in current, flux and torque. This behaviour is mainly due to the absence of information about torque and rotor speed values in the voltage selection algorithm.

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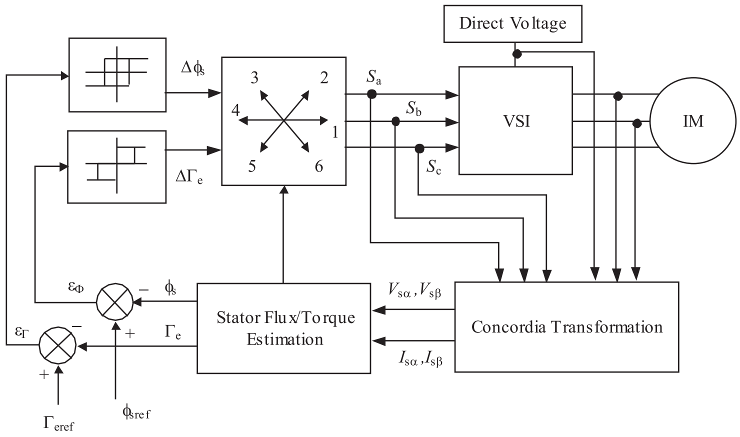

Fig. 1. Block diagram of the induction motor drive system based on DTC scheme

3 FUZZY PROPOSED APPROACH AND TORQUE RIPPLE MINIMISATION

A Torque ripple analysis

Since none of the inverter switching vectors is able to generate the exact stator voltage required to produce the desired changes in torque and flux, torque and flux ripples compose a real problem in DTC induction motor drive. Many solutions were proposed to improve performances [1, 13, 15–23].

According to the principle of operation of DTC, the torque presents a pulsation that is directly related to the amplitude of its hysteresis band. The torque pulsation is required to be as small as possible because it causes vibration and acoustic noise [21].

A small flux hysteresis bands should be preferred when high-switching speed semi- conductor devices are utilized because their switching losses are usually negligible with respect on state losses. In this way the output current harmonic can be strongly reduced [21].

The hysteresis band has to be set large enough to limit the inverter switching frequency below a certain level that is usually determined by thermal restriction of power devices. Since the hysteresis bands are set to cope with the worst case, the system performance is inevitably degraded in a certain operating range, especially in a low speed region [23]. In torque hysteresis controller, an elapsing time to move from lower to upper limit, and vice versa can be changed according to operating condition [23].

Most of these methods are computationally intensive. In the next section a fuzzy approach is proposed to reduce torque ripple. This goal is achieved by the fuzzy controller which determinates the desired amplitude b_Γ of torque hysteresis band.

B. Torque ripple minimization strategy

The torque and mechanical dynamics of the machine are modelled by the following equations:

$$\Gamma_e = \frac{3}{2} p \overline{I}_s \cdot j \overline{\phi}_s \tag{1}$$

$$J \frac{\mathrm{d}\omega}{\mathrm{d}t} = \Gamma_e - \Gamma_{load} \tag{2}$$

where Γ_e: motor torque, J is the moment inertia of the system, and Γ_{load} is the torque load. The variance value of the change of speed error can be used to measure or to estimate the torque smoothness [24].

Replacing the speed error signal $e = \omega - \omega_{ref}$ in (2) gives:

$$J \frac{\mathrm{d}(\omega_{ref} + e)}{\mathrm{d}t} = J \Big[\frac{\mathrm{d}\omega_{ref}}{\mathrm{d}t} + \frac{\mathrm{d}e}{\mathrm{d}t} \Big] = \Gamma_e - \Gamma_{load} \tag{3}$$

For a constant speed reference signal $\frac{\mathrm{d}\omega_{ref}}{\mathrm{d}t} = 0$ and constant load, the change of speed error is related to the electrical motor torque by:

$$\frac{\mathrm{d}e}{\mathrm{d}t} = \frac{\Gamma_e - \Gamma_{load}}{J} \tag{4}$$

From (4), it can be conclude that the change of speed error signal can indeed be a good measurement and good indicator of motor torque ripple.

The speed estimator has the structure of a model reference adaptive controller (MRAC) [25, 26], this technique is based on the error between two models:

The reference model is the rotor flux estimator given by:

$$\dot{\overline{\phi}}_r = \frac{L_r}{M} \big(\overline{V}_s - R_s \overline{I}_s - \sigma L_s \overline{I}_s \big) \tag{5}$$

The adjustable model is given by:

$$\dot{\hat{\overline{\phi}}}_r = \Big(-\frac{1}{T_r} + j\omega \Big) \overline{\phi}_r + \frac{M}{L_r} \overline{I}_s \tag{6}$$

Using the error between the rotor flux of the two models, rotor speed $\hat{\omega}$ is calculated and corrected by a proportional integral (PI) adaptation mechanism as it is shown in Fig. 3.

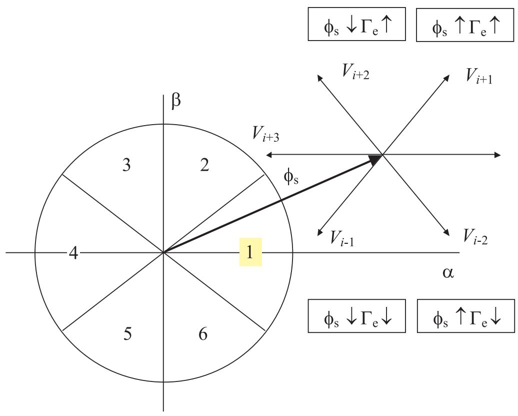

Fig. 2. Stator flux variation ($\overline{\phi}_s$ is in section 1)

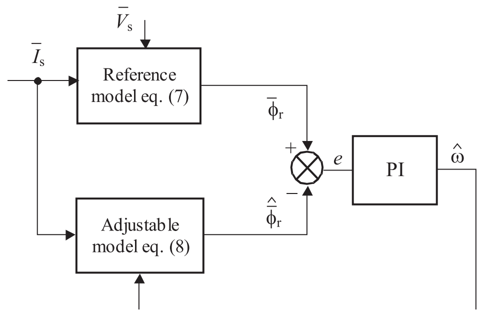

Fig. 3. The MRAS speed estimator

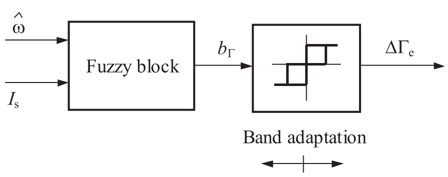

Fig. 4. Torque hysteresis controller adapted band

C. Fuzzy proposed approach to reduce torque ripple

The fuzzy logic has been proved powerful and able to resolve many problems. A fuzzy controller seems to be a reasonable choice to evaluate the amplitude of torque hysteresis band according to the torque ripple level. In this paper, the amplitude of torque hysteresis band is not prefixed but it is determinate by a fuzzy controller. Based on the analysis given in section (B), two inputs are chosen, speed error variation and stator current variation.

$$\begin{aligned} e_1(k) &= \hat{\omega}(k) - \hat{\omega}(k-1) \\ e_2(k) &= I_s(k) - I_s(k-1) \end{aligned} \qquad (7)$$

The magnitude of the stator current is defined as $I_s = \sqrt{I_{\alpha s}^2 + I_{\beta s}^2}$. The crisp output Δb_Γ (incremental amplitude of torque hysteresis band) is integrated in such way that the amplitude of torque hysteresis band is obtained:

$$b_\Gamma(k) = b_\Gamma(k-1) + \Delta b_\Gamma(k) \qquad (8)$$

Figure 4 shows the proposed torque hysteresis controller with adapted band b_Γ.

The fuzzy controller design is based on intuition and simulation. For different values of motor speed and current, the values reducing torque and flux ripple were found. These values composed a training set which is used to extract the table rule $\Delta b_\Gamma(e_1; e_2)$. The shapes of membership functions are refined trough simulation and testing. The rules sets are shown in Table 2. Figure 5 shows the membership functions of input and output variables. The rules were formulated using analysis data obtained from the simulation of the system using different values of torque hysteresis band.

If the amplitude b_Γ is set too small, the overshoot may touch the upper band which will cause a reverse voltage vector to be selected. This voltage will reduce rapidly the torque causing undershoot in torque response, consequently the torque ripple will remain high.

Table 2. Fuzzy rules of torque hysteresis controller

e_2 \ e_1 (Δb_Γ)	NH	NM	NS	ZE	PS	PM	PH
N	N	N	NS	ZE	PS	PS	P
ZE	N	N	NS	ZE	PS	P	P
P	N	NS	NS	ZE	PS	P	P

PH: positive high, NH: negative high,
PM: positive medium, NM: negative medium,
PS: positive small, NS: negative small, ZE: zero

The linguistic rules can be expressed by the following example:

- If (e_1 is NH or NM and e_2 is N) then (Δb_Γ is N):

This case corresponds to a big overshoot in torque error, consequently high torque ripple. To reduce the torque ripple, the value Δb_Γ should be reduced.

- If (e_1 is PH and e_2 is P) then (Δb_Γ is P):

In this case, the overshoot in torque error can touch the upper band which will cause a reverse voltage vector to be selected. This one will result in a torque to be reduced rapidly and causes undershoot in the torque response below the hysteresis band. Thus, Δb_Γ should not be too small, Δb_Γ is set Positive in order to avoid this situation.

4 SIMULATION RESULTS

The simulations of the DTC induction motor drive were carried out using the Matlab/Simulink simulation package.

A. Speed control performance without fuzzy controller

Figure 6 shows the estimated speed, estimated torque, stator and rotor flux and stator current with DTC scheme

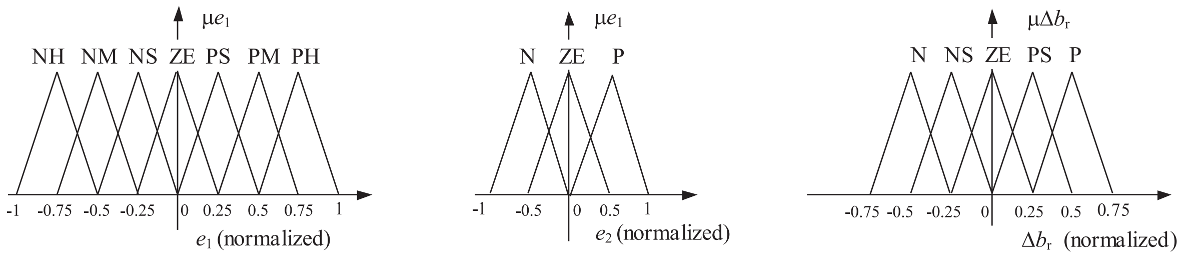

Fig. 5. Input/output variables membership functions

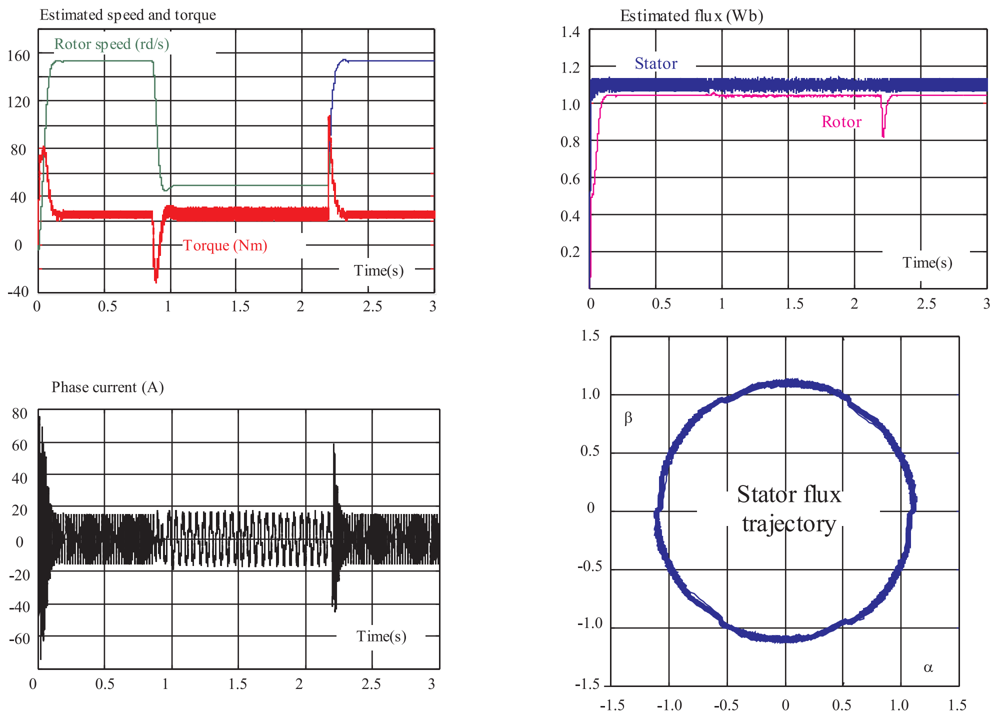

Fig. 6. Speed, torque and flux transients-DTC-MRAS speed estimator.

and MRAC technique. Figure 6 shows the speed transition from 157 rd/s to 50 rd/s with rated torque load. Estimated speed follows the reference speed closely. Some flux oscillations can be observed.

B. Steady state performances with and without fuzzy controller

Figure 7 shows simulation results of the proposed approach at low speed (10 rd/s with rated load $\Gamma_{e-rated} = 25$ Nm), the amplitude b_Γ is adapted by the fuzzy controller according to operating condition, see Fig. 7a. The torque ripple is significantly reduced, the flux and torque effect on speed estimation is clearly reduced. From the stator flux trajectory, it is appreciated that the flux ripple decreases when fuzzy controller is in use.

C. Response to a speed transition at standstill

In order to show the benefits of the improved DTC, a step change of the speed reference (from 157 rd/s to 30 rd/s) has been applied to the control at standstill. Fig. 8b and Fig. 8c show the estimated speed, torque, stator and rotor flux and current. In Fig. 8c, the torque ripple is significantly reduced especially at low speed. The fuzzy controller provides the desired amplitude according to the torque ripple level and operating condition, as it is shown in Fig. 8a. It is seen that the steady state performances of the DTC-with fuzzy controller (Fig. 8c) is much better than of the DTC-without fuzzy controller (Fig. 8b). For dynamic performance, the modified DTC is almost as good as the basic DTC.

5 CONCLUSION

The present paper has presented a sensorless speed DTC drive with fuzzy controller. This controller determinates the desired amplitude of torque hysteresis band. It is shown that the proposed scheme results in improved stator flux and torque responses under steady state condition. The main advantage is the improvement of torque and flux ripple characteristics at low speed region, this provides an opportunity for motor operation under minimum switching loss and noise.

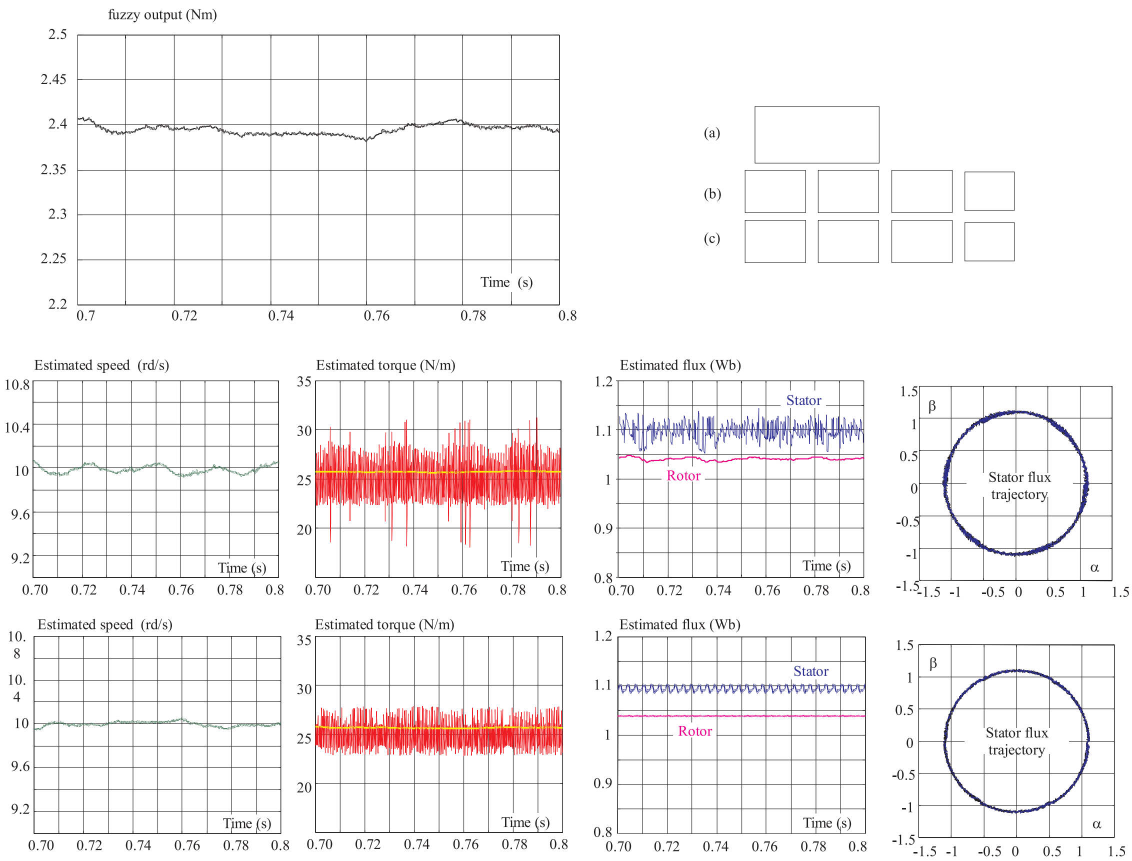

Fig. 7. a) Amplitude of torque hysteresis — output of fuzzy block-steady state, b) Classical DTC with fixed band hysteresis ($b_\Gamma = 10\,\%\,\Gamma_{rated}$) — 10 rd/s with rated load-steady state, c) DTC with variable band hysteresis — 10 rd/s with rated load — steady state — the value of b_Γ is adapted (see figure 7a)

Appendix

INDUCTION MOTOR PARAMETERS

Rated value			
	Power	4	kW
	Voltage (Δ/Y)	220/380	V
	Current (Δ/Y)	15/8.6	A
	Speed	1440	rpm
Parameters			
	R_s	1.2	Ω
	R_r	1.8	Ω
	$L_s = L_r$	0.156	H
	M	0.15	H
	J	0.02	$\mathrm{Kg}\cdot\mathrm{m}^2$
	f	0.001	IS

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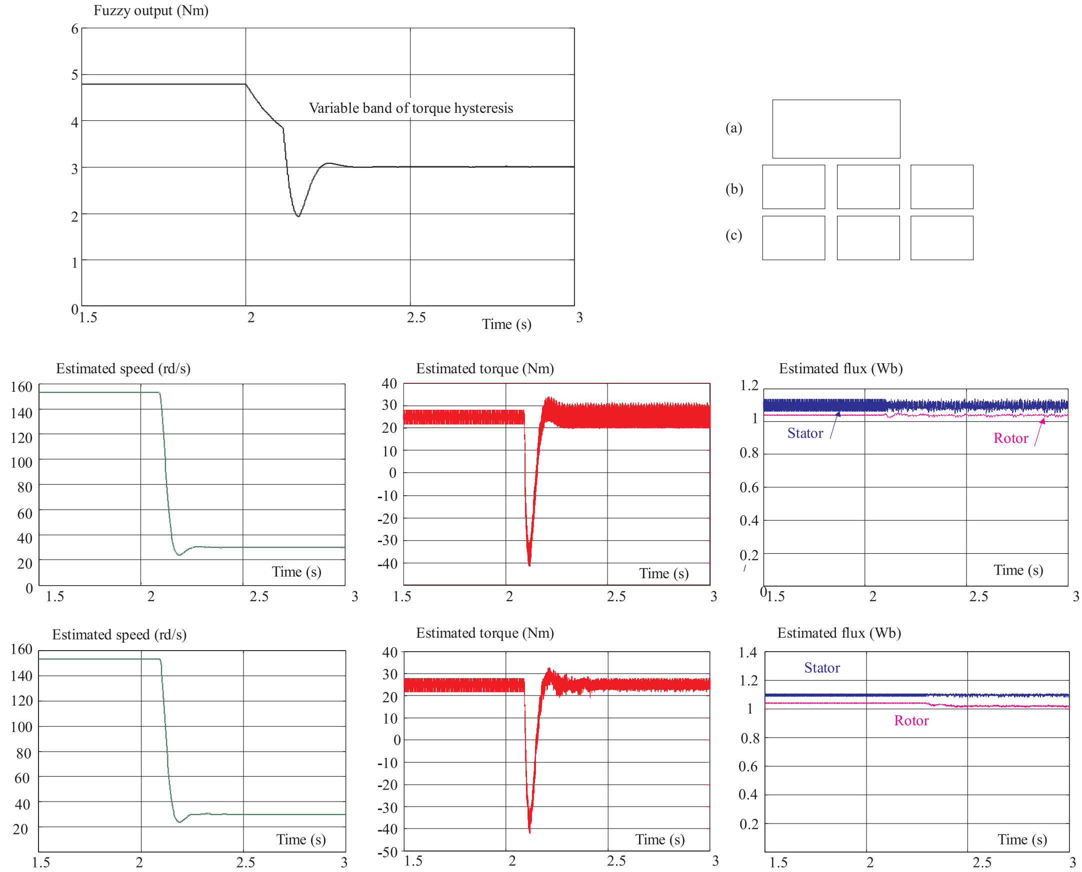

Fig. 8. a) Amplitude of torque hysteresis -output of fuzzy block- speed transition b) Classical DTC with prefixed band hysteresis ($b_\Gamma = 20\,\%\,\Gamma_{rated}$) — speed, torque and flux transition zoom during speed deceleration with rated load c) DTC with variable band hysteresis (b_Γ is adapted, see Fig. 8a) — speed, torque and flux transition zoom during speed deceleration with rated load

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