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New Direct Torque Control of Dual Star Induction Motor using Grey Wolf Optimization Technique

***Abstract**. This document shows a comparative study between two approaches for the direct torque control of the dual star induction motor drive (DSIM), the first is based on conventional PID, the second uses new heuristic optimization technique based on the grey wolf optimizer GWO-PID. The benefits of this combination can reduce the Dual SIM speed control loop problems. The GWO algorithm has been programmed and implemented in MATLAB. In addition, the most importance appropriate GWO-PID scheme combines simultaneously many index such as reducing high torque ripple, steady-state error is reduced, response time is improved and disturbances do not change the drive performance .*

***Streszczenie.** Ten dokument przedstawia badanie porównawcze między dwoma podejściami do bezpośredniego sterowania momentem napędowym silnika indukcyjnego z podwójną gwiazdą (DSIM), pierwsze oparte jest na konwencjonalnym PID, drugie wykorzystuje nową heurystyczną technikę optymalizacji opartą na optymalizatorze szarego wilka GWO-PID. Korzyści z tej kombinacji mogą zmniejszyć problemy z pętlą kontroli prędkości Dual SIM. Algorytm GWO został zaprogramowany i zaimplementowany w MATLAB-ie. Ponadto zaproponowano i zbadano najbardziej odpowiedni schemat GWO-PID łączący jednocześnie wiele wskaźników, takich jak zmniejszenie tętnienia wysokiego momentu obrotowego, zmniejszenie błędu stanu ustalonego, poprawa czasu narastania i brak zmian w działaniu napędu. (**Nowa bezpośrednia kontrola momentu obrotowego silnika indukcyjnego z podwójną gwiazdą przy użyciu techniki optymalizacji Gray Wolf**)*

Keywords: DSIM, DTC, grey wolf optimizer (GWO), PID controller, response time.
Słowa kluczowe: DSIM, DTC, optymalizator szarego wilka (GWO), regulator PID, czas odpowiedzi.

Introduction

Today dual star induction motor (DSIM) takes a great consideration , especially for high-power applications, hence DSIM has widely substituted the asynchronous machines which its role was essential in the most applications [1–5].The dual star induction motor is constituted of two three-phase stator windingssets spatially shifted by π/6. These windings are usually powered by a six-phase inverter fed by variable speed drives. The biggest DSIM benefits are: great torque density [6], higher efficiency,as well as thelow harmonic content of the DC link current. However the control of DSIM is very hard due to the difficulty of obtaining decoupling between the torque and the flux. So to overcome this dilemma, high-performance algorithms have been developed such as FOC, DTC,[8-15].

To satisfy the performance control of an electromechanical system, many strategies have developed and applied , the famous controls the speed of the rotor by a PID regulator to cancel the static error and reduce the response time , however, it is often characterized by an overshoot at startup and depends on the parameters of the machine. PID tuning parameters (Kp, Ki, Kd) are there for essential for the DTC system to improve system performance. Self-Tuning method of induction motor has been the subject of several studies [16, 17]. Self-Tuning mechanism has been introduced in order to tune the fuzzy parameters online in case of any disturbances occurred.

The employment of optimization techniques as better alternative methods for tuning PID controllers has been investigated and applied in electric machines control [18-26].

in order to optimize the efficiency of DTC of DSIM, a novel optimal controller design is characterized as an optimization tool and the Gray Wolf Optimization (GWO) algorithm is used to solve this problem. The GWO algorithm is one of the most best heuristic algorithms which was firstly presented by Mirjalili et al. in 2014 [27]. It can find a superior solution within a shorter time than other random algorithms. We report an improvement of the original GWO algorithm in this paper.

The major contribution of this work is to demonstrate the efficiency of grey wolf optimizer (GWO-PI) for the direct torque control compared to The classical PID-DTC which The classical PID-DTC algorithm prone to failure especially under variable parameters of the machine.

Modeling of the dual star induction motor

By applying the Park transformation to the model of the dual star induction motor, the equations are expressed in a reference frame linked to the rotating field [1]:

$$\begin{cases} V_{ds1} = R_{s1} I_{ds1} + \dfrac{d\Phi_{ds1}}{dt} - \omega_s \Phi_{qs1} \\ V_{qs1} = R_{s1} I_{qs1} + \dfrac{d\Phi_{qs1}}{dt} + \omega_s \Phi_{ds1} \\ V_{ds2} = R_{s2} I_{ds2} + \dfrac{d\Phi_{ds2}}{dt} - \omega_s \Phi_{qs2} \\ V_{qs2} = R_{s2} I_{qs2} + \dfrac{d\Phi_{qs2}}{dt} + \omega_s \Phi_{ds2} \\ V_{dr} = 0 = R_r I_{dr} + \dfrac{d\Phi_{dr}}{dt} - (\omega_s - \omega_r)\Phi_{qr} \\ V_{qr} = 0 = R_r I_{qr} + \dfrac{d\Phi_{qr}}{dt} + (\omega_s - \omega_r)\Phi_{dr} \end{cases} \tag{1}$$

Where the expressions of stator and rotor fluxes are:

$$\begin{cases} \Phi_{ds1} = L_{s1} I_{ds1} + L_m (I_{ds1} + I_{ds2} + I_{dr}) \\ \Phi_{qs1} = L_{s1} I_{qs1} + L_m (I_{qs1} + I_{qs2} + I_{qr}) \\ \Phi_{ds2} = L_{s2} I_{ds2} + L_m (I_{ds1} + I_{ds2} + I_{dr}) \\ \Phi_{qs2} = L_{s2} I_{qs2} + L_m (I_{qs1} + I_{qs2} + I_{qr}) \\ \Phi_{dr} = L_r I_{dr} + L_m (I_{ds1} + I_{ds2} + I_{dr}) \\ \Phi_{qr} = L_r I_{qr} + L_m (I_{qs1} + I_{qs2} + I_{qr}) \end{cases} \tag{2}$$

For studying the dynamic characteristics, the following equation of motion was added:

$$J \frac{d\Omega_r}{dt} = T_{em} - T_r - f_r \Omega_r \tag{3}$$

where J : The moment of inertia.; f_r : The friction coefficient; T_{em} : The electromagnetic torque; T_r : The load torque; Ω_r : Mechanical rotation speed of the rotor.

The model of the machine has been completed by the expression of the electromagnetic torque T_{em} :

(4) $$T_{em} = P\frac{L_m}{L_m + L_r}\left(\Phi_{dr}(I_{qs1} + I_{qs2}) - \Phi_{qr}(I_{ds1} + I_{ds2})\right)$$

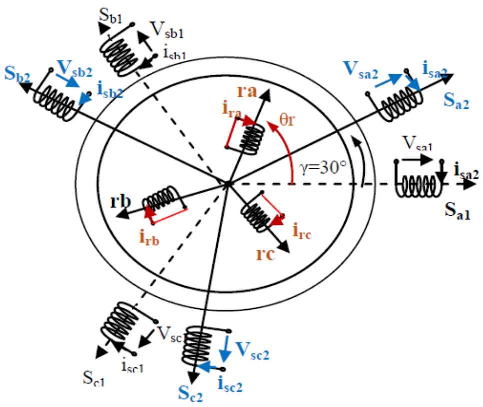


Fig.1 DSIM Windings scheme

DTC strategy of DSIM

The conventional DTC developed in Ref [7] is based on the following steps: Divide the time domain into periods of reduced duration Ts;

- For each clock stroke, measure the line currents and phase voltages of the DSIM;
- Reconstitute the components of the stator flux vector and estimate the electromagnetic torque, through the estimation of the stator flux vector and the measurement of the line current;
- A three level hysteresis comparator based on the error between the estimated torque and the reference torque is employed as input of switching table
- Whereas the error between the estimated stator flux magnitude and the reference stator flux magnitude is the input of a two level hysteresis comparator;
- Select the state of the according voltage vector .

The block diagram of the DTC of DSIM is shown in Fig. 2.

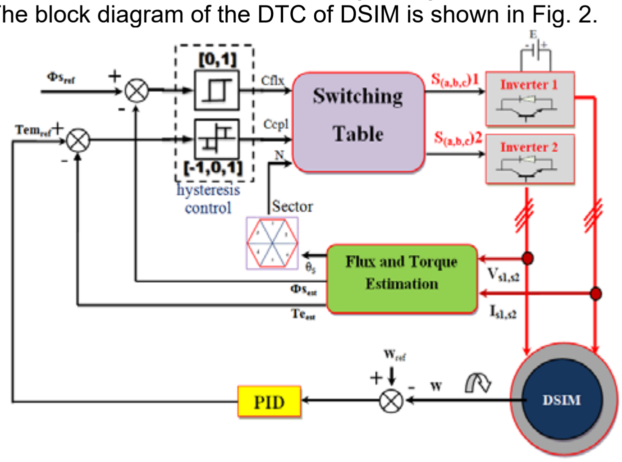


Fig. 2 DTC diagram of DSIM.

Proposed DTC-DSIM-QWO method

A. Grey wolf optimizer

GWO is population based stochastic algorithm that mimics the natural leader ship hierarchy and hunting strategy of grey wolves. It was developed in 2014 by Mirjalili et al. This technique is essentially inspired by searching an hunting mechanism of grey wolves groups. In the nature, wolves prefers to be in pack with a steady hierarchy. Each pack is divided into four categories relays on type and responsibilities of each individual, which helps in the process of hunting. The four categories are called: alpha, beta, delta and omega. The leader of a group is called alpha (α), which is responsible for guiding and directing the whole group during hunting mission, feeding, and migration. Beta (β) wolf stands on the second level of social pyramid. This category can substitute α when they are killed or cannot lead the group anymore. The next class is delta wolves (δ) and the rest of population is called omega (ω) [27-30].

With a view to mathematically modeling the social hierarchy of wolves when designing the GWO, the first three that have the fittest solutions in the population are regarded as: α, β and δ. The rest of search agents are declared as ω. During the optimization process ω group is guided and directed by α, β and δ toward the promising search space in hope to find the best optimal solution.

Basiclly, the mathematical model of GWO is described in three main phases which are:encircling, hunting and attacking the prey and they are detailed as follows:

A.1. Encircling

If a prey is selected, the iteration begins (t = 1). Therefore, α, β and δ wolves leads the rest of search agents to pursue and eventuallyencircle the prey, this behavior of grey wolves is expressed as:

(5) $$\vec{X}(t+1) = \vec{X_p}(t) + \vec{A}.\vec{D}$$

Where $\vec{X}$ is search agents (wolves) positions, $\vec{X_p}$ referenced the prey position. I is the iteration number. And $\vec{A}$ is a vector of coefficient at the (t +1)th iteration, Whereas, $\vec{D}$ is another coefficient that can be described as following:

(6) $$\vec{D} = \left|\vec{C}.\vec{X_p}(t) \quad \vec{X}(t)\right|$$

The parameters $\vec{A}$ and $\vec{C}$ are combinations of controlling paramaters a and random numbers | and $\vec{r_2}$ which can be mathematically expressed as follows:

(7) $$\vec{A} = 2\vec{a}.\vec{r_1} \quad \vec{a}$$

(8) $$\vec{C} = 2.\vec{r_2}$$

Where $\vec{a}$ are linearly decreased from 2 to 0 over the course of iterations and $\vec{r_1}$, $\vec{r_2}$ are random vectors in [0,1].

A.2. Hunting the prey

Grey wolves hunting behavior change position of each pack in the group by approaching to the prey, This behavior is mathematically described as follows: α is considered as the leader and the finest solution, β and δ are exppected to know more information about prey's possible positions. Therefore, ω pack will pursue them and obliged to change locations in the light of α, β and δ in the next iterations. Position updating or hunting behavior is described by the following equations:

(9) $\vec{D}_\alpha = \left|\vec{C}_1^t.\vec{X}_\alpha^t \quad X^t\right|, \vec{D}_\beta = \left|\vec{C}_1^t.\vec{X}_\beta^t \quad X^t\right|, \vec{D}_\delta = \left|\vec{C}_1^t.\vec{X}_\delta^t \quad X^t\right|$

$$\vec{X}_1^t = \vec{X}_\alpha^t \quad A_1^t.\vec{D}_\alpha^t, \vec{X}_2^t = \vec{X}_\beta^t$$

(10) $$A_2^t.\vec{D}_\beta^t, \vec{X}_3^t = \vec{X}_\beta^t \quad A_3^t.\vec{D}_\beta^t,$$

(11) $$X^{t+1} = \frac{X_1^t + X_2^t + X_3^t}{3}$$

A.3. Attacking the prey

The attacking process is controlled by the paramater $\vec{a}$ changes the vector $\vec{A}$ and conduct the omega wolves to approach or run away from the prey (solution), theorically, if $|\vec{A}| > 1$ wolves run a way to explore more search space. Else, they approach to dominants which mean that omega wolves will follow the dominants which exploit the small search space. $\vec{a}$ are linearly decreased from 2 to 0 over the course of iterations are crried on:

(12) $$\vec{a} = 2(1 \quad t/N) \quad)$$

Where N is the total number of iterations and t is the actual iteration number.

Based on these equations, the basic steps of the grey wolf optimization can be shown Fig. 3 [27-32].

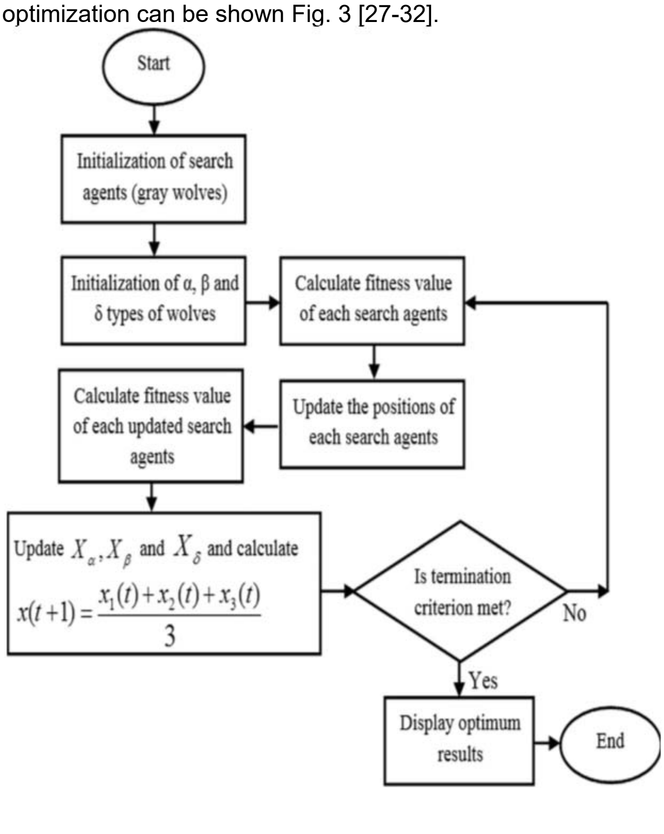


Fig.3 Flow chart of GWO-algorithm .

The employment of these three basic operations creat new individuals, which may be better than their parents. This process is repeated for several generations and finally stops when obtaining individuals that represent the optimum solution to the problem.

B. GWO-based PID Controller Tuning

GWO can be used in the tuning of the PI speed controller's gainsi(Kp ; Ki) to guarantee better control DTC performance at nominal condition for the DSIM. The basic scheme system is shown in Fig. 4.

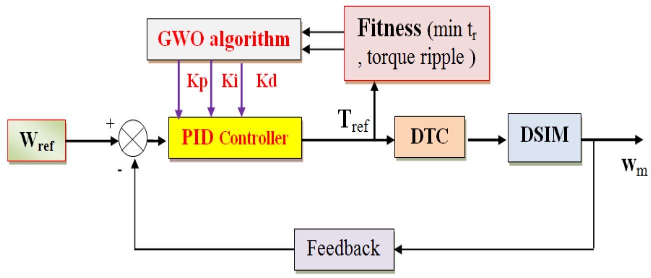


Fig.4 Optimization of PI controller using GWO.

The simulated GWO algorithm parameters used to initialize and generating an initial random population of individuals representing the PI controller gains (Kp and Ki) are given in Table 2.

Table. 2 GWO setup parameters.

Description	Parameters
Number of search agents	30
Maximum number of iterations	50
A	[0, 2]
R1 and r2	[0, 1]

The PI controller grey wolf optimizer tuning process is evaluated by repeated simulations in an offline mode to obtain the optimal PI values. Once found, the optimal PI controller is employed in the online system to control the DSIM speed. Table 3 presents the better obtained PI sets using GWO.

Table. 3 GWO-based optimized PI sets.

PI optimum set	KP	KI
PI set 1	49.04	0.001
PI set 2	46.32	0.95
PI set 3	5.45	0.13
PI set 4	3.47	0.17

C. PI-GWO DTC implementation

The DTC scheme based on grey wolf is shown in Fig. 5.

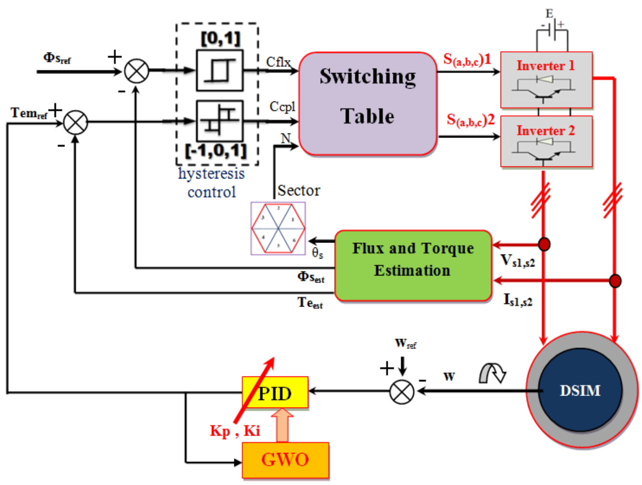
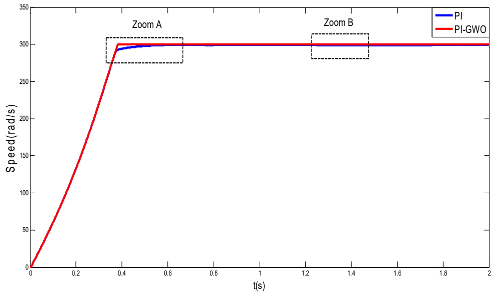


Fig.5 Proposed DTC-DFIM-GWO.

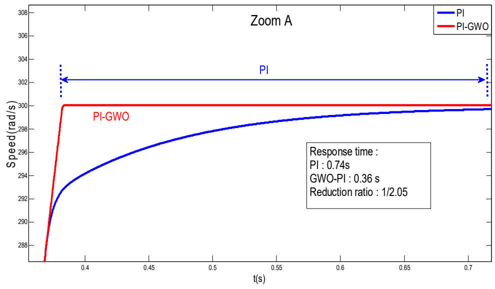
RESULTS SIMULATION and discussion

The obtained results for both control strategies (DTC and proposed DTC-GWO) have been demonstrated by the following figures with the hysteresis band of the torque comparator is fixed in ± 0.25 Nm and that of the comparator of flux in ±0.05 Wb.

The Fig.6 to Fig.8 show the motor speed, electromagnetic torque and flux respectively, under no load as starting up condition and connecting the nominal load as normal operating condition.



a) Zoom A



b) Zoom B

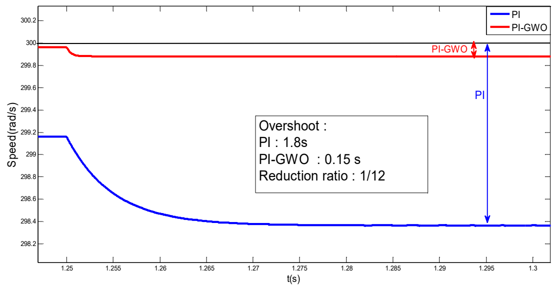
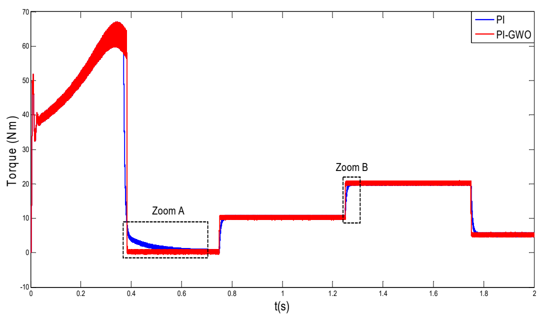


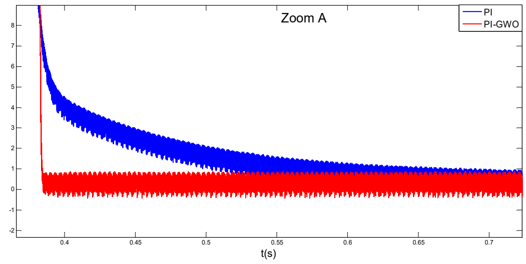
Fig. 6 Simulation results for comparison of the speed regulation of the two controllers.

From Fig. 6, we can remarks that at starting up with no load or in case of nominal load, the DTC-GWO controller reaches its speed reference rapidly without overshoot compared to the conventional DTC.As result, the better dynamic performance of torque and flux control is clear.

The electromagnetic torque tracking is shown in Fig. 7. The proposed DTC-GWO controller shows a important improvement during the period of rapidly changing load conditions in term of response time and overshoot.



a) Zoom A



b) Zoom B

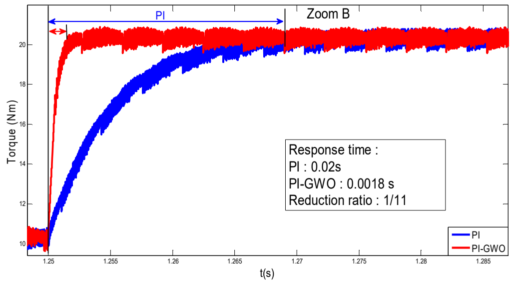
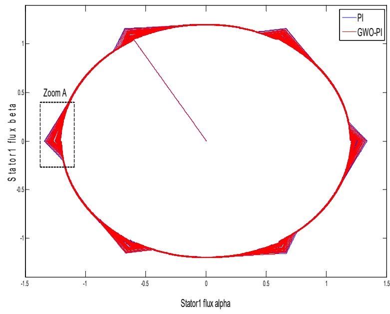


Fig.7 Electromagnetic torque comparison

The DTC-GWO effect controller regarding stator flux ripple in steady state is very clear in Fig. 8.



a) Zoom A

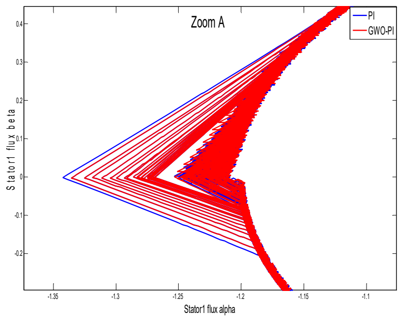
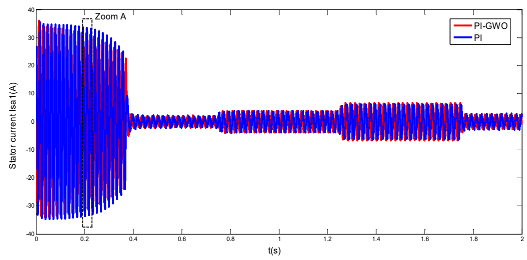


Fig. 8 The stator flux trajectory.

In the iFig.9 . it can be observed that the currents are sinusoidal and current ripple has also a notable reduction in DTC-GWO controller compared to the other controller.



a) Zoom A

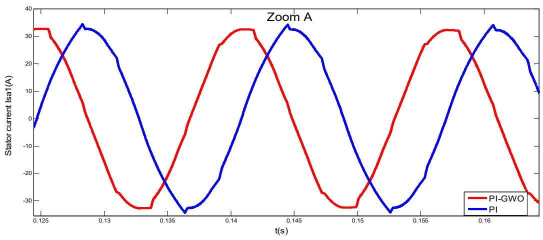


Fig. 9 The phase current in the stator winding using DTC-GWO.

From Figures 6 to 9, and the Table 3, the iproposed DTC-GWO strategy constitutes a practical alternative to the conventional control strategy and it has many features and advantages such as:

a. It has good performances;

b. The ability to follow the electromagnetic torque perfectly;

d. Fast flux and torque responses;

Conclusion

In this study, improved direct torque control of the dual star induction motor drive (DSIM) using Grey wolf optimizer has been proposed and investigated. Firstly, modeling of DSIM and principle of DTC have been illustrated with details. Then, improved DTC-GWO which the PID controller tuned by Grey wolf optimizer algorithm has been presented. Obtained results demonstrate the efficiency of both methods, the conventional DTC and improved DTC-GWO. However, the developed DTC-GWO has provided better performances such as quicker converging speed, high accuracy, and ripple reduction. In addition, the classical PID-DTC algorithm prone to failure especially under variable parameters of the machine. So DTC-GWO will be more suitable to electric drives in some special applications.

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