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Optimization of the DTC control for doubly-fed induction motor using a PID based-genetic algorithm: experimental validation on the dSPACE 1104 board

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Abstract. This article presents a very interesting approach to Direct Torque Control (DTC) for a doubly-fed induction motor utilizing two voltage-source inverters. The speed control of this system is achieved using a proportional-integral-derivative (PID) controller optimized by a genetic algorithm. Although the conventional DTC method offers many advantages, such as effective and dynamic control, robustness, ease of use, and impressive results, it also has drawbacks, including fluctuations in electromagnetic torque and variable switching frequencies, which lead to vibrations and accelerated aging of the machine. The purpose of this article is to improve torque control based on the direct method (DTC) and to address these limitations. To achieve this, a new control strategy called Genetic Algorithm-based DTC (GA-DTC) is proposed. This strategy integrates the optimized PID controller and is implemented across the entire operational range of the system. The entire system is validated using the MATLAB/Simulink environment to analyze the machine's characteristics, its transient behavior, and its performance in steady state. This integration leads to a notable improvement in the machine's performance, particularly in tracking speed and torque set points, reducing response times, and decreasing overshoot. Experimental validation is carried out using a 1.5 kW rotating electrical machine (DFIM-DCM) connected to a resistive load. The experiments are conducted using the DSPACE DS1104 experimental system, and the system's behavior is tested under various operating conditions. The results obtained show the evolution of speed, torque, as well as stator and rotor currents. According to these results, the motor's performance has been improved: response time has decreased, settling time has increased, and torque ripple has been reduced.

Keywords: DFIM, DTC, GA and dSPACE 1104.

1 Introduction

Direct Torque Control (DTC) was developed in the 1980s as an alternative to traditional control methods for induction motors. The pioneering work of TAKAHASHI [1] and DEPENBROCK [2] laid the foundations for this control strategy.

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The principle of DTC is based on the direct detection of commands applied to the switches of the inverter supplying a Doubly-Fed Induction Machine (DFIM). This approach allows for the maintenance of both the torque and the fluxes of the stator and rotor within predefined hysteresis bands. Unlike pulse width modulation (PWM) techniques or coordinate transformation methods, DTC ensures effective decoupling between flux control and torque control.

The advantages attributed to the DTC technique (dynamics, robustness, lower sensitivity to parameters, ease of implementation, high performance) are counterbalanced by the use of the hysteresis comparator. Indeed, the latter allows for variable-frequency operation, unlike a conventional comparator. However, finite frequency sampling leads to pseudo-random overshoot of the hysteresis band [3], which can result in low-speed operation, particularly due to variations in the motor resistance, thus affecting its behavior [4]. Moreover, the application of classical DTC to DFIM induces torque oscillations that can be very bothersome for the user. These oscillations can stimulate mechanical resonances, causing vibrations and audible noise, thereby contributing to the premature aging of the machine [5].

Recently, many researchers have proposed solutions to improve the performance of classical DTC based on artificial intelligence, such as neural networks, fuzzy logic, and hybrid control systems, which do not require knowledge of a mathematical model. These techniques demonstrate good robustness to adapt to parametric variations. In [6-9], the authors propose strategies to enhance the dynamic performance of DTC using intelligent techniques. These approaches are referred to as Direct Neural Torque Control (DTNC) and Direct Neural Fuzzy Torque Control (DTNFC), as well as the use of genetic algorithms.

These techniques have achieved great success in the field of control and identification of nonlinear systems. In the case of DTC, they allow for the control of the switching frequency to obtain rapid responses of flux and torque with less distortion. However, the proposed strategies have drawbacks: the internal structure of DTC is more complex and requires a very powerful computer [10].

In [11], the authors applied a new control strategy for DFIM by optimizing the parameters of the PID speed regulator based on a genetic algorithm applied to the DTC of the stator. However, under these conditions, the DFIM behaves like an induction motor (IM), which does not allow for the benefits of DFIM technology, such as a double-speed band [12]. On the other hand, there are some studies in the literature aimed at improving the robustness of PID in nonlinear systems, such as those by K. Das, Diptanu Das, and Joyashree Das [13], Madadi and Motlagh [14], as well as those by Kanojiya and Meshram [15].

The latter designed a PID controller for a second-order DC motor system and used GWO and PSO algorithms to optimize this controller. Hultmann and do Santos [16] developed a non-dominated sorting genetic algorithm, while [17] presents a PID controller based on a genetic algorithm to solve the constrained optimization problem in a servo motor system. In [18], the authors found that ACO optimization yields very interesting results in terms of response time, overshoot, and system execution speed compared to GA, EP, and PSO algorithms.

In [19], the authors propose a new optimization algorithm called the Mayfly Optimization Algorithm (MOA) to determine the optimal parameters of the PID controller and to find the optimal dataset for training and testing the adaptive neuro-fuzzy inference system (ANFIS) controller. To benefit from the full range of speed variations, minimize Joule losses on the inverters, and overcome issues related to the use of solar energy, it is necessary to implement a speed control system. The analysis of this article will focus on the study and implementation of GA-DTC control applied to the DFIM connected to two voltage inverters.

This architecture presents the best advantages mentioned at the beginning of this paragraph. The parameters Kp, Ki, and Kd of the PID speed regulator of the DTC are optimized by the genetic algorithm (GA), which has been used to solve various types of optimization problems over the past 30 years.

This study aims to address the limitations of conventional DTC by implementing a DTC control on both the stator and rotor sides of the DFIM motor and optimizing the PID regulator parameters using a genetic algorithm (GA). The main objectives of this research are the following:

- Minimize flux and torque ripples.
- Decrease response time.
- Resolve the problem of torque and speed overshoot.
- Implementation of the whole system on a dSPACE board.

This article is divided into four main parts. The first part deals with the mathematical modelling of the double-fed induction machine (DFIM). The operating principle and mathematical modelling of direct torque control (DTC) are presented in the second part. The third section deals with the genetic algorithm research. Section four presents a comprehensive analysis of the experimental results. Finally, the conclusion summarises the control results and suggests possible avenues for future research. In summary, this research summarises the results obtained with regard to control and identifies potential areas for research and development.

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2 Mathematical model of the doubly-fed induction motor

The appropriate mathematical model for studying the DTC in a DFIM is the two-phase model in (α, β) coordinates, as described by the following equations [20]:

Electrical equations:

$$\begin{cases} v_{s\alpha} = R_s.i_{s\alpha} + \dfrac{d\psi_{s\alpha}}{dt} \\ v_{s\beta} = R_s.i_{s\beta} + \dfrac{d\psi_{s\beta}}{dt} \\ v_{r\alpha} = R_r.i_{r\alpha} + \dfrac{d\psi_{r\alpha}}{dt} + \omega_m.\psi_{r\beta} \\ v_{r\beta} = R_r.i_{r\beta} + \dfrac{d\psi_{r\beta}}{dt} - \omega_m.\psi_{r\alpha} \end{cases} \quad \textbf{(1)}$$

Magnetic equations:

$$\begin{cases} \psi_{s\alpha} = L_s i_{s\alpha} + L_m.i_{r\alpha} \\ \psi_{s\beta} = L_s i_{s\beta} + L_m.i_{r\beta} \\ \psi_{r\alpha} = L_r i_{r\alpha} + L_m.i_{s\alpha} \\ \psi_{r\beta} = L_r i_{r\beta} + L_m.i_{s\beta} \end{cases} \quad \textbf{(2)}$$

Mechanical equations:

$$\begin{cases} T_{em} = p.(\psi_{s\alpha} i_{s\beta} - \psi_{s\beta} i_{s\alpha}) \\ J.\dfrac{d\Omega}{dt} + f.\Omega = T_{em} - T_r \end{cases} \quad \textbf{(3)}$$

Vectors control of stator and rotor flux:

The following formulas, in the fixed reference frame (α, β) connected to the rotor and stator, can be used to determine the magnetic fluxes of the rotor and stator [21].

$$\begin{cases} \bar{\psi}_s(t) = \int_0^t (\bar{V}_s + R_s.\bar{I}_s).dt \\ \bar{\psi}_r(t) = \int_0^t (\bar{V}_r + R_r.\bar{I}_r).dt \end{cases} \qquad \textbf{(4)}$$

The modules and positions of the flows are defined by the following relationship:

$$\begin{cases} \hat{\psi} = \sqrt{\hat{\psi}_\alpha^2 + \hat{\psi}_\beta^2} \\ \theta = arctg\left(\dfrac{\hat{\psi}_\beta}{\hat{\psi}_\alpha}\right) \end{cases} \qquad \textbf{(5)}$$

The electromagnetic torque can be determined using a mathematical formula involving the flux in the (α, β) reference frame.

$$\hat{T}_{em} = p.(\hat{\psi}_{s\alpha}.i_{s\beta} - \hat{\psi}_{s\beta}.i_{s\alpha}) \qquad \textbf{(6)}$$

3 Direct torque control approach

Fast and accurate torque response is made possible by the Direct Torque Control strategy's decreased susceptibility to parametric motor changes. This method concentrates on having direct control over machine flux and torque. We continuously compare a calculated number to a target value in order to manage the motor. The optimal voltage to apply is determined by means of a comparator and a lookup table. This procedure is shown in Figure 1.

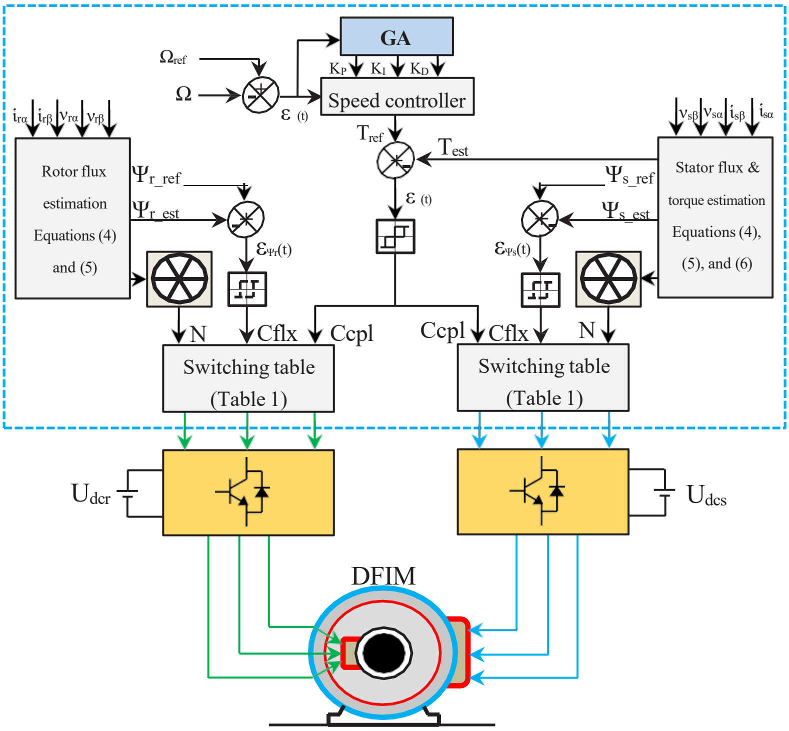


Fig. 1. Optimized structure of the direct torque control approach using a genetic algorithm

3.1 Hysteresis cmparators

The system utilizes two two-level hysteresis comparators. As depicted in Figure 2, their role is to ensure that the end of each flux vector remains within a circular band. Furthermore, Figure 3(a) illustrates a three-level hysteresis comparator that controls the electromagnetic torque generated by the motor, whether in the clockwise or counterclockwise direction. These comparators produce a positive or negative torque.

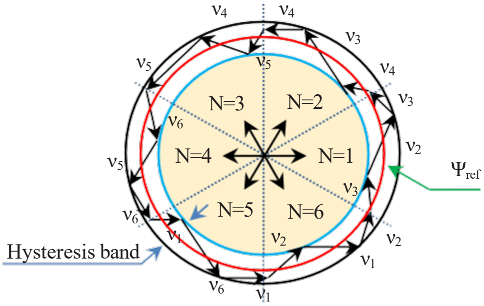
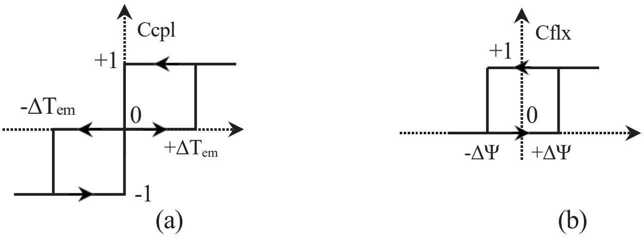


Fig. 2. Magnetic flux trajectory



(a) (b)

Fig. 3. Hysteresis comparators (a) of the three-levels torque (b) of the two-levels flux

3.2 Switching table construction

The choice of the voltage vector to be applied must be made based on the sector as well as the evolution of the torque and flux. Table 1 provides the truth table to select the appropriate voltage vector.

	Sector						
Ψ	Ccpl	S_1	S_2	S_3	S_4	S_5	S_6
1	1	v_2	v_3	v_4	v_5	v_6	v_1
	0	v_7	v_0	v_7	v_0	v_7	v_0
	-1	v_6	v_1	v_2	v_3	v_4	v_5
0	1	v_3	v_4	v_5	v_6	v_1	v_2
	0	v_0	v_7	v_0	v_7	v_0	v_7
	-1	v_5	v_6	v_1	v_2	v_3	v_4

Table 1. Inverter sequences

4 The genetic algorithm is used to optimize control

The aim of genetic algorithm research is to find the best solution for non-linear systems. Variable parameters make the system non-linear, as they affect both the machine and the conventional DTC controller. In this situation, the genetic algorithm is used to generate the optimal values of KP, KI and KD for the PID controller, and this is done every time the system undergoes changes, in order to maintain adequate control. Figure 4 illustrates the simplified structure of the system.

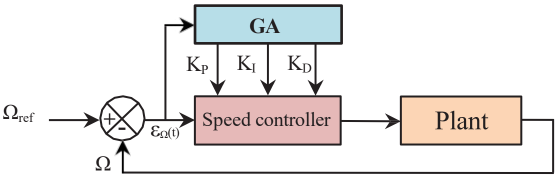


Fig. 4. The genetic algorithm (GA) PID speed controller optimization structure

The genetic algorithm is part of the family of evolutionary algorithms, which are inspired by concepts from evolutionary biology such as selection, crossover, and mutation [22]. Figure 5 presents a flowchart detailing the different steps of the genetic algorithm.

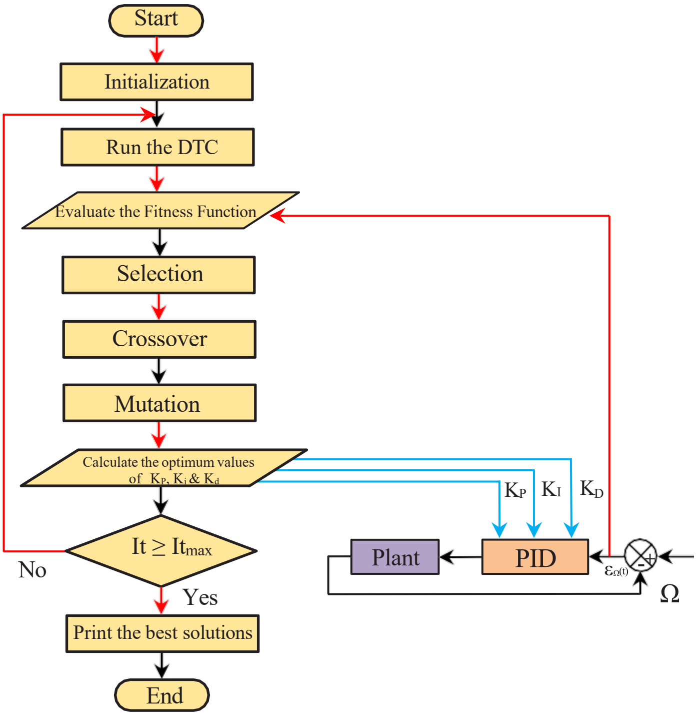


Fig. 5. Flowchart of PID speed controller optimization by GA

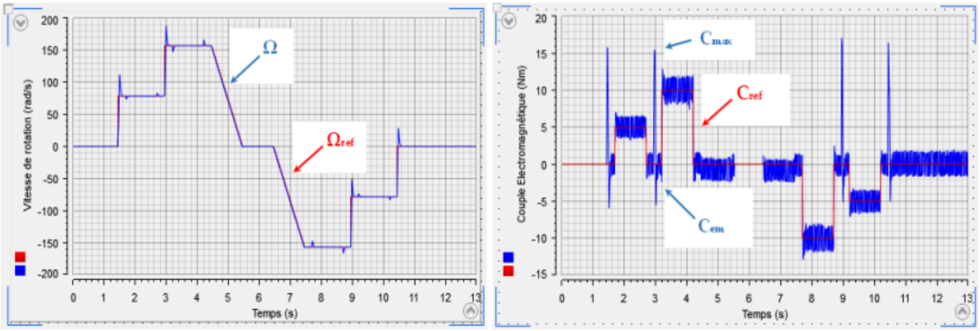
5 Machine experimentation

The experimental validation of our control systems was carried out on a 1.5 kW wound rotor machine. To identify the parameters of the machine used, we conducted a series of tests, including the no-load test, the short-circuit test, as well as the open rotor and open stator tests, and the deceleration test.

The experimental implementation of DFIM control in motor mode generally requires the use of two inverters. However, due to hardware limitations, we validated the controls using a single inverter powering the stator while the rotor was short-circuited. Thus, the DFIM was used as a squirrel-cage induction motor.

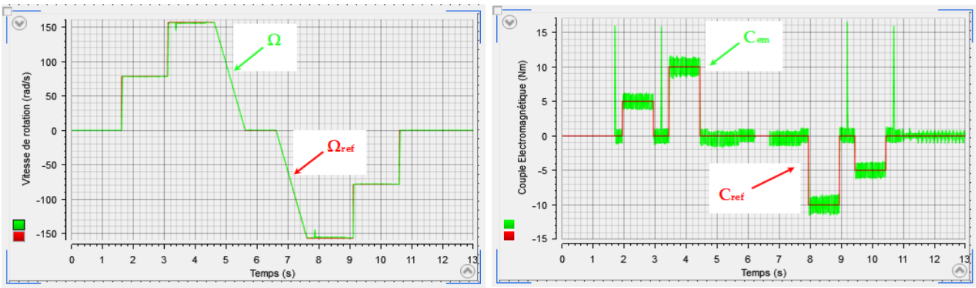
The experimental results were validated using Controldesk, which visualizes all the results validated by the DSPACE 1104 board. The results are presented in the following figures:

We present the control results of the conventional direct torque control (DTC) and the genetic algorithm method (GA-DTC) in terms of speed, torque, rotor current, stator current, and magnetic flux.



(a) (b)

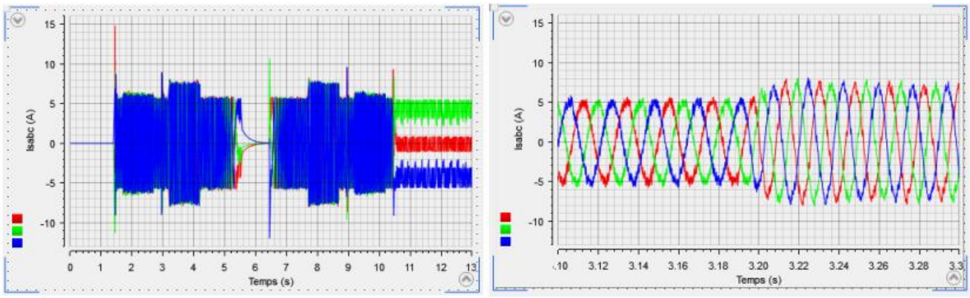
Fig. 6. Speed (a) and torque (b) curves of the CDC controller



(a) (b)

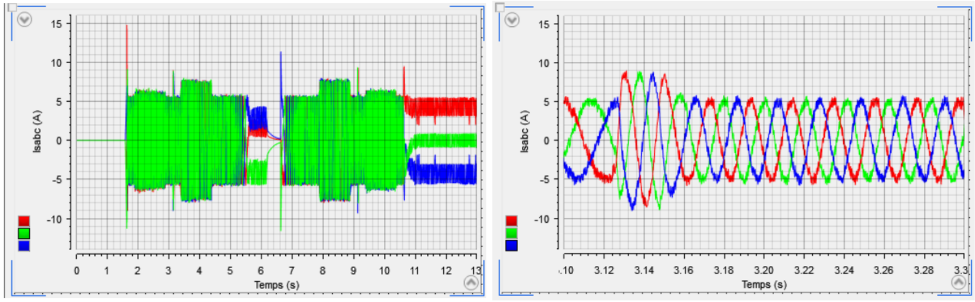
Fig. 7. Responses of speed (a) and torque (b) variations of the GA-DTC

Figures 6 et 7 montrent que les résultats expérimentaux sont consistents avec those obtained durant la simulation. Indeed, the speed response is achieved without exceeding the reference for the GA-DTC control. When a variable torque is applied, speed spikes are observed, but the response time is satisfactory and the static error is practically zero. Furthermore, we can confirm that GA-DTC controls reduce the torque ripples observed with conventional DTC control.



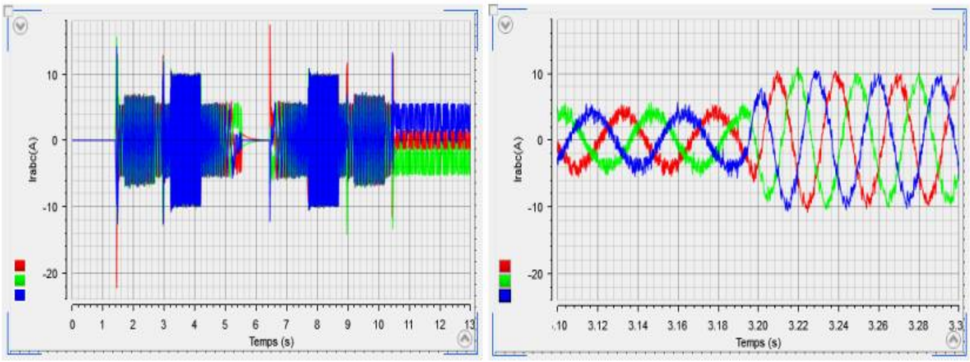
(a) (b)

Fig. 8. Waveforms of the stator currents for the CDC control (a) and a zoom of the currents (b)



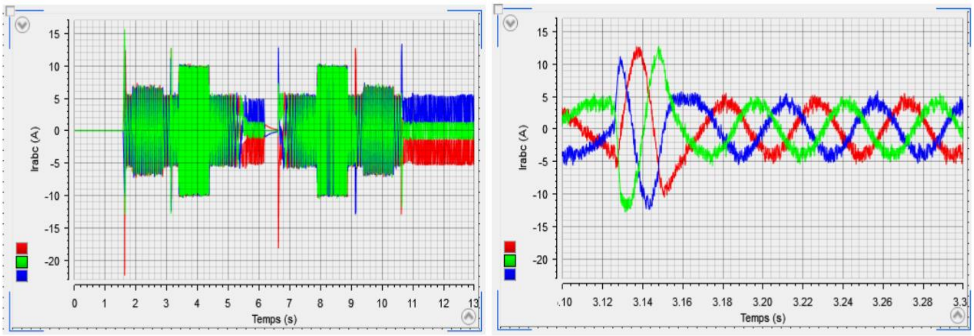
(a) (b)

Fig. 9 Shows the stator current variations of the GA-DTC drive, with an overview (a) and a zoom on the currents (b)



(a) (b)

Fig. 10. Waveforms of the rotor currents for the CDC control (a) and a zoom of the currents (b)



(a) (b)

Fig.11. Shows the rotor current variations of the GA-DTC control, with an overview (a) and a zoom on the currents (b)

For the control studied in this phase, the stator currents (Figures 8 and 10) and rotor currents (Figures 9 and 11) exhibit a sinusoidal shape with an amplitude that varies according to the load. The agreement between the simulation results and those obtained during practical tests is excellent.

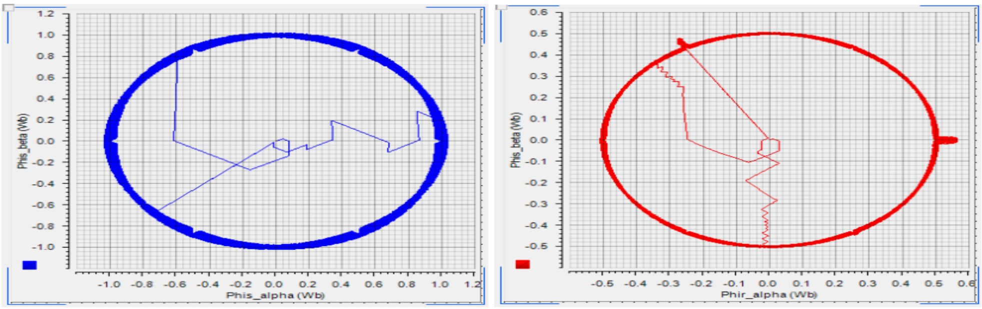
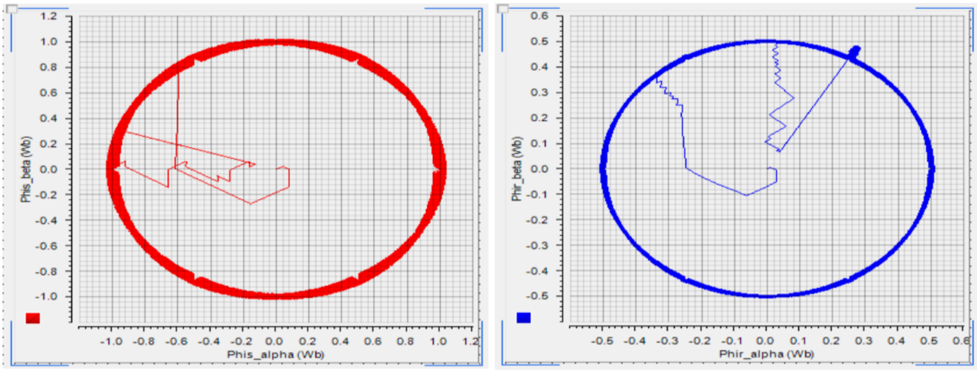


Fig. 12. Waveforms of the stator flux (a) and rotor flux (b) for the CDC control



(a) (b)

Fig. 13 Shows variations in stator flux (a) and rotor flux (b) for GA-DTC control

The GA-DTC scheme (direct torque control based on a genetic algorithm) has been implemented in the MATLAB/Simulink environment. Tables 4, 5, and 6 present the parameters used to define the overall system configuration. To simulate real situations and evaluate the system's behavior, variable speed and torque references were used. The results of the simulation of this GA-DTC control method were tested on a 1.5 kW machine. Figures 7, 8, 9, and 10, 11, 12 show the variations in speed, electromagnetic torque, stator current, as well as current and flux.

6 Conclusion

This paper proposes the use of a genetic algorithm to optimize the PID controller of the traditional DTC (Direct Torque Control) scheme. This approach was applied to a double-fed induction motor, powered by two inverters. The system was modeled and implemented in Matlab/Simulink and then executed on a dSPACE 1104 board. The results show an improvement in the motor's performance: the response time has decreased, the rejection time has increased, and the torque ripple has been reduced. The proposed control scheme, which combines the genetic algorithm and the DTC control, exhibits better performance than the conventional DTC control, particularly in transient and dynamic regimes.

Appendix

Parameters	**Description**
$V_{s\alpha}$,$V_{s\beta}$,$V_{r\alpha}$ and $V_{r\beta}$	Stator and rotor voltages in (α, β) plan
U_{dcs} and U_{dcr}	Stator and rotor directs voltages
$I_{s\alpha}$,$I_{s\beta}$,$I_{r\alpha}$ and $I_{r\beta}$	Stator and rotor currents in (α, β) plan
$\Psi_{s\alpha}$, $\Psi_{s\beta}$, $\Psi_{r\alpha}$ and $\Psi_{r\beta}$	Stator and rotor flux in (α, β) plan
R_s, R_r	Stator and rotor resistors
L_s, L_r	Stator and rotor inductors
L_m	Mutual Inductance
P	Number of pairs of poles
ω_r	Rotor angular speed
ω_s	Stator angular speed
Ω	Rotation speed
T_{em}	Electromagnetic torque
T_r	Resistant torque
F	Viscous friction coefficient

Table 2. Nomenclature

Abbreviation	**Wording**
DFIM	Doubly Fed Induction Motor
DTC	Direct Torque Control
GA	Genetic Algorithm
GA-DTC	Genetic Algorithm-Direct Torque Control
PID	Proportional Integrator Derivator
DTFC	Direct Torque Fuzzy Control
DTNC	Direct Torque Neural Control
DTNFC	Direct Torque Neural-Fuzzy Control
ANFIS	Adaptive Neuro-Fuzzy Inference System

Table 3. Abbreviations

Symbols	**Values (Unit)**
P_n	1.5Kw
V_s	230v
V_r	130v
P	2
f	50Hz
R_s, R_r	1.75Ω,168Ω
L_s	0.295H
L_r	0.104H
L_m	0.165H
f	0.0027kg.m2/s
J	0.001kg.m2

Table 4. DFIM parameters

Parameters/Control	**GA-DTC**	**Classic DTC**
K_P	96.4889	50
K_I	0.1576	4
K_D	0.9706	0

Table 5. Parameters of the PID of GA-DTC and PID of Classic DTC

Description	**Type/Value**
Population size	20
Maximum iteration	50
Selection	Uniform
Crossover	Roulette Wheel Selection
Mutation	Uniform

Table 6. Parameters of the genetic algorithm

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