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Application of the type-2 fuzzy logic controller and the fractional order controller to regulate the DTC speed in an induction motor

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Abstract:

Introduction/purpose: Among excellent strategies available to control the torque of asynchronous motors, we distinguish direct torque control. This technique of control allows direct control of magnetic flux and electromagnetic torque without the need to decouple them. Also, direct torque control like each control strategy has some drawbacks, the major drawbacks of this technique being operation at a variable switching frequency and flux and electromagnetic ripples due to the use of hysteresis regulators. It worsens acoustic noise, especially at low speeds, as well as the control performances.

Methods: To improve the performance of direct torque control especially at low speeds, the authors propose using fractional order PID in combination with type-2 fuzzy logic controllers to regulate the speed of an induction motor controlled by direct torque control.

Results: The results obtained by the proposed regulators show the improvements made to the system.

Conclusion: The proposed contribution can exert better control efforts.

Keywords: direct torque control (DTC), fuzzy logic controller (FLC), fractional order controller (FO), induction motor (IM), FFT analysis.

Introduction

Induction motors (IMs) are widely used in many industrial applications because of their low cost and simple construction (Berrabah et al, 2017). In comparison between IMs and direct current motors, IMs have a simple and rugged structure, higher maintainability, and economy (Belhamdi & Amar, 2017). On the other hand, these motors are not without inconvenience: their dynamic behavior is often very complex since their modeling results in a system of nonlinear equations, strongly coupled and multivariable. Some of its variables are not measurable, e.g. magnetic flux. For these reasons, the IM requires an advanced algorithm to control the torque and flux. From such algorithms, we distinguish direct torque control (DTC) which was proposed by Mr. Takahashi in 1985 as an alternative to field-oriented control (Prasad & Durgasukuamar, 2021). Fast dynamic reaction, a straightforward control strategy, the lack of coordinate transformations, the absence of position feedback, and current regulators are all benefits of DTC (Quang & Dittrich, 2015; Trabelsi et al, 2012). Despite all these advantages, this control has disadvantages such as high torque and flux ripples due to the use of a hysteresis band, stator current distortions, and poor performance at low and starting speeds (Trabelsi et al, 2012). For these reasons, several research studies were developed to master the performance of this control technique such as the use of artificial intelligence techniques to replace the hysteresis regulators and the switching table (Bounar et al, 2015; El Ouanjli et al, 2018), to control the motor speed (Sai Krishna & Narasimha Reddy, 2019; Lakshmi Prasanna et al, 2018), a combination between the SVM and DTC was proposed in (Cherif & Yahia, 2020; Massoum et al, 2021). In (Benbouhenni et al, 2017), the authors proposed to replace the conventional controller used to control the speed of the IM by an adaptive fuzzy logic controller. In (Ben Salem & Derbel, 2017), the authors proposed to control the speed of the motor by sliding mode control and used AI to improve the DTC performances.

As mentioned previously, among the disadvantages of the DTC command is that it presents poor performance at low and starting speeds, as well as the noise caused by the torque ripples. For these reasons, researchers have always worked to improve the performance of this control, and they have used several techniques as we cited previously. Among the best control strategies, we distinguish fuzzy logic controllers (FLCs) which offer several benefits in various applications due to their ability to handle imprecise, uncertain, or vague information. Also, FLCs can model complex, nonlinear systems without requiring precise mathematical models, and manage uncertainty and imprecision in input data and system parameters. For these reasons, we propose in this paper to replace the conventional regulator used to control the speed of the IM with a developed one, such as type-2 fuzzy logic controller and the fractional-order PID regulator after that to see the improvements made to the system. In the second section, we present the model of the IM in the stationary frame; after that we discuss the basics of DTC control, and then in section 4, we present the different regulators used in this work. The simulation results and their discussion make the objective of section 5. Finally, we conclude the paper with a conclusion.

Model of the IM

The representation of the IM in the stationary reference to the α and β axes is given by the following equations (Cherif & Yahia, 2020).

For the electrical variables

$$\begin{cases} \frac{d\varphi_{\alpha s}}{dt} = V_{\alpha s} - R_s I_{\alpha s} \\ \frac{d\varphi_{\beta s}}{dt} = V_{\beta s} - R_s I_{\beta s} \\ \frac{d\varphi_{\alpha r}}{dt} = -R_r I_{\alpha r} - \omega_m \varphi_{\beta r} \\ \frac{d\varphi_{\beta r}}{dt} = -R_r I_{\beta r} + \omega_m \varphi_{\alpha r} \end{cases} \tag{1}$$

where the subscripts *s* and *r* refer to the stator and the rotor, *α* and *β* refer to the components in the (*α, β*) frame, the terms *V*, *I*, and *φ* are used to describe voltage, current, and flux, respectively, while R_s and R_r refer to the stator and the rotor resistances and ω_m is rotor pulsation.

The relationships between currents and flux are given by equation (2)

$$\begin{bmatrix}\varphi_{s\alpha}\\ \varphi_{r\alpha}\end{bmatrix} = \begin{bmatrix}L_s & M\\ M & L_r\end{bmatrix}\begin{bmatrix}I_{\alpha s}\\ I_{\alpha r}\end{bmatrix},$$

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

L and *M* represent the motor and the mutual inductance, respectively.

The mechanical component of the motor is explained as follows (Cherif & Yahia, 2020):

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

T_{em} and T_L represent respectively the electromagnetic torque and load one, and J represents the motor inertia.

Direct torque control of an IM

DTC is a technique that directly controls the torque and flux of an IM by adjusting the inverter voltage and frequency. This allows for precise control of the motor speed and torque, without the need for complex feedback control loops. It also enables an IM to have an accurate and quick electromagnetic torque response.

The appropriate voltage vector is selected by means of a switching table. The variation in the motor stator flux and torque is directly related to the selection of switching states.

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 (Takahashi & Noguchi, 1986; Depenbrock, 1987).

The inputs of hysteresis controllers are flux and torque errors, and the voltage vector that is appropriate for each commutation period is determined by the controllers' outputs (Shyu et al, 2010).

Generally, the purpose of this control is to regulate the stator flux and the electromagnetic torque without having measured the speed, flux, or torque. Only the measurements of voltages and currents are necessary. A synoptic schema of the DTC of an IM is shown in Figure 1.

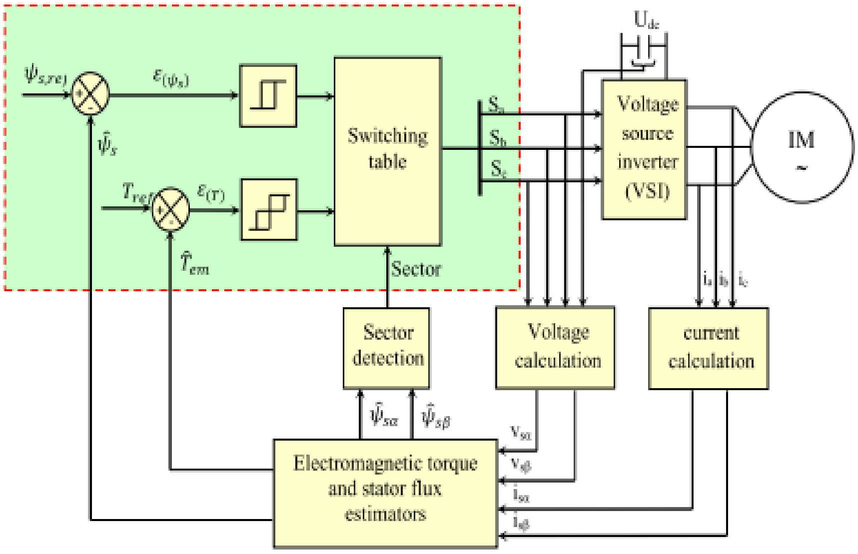

Figure 1 – Synoptic schema of the DTC of an IM
Рис. 1 – Наглядная схема прямого регулирования крутящего момента в асинхронном двигателе
Слика 1 – Синоптичка шема директног управљања моментом у индукционом мотору

Estimation of flux and electromagnetic torque

In DTC, the electromagnetic torque and stator flux are calculated from the primary motor inputs, stator voltages, and currents (V_s and I_s). The expressions of the flux into the stator can be evaluated as in equation (4).

$$\varphi_s = \sqrt{\varphi_{\alpha s} + \varphi_{\beta s}} \tag{4}$$

The variables in equation (4) are given as (Cherif & Yahia, 2020)

$$\begin{cases} \varphi_{\alpha s} = \int (V_{\alpha s} - R_s I_{\alpha s}) \\ \varphi_{\beta s} = \int (V_{\beta s} - R_s I_{\beta s}) \end{cases} \tag{5}$$

$\varphi_{\alpha s}$ and $\varphi_{\beta s}$ are the components of the flux in the (*α,β*) frame (Cherif & Yahia, 2020).

The angle θ between the components of the flux is given in (6).

$$\theta = arctg\frac{\varphi_{\beta s}}{\varphi_{\alpha s}} \tag{6}$$

To determine the electromagnetic torque produced by the IM, the cross-product of the stator quantities (stator flux and stator currents) can be employed as follows

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

where *p* is the number of poles pairs.

The conventional switching DTC table

The conventional switching DTC table used to select the appropriate voltage vector proposed by Takahashi (Takahashi & Noguchi, 1986), is given in the following table.

Table 1 – DTC switching table
Таблица 1 – Таблица переключателей прямого управления крутящим моментом
Табела 1 – Табела прекидача при директном управљању моментом силе

Sector		1	2	3	4	5	6
Flux	Torque						
C_{flx}=1	C_{trq}=1	V2	V3	V4	V5	V6	V1
	C_{trq} =0	V7	V0	V7	V0	V7	V0
	C_{trq} =-1	V6	V1	V2	V3	V4	V5
C_{flx}=0	C_{trq} =1	V3	V4	V5	V6	V1	V2
	C_{trq} =0	V0	V7	V0	V7	V0	V7
	C_{trq} =-1	V5	V6	V1	V2	V3	V4

C_{flx} and C_{trq} represent the flux and electromagnetic torque errors, respectively (Mokhtari, 2014).

Fuzzy Logic Controller

Fuzzy Logic Controllers (FLCs) are used in applications where traditional binary logic controllers may not be suitable or efficient. FLCs introduce a degree of "fuzziness" or uncertainty into decision making, which can be advantageous in various scenarios. We need to use FLCs for many reasons, such as: handling uncertainty, human-like reasoning, tolerance to noise and adaptive control (Aib et al, 2023).

FLC structure

Four principal components build the FLC controller: (Kamalapur & Aspalli, 2023)

Fuzzification

The following operations are performed via the fuzzification interface which

- measures the input variable's values, and
- performs the fuzzification function, which transforms input data into appropriate linguistic values.

Knowledge base

A linguistic control rule base plus a database make up a knowledge base.

- The definitions needed to define linguistic control rules are provided by the database;
- Using a set of language control rules, the rule base described the domain experts' control objectives and control strategy.

Decision

An FLC's core is the logic for making decisions. It can use fuzzy implications and the rules of inference from fuzzy logic to infer fuzzy control actions and simulate human decision making based on fuzzy concepts.

Defuzzification

The defuzzification interface performs the following functions:

- A scale mapping that converts the distribution of output variable values into the associated discourse universe, and

- Defuzzification, which involves changing an implied fuzzy control action into an explicit control action (Aib et al, 2023; Kamalapur & Aspalli, 2023).

Inference and the formulation of rules

Fuzzy systems typically map input fuzzy sets to output fuzzy sets. The relations between input and output fuzzy sets are known as fuzzy rules. Any of the following can be used to derive fuzzy rules:

- Master insight and control designing information,
- Control actions were taken by the operator, or
- Gaining knowledge from the training examples.

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 is A_i AND y is B_i THEN $z = f_i(x, y)$

Where x, y, and z are the linguistic variables that, respectively, indicate the control variable and the process state variables. A first-order Sugeno fuzzy model is the outcome of a fuzzy inference system (FIS) that takes the form of a first-order Sugeno fuzzy model. Ai and Bi are the linguistic values of the linguistic variables, $f_i(x, y)$ is a function of the process state variables x, y.

Engine for fuzzy inference

The feature of the inference engine is to calculate the general price of the manipulated output variable primarily based on the character contributions of each rule in the rule of thumb base, i.e., the defuzzification system. There's no systematic method for choosing defuzzification. In the first-order Sugeno fuzzy model, each rule has a crisp output and the usual output is acquired as weighted common as a consequent hence averting the time-ingesting manner of defuzzification required in a conventional FLC (Precup et al, 2020).

Type-2 fuzzy logic controller

A type-2 FLC is an extension of the traditional FLC, which allows for the handling of uncertainties and higher levels of complexity in the system being controlled. While a traditional FLC uses linguistic variables and fuzzy rules to make decisions, a type 2-FLC (T2-FLC) goes a step further by considering the uncertainties associated with the linguistic variables. In a T2-FLC, each linguistic variable has a fuzzy set associated with it, and each fuzzy set has a footprint of uncertainty (FOU) associated with it (Aib et al, 2023). The FOU represents the level of confidence or uncertainty in the membership values of the fuzzy set. By incorporating this uncertainty information, a T2-FLC can handle situations where the membership values are not precise or known with certainty. T2-FLCs are particularly useful in systems with highly uncertain or imprecise input data. They allow for the modeling and control of complex systems that exhibit varying degrees of uncertainty. However, the increased complexity of T2-FLCs also means that they require more computational resources and are often more challenging to design and implement compared to traditional FLCs (Saidi et al, 2020; Henini et al, 2021).

General type-2 fuzzy sets

A kind-1 fuzzy unit A on a time-honored set X can be characterized by the club function as (8). (Shi, 2020)

$$A = \{\, x, \mathrm{u}(x) | \forall \mathrm{x} \in \mathrm{X}, \mu(\mathrm{x}) \in [0,1]\} \tag{8}$$

α cuts of A can be defined as (9).

$$\mathrm{A}\alpha = \{\mathrm{x}, |\mu(\mathrm{x}) \geq \alpha, \alpha \in [0,1]\} \tag{9}$$

Aα consists of all of the element's x within the domain X whose club degree is extra than or identical to α, the function characteristic of which is proven as:

$$\mu_{A\alpha} = \begin{cases} 1 \quad , x \in A\alpha \\ 0 \, , x \in A\alpha \end{cases} \tag{10}$$

The definition of fuzzy units of variety multiplication is shown as (11).

$$\forall x \in X, \alpha A(x) = \alpha \wedge A(x) = \begin{cases} \alpha & A(x) > \alpha \\ A(x) & A(x) \le \alpha \end{cases} \tag{11}$$

Then, type-1 fuzzy unit A may be represented through its α cuts as (12).

$$A = \cup_{\alpha \in [0,1]} \alpha A_{\alpha} \tag{12}$$

Type-2 fuzzy sets have 2 club capabilities, and a kind-2 fuzzy set A˜ an established set X may be characterized by the way of the membership function as (sixteen), where x ∈ X.

$$A\tilde{} = \{(x,u), u_{A\sim}(x,u) | \forall x \in X, \forall u \ Jx \in [0,1]\} \tag{13}$$

μ is the primary club function and μA˜(x,u) is the secondary membership function. Liu extended α cuts of type-1 fuzzy sets to popular type-2 fuzzy sets and α cuts (α planes) of widespread type-2 fuzzy units A˜ α can be described as

$$A\tilde{}\alpha = \{(x,u), \mu A\tilde{}(x,u) | \forall x \in X, \forall u \in Jx \in [0,1]\} \tag{14}$$

A well-known kind-2 fuzzy units A˜ can be represented because the union of its associated kind-2 fuzzy sets Aα˜

$$A = \cup_{\alpha \in [0,1]} FOU \ (A\tilde{}\alpha) \tag{15}$$

For a general type-2 fuzzy set, A is the union of the centroids of its associated type-2 fuzzy sets for the minimum t-norm operation. A˜ α, with α ∈ [0, 1]:

$$CA\tilde{}\ \alpha(x) = [lA\tilde{}\ \alpha \, , rA\tilde{}\ \alpha\,] \tag{16}$$

{lA˜ α ,rA˜ α] represent each -plane's estimated endpoints using the KM type reduction procedure. Therefore, D times of the KM technique will be used if the number of planes is D to produce the defuzzification result of general type-2 fuzzy sets. (Shi, 2020).

The design of the type-2 FLC system

The structure of T2-FLC shown in Figure 2 is similar to that of type-1, the only difference between them being the type of sets (Figure 3), and in type-2 we have to use another step called type-reducer to change the output of fuzzy into a type-1 fuzzy set.

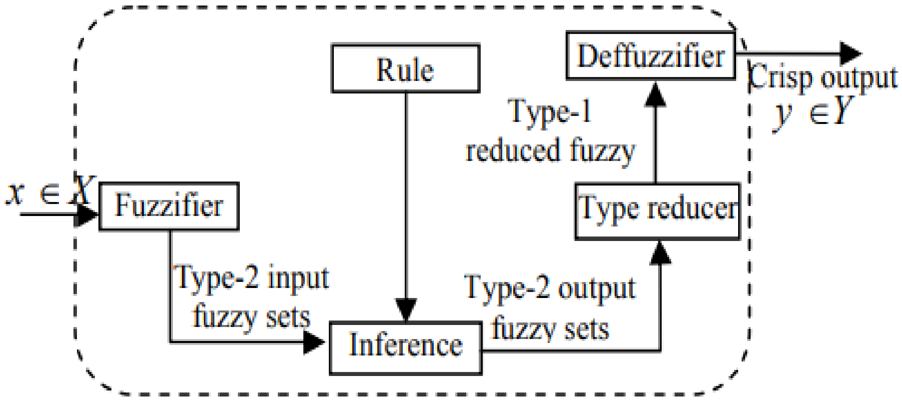

Figure 2 – Structure of a T2FLC
Рис. 2 – Структура T2FLC
Слика 2 – Структура T2FLC

In the type reduction stage, the type 2 interval fuzzy outputs of the inference engine are converted into the type 1 interval fuzzy in order to do defuzzification. The type reduction block is the primary distinction between types 1 and 2 of fuzzy logic systems (Henini et al, 2021).

Consider a T2FLS having:

n, inputs, $x= [x_1 \ldots x_n] \in X1 \times \ldots \times Xn$;

one output $y \in Y$, and M rules, where the i^{th} rules have the form:

R^i IF x_1 is F_1^i and …and x_n is F_n^i THEN $y^i=C^i$; i=1,…,M.

With F_1^i, $F_2^i \ldots F_n^i$ are the linguistic terms used in the past. The interval Type-2 Gaussian fuzzy sets serves as their model (Fig. 11).

y is the output of the i^{th} rule R^i ; C^i is the consequent parameter.

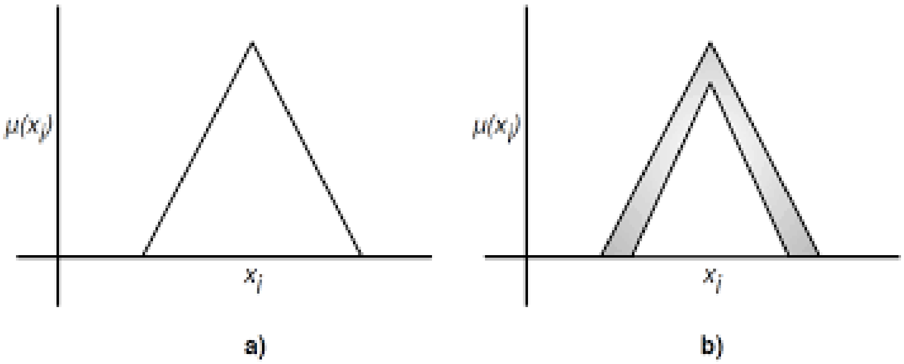

Figure 3 – Difference between type-1 and type-2 membership functions
Рис. 3 – Разница между функциями принадлежности типа 1 и типа 2
Слика 3 – Разлика између функција припадности типа 1 и типа 2

In Fig. 3, the upper membership function $\bar{u}_{\overline{FIJ}}(xj)$ can be used to represent the footprint of uncertainty (FOU) as a bound interval and the lower membership function $\underline{u_{Fij}\ (xj)}$,where

$$\bar{u}_{\overline{FIJ}}(xj) = \exp\left[-\frac{1}{2}\left(\frac{x_j-m_j}{\sigma_{kj}}\right)^2\right] = N(m_j, \sigma_j, x_j) \quad (17)$$

and:

$$\underline{u_{Fij}}\ (xj) = 0.8\ \bar{u}_{\overline{FIJ}}(xj) \quad (18)$$

m_j , and σ_j are respectively the imply and the usual deviation of Gaussian primary MF of the kind-2 fuzzy set $\widetilde{F_j^i}$ (Shi, 2020).

In this study, we use T2-FLC to control the speed of the IM; for this, three membership functions (MFs) are established for output and are used to characterize the range of fuzzy controller inputs (speed error and speed error variation). The fuzzy inference system bases its inference of gains on nine rules. MFs for both inputs and output are Negative (Ne), Zero (Zo), and Positive (Po). Two trapezoidal mfs for the two fuzzy sets (Po) and (Ne) and a triangular one for the fuzzy set (Zo) are used in this study.

Fractional order PID

A fractional order PID (Proportional-Integral-Derivative) controller, often referred to as a FO-PID controller, is an advanced control strategy that extends the classical PID controller by introducing fractional calculus principles. In a regular PID controller, the control action is determined based on the current error, the integral of the error, and the derivative of the error (Maiti et al, 2020). The goal is to minimize the difference between the desired setpoint and the actual process variable by adjusting a control signal. In a FO-PID controller, the integral and derivative terms are modified by using fractional calculus operators such as fractional integrals and derivatives. Instead of the usual integer values for the integral and derivative terms, fractional orders (non-integer values) are employed, allowing for a more flexible and adaptable control action (Sharma et al, 2015).

The FO-PID controller can be mathematically represented as follows:

u(t) = K_p * e(t) + K_i * D^(m) * e(t) + K_d * D^(n) * e(t) (19)

where:

- u(t) is the control output (control signal) at time t,
- e(t) is the error at time t, calculated as the difference between the desired setpoint and the actual process variable,
- K_p, K_i, and K_d are the traditional PID gains for the proportional, integral, and derivative terms, respectively,
- D^(m) represents the fractional integral operator of the order 'm', and
- D^(n) represents the fractional derivative operator of the order 'n'.

The use of fractional orders in the integral and derivative terms allows for more control flexibility and better performance in systems with non-linear dynamics or time-varying processes. It can effectively deal with processes that exhibit fractional-order behavior, which cannot be adequately controlled by traditional integer order PID controllers (Sharma et al, 2015).

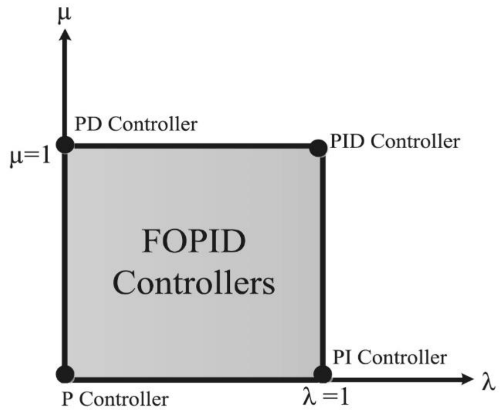

Figure 4 – Structure schema of the FO-PI$^{\lambda}$D$^{\mu}$ controller
Рис. 4 – Схема структуры контроллера FO-PI$^{\lambda}$D$^{\mu}$
Слика 4 – Шема структуре контролера FO-PI$^{\lambda}$D$^{\mu}$

FO-PID controllers have been applied in various fields, including industrial process control, robotics, aerospace, and biomedical engineering, where precise and adaptable control is required. However, it is worth noting that the design and tuning of fractional order PID controllers can be more complex than that of their classical counterparts, as the choice of fractional orders introduces additional degrees of freedom that need to be carefully optimized for optimal control performance.

We propose in this part to use T2-FLC, and FO-PID to control the speed of an IM controlled by DTC. In the following section, we present and discuss the simulation results of this proposition.

Simulation results and the discussion

We present a discussion which follows the simulation results and the current spectral analysis of the DTC control applied to an IM, with three different speed regulators, a load torque applied between t=0.2s and t=0.4s and the rotation speed reduced from 150 to 50 at t=0.5s.

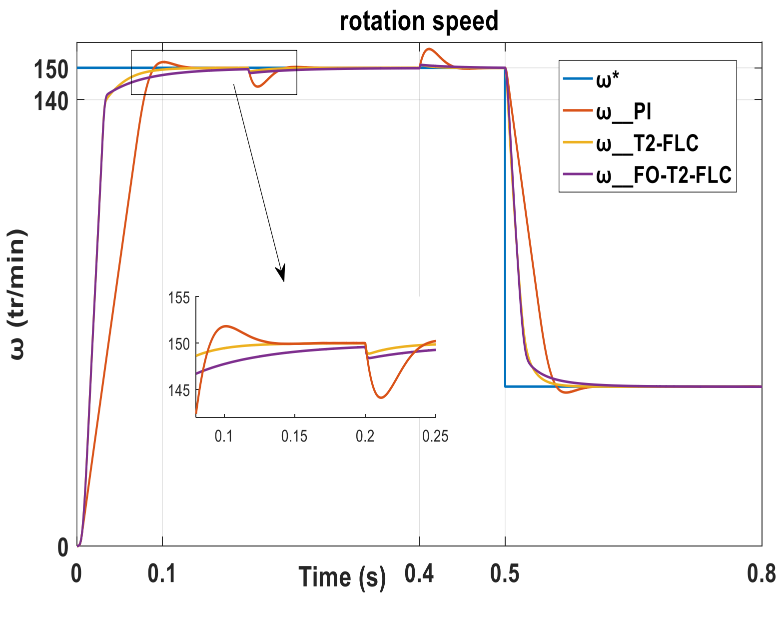

Figure 5 – Rotation speed of the IM
Рис. 5 – Скорость вращения асинхронного двигателя
Слика 5 – Брзина ротације индукционог мотора

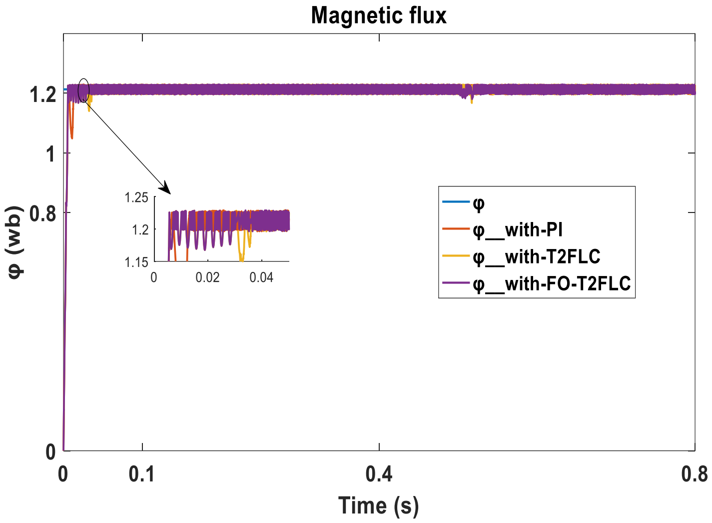

Figure 6 – Magnetic flux
Рис. 6 – Магнитный поток
Слика 6 – Магнетни флукс

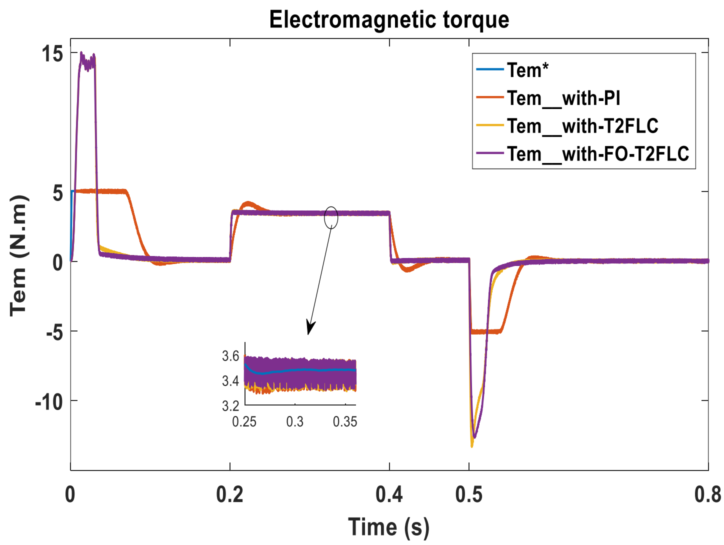

Figure 7 – Electromagnetic torque
Рис. 7 – Электромагнитный момент
Слика 7 – Електромагнетни моменат силе

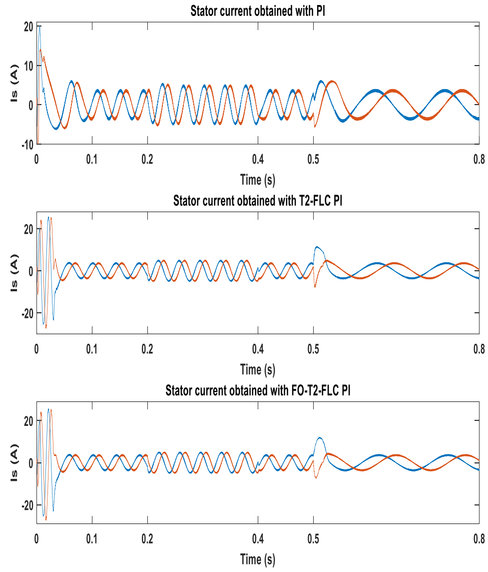

Figure 8 – Stator currents
Рис. 8 – Ток статора
Слика 8 – Струје статора

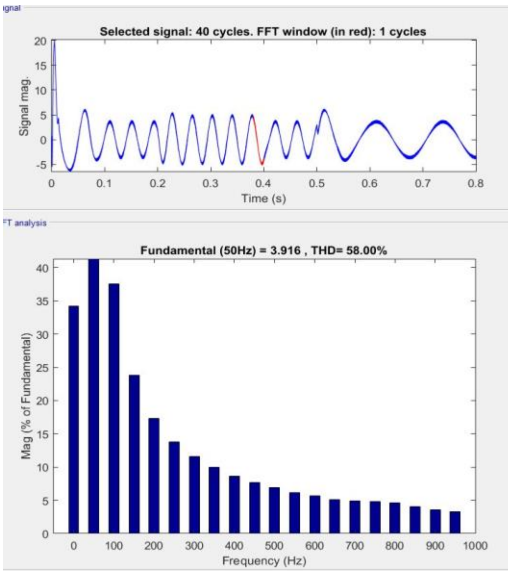

Figure 9 – FFT analysis of the stator current obtained with a classical regulator
Рис. 9 – БПФ-анализ тока статора, полученного с помощью классического регулятора
Слика 9 – ФФТ анализа струје статора добијена помоћу класичног регулатора

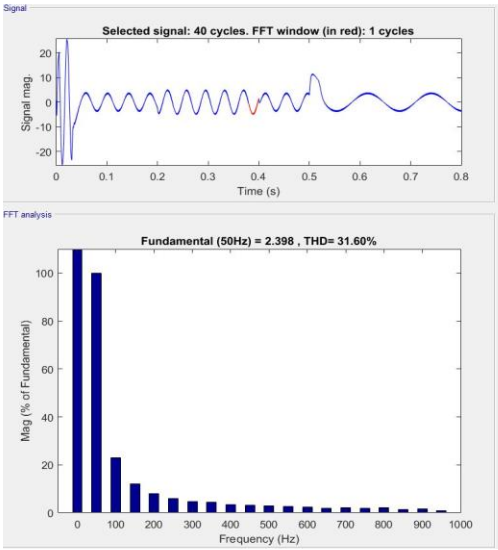

Figure 10 – FFT analysis of the stator current obtained with a T2FLC regulator
Рис. 10 – БПФ-анализ тока статора, полученный с помощью регулятора T2FLC
Слика 10 – ФФТ анализа струје статора добијена помоћу регулатора T2FLC

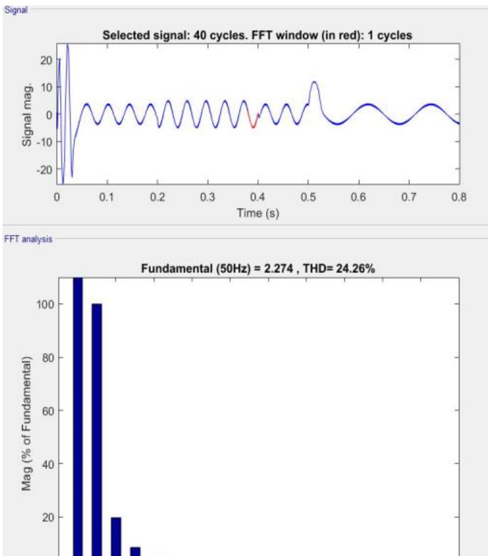

Figure 11 – FFT analysis of the stator current obtained with a FO-T2FLC regulator
Рис. 11 – БПФ-анализ тока статора, полученный с помощью регулятора FO-T2FLC
Слика 11 – ФФТ анализа струје статора добијена помоћу регулатора FO-T2FLC

From the results shown in Figures (5 to 9), we can notice that:

With the T2-FLC and FO-T2-FLC regulators, the dynamics of the IM is faster than with the classical one (Fig. 5), and the rotational speed reaches its reference without any exceeding; also, we can notice that the effect of the load torque with the T2-FLC and FO-T2-FLC is inconsiderable.

The magnetic flux and the electromagnetic torque (Figs. 6 and 7) follow their references with a good dynamics and fewer ripples when using T2-FLC and FO-T2-FLC regulators.

From the spectral analysis of the stator current (Figs. 9, 10, and 11), we can conclude that with the FO-T2-FLC we obtained the best quality of the current (as shown in the peaks in Fig. 8) with a reduced THD value.

Conclusion

This paper deals with a DTC scheme applied to an IM. Initially, the motor system was studied and modeled, and all the corresponding equations were given. Then, based on the hysteresis controller, the conventional DTC design was presented and then explained. As this traditional technique has numerous problems, such as torque and flux ripples, and especially poor motor speed performances, we proposed using a type-2 fuzzy logic controller (FLCT2) and the fractional order controller (FOC) to regulate the rotation speed of this motor, and show its influence on the behaviour of the motor. The simulation results showed that the use of the t2-FLC and the FO-PID made it possible to bring several improvements to the performance of DTC such as the speed of the dynamic response, the improvement of the quality of the current by reducing its THD value and the minimization of torque ripples. We propose to carry out an experimental study of this strategy in future work.

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Применение контроллера нечеткой логики типа 2 и контроллера дробного порядка при регулировании скорости прямого управления крутящим моментом в асинхронном двигателе

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РУБРИКА ГРНТИ: 27.47.19 Исследование операций,
28.17.00 Теория моделирования,
45.29.00 Электрические машины
ВИД СТАТЬИ: оригинальная научная статья

Резюме:

Введение/цель: Среди отличных стратегий в управлении крутящим моментом асинхронных двигателей выделяется прямое регулирование крутящего момента. Этот метод управления позволяет напрямую управлять магнитным потоком и электромагнитным моментом без необходимости их разъединения. Однако прямое регулирование крутящего момента, как и любая другая стратегия управления, имеет некоторые недостатки. Основными недостатками этого метода являются работа при переменных частотах переключения, а также электромагнитные колебания вследствие использования гистерезисных регуляторов. Это приводит к увеличению акустического шума, особенно на малых скоростях, а также ухудшению характеристик рулевого управления.

Методы: В целях улучшения производительности прямого регулирования крутящего момента, особенно на низких скоростях, предлагается использовать PID дробного порядка в сочетании с контроллерами нечеткой логики типа 2 для регулирования частоты вращения асинхронного двигателя, управляемого прямым регулированием крутящего момента.

Результаты: Результаты, полученные при использовании предлагаемых регуляторов, показывают заметное улучшение в системе.

Выводы: Результаты данного исследования могут внести вклад в улучшение управления.

Ключевые слова: прямое регулирование крутящего момента (DTC), контроллер нечеткой логики (FLC), контроллер дробного порядка (FO), асинхронный двигатель (IM), анализ БПФ.

Примена фази логичког контролера типа 2 и контролера фракционог реда за регулисање брзине директног управљања моментом силе у индукционом мотору

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Сажетак:

Увод/циљ: Међу одличним стратегијама за управљање моментом силе код асинхроних мотора издваја се директно управљање моментом силе. Ова техника омогућава директно управљање магнетним флуксом и електромагнетним моментом силе без потребе да се раздвајају. Такође, директно управљање моментом, као и свака стратегија управљања, има своје недостатке од којих су највећи рад на променљивим прекидачким фреквенцијама, као и електромагнетна таласност услед коришћења регулатора хистерезе. То доводи до погоршања акустичке буке, нарочито при малим брзинама, као и до погоршања перформанси управљања.

Методе: Да би се побољшале перформансе директног управљања моментом, нарочито при малим брзинама, предлаже се коришћење ПИД контролера фракционог реда у комбинацији са фази логичким контролером типа 2, *како би се регулисала брзина индукционог мотора контролисаног путем директног управљања моментом.*

Резултати: Испитивања која су вршена помоћу предложених регулатора показују да је дошло до побољшања у систему.

Закључак: Предложена решења могу да доведу до бољег управљања.

Кључне речи: директно управљање моментом силе, фази логички контролер, контролер фракционог реда, индукциони мотор, ФФТ.

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