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A Novel Direct Active and Reactive Power Control Method Using Fuzzy Super Twisting Algorithms and Modified Space Vector Modulation Technique for an Asynchronous Generator-based Dual-rotor Wind Powers

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A B S T R A C T

This work presents a novel direct active and reactive powers command (DARPC) scheme based on fuzzy super twisting algorithms (FSTAs) of an asynchronous generator (ASG) integrated into dual-rotor wind power (DRWP) systems. The DRWP has two sets of blades. So it is more efficient for collecting power from wind in comparison to a traditional wind turbine. The scientific works indicate that a DRWP could extract additional 20-30% power compared to a traditional wind turbine. The conventional DARPC control scheme using the conventional integral-proportional (PI) regulators (DARPC-PI) has considerable reactive and active power oscillations. In order to guarantee an effective DARPC technique for the ASG-based DRWP system and minimize these oscillations, FSTAs are used in this work. Both DARPC strategies are presented and simulated from two tests using Matlab software. Simulation results showed the effectiveness of the designed DARPC control technique especially on the quality of the provided active and reactive power comparatively to the traditional DARPC control scheme with PI controllers.

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INTRODUCTION

DARPC or direct active and reactive powers command is a technique to control asynchronous generators (ASGs) by utilizing stator active and reactive powers. But the reactive and active power oscillations are occurred in the traditional DARPC strategy [1]. The principle of the DARPC strategy is detailed in literature [2–4]. In addition, DPC offers many advantages include: simplicity in calculations, robustness against ASG parameters, and fast dynamic response [5–7]. Although the DARPC strategy is getting more and more popular, it suffers from some drawbacks such as the large ripples of reactive and active powers. In order the overcome these disadvantages many researchers have been investigating on the DARPC strategy and they can be grouped under several headlines:

- Using artificial intelligence methods (Neural networks and fuzzy logic) on different sections of the system;
- Using different inverter topologies;
- Using sliding mode controller (SMC).

In this work, a novel fuzzy super-twisting algorithm (FSTA) and modified space vector modulation (MSVM) strategy has been designed to improve the stator active and reactive powers of the ASG on the DARPC technique.

The aim of this work is to improve the performance of the DARPC using FSTA controllers for ASG-based dual-rotor wind turbine (DRWT) system under variable speed wind and also to reduce fluctuations in reactive power, current, torque, and active power.

The FSTA method in the proposed technique rates active and reactive power errors and described the optimum space vector to reduce stator reactive and active power errors and oscillations. The simulation studies have been performed using Matlab logiciel board to effectiveness testing of the designed control strategy. In part II of this paper, the basic principles of the DARPC

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technique with PI controllers are presented. In part III, detailed information about the proposed strategy is introduced. Part IV gives the simulation results of the proposed technique. In conclusion, we provided a summary of the work performed.

MATHEMATICAL MODELING OF DRWP SYSTEM

The DRWP system with ASG is shown in Figure 1. The DRWP consists of two wind powers. The mechanical power captured from the DRWP system is given by Benbouhenni [8]:

$$P_{DRWP} = P_{AT} + P_{MT} \quad (1)$$

where, P_{AT} is the mechanical power of auxiliary turbine, and P_{MT} is the mechanical power of auxiliary turbine.

The torque of DRWP is given by:

$$T_{DRWP} = T_{AT} + T_{MT} \quad (2)$$

where, T_{AT} is the torque of auxiliary turbine, and P_{MT} is the torque of auxiliary turbine.

Equations (3) and (4) represent the torque of the output main and auxiliary turbines [9].

$$T_{AT} = \frac{1}{2\lambda_{AT}^3}.\rho.\pi.R_{AT}^5.C_p.w_{AT}^2 \quad (3)$$

$$T_{MT} = \frac{1}{2\lambda_{MT}^3}.\rho.\pi.R_{AT}^5.C_p.w_{MT}^2 \quad (4)$$

where λ_{AT}, λ_{MT}: the tip speed ration of the main and auxiliary turbines, R_{MT}, R_{AT}: blade radius of the auxiliary and main turbines, ρ: the air density and w_{AT}, w_{MT} the mechanical speed of the auxiliary and main turbines.

The tip speed ratios of the auxilliary and main turbines are given below:

$$\lambda_{AT} = \frac{\Omega_{AT}.R_{AT}}{V_{AT}} \quad (5)$$

$$\lambda_{MT} = \frac{\Omega_{MT}.R_{MT}}{V_{MT}} \quad (6)$$

where Ω_{MT} is the rotational speed of the main rotor, and Ω_{AT} is the rotational speed of the auxiliary rotor.

The power coefficient C_P equation is approximated using a non-linear function according to.

$$C_p(\lambda,\beta) = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \quad (7)$$

where, β is pitch angle.

The wind speed on the main turbine is given below [10]:

$$V_x = V_1\left(1 - \frac{1-\sqrt{(1-C_T)}}{2}\left(1 + \frac{2.x}{\sqrt{1+4.x^2}}\right)\right) \quad (8)$$

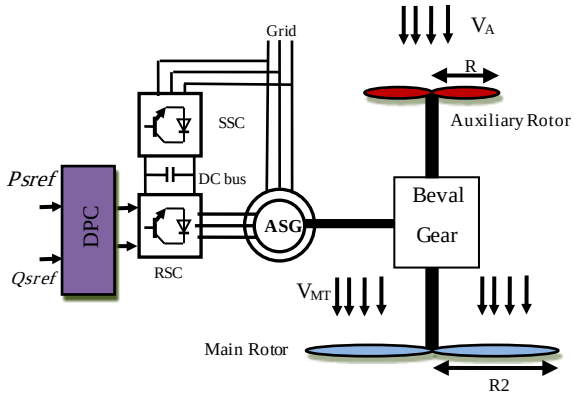

Figure 1. Structure of DRWP system with a ASG

with Vx: is the velocity of the disturbed wind between rotors at point x and C_T the trust coefficient, which is taken to be 0.9; x: the non-dimensional distance from the auxiliary rotor disk. So, with respect to x=15, the value of the Vx close to the main rotor is computable (rotors are located 15 meters apart from each other).

MODIFIED SVM TECHNIQUE

The proposed SVM technique named as modified SVM (MSVM) technique is an effective modulation technique for uncertain inverter and it overcomes the main disadvantages of the traditional SVM strategy.

Figure 2 shows a block diagram representation of the MSVM technique approach for a two-level inverter in wind power. The principle of MSVM is detailed by Benbouhenni et al. [11]. This proposed strategy is based on calculation of the minimum and maximum of three-phase voltages. In this strategy, the sector and angle are not necessary to calculate. Modified SVM technique is used to minimize harmonic distortion (THD) in three-phase output current waveform compared to PWM technique.

The MSVM modulation technique is used to generate gate pulses to the IGBT switches of the ASG-based DRWP systems. The proposed MSVM technique is a simple algorithm compared to the classical SVM method and is more robust compared to the traditional PWM strategy. Benbouhenni et al. [12] proposed the use of an MSVM technique applied to the four-level inverter of ASG. The fuzzy MSVM technique is proposed to reduces the active and reactive powers [13]. The simulation results have shown the superiority of the two-level fuzzy MSVM strategy. Mehedi et al. [14], have proposed an MSVM to control the five-phase inverter and the results indicate that the proposed MSVM strategy-based technique is good at minimizing the torque undulation, THD value of stator current, and stator flux undulation.

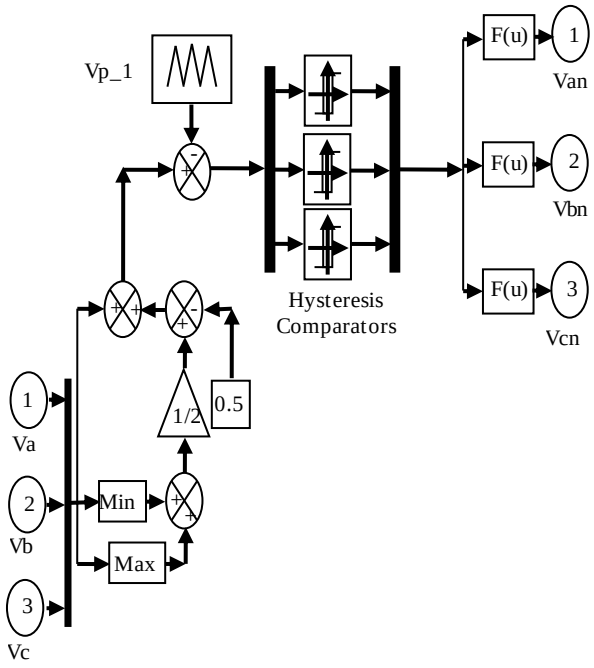

Figure 2. Modified SVM technique

DARPC STRATEGY WITH PI CONTROLLERS

In the DARPC-PI technique, the control of an ASG involves the direct command of the active and reactive powers by using two PI regulators [15]. This technique is a robust, easy, and simple technique. Stator active and reactive powers are estimated using Equations (9) and (10) [16].

$$P_s = -\frac{3}{2}\frac{L_m}{\sigma.L_s.L_r}\cdot(V_s.\psi_{r\beta}) \tag{9}$$

$$Q_s = -\frac{3}{2}\left(\frac{V_s}{\sigma.L_s}\cdot\psi_{r\beta} - \frac{V_s.L_m}{\sigma.L_s.L_r}\cdot\psi_{r\alpha}\right) \tag{10}$$

while,

$$\sigma = 1 - \frac{M^2}{L_r L_S} \tag{11}$$

These estimated values are compared to reference values and the resultant errors are applied to the PI regulators. Two PI controllers, as reactive and active PI regulators, generate other command parameters on the DARPC-MSVM technique or (DARPC-PI). The basic schematic representation of the DARPC-PI technique for ASG is shown in Figure 3.

The rotor flux can be estimated by:

$$\begin{cases} \psi_{r\alpha} = \int_0^t (v_{r\alpha} - R_r i_{r\alpha})dt \\ \psi_{r\beta} = \int_0^t (v_{r\beta} - R_r i_{r\beta})dt \end{cases} \tag{12}$$

The rotor flux amplitude is given by:

$$\psi_r = \sqrt{\psi_{r\alpha}^2 + \psi_{r\beta}^2} \tag{13}$$

where:

$$\left|\psi_r\right| = \frac{\left|V_r\right|}{w_r} \tag{14}$$

The reactive and active PI regulators gains (Ki and Kp) were found after performing simulations in Matlab logiciel. The gianes of PI regulator is stated in Table 1.

THE FSTA METHOD BASED DARPC METHOD

The DARPC scheme with PI controllers (DARPC-PI) offers some drawbacks associated with the large active and reactive powers ripples. In order to reduce these ripples, an STA technique with a fuzzy controller (FC) was designed. The origin of the DARPC-FSTA method is like to the DARPC-PI technique. The difference is using an FSTA algorithm to replace the conventional PI controllers. Also, the FLC is not dependent on the accurate mathematical model of the system [17]. It is based on 'IF…THEN' rules and experiences of human beings. In this work, using the advantage of FLC and STA, a DARPC method is presented.

A. Design of PI controller based on STA algorithm

The STA algorithm is based on the design of the discontinuous command signal that drives the system states toward special surfaces in state space [18]. Two

Table 1. PI regulator gaines

Ki	0.6
Kp	0.00005

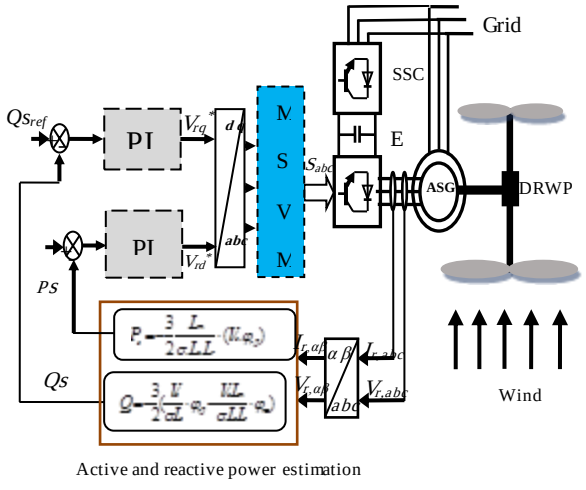

Figure 3. DARPC-PI technique

STA algorithms are selected for stator reactive and active power command. On the other hand, the STA algorithm is one of the robust techniques [19]. It is a particular operation mode of variable structure control systems. These techniques were used in numerous research works in the past years [20–24]. In the ASG command using the STA algorithm, the manifolds are chosen according to the error between the measured signals and the reference input signal. Considering that e_1 and e_2 are the errors of the stator active and the reactive power, we have the following:

$$\begin{bmatrix} e_1 \\ e_2 \end{bmatrix} = \begin{bmatrix} P_{sref} - Ps \\ Q_{sref} - Q_s \end{bmatrix} \quad (15)$$

The expression of the manifolds has the following form.

$$\begin{bmatrix} S(Ps) \\ S(Qs) \end{bmatrix} = \begin{bmatrix} P_{sref} - Ps \\ Q_{sref} - Q_s \end{bmatrix} \quad (16)$$

The STA algorithms active and reactive power controllers are designed to respectively change the q and d-axis voltages as in Equations (17) and (18) [11].

$$\begin{cases} V_{dr} = K_1 \left| S_{Q_r} \right|^r sign(S_{Q_r}) + V_{dr1} \\ \dot{V}_{dr1} = K_2 \, sign(S_{Q_r}) \end{cases} \quad (17)$$

$$\begin{cases} V_{qr} = K_1 \left| S_{Tem} \right|^r sign(S_{Tem}) + V_{qr1} \\ \dfrac{dV_{qr1}}{dt} = K_2 \, sign(S_{Tem}) \end{cases} \quad (18)$$

where, the constant gains $k1$ and $k2$ must check the stability conditions.

Figure 4 shows the block diagram of STA algorithms of active and reactive powers.

B. Designe of FLC based on STA algorithm

FSTA algorithm is a merge between the STA algorithm and FLC technique, where the switching term, Sign(S(x)), has been replaced by the FLC technique. The proposal of an STA algorithm incorporating the FLC method helps in achieving minimized active and reactive powers oscillations, easy method, simple technique, and robust technique compared to vector command method. The proposed FSTA algorithm, which is proposed to command the active and reactive powers of the ASG is shown in Figure 5. The fuzzy sets have been defined as follows: NB: Negative Big, NM: Negative Middle, NS: Negative Small, PS: Positive Small, PB: Positive Big, EZ: Equal Zero, and PM: Positive Middle. Membership functions in triangular shape are shown in Figures 6 and 7, respectively. Table 2 shows the proposed rule bases for the FSTA algorithms [25, 26].

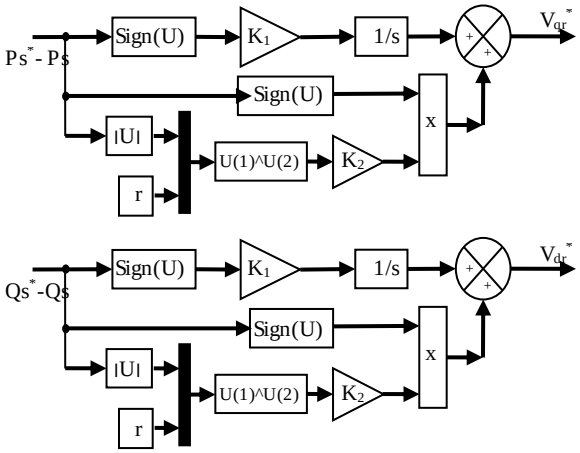

Figure 4. Block diagram of STA technique

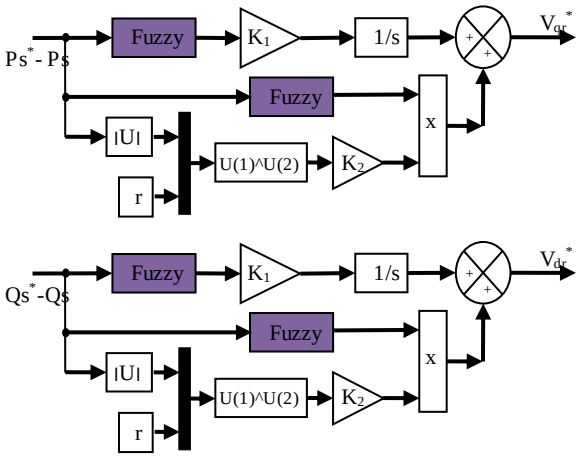

Figure 5. Block diagram of FSTA technique

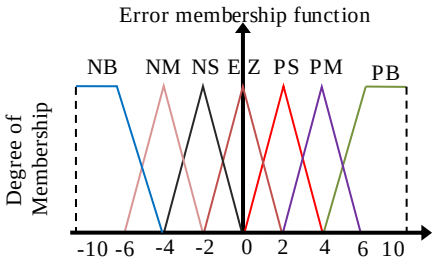

Figure 6. Membership functions for sliding surface

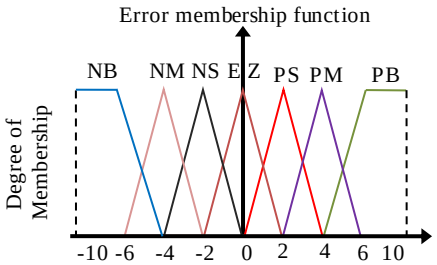

Figure 7. Membership functions for output variables

Table 2. FSTA algorithm rule bases

e / Δe	NB	NM	NS	EZ	PS	PM	PB
NS	NB	NB	NM	NS	EZ	PS	PM
NM	NB	NB	NB	NM	NS	EZ	PS
NB	NB	NB	NB	NB	NM	NS	EZ
PS	NM	NS	EZ	PS	PM	PB	PB
EZ	NB	NM	NS	EZ	PS	PM	PB
PB	EZ	PS	PM	PB	PB	PB	PB
PM	NS	EZ	PS	PM	PB	PB	PB

The proprieties of our regulators are given in the Table 3.

The structure of the DARPC technique with the FSTA algorithms applied to the ASG-DRWP is illustrated in Figure 8.

SIMULATION RESULTS

To study the effectiveness of the designed DARPC DARPC-PI and DARPC-FSTA technique, the simulation of the system was accomplished using Matlab logiciel and fuzzy logic Toolbox. The DFIG used in this case study is a 1,5MW, 380/690V, 50Hz, two poles, with the following parameters: Rs= 0.012Ω, Lr=0.0136 H, M= 0.0135 H, Rr= 0.021Ω, Ls=0.0137 H [27].

The ASG has the following mechanical parameters: J = 1000 Kg.m2, fr= 0.0024 Nm/s.

From the simulation results are presented in Figures 9 and 10. It is apparent that the THD value of current for the DARPC-FSTA strategy is reduced (see Table 4).

From the system responses given in Figures 11 and 12 for DARPC-PI and DARPC-FSTA technique the stator active and reactive power tracks the reference powers without overshoot, with zero steady-state error. Figure 13 shows the torque of both techniques. Note that torque is related to active power.

From Figure 14 can be seen that the amplitudes of the stator phase currents depend on the state of the drive system and the value of the load active power.

The zoom in the active power, torque, and stator current are shown in Figures 15, 16 and 17, respectively. It can be seen that the DARPC control with FSTA algorithms minimized the undulations in active power, torque, and current compared to the DARPC strategy with PI controllers.

Table 3. Proprieties of the FLC technique

Fis type	Mamdani
And method	Min
Or method	Max
Implication	Min
Aggregation	Max
Defuzzification	Centroid

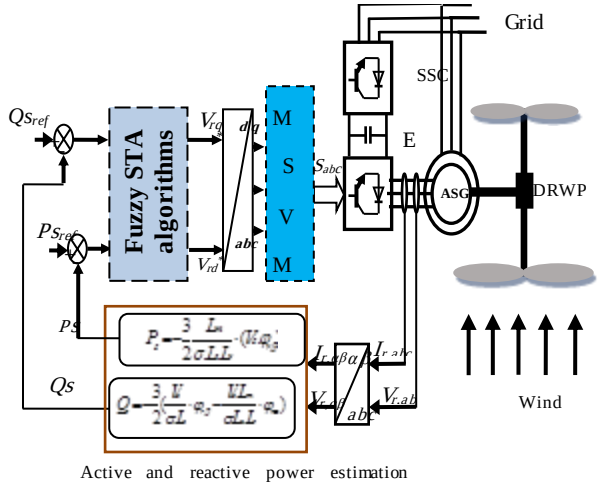

Figure 8. Block diagram of DARPC-FSTA control

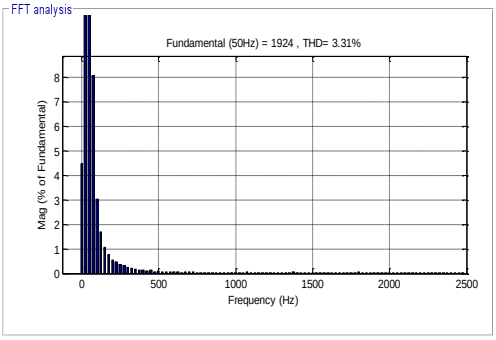

Figure 9. THD value of the current (DARPC-PI)

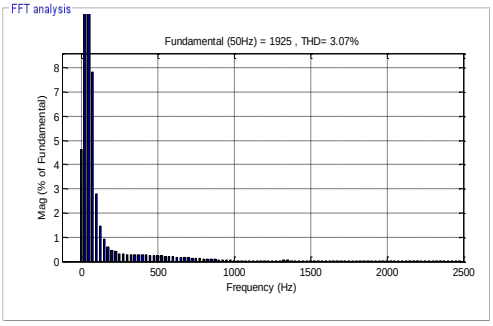

Figure 10. THD value of the current (DARPC-FSTA)

Table 4. THD value of both techniques

DARPC-PI	3.31%
DARPC-FSTA	3.07%

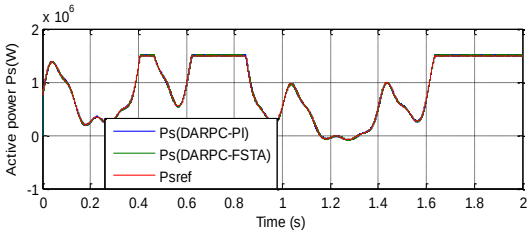

Figure 11. Active power

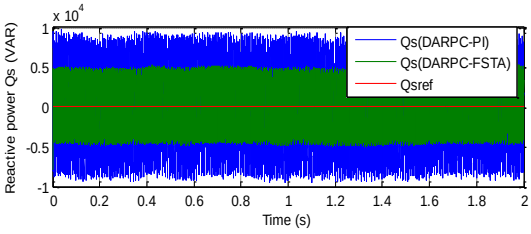

Figure 12. Reactive power

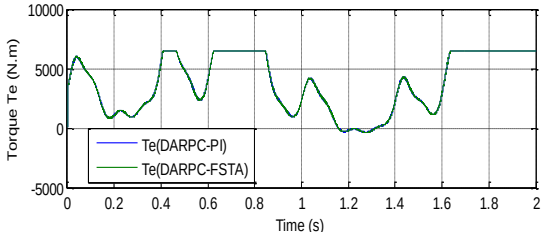

Figure 13. Electromagnetic torque

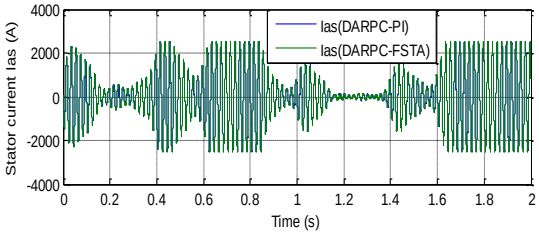

Figure 14. Stator current

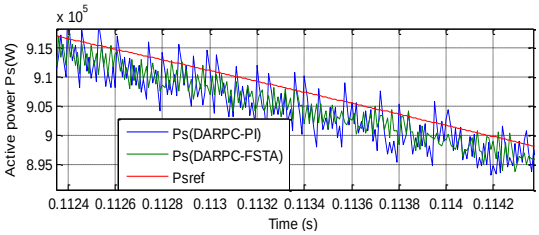

Figure 15. Zoom in the active power

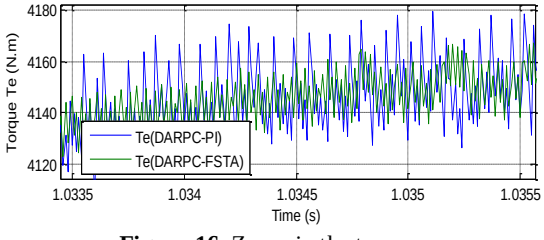

Figure 16. Zoom in the torque

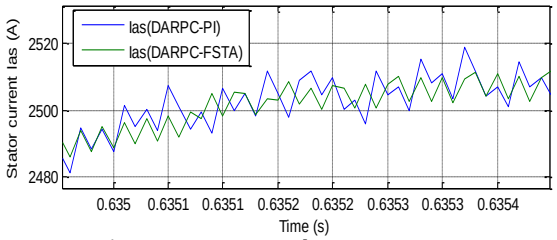

Figure 17. Zoom in the stator current

Robustness test (RT)

In this test, the nominal value of the R_r and R_s is multiplied by 2, the values of inductances L_s, M, and L_r are multiplied by 0.5. Simulation results are presented in Figures 18-23. As it's shown by these figures, these variations present an apparent effect on the torque, current, active and reactive power curves, and that the effect appears more significant for the DARPC using PI controllers compared to DARPC using FSTA algorithms (See Figures. 24-26).

The THD value of the current in the DARPC using the FSTA algorithms has been minimized significantly (See Figures 22 and 23). Table 5 shows the THD value of both strategies. Thus it can be concluded that the proposed DARPC using FSTA algorithms is more robust than the DARPC using the PI controllers.

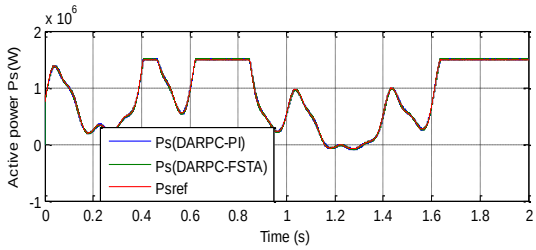

Figure 18. Active power

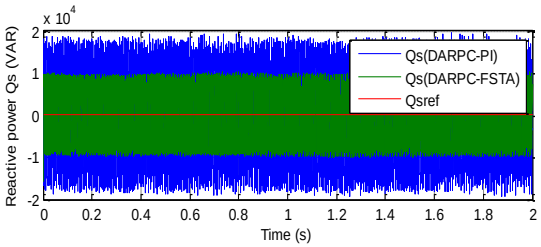

Figure 19. Reactive power

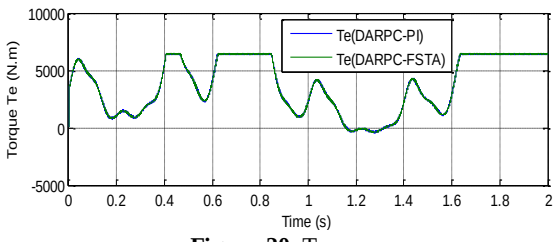

Figure 20. Torque

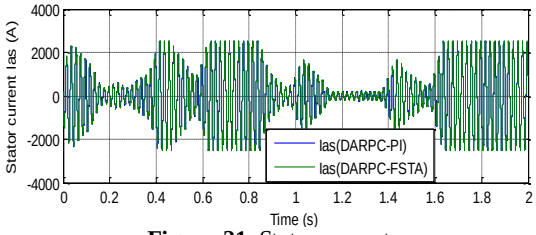

Figure 21. Stator current

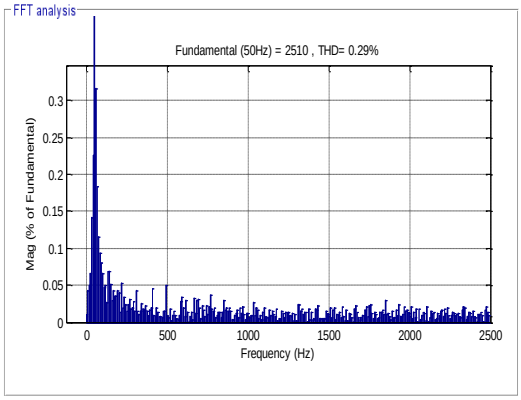

Figure 22. THD value of the current (DARPC-PI)

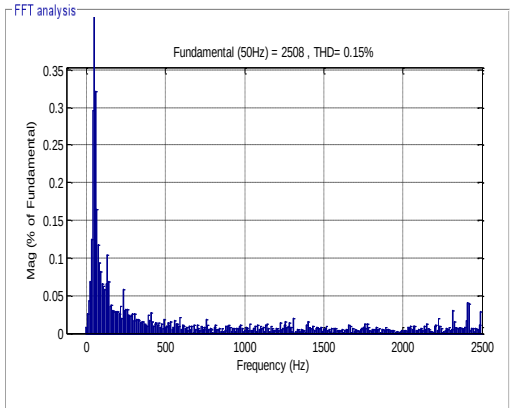

Figure 23. THD value of the current (DARPC-FSTA)

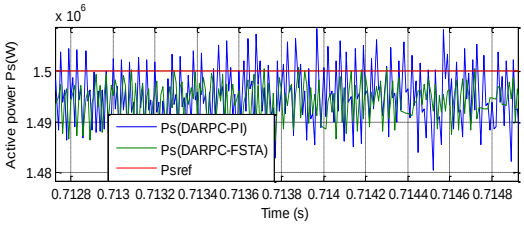

Figure 24. Zoom in the active power

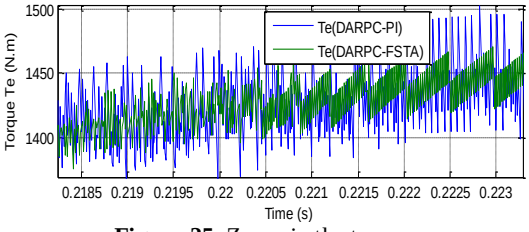

Figure 25. Zoom in the torque

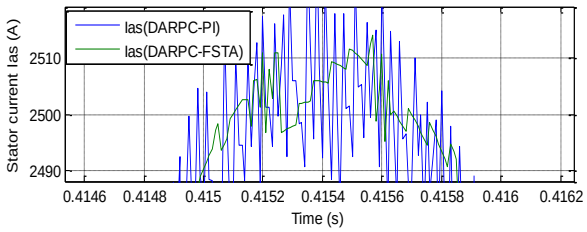

Figure 26. Zoom in the stator current

On the other hand, this designed technique reduced the THD value of current compared to other techniques (see Table 5). Based on the results above, it can be said that the DARPC-FSTA control technique has proven its efficiency in reducing ripples and chattering phenomena in addition to keeping the same advantages of the traditional DARPC method.

Table 5. Compare results with other methods

Ref.	Method Name	THD (%)
[22]	Second Order Continuous Sliding Mode – Direct Torque Control SOCSM-DTC	0.98
[27]	Direct Power Control DPC	4.88
	Virtual-Flux Direct Power Control VFDPC	4.19
[28]	Sliding Mode Control SMC	3.05
[29]	Field Oriented Control FOC	3.7
Proposed techniques	DARPC-PI	0.29
	DARPC-FSTA	0.15

CONCLUSION

In this work, a robust strategy is designed to improve the effectiveness of the DARPC-PI for the ASG-based DRWP systems. FSTA technique is proposed to replace the classical PI controllers of the DARPC-PI control scheme. The proposed strategy preserves the advantages of the traditional DARPC such as less parameter dependence and simplicity. The effectiveness of DARPC-PI and designed strategy is studied under, THD value of current and powers oscillations. By comparing the performances of the designed strategy with conventional DARPC-PI, it can conclude that the designed strategy has minimized the THD value of current. The proposed strategy has been very successful in improving the energy quality provided by the wind generator.

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Persian Abstract

چکیده

این کار یک طرح جدید قدرت مستقیم و راکتیو فرمان (DARPC) مبتنی بر الگوریتم‌های پیچش فوق‌العاده فازی (FSTA) یک ژنراتور ناهمزمان (ASG) یکپارچه شده در سیستم‌های قدرت باد دو روتور (DRWP) را ارائه می‌دهد. DRWP دارای دو مجموعه تیغه است. بنابراین در مقایسه با یک توربین بادی سنتی برای جمع‌آوری انرژی از باد کارآمدتر است. کارهای علمی نشان می‌دهد که یک DRWP می‌تواند در مقایسه با یک توربین بادی سنتی ۲۰-۳۰ درصد انرژی اضافی استخراج کند. طرح کنترل DARPC متداول با استفاده از تنظیم‌کننده‌های متناوب متناسب با انتگرال (DARPC-PI) دارای نوسانات توان واکنش‌پذیر و فعال قابل توجهی است. به منظور تضمین روش موثر DARPC برای سیستم DRWP مبتنی بر ASG و به حداقل رساندن این نوسانات، از FSTA در این کار استفاده می‌شود. هر دو استراتژی DARPC با استفاده از نرم‌افزار Matlab از دو آزمون ارائه و شبیه‌سازی شده‌اند. نتایج شبیه‌سازی اثربخشی روش کنترل DARPC طراحی شده به ویژه بر کیفیت توان فعال و راکتیو ارائه شده را نسبتاً به طرح کنترل سنتی DARPC با کنترل‌کننده‌های PI نشان می‌دهد.