Comparative Study of Synergetic Controller With Super Twisting Algorithm for Rotor Side Converter of DFIG

Habib Benbouhenni[1*], and Hamza Gasmi[2]

[1]Faculty of Engineering and Architecture, Department of Electrical & Electronics Engineering, Nisantasi University, 34481742 Istanbul, Turkey

[2]Laboratoire Controle Avancé (LABCAV), Department of Electronics and Telecommunications, Université 8 Mai 1945 Guelma BP 401, Guelma 24000, Algeria

(habib.benbouenni@nisantasi.edu.tr, gasmi.hamza@univ-guelma.dz)

‡ Corresponding Author; Habib Benbouhenni, BP: 50B Ouled Fares Chlef Algeria, Tel: +213663956329, habib.benbouenni@nisantasi.edu.tr

Received: 15.12.2022 Accepted:31.12.2022

Abstract- This work presents the implementation of direct active and reactive powers control (DARPC) with nonlinear controllers (synergetic controller (SC) and super twisting algorithm (STA)) for the rotor side converter of doubly-fed induction generator (DFIG) connected to the multi-rotor wind turbine (MRWT) system, as an alternative to the DARPC technique with STA controllers. In this work, DARPC is based on the nonlinear controllers and space voltage vector technique. Modified space vector modulation (MSVM) technique is applied to compose fixed-switching-frequency DARPC strategy, which replaces the switching table and hysteresis comparators technique in classical DARPC technique. DFIG's mathematics model and the two control techniques are given, and the simulations of DFIG based on DARPC-SC and DARPC-STA are made separately by Matlab software. In this work, two tests are proposed in order to verify the behavior of the proposed strategies, where the comparison between the strategies is in several aspects such as current quality, traceability of references, robustness, and ripple ratio. Simulation results show that the strategy based on synergetic control is better in terms of response time, ripple ratio, and electric current quality compared to other strategies.

Keywords: Super twisting algorithm, synergetic controller, multi-rotor wind turbine, direct active and reactive powers control, DFIG.

Nomenclature

DFIG	Doubly-fed induction generator
SC	Synergetic control
HAWT	Horizontal axis wind turbine
DARPC	Direct active and reactive power control
SMC	Sliding mode controller
VAWT	Vertical axis wind turbine
STA	Super-twisting algorithm
PI	Proportional integral
MRWT	Multi-rotor wind turbine
SVM	Space vector modulation
FOC	Field-oriented control
PWM	Pulse width modulation
THD	Total harmonic distortion
WTS	Wind turbine system
MSVM	Modified space vector modulation
Ps	Active power
Qs	Reactive power

1.Introduction

Electric energy is among the electrical energies that have affected human life, as this energy is used in several different fields. Several power sources can be used to obtain electrical energy such as wind power [1] and solar power [2]. Mechanical power is one of the most important sources used in generating electrical energy, where several types of power sources can be used to obtain mechanical energy, such as wind energy [3], hydropower [4], nuclear energy [5], thermal energy [6],...etc. Wind turbine (WT) is one of the most prominent energies that has spread in recent years for several reasons, including simplicity, low cost and the resulting energy return [7]. To obtain mechanical energy from wind energy, turbines are used [8]. The latter can be divided into two types: horizontal axis WTs (HAWTs) [9] and vertical axis WTs (VAWTs) [10]. HAWTs are characterized by greater efficiency compared to the VAWTs, as they are more widespread on land and at sea [11]. To increase the mechanical power gained from the wind, a novel technology was introduced based on the use of several rotor in the turbine [12]. The use of several rotors leads to an increase in the power gained from the wind, as the greater the number of turbines, the greater the mechanical power gained from the wind [13]. In addition to the turbines, electric generators are used, as these generators convert mechanical power into electrical power. In order to convert mechanical energy, several generators can be used, such as asynchronous generators [14, 15], synchronous generators [16], doubly-fed induction generators (DFIGs) [17, 18], and DC generators [19].

In the case of variable wind speed, DFIG is the best reliable solution in generating systems due to its simplicity, low maintenance, long life, low cost, easy to control and acceptable efficiency [20].

In the field of wind turbines, the inverter is used to feed the generators (DFIG), adjust the frequency (f) and improve the quality of the current, where the AC-DC-AC inverter is used to feed the rotor and control the active and reactive power of the DFIG [21]. To control the inverter, several techniques can be used, such as pulse width modulation (PWM) [22, 23], space vector modulation (SVM) [24], intelligent PWM [25, 26], and simplified SVM techniques [27, 28]. Using SVM technique to generate control signals in IGBTs increases the cost of the system, complicates and difficult to implement the system especially in the case of a multi-level inverter. Therefore, using PWM to generate control pulses makes the system simple, uncomplicated, easy to implement and low cost. But a lower quality current is obtained at the output of the inverter compared to the SVM strategy.

Besides these techniques, different controls are used to control the active and reactive power of the DFIG-WT system. These controls can be classified into hybrid controls [29-32], intelligent controls [33-35], linear controls [36, 37] and non-linear controls [38-42]. The use of these controls leads to obtaining an electric current of acceptable quality with the presence of ripples. Also, there are ripples at the level of active power, torque and reactive power of the DFIG.

Synergetic control (SC) theory and super twisting algorithm (STA) are among the most widely used and famous nonlinear controls in the field of control, these techniques are characterized by simplicity, durability, low cost, ease of implementation and can be applied to complex systems easily [43, 44]. The use of these techniques significantly minimizes the problem of chatterring compared to sliding mode control (SMC) [44, 45]. In [46], STA strategy is used to improve the efficiency of a field-oriented control (FOC) of seven-phase induction motor. The use of STA technique significantly improved the dynamic response of the engine while reducing torque ripples compared to the FOC strategy. In [47], neural networks and STA are combined to control the reactive and active power of DFIG-based WTS. The simulation results showed the high efficiency of neural STA technique compared to STA technique. Fuzzy logic and STA controller was combined to improve the quality of current of DFIG-based WTS [48]. The use of fuzzy logic led to an increase in the efficiency and robustness of STA technique, and this is shown by the simulation results in the case of changing or not changing the parameters of the system under study. In [49], terminal synergetic control is used as a new strategy to control and reduce the active and reactive power ripples of DFIG-based multi-rotor wind turbine (MRWT) system. The use of terminal synergetic control has improved the characteristics of DFIG compared to the classic control, where simplicity and durability are among the most important features of terminal synergetic control. In [50], a new nonlinear strategy based on the use of both synergetic control and SMC to control the DFIG-MRWT system. Simulation results showed that the synergetic-SMC (SSMC) strategy is one of the best reliable strategies in the field of renewable energies due to its great ability to significantly improve the current quality compared to the classical technique. Direct active and reactive power control (DARPC) based on synergetic-STA techniques was designed to control the DFIG, where the hysteresis controllers and switching table are eliminated and replaced by the SC strategy and PWM [51]. The use of synergetic control with PWM technique increased the robustness of the system and significantly improved the current quality compared to the traditional control scheme.

In this work, a comparison is made between two different approaches in principle, concept and idea. The two strategies are synergetic control theory and STA controller, which are used to improve the performance of the DARPC of the DFIG-MRWT system. This work aims to determine the best controller that can be relied upon in the future for the control of electrical machines. In order to accomplish this work, Matlab software is used to investigate and compare the proposed controls in terms of active and reactive power ripples, tracking references, total harmonic distortion (THD), robustness, overshoot, steady-state performance, current quality, and time response.

2.MRWT System

MRWT is among the new systems that have emerged recently as a solution to overcome the disadvantages of traditional turbines, where two turbines of different capacity are used to increase the mechanical energy gained from wind energy [52]. Fig. 1 represents the MRWT system designed in this work for electrical power generation. The advantage of this system is that it is simple, robust, and highly efficient compared to systems that use ordinary turbines. The two turbines are located in the same shaft and the torque is used to rotate the generator [53].

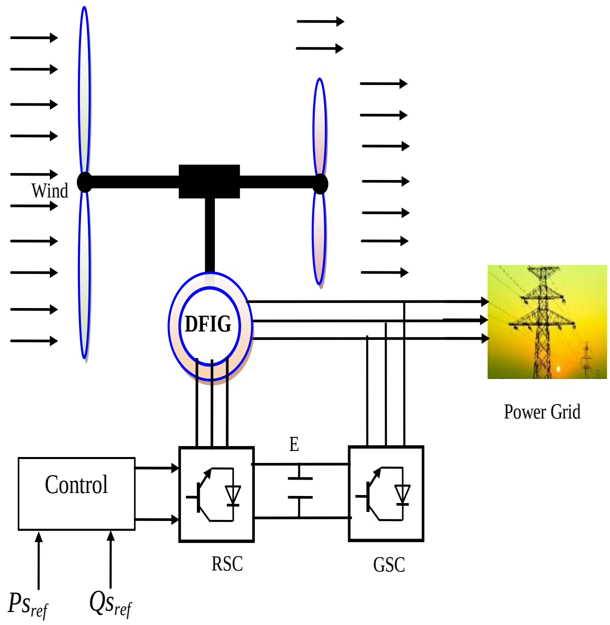


Fig. 1 MRWT system.

The torque produced by the MRWT is the sum of the torques of two turbines and is represented in equation (1).

$$T = T_1 + T_2 \tag{1}$$

where, T_1 is the torque of first turbine, T_2 is the torque of the second turbine.

Each turbine has a different torque than the other turbine because of the size of the two different turbines, where a large capacity turbine is used with a small capacity turbine in the same axis. The torques of the two turbines can be expressed by equation (2). Through this equation, it is noted that the wind speed differs between the two turbines as a result of the effect of the first turbine [54].

$$\begin{cases} T_1 = \dfrac{1}{2\lambda_1^3}.\rho.\pi.R_1^5.C_p.V_1^2 \\ T_2 = \dfrac{1}{2\lambda_2^3}.\rho.\pi.R_2^5.C_p.V_2^2 \end{cases} \tag{2}$$

The torque produced by the turbine is related to a parameter called the coefficient of power (Cp), which can be calculated using tip speed ratio (λ) and both pitch angle (β) using equation (3).

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

Each turbine has a different value for tip speed ration due to the difference in wind speed of two turbines and also the rotational speed of the two turbines are different from each other, using equation (4) we can calculate tip speed ratio for each turbine [52].

$$\begin{cases} \lambda_1 = \dfrac{w_1 . R_1}{V_1} \\ \lambda_2 = \dfrac{w_2 . R_2}{V_2} \end{cases} \tag{4}$$

In the DRWT system, the wind speed between the two turbines differs from the wind speed before the first turbine as a result of the wind speed being affected by the blades of the first turbine, where the wind speed between the two turbines is calculated at a point by equation (5). This speed is affected by the distance (x) between the two turbines and the wind speed before the main turbine (V1) with a constant coefficient (CT) of 0.9 [55].

$$V_2 = V_1 \left(1 - \frac{1 - \sqrt{(1 - C_T)}}{2} \left(1 + \frac{2.x}{\sqrt{1 + 4.x^2}}\right)\right) \tag{5}$$

In addition to the turbine, a DFIG generator is used to produce energy, where the energy produced is reactive and active power. The output power of the generator can be expressed by equation (6).

$$\begin{cases} P_s = \dfrac{3}{2}(V_{ds} I_{ds} + V_{qs} I_{qs}) \\ Q_s = \dfrac{3}{2}(V_{qs} I_{ds} - V_{ds} I_{qs}) \end{cases} \tag{6}$$

As is known, the generator is made up of two main parts, one of which is fixed and the other is rotating. The rotating part is what gives us the torque and the resulting speed, and it is the part that is connected to the turbine and it can be expressed by equation (7). Using equation (7), it is possible to study the evolution of speed in terms of the two torques (generator torque and turbine torque) [56].

$$\begin{cases} T_e - T_r = J \cdot \dfrac{d\Omega}{dt} + f \cdot \Omega \\ T_e = \dfrac{3}{2} p \dfrac{M}{L_r} (I_{dr} .\psi_{qs} - I_{qr} .\psi_{ds}) \end{cases} \quad (7)$$

where, T_e is the torque of generator.

In the rotor, there is also a coil in which the flux is generated, which can be expressed by equation (8).

$$\begin{cases} \psi_{dr} = L_r I_{dr} + M I_{dr} \\ \psi_{qr} = L_r I_{qr} + M I_{qr} \\ V_{dr} = R_r I_{dr} + \dfrac{d}{dt} \psi_{dr} - \omega_r \psi_{qr} \\ V_{qr} = R_r I_{qr} + \dfrac{d}{dt} \psi_{qr} + \omega_r \psi_{dr} \end{cases} \quad (8)$$

In DFIG, the stator is the part that connects to the electrical network using a transformer and is the part responsible for generating power, as it is a coil. The stator can be expressed by equation (9) [53].

$$\begin{cases} V_{ds} = R_s I_{ds} + \dfrac{d}{dt} \psi_{ds} - \omega_s \psi_{qs} \\ V_{qs} = R_s I_{qs} + \dfrac{d}{dt} \psi_{qs} + \omega_s \psi_{ds} \\ \psi_{ds} = L_s I_{ds} + M I_{dr} \\ \psi_{qs} = L_s I_{qs} + M I_{qr} \end{cases} \quad (9)$$

3.DARPC Based on Nonlinear Controllers

DARPC is among the linear techniques that have spread a lot recently in the field of renewable powers because of its many and many advantages, as it is characterized by ease, durability, fast dynamic response, and low cost of implementation compared to the vector control [57]. The principle of this control for DFIG is detailed in [58, 59]. Due to its many advantages, there are negatives that hinder the use of this control in the field of WTS, where power fluctuations and low quality of electric current are among the most important negatives as a result of using a hysteresis controller [60]. This control was used to control synchronous generators [61] and asynchronous generators [62]. To overcome the defects of DARPC, intelligent strategies such as neural networks [63] and fuzzy logic [64] have been used. Besides the intelligent strategies, nonlinear controls were used to improve the efficiency of the DARPC, such as using SMC [65] and backstepping controller [66].

In this part, a new idea is presented for DARPC based on the use of nonlinear strategies to increase robustness, reduce power ripples and improve dynamic response. These nonlinear strategies are represented by the use of both synergetic control and super twisting algorithm. So, two different approaches in concept and principle are dealt with in detail in this part of the paper. The two proposed controls are two modifications of the classical control, in which the hysteresis controller is removed and replaced by both synergetic control and STA controller. Also, the switching table is dispensed with and replaced with the modified SVM technique. The two proposed controls are represented in Fig. 2, where the two proposed controls are similar in several matters and differ in terms of the type of control used in controlling the capacities. Compared with the classical technique, the two proposed controls are characterized by durability, fast dynamic response and fewer ripples.

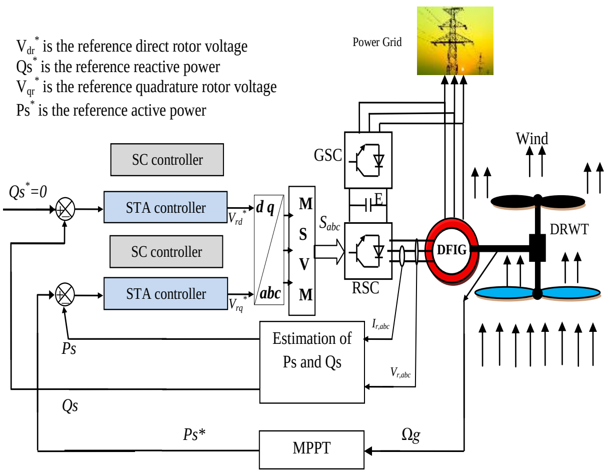


Fig. 2 The proposed nonlinear DPC techniques

In the two proposed techniques, both the capacities and the flux are estimated, as the same estimation equations used in the classical strategy are used. These estimation equations can be expressed by equations (10) through (11) [57, 61].

$$\begin{cases} \Psi_{r\alpha} = \int_0^t (v_{r\alpha} - R_r i_{r\alpha}) dt \\ \Psi_{r\beta} = \int_0^t (v_{r\beta} - R_r i_{r\beta}) dt \end{cases} \quad (10)$$

$$\begin{cases} \Psi_{s\alpha} = \int_0^t (-R_s i_{s\alpha} + V_{s\alpha}) dt \\ \Psi_{r\beta} = \int_0^t (-R_s i_{s\beta} + V_{s\beta}) dt \end{cases} \quad (11)$$

$$\begin{cases}\Psi s=\sqrt{\Psi_{s\alpha}^2+\Psi_{s\beta}^2}\\ \Psi r=\sqrt{\Psi_{r\alpha}^2+\Psi_{r\beta}^2}\end{cases} \quad (12)$$

To estimate the capabilities, equations (13) and (14) are used. To obtain good estimates, high-quality measuring devices must be used, where voltage and current are measured [63, 66].

$$P_s=-\frac{3}{2}\frac{Lm\times(Vs.\Psi_{r\beta})}{\sigma\times Ls\times Lr} \quad (13)$$

$$Q_s=-\frac{3}{2}\left(-\frac{Vs.Lm}{\sigma.Ls.Lr}\cdot\Psi_{r\alpha}+\frac{Vs}{\sigma.Ls}\cdot\Psi_{r\beta}\right) \quad (14)$$

3.1 Design of the Synergetic Reactive and Active Power Controllers

In this section, SC strategy is used to command the powers of DFIG, and this controller was chosen because of its robustness, simplicity, responsiveness, and ease of implementation [49]. As it is known, SC strategy significantly reduces chattering problem compared to the SMC [40]. To apply this controller, you must first determine the surface on which the synergetic controller is applied. The surface is determined by the equation (15), where the powers (Ps and Qs) are controlled. So, two synergetic controls are used, where the inputs are errors in the capacities (Ps and Qs) and the outputs are the reference values for the rotor voltage (V_{dr}^* and V_{qr}^*).

$$\begin{cases}S_{Qs}=Q_{sref}-Q_s\\ S_{Ps}=P_{sref}-P_s\end{cases} \quad (15)$$

The two equations (16) and (17) represent the proposed controller in this part for the control of powers (Ps and Qs).

$$V_{dr}^*=K_1\frac{dS_{Qs}}{dt}+S_{Qs} \quad (16)$$

$$V_{qr}^*=K_2\frac{dS_{Ps}}{dt}+S_{Ps} \quad (17)$$

where, K_1 and K_2 are constants. These constants are used to adjust and modify the response.

Fig. 3 expresses the synergetic controller used to command the DFIG powers. Through this form, the designed controller is simple, uncomplicated and does not require a specialist. Thus, this designed command can significantly reduce torque and current ripples, significantly increase system robustness, reduce steady-state error (SSE) of reactive and active power, and improve system dynamic response.

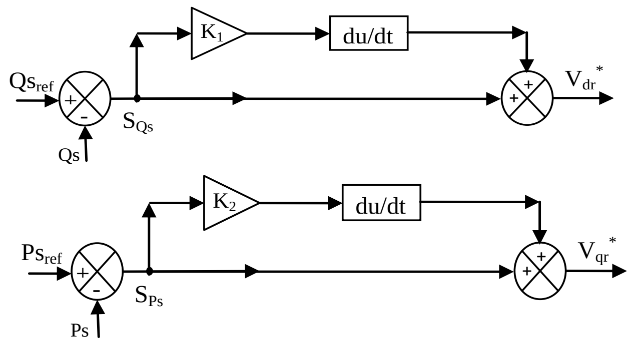


Fig. 3 Synergetic controller for reactive and active power.

3.2 Design of the STA-reactive and Active Power Controllers

The second nonlinear controller used to improve and reduce power fluctuations is the STA controller. This controller is among the nonlinear techniques that are characterized by high durability and ease of implementation, as it is applied directly without making calculations after determining the surface [67, 44]. Equation (18) represents the proposed STA controller in this work to perform a comparative study with the synergetic control technique [31, 44].

$$u(t)=\alpha_2\int sign(S(t))+\alpha_1\sqrt{|S(t)|}.sign(S(t)) \quad (18)$$

The same work done with the synergetic controller is followed with the STA controller. Two STA controllers are used to control the powers (Qs and Ps), where the inputs are the error in the powers and the outputs are the V_{dr}^* and V_{qr}^*.

The two equations (19) and (20) represent the proposed STA controller for controlling the powers (Qs and Ps) and calculating the reference values for the rotor voltage (V_{dr}^* and V_{qr}^*).

$$V_{qr}^*=\alpha_1\sqrt{|S_{Ps}(t)|}.sat(S_{Ps}(t))+\alpha_2\int sat(S_{Ps}(t)) \quad (19)$$

$$V_{dr}^*=\alpha_3\sqrt{|S_{Qs}(t)|}.sat(S_{Qs}(t))+\alpha_4\int sat(S_{Qs}(t)) \quad (20)$$

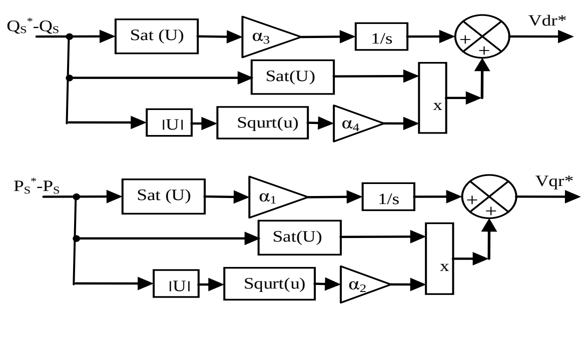


Fig. 4 STA controller for active and reactive powers.

Fig. 4 represents the proposed STA controller for power control for DFIG-DRWT system. Through this form, this control is characterized by simplicity and does not need to know the mathematical form of the system under study.

Table 1 presents a comparative study between the three controls (DARPC, DARPC-SC, and DARPC-STA) proposed in this work in terms of complexity, durability, ease of achievement, steady-state performance, Qs and Ps ripples,...etc. The table was filed by this completed study and the results obtained.

Table 1. A comparative study between the designed techniques.

	DARPC	**DARPC-SC**	**DARPC-STA**
Ps estimation	Yes	Yes	Yes
Simplicity	Simple	Very simple	Simple
Set-point tracking	Good	Very good	Very good
Response dynamic	Slow	Quick	Very quick
Overshoot	Important	Very low	Low
STA controller	No	No	Yes
Steady-state performance	High	Very low	Low
Synergetic controller	No	Yes	No
Implementation	Easy	Easy	Easy
Qs estimation	Yes	Yes	Yes
Degree of complexity	Low	Very low	Low
Quality of power	Low	High	Medium
Rise time	High	Low	Low
Modified SVM technique	No	Yes	Yes
THD	High	Low	Medium
Qs and Ps ripples	High	Low	Medium
References	Ps and Qs	Ps and Qs	Ps and Qs
Precision	Low	High	Medium
Switching table	No	Yes	Yes
Robustness	Low	High	High
MPPT technique	Yes	Yes	Yes
Hysteresis controller	Yes	No	No

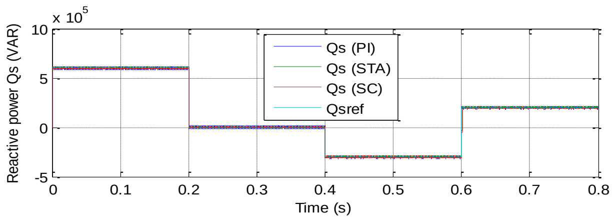
4.Results

In this part, verification, comparison, and analysis of results of three different approaches in principle, concept and idea using Matlab software are done. To accomplish this study, DFIG with the following parameters is used: p = 2, 380/696V, 50Hz, J = 1000 kg.m^2, P_{sn}=1.5 MW, L_m = 0.0135H, R_s = 0.012 Ω, L_s = 0.0137H, L_r = 0.0136H, R_r = 0.021 Ω, and f_r = 0.0024 Nm/s [68, 69].

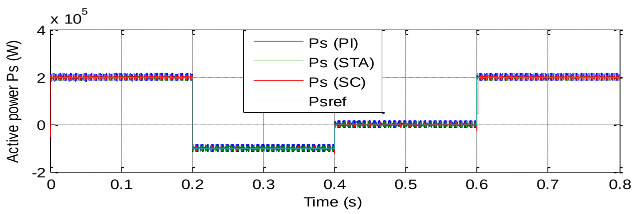
4.1 Tracking Test

The objective of this test is to evaluate the behavior of synergetic controller, STA, and PI controller. Steady-state performance of powers, ratio ripples in reactive and active power, overshoot of power, and THD value of current are certified for a fair comparison. As shown in Fig. 5, for the three control techniques, the active and reactive power perfectly tracks its reference values, for which the DARPC based on SC strategy gives better performance in terms of increased damping, ripple value, overshoot, settling time, and diminished SSP compared to the PI and STA controllers. However, the STA controller offers a faster response time, where the response time of active power is better for STA controller (0.265 ms) when compared to that of the PI (0.474 ms) and synergetic controller (1.45 ms).

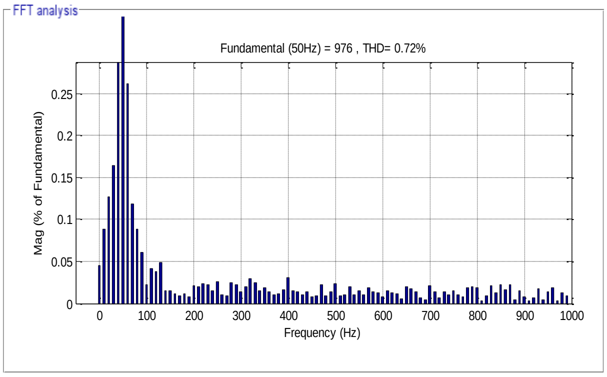
Fig. 6 shown the zoom in the reactive and active power of the DFIG. The ripple values for the powers are given in Table 2. Table 3 represents the overshoot values for the powers. It can be seen from Tables 2 and 3 that the nonlinear controllers offer good tracking performance with marked superiority of the synergetic controller in terms of overshoot value and power ripples value decreasing. Synergetic controller reducing active power ripples by 66% and 49% compared to PI and STA controllers, respectively. As for the reactive power, the reduction ripples ratios were 70.09% and 25% compared to each of the PI and STA techniques, respectively. For further comparison of the performance of this route, the harmonic spectra of stator current are compared. Figs. 5c to 5e shows that the current THD is better for the synergetic controller (THD = 0.30%) when compared to that of the PI (THD = 0.72%) and STA (THD = 0.52%).



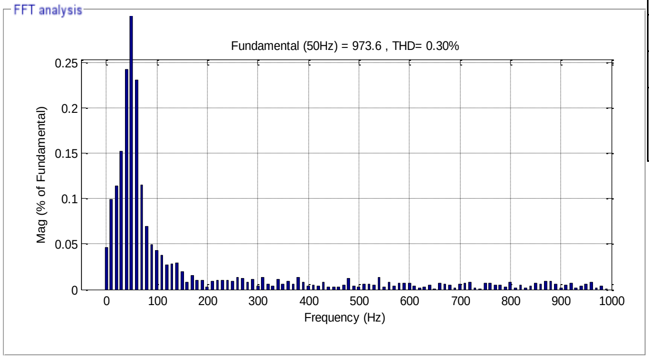
a)Reactive power



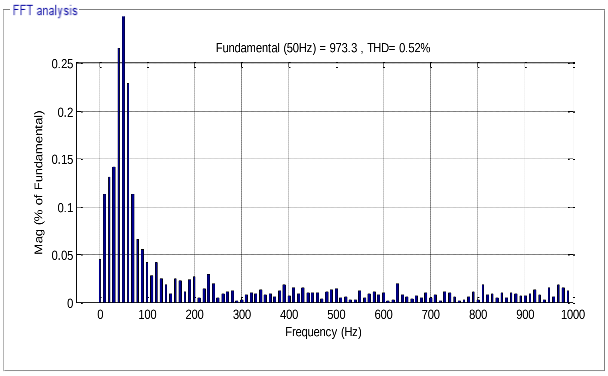
b)Active power



c)THD (PI controller)

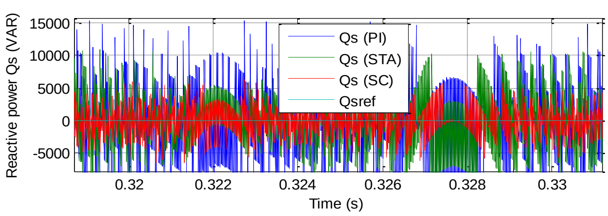


d) THD (Synergetic controller)

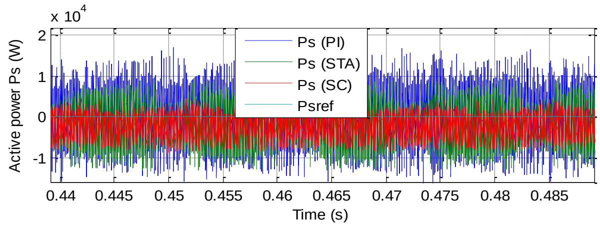


e)THD (STA controller)

Fig. 5 Results of first test



a)Reactive power



b)Active power

Fig. 6 Zoom in the powers (First test).

Table 2. Ripples value (First test)

		Qs (VAR)	Ias (A)	Ps (W)
PI controller		30100	64	30000
Synergetic controller		9000	13	10200
STA controller		12000	31.5	20000
Ratios (%)	**STA**	60.13	50.78	33.33
	SC	70.09	79.68	66.00

Table 3. Overshoot in powers (First test)

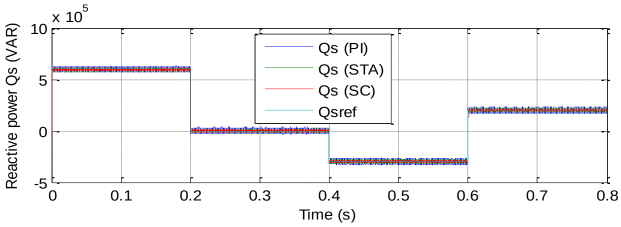
		Qs (VAR)	Ps (W)
PI controller		15600	14320
Synergetic controller		3850	4960
STA controller		7500	8940
Ratios (%)	**STA**	51.92	37.56
	SC	75.32	65.36

4.2 Robustness Test

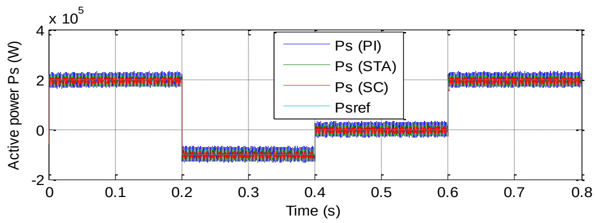
A comparative study will be studied in terms of the effect of DFIGs parameter variables on the effectiveness of designed techniques. Accordingly, the behavior of PI, STA, synergetic controllers are investigated. Fig. 7, Tables 4 to 6 show the simulation results in this test. In this test, the figures will be shown for the reactive/active power and THD of current. The powers keep track of the references well despite the change of DFIG parameters with an advantage for STA controller in terms of time response compared to both PI and synergetic controllers, where the response time for the reactive power was about 0.135 ms for STA controller, 0.245 ms for PI controller and 0.794 ms for synergetic controller (Table 4). For active power, response times were 0.659 ms, 0.251 ms, and 0.801 ms for STA, PI, and synergetic controllers, respectively. Table 6 represents the overshoot values for reactive and active power of the DFIG. The table indicates that the synergetic controller offers better overshoot values compared to both PI and STA controllers. Therefore, the overshoot of active power reduction percentages were 79.93% and 63.40% for PI and STA techniques, respectively. While the overshoot of the reactive power reduction ratios were 93.33% and 26.33% for PI and STA controllers, respectively. In addition, Fig. 8 shows zoom in both the reactive and active power of the three designed controls. We can clearly conclude that the changes of the parameters have a clear effect on the dynamic performance of the active and reactive power when using the PI controller compared to both SC and STA controllers. With the ripple values listed in Table 5, the synergetic controller provides better values for active and reactive power ripples than both PI and STA controllers. Therefore, the active power ripples reduction ratios were 66.66% and 50% compared to the PI and STA controllers, respectively. While the reactive power ripples reduction ratios were 75.86% and 65% compared to the PI and STA controllers, respectively. Also, the value of THD is much affected in the case of PI controller compared to both synergetic and STA controllers. Moreover, the separation of reactive and active powers is not guaranteed in this case, while the synergetic controller approach is more robust against parameter changes and the ripples and THD value are significantly reduced. The synergetic controller reduced the THD value of current by 56.05% and 40% compared to the PI and STA controllers, respectively.

Table 4. Response time in powers (Second test)

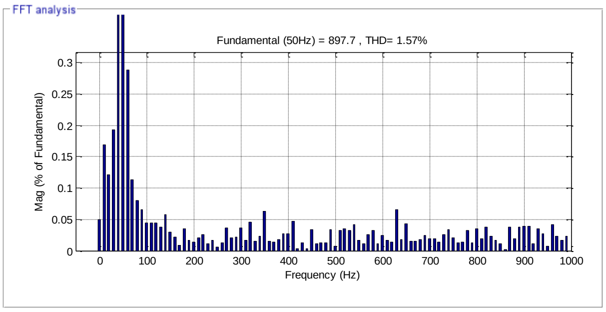
	Qs (VAR)	Ps (W)
PI controller	0.251 ms	0.245 ms
Synergetic controller	0.801 ms	0.794 ms
STA controller	0.659 ms	0.135 ms



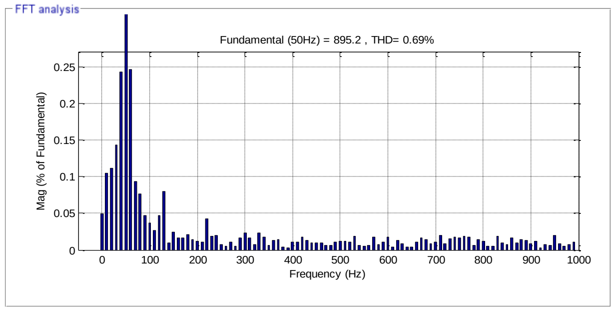
a)Reactive power



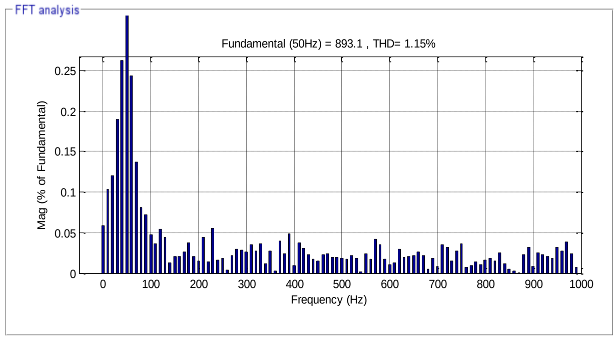
b)Active power



c)THD (PI controller)

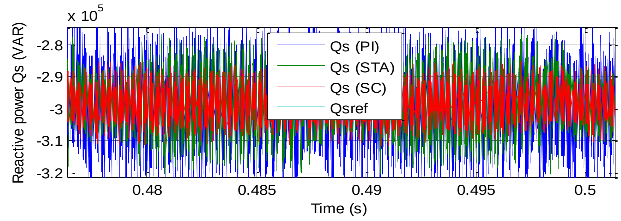


d) THD (Synergetic controller)

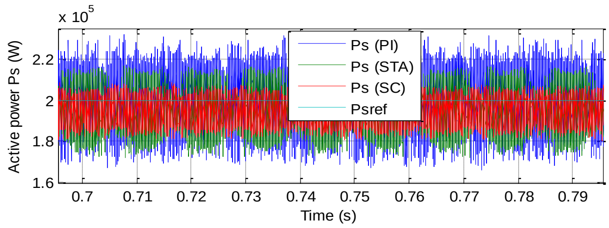


e)THD (STA controller)

Fig. 7 Results in the second test



a)Reactive power



b)Active power

Fig. 8 Zoom in the powers (Second test)

Table 5. Ripples value (Second test)

		Qs (VAR)	Ps (W)
PI controller		58000	60000
Synergetic controller		14000	20000
STA controller		40000	40000
Ratios (%)	**STA**	31.03	33.33
	SC	75.86	66.66

Table 6. Overshoot value in power (Second test)

		Qs (VAR)	Ps (W)
PI controller		60000	28560
Synergetic controller		4000	5730
STA controller		5430	15660
Ratios (%)	**STA**	90.95	45.16
	SC	93.33	79.93

To demonstrate the properties and superiority of a DARPC based on SC techniques, it is interesting to compare it with published work in the same discipline (DFIG Control). All the proposed comparison work is done on DFIG, where the proposed method is compared with the published work in terms of ripple reduction ratio of the reactive and active power, response time, and THD value. The results of the comparison are recorded in Tables 7 and 8. From Table 8, it can be noted That the designed DARPC based on synergetic controllers provides a low THD value (0.30%) compared to with published works. In addition, the work done in this paper (DARPC based on synergetic controllers) provided very satisfactory results in terms of ripple value for reactive and active power and response time compared to other methods, for more information see Tables 7 and 8.

Table 7. Compare ripple reduction ratios

Methods		**Ratios**		
		Current ripples	**Active power ripples**	**Reactive power ripples**
Proposed techniques	**DPC-STA**	50.78%	33.33%	60.13%
	DPC-SC	79.68%	66%	70.09%
Ref. [70]	**DPC with neural algorithm**	67.79%	45.26%	66.29%
	DPC with neuro-fuzzy algorithm	69.33%	57.74%	67.13%
Ref. [71]	**STA**	3.58%	7.35%	2.01%
	Modified STA	0.21%	13.44%	8.96%

Table 8. Compare response time and THD value

References	**Response time**		**THD (%)**	**Strategies**
	Ps	**Qs**		
[72]	0.0338 s	0.0345 s	0.87	Sliding-Backstepping mode control
[73]	0.150 s	0.080 s	0.94	Observer Sliding Mode Control
[74]	0.32 s	-	-	Fuzzy SMC
[75]	0.030 s	-	-	PI
	0.028 s	-	-	RST
[76]	0.12 s	-	18.8	DTC
	0.16 s	-	8.26	FSC
	0.15 s	-	8.17	MPDC
[77]	0.05 s	-	2.98	SMC based backstepping
Proposed controls	0.245 ms	0.251 ms	0.72	PI controller
	0.135 ms	0.659 ms	0.52	STA controller
	0.794 ms	0.801 ms	0.30	Synergetic controller

5. Conclusion

This paper discusses and implements three different DPC schemes based on PI, STA, and synergetic controllers in a wind turbine system-based RSC-DFIG circuit. The proposed strategies for the comparative study are characterized by simplicity and ease of implementation and have disadvantages such as power fluctuations and low current quality. A comparative study was completed between the three techniques in terms of complexity, ripples ratio, response dynamic, steady-state performance, simplicity, overshoot, robustness, and THD value of current. To verify and complete a comparative study and to show the best control, Matlab software was used using 1.5 MW DFIG.

The simulation results showed that the non-linear controllers (STA and synergetic controllers) have very high efficiencies, durability and an increase in the quality of the electric current in addition to attenuation of the chatterring phenomena compared to the PI. The results confirm that the DPC based on synergetic controller is a suitable control for regulating DFIG system by under estimating the overshoot of the power and not being affected too much by changing the system parameters compared to both DPC-PI and DPC-STA techniques. However, the DPC-STA technique has a faster dynamic response than the two techniques are DPC-PI and DPC-SC.

The study carried out at the present time is limited as a result of using a constant wind speed, and the comparative study is limited to simulation only. In addition, the comparative study was limited to ripple reduction ratio, overshoot, response dynamic, and THD value. A comparative study will be carried out experimentally under previous concerns in future work. This will be implemented by further testing of DFIGs with the use of new control techniques, such as neural network controller. The use of these solutions is of great importance in overcoming the defects and problems of the wind power generation system.

References

1. K. Okedu, " A Variable Speed Wind Turbine Flywheel Based Coordinated Control System for Enhancing Grid Frequency Dynamics, " International Journal of Smart Grid, Vol 2, No 2, pp.123-134, 2018. https://doi.org/10.20508/ijsmartgrid.v2i2.22.g158.

2. A. O. Amole, D. O. Akinyele, O. E. Olabode, O. Idogun, A. O. Adeyeye, B. S. Olarotimi, " Comparative Analysis of Techno-Environmental Design of Wind and Solar Energy for Sustainable Telecommunications Systems in Different Regions of Nigeria, " International Journal of Renewable Energy Research-IJRER, Vol 11, No 4, pp.1700-1712, (2021), https://doi.org/10.20508/ijrer.v11i4.12524.g8329.

3. Z. Sun, W. Zhu, W. Shen, Q. Tao, J. Cao, X. Li, " Numerical Simulations of Novel Conning Designs for Future Super-Large Wind Turbines, " Appl. Sci., Vol. 11, 147, 2021. https://doi.org/10.3390/app11010147.

4. A. Tayebiyan, T. A. Mohammad, N. Al-Ansari, M. Malakootian, " Comparison of Optimal Hedging Policies for Hydropower Reservoir System Operation, " Water, Vol. 11, 121, 2019. https://doi.org/10.3390/w11010121.

5. H. A. Gabbar, M. R. Abdussami and M. I. Adham, " Optimal Planning of Nuclear-Renewable Micro-Hybrid Energy System by Particle Swarm Optimization, " in IEEE Access, vol. 8, pp. 181049-181073, 2020, doi: 10.1109/ACCESS.2020.3027524.

6. E. Doroudchi, H. Khajeh and H. Laaksonen, " Increasing Self-Sufficiency of Energy Community by Common Thermal Energy Storage, " in IEEE Access, vol. 10, pp. 85106-85113, 2022, doi: 10.1109/ACCESS.2022.3195242.

7. M. Yin, Y. Xu, C. Shen, J. Liu, Z. Y. Dong and Y. Zou, " Turbine Stability-Constrained Available Wind Power of Variable Speed Wind Turbines for Active Power Control, " in IEEE Transactions on Power Systems, Vol. 32, No. 3, pp. 2487-2488, May 2017, doi: 10.1109/TPWRS.2016.2605012.

8. J. R. de Oliveira and A. L. Andreoli, " Wind Turbine Emulator: A Tool for Experimental and Computational Study, " in IEEE Latin America Transactions, Vol. 19, No. 11, pp. 1832-1839, Nov. 2021, doi: 10.1109/TLA.2021.9475616.

9. J. Xie, X. Zhang, S. Huang, F. Huang, Z. Peng, Y. Dai, X. Wu, " Characteristics Simulation Method of Megawatt Three-Blade Horizontal Axis Wind Turbine Based on Laboratory Kilowatt Low-Power Motor System, " in IEEE Transactions on Industry Applications, Vol. 58, No. 1, pp. 645-655, Jan.-Feb. 2022, doi: 10.1109/TIA.2021.3123116.

10. C. J. Li, R. Bhalla and H. Ling, " Investigation of the Dynamic Radar Signatures of a Vertical-Axis Wind Turbine, " in IEEE Antennas and Wireless Propagation Letters, Vol. 14, pp. 763-766, 2015, doi: 10.1109/LAWP.2014.2377693.

11. M. S. Davis, A. Jafarian, F. Ferdowsi and M. R. Madani, " Wind Energy Harvesting Capability of a Novel Cascaded Dual-Rotor Horizontal-Axis Wind Turbine, " 2021 International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME), pp. 01-05, 2021, doi: 10.1109/ICECCME52200.2021.9590963.

12. H. Benbouhenni, N. Bizon, " Advanced Direct Vector Control Method for Optimizing the Operation of a Double-Powered Induction Generator-Based Dual-Rotor Wind Turbine System, " Mathematics, Vol.9, No.19, 2021, 2297. doi: 10.3390/math9182297.

13. R. P. Jastrzebski, A. Putkonen, E. Sikanen, A. Zhuravlev, T. Choudhury, E. Kurvinen, J. Pyrhönen, "Dynamics of High-Power Multi-Rotor System, " 2022 International Conference on Electrical Machines (ICEM), pp. 1225-1231, 2022, doi: 10.1109/ICEM51905.2022.9910631.

14. D. R. Absalyamov, P. V. Druzhinin and N. B. Litvinova, " Regulation of Diesel Electric Installations with Asynchronous Generators in Static and Dynamic Modes, " 2020 International Multi-Conference on Industrial Engineering and Modern Technologies (FarEastCon), pp. 1-4, 2020, doi: 10.1109/FarEastCon50210.2020.9271422.

15. S. Omar, D. Dobrilov and N. Ratajov, " Possibilities for connection of asynchronous generators over 500 kW in the distribution network, " 2020 12th Electrical Engineering Faculty Conference (BulEF), pp. 1-4, 2020 doi: 10.1109/BulEF51036.2020.9326023.

16. Z. Xiaolin, D. Wei, Y. Guanzxiu and Z. Junjun, " Test Method for Inertia and Damping of Photovoltaic Virtual Synchronous Generator Based on Power Angle Transfer Function, " 2018 2nd IEEE Conference on Energy Internet and Energy System Integration (EI2), pp. 1-5, 2018, doi: 10.1109/EI2.2018.8581880.

17. S. R. Mohanrajan, A. Vijayakumari, K. Kottayail Sasi, " Dynamic Frequency Tracking for Voltage and Frequency Regulation of Wind Driven Doubly Fed Induction Generator in Standalone mode, " International Journal of Renewable Energy Research-IJRER, Vol. 10, No. 4, pp.1927-1939, 2020.

18. F. Bouaziz, A. Masmoudi, A. Abdelkafi, L. Krichen, " Coordinated Control of SMES and DVR for Improving Fault Ride-Through Capability of DFIG-based Wind Turbine, " International Journal of Renewable Energy Research-IJRER,Vol. 12, No. 1, pp.359-371, 2022.

19. L. Yu, Z. Zhang, Z. Chen and Y. Yan, " Analysis and Verification of the Doubly Salient Brushless DC Generator for Automobile Auxiliary Power Unit Application, " in IEEE Transactions on Industrial Electronics, vol. 61, no. 12, pp. 6655-6663, Dec. 2014, doi: 10.1109/TIE.2014.2320224.

20. M. Mehta, B. Mehta, " Modified Rotor Flux Estimated Direct Torque Control for Double Fed Induction Generator, " International Journal of Renewable Energy Research-IJRER, Vol 12, No. 1, pp. 124-133, 2022. https://doi.org/10.20508/ijrer.v12i1.12615.g8380.

21. S. A. nasef, A. A. Hassan, H. T. Elsayed, M. B. Zahran, M. K. El-Shaer, A. Y. Abdelaziz, " Optimal Power Management and Control of Hybrid Photovoltaic-Battery for Grid-Connected Doubly-Fed Induction Generator Based Wind Energy Conversion System, " International Journal of Renewable Energy Research-IJRER, Vol. 12, No. 1, pp.408-421, 2022.

22. H. Benbouhenni, " Comparative study between PWM and SVPWM technique for a DFIG-based wind turbine

system controlled by fuzzy sliding mode," Majlesi Journal of Energy Management, Vol. 7, No. 4, 2018.
23. H. Benbouhenni, "Comparison study between FPWM and NSVM inverter in neuro-sliding mode control of reactive and active power control of a DFIG-based wind energy," Majlesi Journal of Energy Management, Vol. 6, No. 4, pp.15-23, 2017.
24. Z. Boudjema, H. Benbouhenni, A. Bouhani, F. Chabni, " DSPACE implementation of a neural SVPWM technique for a two level voltage source inverter," Iranian Journal of Electrical & Electronic Engineering, Vol. 17, No. 3, pp.1-9, 2021.
25. H. Benbouhenni, "FPWM technique based based converter for IM drives," Acta Electrotechnica et Informatica, Vol. 19, No. 1, pp. 32-41, 2019.
26. H. Benbouhenni, "A new SVM scheme based on ANN controller of a PMSG controlled by DPC strategy," Majlesi Journal of Energy Management, Vol. 7, No. 1, pp. 11-19, 2018.
27. H. Benbouhenni, "Direct vector control for doubly fed induction generator-based wind turbine system using five-level NSVM and two-level NSVM technique," International Journal of Smart Grid, Vol. 3, No. 1, pp. 25-32, 2019.
28. H. Benbouhenni, N. Bizon, I. Colak, " A Brief Review of Space Vector Modulation (SVM) Methods and a New SVM Technique Based on the Minimum and Maximum of the Three-Phase Voltages, " Iranian Journal of Electrical & Electronic Engineering, Vol. 18, No. 3, pp.1-18, 2022. Doi:10.22068/IJEEE.18.3.2358.
29. H. Benbouhenni, "Comparison study between SVPWM and FSVPWM strategy in fuzzy second order sliding mode control of a DFIG-based wind turbine," Carpathian Journal of Electronic and Computer Engineering, Vol. 12, No. 2, pp. 1-10, 2019.
30. L. Shang, J. Hu, " Sliding-Mode-Based Direct Power Control of Grid-Connected Wind-Turbine-Driven Doubly Fed Induction Generators Under Unbalanced Grid Voltage Conditions, " IEEE Trans. Energy Convers., Vol. 27, pp. 362–373, 2012.
31. D. Sun, X. Wang, " Low-Complexity Model Predictive Direct Power Control for DFIG under both Balanced and Unbalanced Grid Conditions, " IEEE Trans. Ind. Electron., Vol. 63, pp. 5186–5196, 2016.
32. S. Bouallègue, J. Haggège, M. Ayadi, M. Benrejeb, " PID-type fuzzy logic controller tuning based on particle swarm optimization, " Eng. Appl. Artif. Intell., Vol. 25, pp. 484-493, 2012.
33. M. E. I. Azzaoui, H. Mahmoudi, " Fuzzy-PI control of a doubly fed induction generator-based wind power system, " Int. J. Autom. Control., Vol. 11, pp. 54-66, 2017.
34. M. R. Douiri, A. Essadki, M. Cherkaoui, " Neural Networks for Stable Control of Nonlinear DFIG in Wind Power Systems, " Procedia Comput. Sci., Vol. 127, pp. 454-463, 2018.
35. W. Zhi-nong, Y. Xiao-yong, W. Jia-jia, H. Lian-shan, X. Xiang, C. Dan, W. Yue, "The intelligent control of DFIG-based wind generation, " 2009 International Conference on Sustainable Power Generation and Supply, pp. 1-5, 2009, doi: 10.1109/SUPERGEN.2009.5348146.
36. P. Pura, G. Iwanski, " Direct torque control of a doubly fed induction generator working with unbalanced power grid, " Int. Trans. Electr. Energy Syst., Vol. 29, e2815, 2019.
37. L. Li, H. Nian, L. Ding, B. Zhou, " Direct Power Control of DFIG System Without Phase-Locked Loop Under Unbalanced and Harmonically Distorted Voltage, " IEEE Trans. Energy Convers., Vol. 33, pp. 395–405, 2018.
38. A. Djoudi, H. Chekireb, E. M. Berkouk, S. Bacha, " Low-cost sliding mode control of WECS based on DFIG with stability analysis, " Turk. J. Electr. Eng. Comput. Sci., Vol. 23, pp. 1698–1714, 2015.
39. K. R. Rajasekhara, V. B. R. Naga, M. K. Vijaya, " A Sliding Mode Controller Approach for Three Phase Single Stage Seven Level Multilevel Inverter for Grid Connected Photovoltaic System, " International Journal of Renewable Energy Research-IJRER, Vol. 10, No. 4, pp.1674-1684, 2020.
40. A. Ardjal, M. Bettayeb, R. Mansouri and A. Mehiri, " Nonlinear synergetic control approach for dc-link voltage regulator of wind turbine DFIG connected to the grid, " 2018 5th International Conference on Renewable Energy: Generation and Applications (ICREGA), pp. 94-97, 2018, doi: 10.1109/ICREGA.2018.8337639.
41. H. Xue, Y. Wang and F. Yang, " Adaptive passivity-based control strategies of doubly fed induction wind power generator systems, " The 2nd International Symposium on Power Electronics for Distributed Generation Systems, pp. 731-734, 2010, doi: 10.1109/PEDG.2010.5545935.
42. H. Mokhliss, E. Baghaz, R. Rmaily, K. Rais, " Validation of Synergetic Control Theory approach for parameters extraction of four parameters model, " International Journal of Renewable Energy Research-IJRER, Vol 11, No 4, pp.1841-1849, 2021. https://doi.org/10.20508/ijrer.v11i4.12361.g8337.
43. H. Benbouhenni, N. Bizon, " Terminal Synergetic Control for direct active and reactive powers in Asynchronous Generator-based Dual-Rotor Wind Power Systems, " Electronics, Vol.10, No.16, pp.1-23, 2021. https://doi.org/10.3390/electronics10161880.
44. A. P. Shah and A. J. Mehta, " Direct power control of grid-connected DFIG using variable gain super-twisting sliding mode controller for wind energy optimization, " IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society, pp. 2448-2454, 2017, doi: 10.1109/IECON.2017.8216412.
45. X. Yu, Z. Jiang, Y. Zhang, " A synergetic control approach to grid-connected, wind-turbine doubly-fed induction generators, " 2008 IEEE Power Electronics Specialists Conference, pp. 2070-2076, 2008, doi: 10.1109/PESC.2008.4592248.
46. J. Listwan, " Application of super-twisting sliding mode controllers in direct field-oriented control system of six-phase induction motor: experimental studies, " Power Electronics and Drives, Vol. 3, No. 1, pp. 23-34, 2018. doi: https://doi.org/10.2478/pead-2018-0013.
47. H. Benbouhenni, " A comparative study between DTC-NSTMC and DTC-FSTSMC control scheme for a DFIG-based wind turbine, " Majlesi Journal of Energy Management, Vol. 7, No. 4, 2018.

48. H. Benbouhenni, “ Stator current and rotor flux ripples reduction of DTC DFIG drive using FSTSMC algorithm,” International Journal of Smart Grid, Vol. 3, No. 4, 2019.

49. H. Benbouhenni, N. Bizon, “ Terminal Synergetic Control for direct active and reactive powers in Asynchronous Generator-based Dual-Rotor Wind Power Systems, ” Electronics, Vol.10, No.16, pp.1-23, 2021. https://doi.org/10.3390/electronics10161880.

50. H. Benbouhenni, Fayçal Mehedi, Lemdani Soufiane, “ New direct power synergetic-SMC technique based PWM for DFIG integrated to a variable speed dual-rotor wind power, ” Automatika, Vol. 63, No.4, pp.718-731, 2022. DOI: 10.1080/00051144.2022.2065801.

51. H. Benbouhenni, S. Lemdani, “ Combining synergetic control and super twisting algorithm to reduce the active power undulations of doubly fed induction generator for dual-rotor wind turbine system, ” Electrical Engineering & Electromechanics, 2021, No. 3, pp. 8-17, 2021. doi: https://doi.org/10.20998/2074-272X.2021.3.02.

52. R. W. Y. Habash, V. Groza and P. Guillemette, “ Performance optimization of a dual-rotor wind turbine system, ” 2010 IEEE Electrical Power & Energy Conference, pp. 1-6, 2010, doi: 10.1109/EPEC.2010.5697229.

53. M. S. Islam, S. M. Tanbinul Hoque, M. R. Hazari, M. M. Hasan and M. Uddin, “ Design and Simulation of a Dual Rotor Wind Turbine based PMSG System, ” 2021 2nd International Conference on Robotics, Electrical and Signal Processing Techniques (ICREST), pp. 17-20, 2021, doi: 10.1109/ICREST51555.2021.9331134.

54. S. A. Kale and S. N. Sapali, “ Power output prediction and primary evaluation of a unidirectional co-axial series rotors wind turbine, ” 2013 Annual International Conference on Emerging Research Areas and 2013 International Conference on Microelectronics, Communications and Renewable Energy, pp. 1-3, 2013, doi: 10.1109/AICERA-ICMiCR.2013.6576030.

55. O. Beik and A. S. Al-Adsani, “ Active and Passive Control of a Dual Rotor Wind Turbine Generator for DC Grids, ” in IEEE Access, vol. 9, pp. 1987-1995, 2021, doi: 10.1109/ACCESS.2020.3047267.

56. J. Ma, D. Zhao, L. Yao, M. Qian, K. Yamashita and L. Zhu, “ Analysis on application of a current-source based DFIG wind generator model, ” in CSEE Journal of Power and Energy Systems, vol. 4, no. 3, pp. 352-361, September 2018, doi: 10.17775/CSEEJPES.2018.00060.

57. A. Ejlali and D. Arab khaburi, “ Power quality improvement using nonlinear-load compensation capability of variable speed DFIG based on DPC-SVM method, ” The 5th Annual International Power Electronics, Drive Systems and Technologies Conference (PEDSTC 2014), pp. 280-284, 2014, doi: 10.1109/PEDSTC.2014.6799386.

58. B. Hu, H. Nian, J. Yang, M. Li and Y. Xu, “ High-Frequency Resonance Analysis and Reshaping Control Strategy of DFIG System Based on DPC, ” in IEEE Transactions on Power Electronics, Vol. 36, No. 7, pp. 7810-7819, July 2021, doi: 10.1109/TPEL.2020.3045860.

59. F. Mazouz, S. Belkacem, I. Colak, “ DPC- SVM of DFIG Using Fuzzy Second Order Sliding Mode Approach, ” International Journal of Smart Grid, Vol 5, No 4, pp.174-182, 2021. https://doi.org/10.20508/ijsmartgrid.v5i4.219.g175.

60. K. Xiahou, M. S. Li, Y. Liu and Q. H. Wu, “ Sensor Fault Tolerance Enhancement of DFIG-WTs via Perturbation Observer-Based DPC and Two-Stage Kalman Filters, ” in IEEE Transactions on Energy Conversion, vol. 33, no. 2, pp. 483-495, June 2018, doi: 10.1109/TEC.2017.2771250.

61. H. B. Mahdhi, H. B. Azza and M. Jemli, “ Direct Power Control of a PMSG in Wind Power Conversion System under Faulty Rectifier Conditions, ” 2019 19th International Conference on Sciences and Techniques of Automatic Control and Computer Engineering (STA), pp. 394-398, 2019, doi: 10.1109/STA.2019.8717311.

62. H. Benbouhenni, “ 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, ” Iranian (Iranica) Journal of Energy and Environment, Vol.12, No.2, pp. 109-117, 2021.

63. A. Fekik, H. Denoun, M. L. Hamida, A. T. Azar, M. Atig and Q. M. Zhu, “ Neural Network Based Switching State Selection for Direct Power Control of Three Phase PWM-Rectifier, ” 2018 10th International Conference on Modelling, Identification and Control (ICMIC), pp. 1-6, 2018, doi: 10.1109/ICMIC.2018.8529997.

64. M. Pichan, H. Rastegar and M. Monfared, “ Fuzzy-based direct power control of doubly fed induction generator-based wind energy conversion systems, ” 2012 2nd International Conference on Computer and Knowledge Engineering (ICCKE), pp. 66-70, 2012, doi: 10.1109/ICCKE.2012.6395354.

65. L. Shang and J. Hu, “ Sliding-Mode-Based Direct Power Control of Grid-Connected Wind-Turbine-Driven Doubly Fed Induction Generators Under Unbalanced Grid Voltage Conditions, ” in IEEE Transactions on Energy Conversion, vol. 27, no. 2, pp. 362-373, June 2012, doi: 10.1109/TEC.2011.2180389.

66. X. Wang, D. Sun and Z. Q. Zhu, “ Resonant-Based Backstepping Direct Power Control Strategy for DFIG Under Both Balanced and Unbalanced Grid Conditions, ” in IEEE Transactions on Industry Applications, vol. 53, no. 5, pp. 4821-4830, Sept.-Oct. 2017, doi: 10.1109/TIA.2017.2700280.

67. A. Swikir and V. Utkin, “ Chattering analysis of conventional and super twisting sliding mode control algorithm, ” 2016 14th International Workshop on Variable Structure Systems (VSS), pp. 98-102, 2016, doi: 10.1109/VSS.2016.7506898.

68. S. Velpula, R. Thirumalaivasan and M. Janaki, “ Stability Analysis on Torsional Interactions of Turbine-Generator Connected With DFIG-WECS Using Admittance Model, ” in IEEE Transactions on Power Systems, vol. 35, no. 6, pp. 4745-4755, Nov. 2020, doi: 10.1109/TPWRS.2020.2992111.

69. Z. -C. Zou and J. Yao, “ Efficient HVRT Scheme of DFIG Using a SSFCL-Chopper Considering Grid Voltage Recovery, ” in IEEE Transactions on Applied Superconductivity, vol. 31, no. 8, pp. 1-3, Nov. 2021, Art no. 5403803, doi: 10.1109/TASC.2021.3110469.

70. S. Younes, T. Salah, H. Farid, L. B. Sofia, B. Mohit, M. A. Mosleh, S. A. Mohammed, S. M. G. Sherif, " New intelligent direct power control of DFIG-based wind conversion system by using machine learning under variations of all operating and com-pensation modes, " Energy Reports, Vol. 7, pp. 6394–6412, 2021. https://doi.org/10.1016/j.egyr.2021.09.075.

71. H. Ravikiran, M. Tukaram, " Modified Super Twisting algorithm based sliding mode control for LVRT enhancement of DFIG driven wind system, " Energy Reports, Vol. 8, pp. 3600–3613, 2022. https://doi.org/10.1016/j.egyr.2022.02.235.

72. F. Echiheb, Y. Ihedrane, B. Bossoufi, M. Bouderbala, S. Motahhir, M. Masud, S. Aljahdali, M. El Ghamrmi, " Robust sliding-backstepping mode control of a wind system based on the DFIG generator, " Scientific reports, Vol.22, 2022.

73. H. E. Alami, B. Bossoufi, S. Motahhir, E. H. Alkhammash, M. Masud, M. Karim, M. Taoussi, M. Bouderbala, M. Lamnadi, M. El Mahfoud, " FPGA in the Loop Implementation for Observer Sliding Mode Control of DFIG-Generators for Wind Turbines, " Electronics, Vol. 11, 116, 2022. https://doi.org/10.3390/electronics11010116.

74. B. Bossoufi, M. Karim, A. Lagrioui, M. Taoussi, " FPGA-Based Implementation nonlinear backstepping control of a PMSM Drive, " IJPEDS Int. J. Power Electron. Drive Syst., Vol. 4, pp. 12–23, 2014.

75. B. Bossoufi, M. Karim, A. Lagrioui, M. Taoussi, " FPGA-Based Implementation Sliding Mode Control and nonlinear Adaptive Backstepping control of a Permanent Magnet Synchronous Machine Drive, " Wseas Trans. Syst. Control, Vol. 9, pp. 86-100, 2014.

76. X. Yang, G. Liu, V. D. Le, C. Q. Le, " A novel model-predictive direct control for induction motor drives, " IEEJ Trans. Electr. Electron. Eng., Vol. 14, pp. 1691-1702, 2019.

77. M. Chakib, A. Essadki, T. Nasser, " A comparative study of PI, RST and ADRC control strategies of a doubly fed induction generator based wind energy conversion system, " Int. J. Renew. Energy Res., Vol. 8, pp. 964-973, 2018.