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Y.A. Mabrouk, B. Mokhtari, T. Allaoui

Frequency analysis of stator currents of an induction motor controlled by direct torque control associated with a fuzzy flux estimator

Introduction. *The best way to control the torque of an induction motor is conventional direct torque control (DTC); this control method is the most used approach in the industrial sector due to its many advantages. Its main advantages are its simplicity and its exclusive dependence on the stator resistance of the induction motor. However, the use of hysteresis comparators reduces its effectiveness, causing more torque ripple. Additionally, this results in variable operating frequency and limited frequency sampling, resulting in pseudo-random overshoot of the hysteresis band.* ***Purpose****. For these reasons, this article presents a new study aimed at confirming its shortcomings and improving the effectiveness of the control.* ***Novelty****. We propose to use fuzzy logic methods to estimate the two components of the stator flux.* ***Methods****. In traditional DTC the flux components are estimated from an equation relating the stator resistance to the stator voltage and current. In the proposed method, only stator currents and voltages are used for this evaluation, which eliminates the dependence of DTC on stator resistance. The aim of this proposal is to make DTC robust to parametric changes.* ***Results****. General harmonic distortions, rotational speed of the induction motor, electromagnetic moment, magnetic flux and stator currents are analyzed.* ***Practical value****. With this proposed technique, validated in Simulink/MATLAB, several improvements in motor behavior and control are endorsed: torque fluctuations are reduced, overshoot is completely eliminated, and total harmonic distortion is significantly reduced by 48.31 % for stator currents. This study also confirmed the robustness of DTC to changes in stator resistance.* References 26, table 3, figures 11.

Key words: **direct torque control, fuzzy logic controller, fuzzy logic estimator, induction motor, spectral analysis, total harmonic distortion.**

Вступ*. Найкращим способом управління крутним моментом асинхронного двигуна є традиційне пряме управління крутним моментом (DTC); цей метод управління є найбільш використовуваним у промисловому секторі через його численні переваги. Його основними перевагами є простота та виключна залежність від опору статора асинхронного двигуна. Однак використання гістерезисних компараторів знижує його ефективність, викликаючи велику пульсацію крутного моменту. Крім того, це призводить до зміни робочої частоти та обмеження вибірки частоти, що призводить до псевдовипадкового виходу за межі смуги гістерезису.* ***Мета****. З цих причин у цій статті представлено нове дослідження, спрямоване на підтвердження його недоліків та підвищення ефективності контролю.* ***Новизна****. Ми пропонуємо використовувати методи нечіткої логіки з метою оцінки двох компонентів потоку статора.* ***Методи****. У традиційному DTC компоненти потоку оцінюються за рівнянням, що зв'язує опір статора з напругою та струмом статора. У запропонованому методі цієї оцінки використовуються лише струми і напруги статора, що виключає залежність DTC від опору статора. Мета цієї пропозиції – зробити DTC стійким до параметричних змін.* ***Результати****. Аналізуються загальні гармонічні спотворення, швидкість обертання асинхронного двигуна, електромагнітний момент, магнітний потік та струми статору.* ***Практична цінність****. За допомогою цього запропонованого методу, перевіреного в Simulink/MATLAB, підтверджено кілька покращень у поведінці та управління двигуном: коливання крутного моменту зменшуються, перерегулювання повністю усувається, а загальні гармонічні спотворення значно зменшуються на 48,31% для струмів статора. Це дослідження підтвердило стійкість DTC до змін опору статора.* Бібл. 26, табл. 3, рис. 11.

Ключові слова: **пряме управління крутним моментом, контролер нечіткої логіки, пристрій оцінки нечіткої логіки, асинхронний двигун, спектральний аналіз, повне гармонійне спотворення.**

Introduction. Owing to their affordability and ease of construction, induction motors (IM) are widely used in variable-speed drive systems [1]. IM compared to DC motors, are more durable, easier to maintain, and more economical [2]. Additionally, they are sturdy and resistant to big loads [3]. These many benefits, however, are not without drawbacks. The motor's dynamic behavior is frequently quite complicated [4], as a result of the strongly coupled, multivariable, nonlinear equations that come from its modeling. Furthermore, some of its state variables, including flux, cannot be measured or quantified [5-7]. To continuously control the torque and flux of these motors under these limits, more sophisticated control algorithms are needed [8]. Academic and commercial research has been conducted for a number of years to address the IM's control issue and create reliable controls [9]. For high-performance applications, there are two types of control used to control the electromagnetic torque of AC drives:

- Vector Control based on pulse width modulation inverter control for stator current regulation in the field rotational reference;
- Direct Torque Control (DTC) was proposed as an alternative to field-oriented control for high-performance AC drives. The fundamental idea behind this control method is the direct control of electromagnetic torque and flux by direct selection of the control sequence to be used with voltage inverters. This control strategy was proposed for the 1st time in the 1980s [10, 11]. The idea of torque control in the DTC scheme [12] is to increase the torque angle (angle between the stator and rotor flux) in case torque output needs to be increased. To reduce torque, one performs the reverse. However, it is maintained at the desired magnitude for the stator-linked flux [13].

Among the advantages of DTC control, it depends only on the motor stator resistance (R_s). Unfortunately, this solution can degrade the control's robustness because the resistance value varies over time due to heating. For this reason, we propose in this paper to replace the «classic estimator» of the two flux components which is described in equation (5) with another fuzzy one, in this fuzzy estimation we eliminate the dependence of the flux estimator to the R_s, and the only quantities used in this operation are the stator currents and voltages. This technique allowed us to improve the DTC control performance by minimizing the undulations of the controlled quantities.

To date, several studies have investigated the fuzzy estimator in DTC control. Khadar et al. in [14] propose a method for stator resistance estimation of a double-fed induction motor (DFIM) by a three-level neutral point-clamped inverter based on the DTC technique. Also, Zidani et al. in [15] propose a new stator resistance estimator using fuzzy logic. While in [13], Kamalapur et al. implement the estimation method using the proportional-integral (PI) control and fuzzy logic control schemes. Also, El Ouanjili et al. in [9] for a DFIM driven by two voltage source inverters operating at two levels, show an improved DTC technique.

Model of the IM in the stationary frame. In the literature, there are several mathematical models representing the dynamic behavior of IMs. In the following, a state space model related to α and β axes, for electrical variables, is considered [4]:

$$\begin{cases} \frac{d\varphi_{\alpha s}}{dt} = V_{\alpha s} - R_s I_{\alpha s}; & \frac{d\varphi_{\beta s}}{dt} = V_{\beta s} - R_s I_{\beta s}; \\ \frac{d\varphi_{\alpha r}}{dt} = -R_r I_{\alpha r} - \omega_m \varphi_{\beta r}; & \frac{d\varphi_{\beta r}}{dt} = -R_r I_{\beta r} + \omega_m \varphi_{\alpha r}, \end{cases} \quad (1)$$

where $\omega_m = p\Omega_m = \omega_s - \omega_r$, where p is the pole pairs; subscripts s and r refer to the stator and rotor; α and β refer to components in (α, β) frame; V, I, φ are used to describe respectively voltage, current, and flux; R_s and R_r refer to the stator and rotor resistances; Ω_m is the mechanical speed; ω_s is the rotation speed of the stator field; ω_r is the rotation speed of the rotor one.

Currents and flux relationships are [16]:

$$\begin{bmatrix} \varphi_{\alpha s} \\ \varphi_{\alpha r} \end{bmatrix} = \begin{bmatrix} L_s & M \\ M & L_r \end{bmatrix} \begin{bmatrix} I_{\alpha s} \\ I_{\alpha r} \end{bmatrix}, \begin{bmatrix} \varphi_{\beta s} \\ \varphi_{\beta r} \end{bmatrix} = \begin{bmatrix} L_s & M \\ M & L_r \end{bmatrix} \begin{bmatrix} I_{\beta s} \\ I_{\beta r} \end{bmatrix}; \quad (2)$$

where L and M are respectively the inductance of motor and the mutual one.

The next equation represents the mechanical part of the motor [16]:

$$\frac{d\Omega_m}{dt} = \frac{1}{J} \cdot (T_{em} - T_L); \quad (3)$$

where T_{em} and T_L are respectively the electromagnetic torque and load one; J is the motor inertia.

Presentation of the DTC control. The DTC principle was first developed by Takahashi and Depenbrock [10, 11] around the end of the 1980s. It accomplishes decoupled control of the electromagnetic torque and stator flux, allowing IMs to respond to electromagnetic torque accurately and quickly in the stationary frame (α, β). A switching table is used to select the proper voltage vector. The choice of switching states has a direct impact on changes in the stator flux and torque of the motor. As a result, the choice is made by keeping the magnitudes of the flux and torque within two hysteresis bands. These controllers ensure that these two quantities are controlled separately [17, 18]. The flux and torque errors are the inputs of hysteresis controllers, and the voltage vector that is appropriate for each commutation period is determined by the controllers' outputs [19]. In DTC, the inverter voltage and frequency are adjusted based on the measured stator current and voltage. The torque and flux of the motor are then estimated based on these measurements, and the inverter voltage and frequency are adjusted to maintain the desired torque and flux. The schema of direct torque control is shown in Fig. 1.

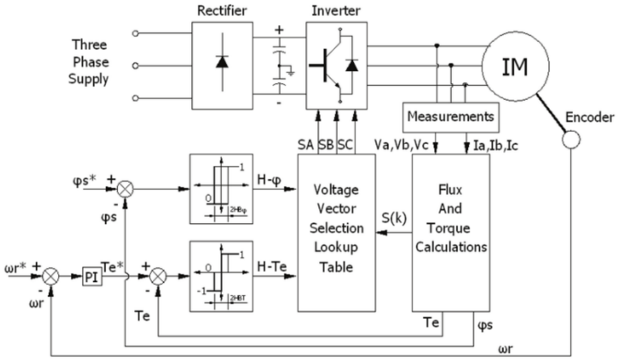

Fig. 1. Basic diagram of DTC control of IM

a) electromagnetic torque and flux estimation equations. To control the IM, a DTC loop is selected. First, the principal motor inputs, stator voltages, and currents are used to determine the T_{em} and φ_s. Then, the selection of the optimal voltage vector is applied inside the inverter. It is mandatory to express the used mathematical models for estimating the T_{em} and φ_s. The expressions of the flux into the stator can be evaluated as:

$$\varphi_s = \sqrt{\left(\varphi_{\alpha s}^2 + \varphi_{\beta s}^2\right)}, \quad (4)$$

where the variables in (4) are given in (5):

$$\varphi_{\alpha s} = \int (V_{\alpha s} - R_s I_{\alpha s}); \quad \varphi_{\beta s} = \int (V_{\beta s} - R_s I_{\beta s}), \quad (5)$$

where $\varphi_{\alpha s}$ and $\varphi_{\beta s}$ represent the two components of flux in (α, β) reference frame.

The angle θ between $\varphi_{\alpha s}$ and $\varphi_{\beta s}$ is calculated as follows:

$$\theta = \arctan(\varphi_{\beta s} / \varphi_{\alpha s}). \quad (6)$$

The cross-product of the stator quantities (stator flux and stator currents) can be used to calculate the IM's produced electromagnetic torque as:

$$T_{em} = \frac{3}{2} p (\varphi_{\alpha s} I_{\beta s} - \varphi_{\beta s} I_{\alpha s}). \quad (7)$$

b) presentation of the conventional switching DTC table. Table 1 displays the switching table for the conventional DTC control [13].

Table 1

DTC switching table*

Sector		1	2	3	4	5	6	
Flux	Torque							
$\Delta\varphi_s = 1$	ΔT_{em}=1	V2	V3	V4	V5	V6	V1	2 level
	ΔT_{em}=0	V7	V0	V7	V0	V7	V0	
	ΔT_{em}= –1	V6	V1	V2	V3	V4	V5	3 level
$\Delta\varphi_s = 0$	ΔT_{em}= 1	V3	V4	V5	V6	V1	V2	2 level
	ΔT_{em}= 0	V0	V7	V0	V7	V0	V7	
	ΔT_{em} = –1	V5	V6	V1	V2	V3	V4	3 level

*$\Delta\varphi_s$ is the difference between the reference flux and the estimated one, $\Delta\varphi_s = \varphi_s^* - \varphi_s$; ΔT_{em} is the difference between the reference electromagnetic torque and the estimated one, $\Delta T_{em} = T_{em}^* - T_{em}$.

DTC with a fuzzy estimator. Principle of the fuzzy logic controller. A fuzzy logic controller (FLC) is a type of control system that uses fuzzy logic (FL) to control a system or process. FL is a mathematical approach that deals with uncertainty and imprecision, allowing for more flexible and robust control than traditional control techniques. In an FLC, the inputs to the system are represented as fuzzy sets, which are defined by membership functions (MF) that assign degrees of membership to each input. These MFs allow for a more natural representation of inputs that may be difficult to define using traditional crisp sets.

The output of the FLC is then determined using a set of fuzzy rules, which define the relationship between the inputs and the output. These rules are typically defined by expert knowledge or by analyzing data from the system [20, 21].

The output of the FLC is then defuzzified to produce a crisp value that can be used to control the system. This defuzzification process can be done using a variety of techniques, such as centroid or max-min.

One of the advantages of FLC is its ability to deal with complex and nonlinear systems, which may be difficult to control using traditional control techniques. FLCs can also adapt to changing system conditions, making them suitable for systems that may experience changes in operating conditions. FLCs are commonly used in a variety of applications, such as process control, robotics, and intelligent transportation systems. They have also been used in many consumer products, such as washing machines, air conditioners, and cameras, to provide intelligent control and improve performance [22, 23].

In summary, FLCs provide a flexible and robust approach to control systems and processes, using fuzzy logic to deal with uncertainty and imprecision. Their ability to deal with complex and nonlinear systems makes them suitable for a wide range of applications, from industrial control to consumer.

Inference and formulation of rules. In most cases, fuzzy systems translate input fuzzy sets into output fuzzy sets. Relations between input and output fuzzy sets are known as fuzzy rules. Any one of the following can be used to derive fuzzy rules:

- master insight and control designing information;
- control actions were taken by the operator;
- gaining knowledge from the training examples [24].

The fuzzy rules in this study are created by learning from the training instances. In this instance, the fuzzy control rules' general form is: if x and y are A_i and B_i, respectively, then $z = f_i(x, y)$ denotes the linguistic variables that, in turn, denote the control variable and the process state variables. A first-order Sugeno (FOS) fuzzy model is the outcome of a fuzzy inference system (FIS) that takes the form of a FOS fuzzy model. A_i and B_i are the language-specific values of the linguistic variables, $f_i(x, y)$ is a function of the process state variables x, y [25, 26].

The proposed flux estimator In our research we propose the use of fuzzy logic to estimate the components of the stator flux ($\varphi_{\alpha s}$, $\varphi_{\beta s}$), such that we use as inputs of the fuzzy system the stator voltages V_s and currents I_s of the motor, and the outputs of this system are the components of the flux without having introduced the stator resistance (R_s) in this estimate. The outputs of the fuzzy system are used to calculate the electromagnetic torque T_{em} and the position of the flux θ. Figure 2 shows the proposed estimation block.

The range of fuzzy controller inputs (V_s, I_s) are characterized into three MFs, and two constants MFs are defined for output. There are 9 rules based on which the FIS infers the gains, these rules represented in Table 2. MFs used for inputs are Negative (Ne), Zero (Z), Positive (Po), and for outputs we choose: flux exists (exist), and flux doesn't exist (no).

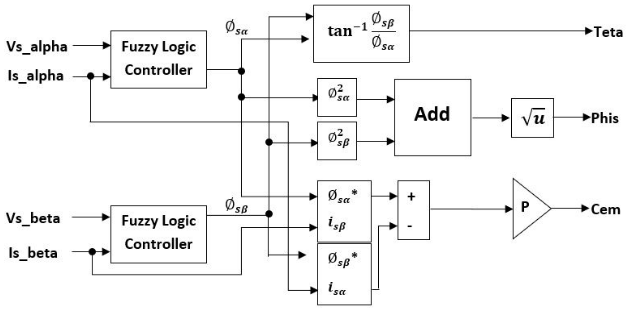

Fig. 2. Fuzzy flux estimator block

Table 2

Inference matrix

V_s, I_s	Ne	Z	Po
Ne	exist	no	exist
Z	no	no	no
Po	exist	no	exist

Trapezoidal MFs are chosen for the three fuzzy sets (P), (N) and (Z) as shown in Fig. 3, 4, and we choose constant MF for the output (Fig. 5).

The FIS used in this work is a FOS fuzzy model, its principle of operation is given as: if V_s is Po and I_s is Po then flux exist.

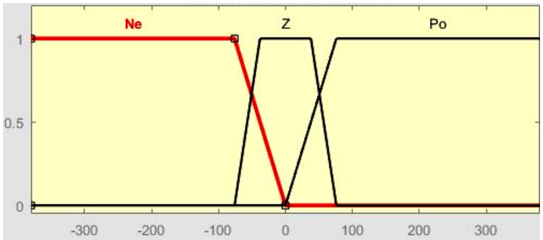

Fig. 3. Trapezoidal MFs used for the voltage input

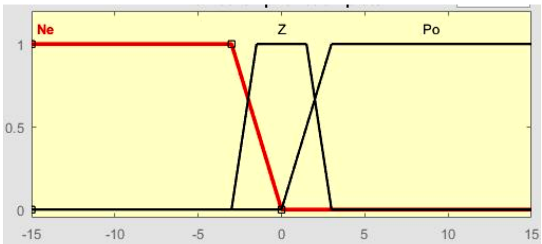

Fig. 4. Trapezoidal MFs used for the current input

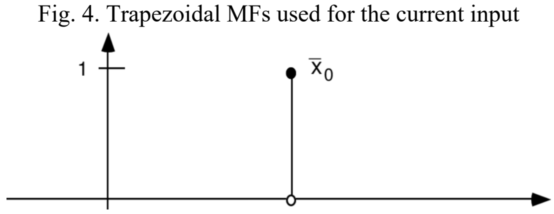

Fig. 5. MFs used for the decision output

Results and discussion. In this section, we are going to present and discuss the simulation results of conventional DTC of an IM, and the simulation results of the proposed strategy with the analysis spectral of the current. Motor and simulation parameters are listed in Appendix.

The simulation results in Fig. 6-9 show that the proposed strategy improved the performance of the DTC, minimizing torque ripples, the overshoot is absolutely removed and decreasing important values of total harmonic distortion (THD) by 48.31 %, and rotation with some oscillations.

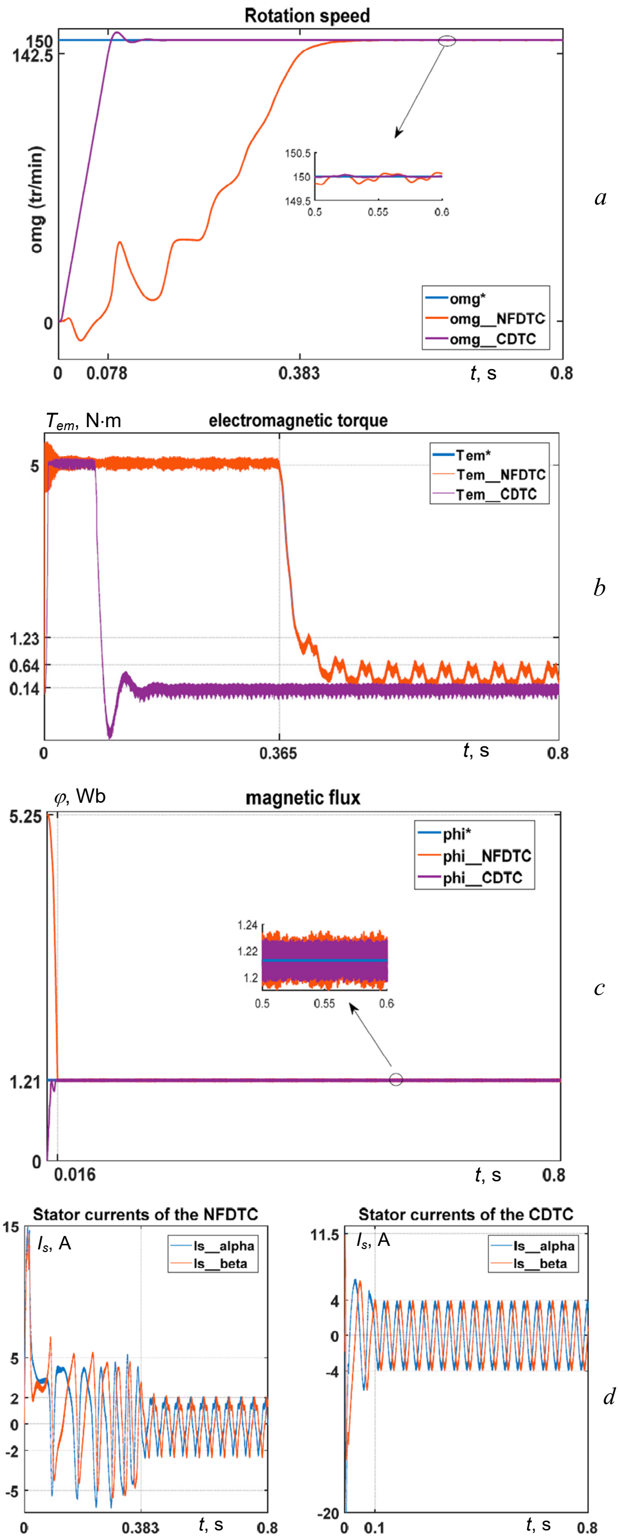

Fig. 6. Simulation results of conventional and the proposed DTC of an IM: *a* – rotation speed; *b* – electromagnetic torque; *c* – magnetic flux; *d* – stator current

From the analysis of Fig. 7, 8, we can notice the influence of the proposed method on the waveform of the current. The use of a fuzzy estimator also makes it possible to reduce the effect of harmonics of orders 3, 5, and 7. Figure 9 shows that the two components of flux obtained by a fuzzy estimator have a perfectly sinusoidal shape as desired. Table 3 presents a comparative study between the classic DTC and the proposed strategy.

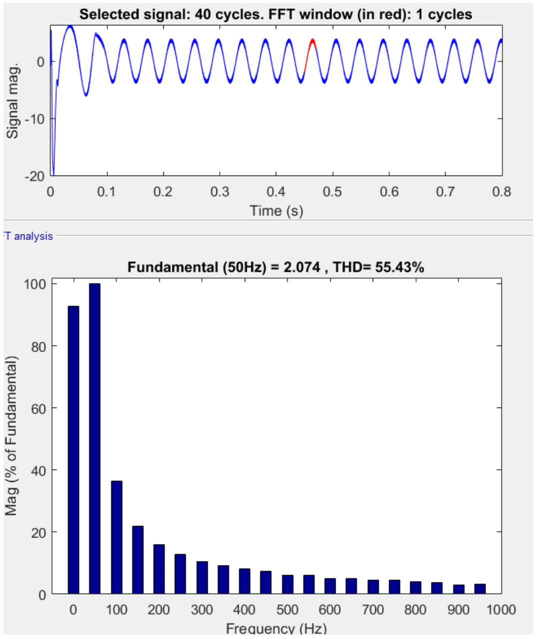

Fig. 7. The current spectral analysis of the conventional DTC control

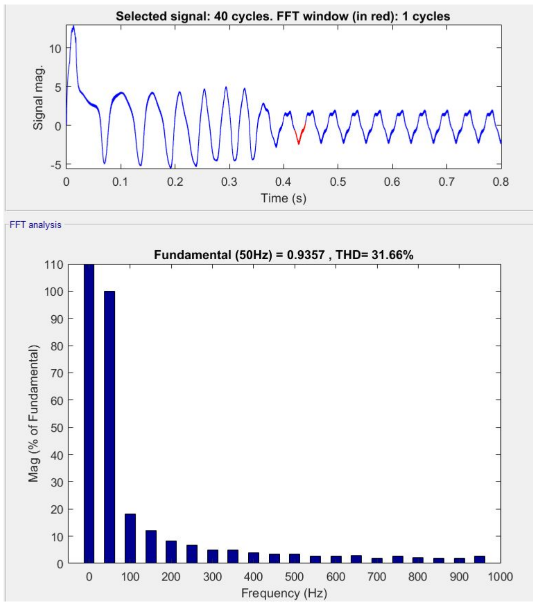

Fig. 8. The current spectral analysis of the proposed DTC control

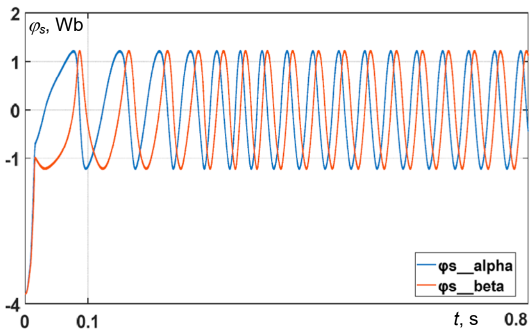

Fig. 9. The two components of flux obtained with fuzzy estimator

Table 3

Comparative study between the CDTC and the proposed one

	Dynamic response	Parameter sensitivity R_s	Current THD
Conventional DTC	fast	sensitive	important distortion
DTC with fuzzy observatory	slow	insensitive	less distortion

Robustness test. As shown in the introduction, the propose FLC-DTC, is independent of the stator resistance, to check the performance and the robustness of this proposed control, we propose to vary the value of the resistance R_s (increase it and decrease it) and see its influence on the behavior of the motor.

In the following, we show the simulation results of the FLC-DTC control, we increase the value of the resistance by 50 % of its nominal value (Fig. 10) and decrease it by 25 % of its nominal value (Fig. 11). These results confirm the effectiveness of the proposed strategy when we have a stator resistance variation.

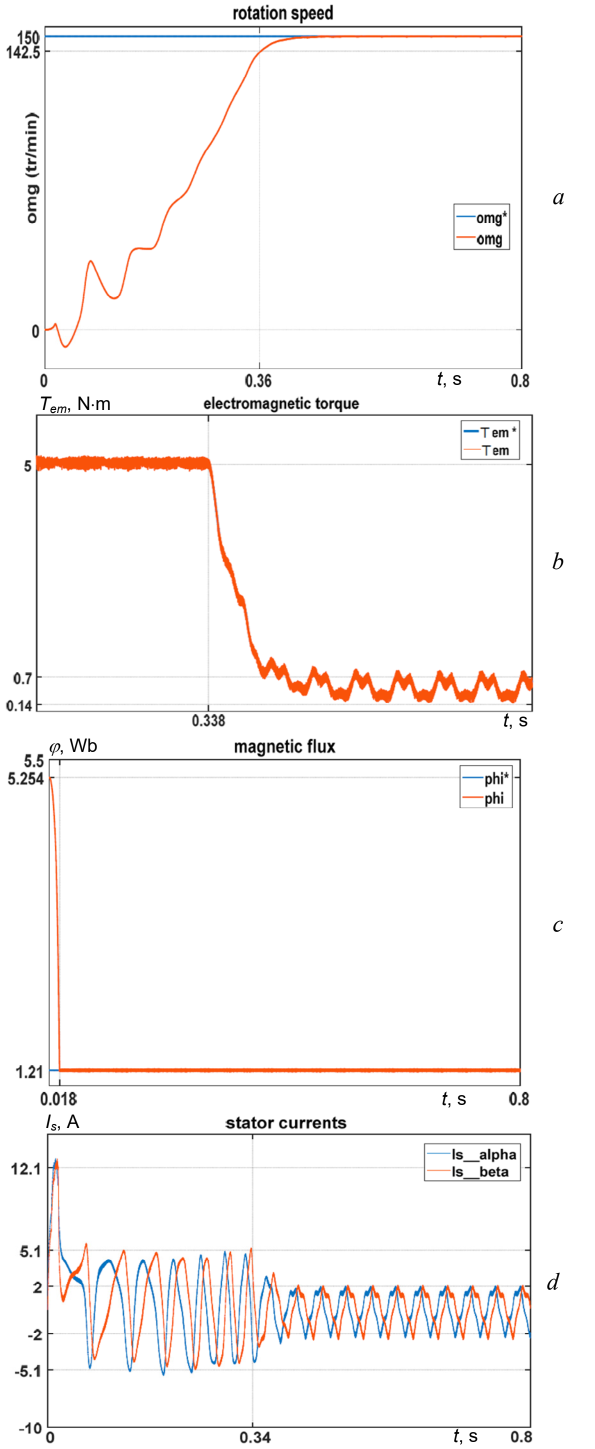

Fig. 10. Simulation results of the proposed DTC of an IM decreasing R_s by 50 % of its nominal value: *a* – rotation speed; *b* – electromagnetic torque; *c* – magnetic flux; *d* – stator current

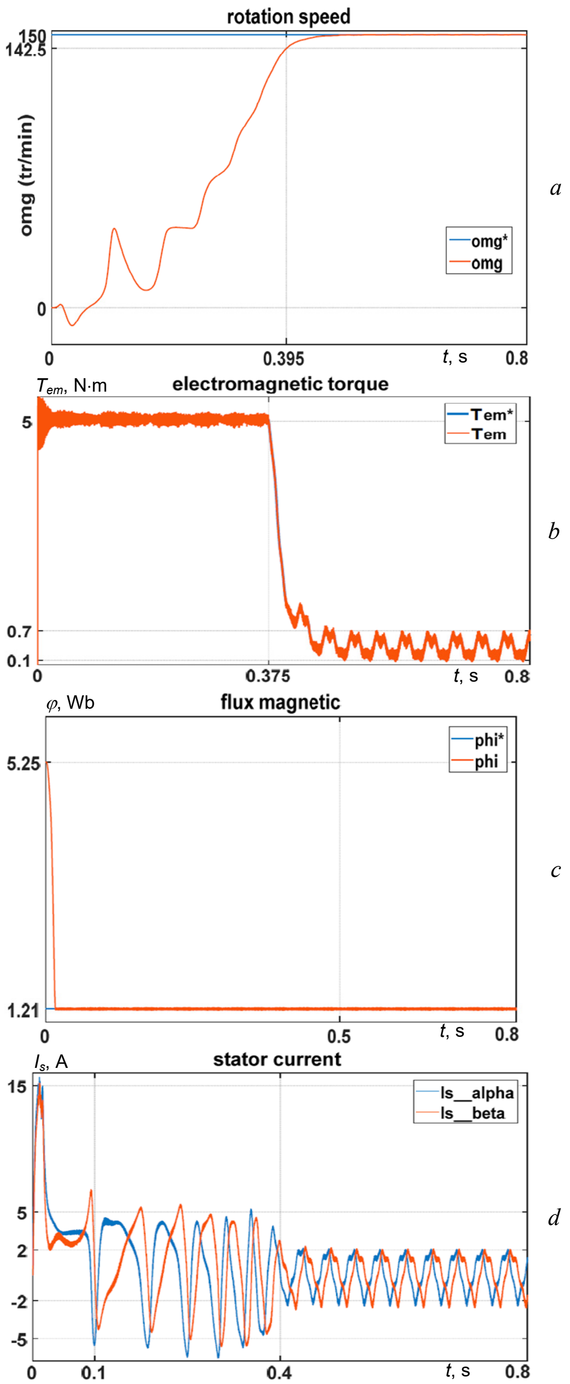

Fig. 11. Simulation results of the proposed DTC of an IM decreasing R_s by 25 % of its nominal value: *a* – rotation speed; *b* – electromagnetic torque; *c* – magnetic flux; *d* – stator current

Conclusions. In this paper, we suggested a new approach to the direct torque control of an induction motor, we used fuzzy logic to estimate the two components of the stator flux this strategy brought improvements to this control and the behavior of the motor. On the other hand, the simulation results demonstrated the stability of direct torque control to stator resistance variations, but it also has some drawbacks such as a speed response time that is a bit slow with some speed oscillations. We, therefore, propose in future studies to replace the fuzzy logic controller with a neuro-fuzzy controller and to use techniques to improve the dynamic response of the system.

Conflict of interest. The authors of the article declare that there is no conflict of interest.

Appendix

Pole pairs p	1
Stator resistance, Ω	4.7333
Power, W	1000
Moment of inertia, kg·m^2	0.0026
Coefficient of viscous friction	$6.1704 \cdot 10^{-4}$
Fuzzy logic gains	k_1 = 18,25; k_2 = 3.71

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Younes Abdelbadie Mabrouk[1], *PhD Student,*
Bachir Mokhtari[1], *Lecturer,*
Tayeb Allaoui[2], *Full Professor,*
[1] Electrotechnics Department, LEDMASD Laboratory,
University of Laghouat, Algeria,
e-mail: mab.younes@lagh-univ.dz (Corresponding Author);
ba.mokhtari@lagh-univ.dz
[2] Department of Electrical Engineering, L2GEGI Laboratory,
University of Tiaret, Algeria,
e-mail: tayeb.allaoui@univ-tiaret.dz

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