

RESEARCH ARTICLE

Super-twisting Control for a Stand-alone Double Star Induction Generator WECS with Battery Storage

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ABSTRACT

Many researchers are tending to develop non-linear controllers in order to overcome the limitations of proportion integral controllers (PI). This paper discusses a super-twisting strategy for controlling a new stand-alone wind power system based on a dual star induction generator (DSIG) with battery storage. This robust controller permits an amelioration in the quality of energy consumed by the load, despite the parametric variation, under random conditions. To attain this goal a Super-Twisting controller (STC) is used to regulate both the machine's rotation speed and the rotor flux, in order to extract the optimal power from the turbine; improve the dynamic performance of the system, and adapt to the variation of the magnetizing inductance. The performance and efficiency of the STC controllers are presented and compared with conventional sliding mode controller (SMC), backstepping controller (BC), and fuzzy proportional-integral controller (fuzzy-PI). The suggested STC method offers interesting features such as chattering reduction, finite convergence time, and robustness to parameter changes and system disturbances.

Keywords

Autonomous WECS;
Self-excited dual star;
Induction generator;
Battery storage;
Vector control;
Backstepping control;
Sliding mode control;
Fuzzy-PI control;
Super twisting control

Article History

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I. INTRODUCTION

For a long time, generating energy using fuel was a simple and efficient option in isolated places. Nevertheless, the problems of climate change and pollution have motivated studies to explore more ecological alternatives. Exploiting renewable energy sources appears to be a viable alternative. Wind power is the quickest-growing renewable energy source, increasing in popularity in both academic and industrial sectors [1, 2].

There are several types of wind turbine generators available for variable speeds. But, the doubly-fed induction generators (DFIG) remain the dominant and most extensively used technology in today's wind energy industry. The operation of DFIG in a wide speed range is assured by the way of the slip rings rotor connections [3]. DFIG provides benefits of a reduced inverter rating, increased system efficiency, low-cost power factor, and so on [4, 5]. Nevertheless, the existence of brushes and slip rings diminishes the (WECS)'s reliability and raises its maintenance expenses [6]. To overcome this challenge, brushless machines appear to provide a promising solution, especially the squirrel cage induction machine (IM).

The IM has met a particular interest in the production of electric energy. The success of this machine is due to its simplicity of construction, robustness, brushless, and high reliability [1-2], [7]. In addition, the DSIG

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brings more advantages to the classical three-phase machine such as power segmentation, torque ripple reduction and fault tolerance [3]. Consequently, this machine is chosen for this paper.

In wind power applications, the traditional setup consists of connecting the battery to the DC bus voltage through a bidirectional buck-boost converter. In this structure, the battery bank stores surplus energy while the charge demand is low [8]. Using DSIG allows us for more configurations, such as the one proposed in [9], in which the battery is linked to a storage winding via an inverter, allowing the battery to be charged while the charge demand is supplied with its nominal value while the wind allows; additionally, the suggested structure permits the primary converter to deliver nearly continuous power, see figure 1. Few studies have been done on this novel topology, which inspired us to work on it.

On the other hand, the DSIG is difficult to control because of the strong coupling between the electromagnetic torque and the flux. This problem can be solved by rotor flux-oriented control (RFOC). This technique permits the decoupling of these two quantities. For simplification reasons, many works consider that the magnetic circuit of the DSIG is not saturated, which causes a large divergence between simulation and reality [4], [6]. In the present work, a machine model taking into account the nonlinearity caused by the saturation effect is adopted.

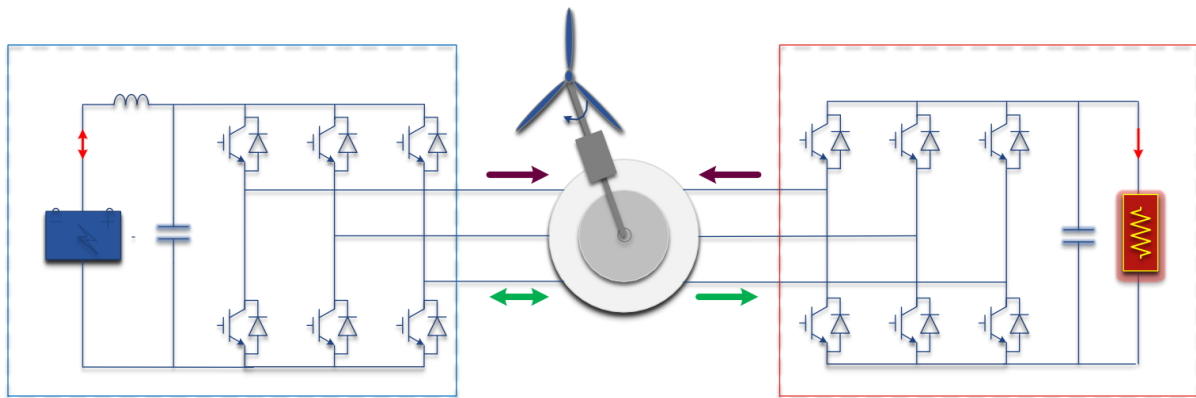


Fig 1. DSIG dc power system

Traditional PI controllers, are commonly used in several applications [10]. The main weakness of this controller is its sensitivity to external disturbances and parameter fluctuations. This sort of traditional controller does not provide the required quality power production and tracking references provided by an MPPT [11]. To address this issue, researchers are focusing on nonlinear controllers. The authors in [12] have presented the SMC controller. And in [13,14], the BC controller is used for highly nonlinear wind power systems with good dynamics during transients, but these regulators take more harmonics from the chattering phenomenon. Many researchers have proposed a PI-Fuzzy and a neural network controller to handle the problems of DSIG voltage change, high undershoot / overshoot of electromagnetic torque, and DC link voltage deviation. When compared to traditional controllers, the results achieved are more efficient. Though the dynamics might degrade if there are major changes in driving speed or load [15]. On the other hand, these controllers are more complicated and expensive in terms of calculations. Recently, the super-twisting approach has recently emerged as an interesting option for nonlinear system control. This approach ensures a nonlinear system's resilience and finite-time convergence. This method has resulted in the publication of several works [10],[16]. Applying this controller to the new topology looks to be fascinating.

In this article, we apply the super twisting control on the new autonomous WECS presented in figure 1. This controller is applied for the machine rotation speed, and the rotor flux regulation.

To accomplish this objective, this document is structured as follows: The model of the wind turbine and the DSIG are presented in sections 2 and 3, respectively. Section 4 discusses the theoretical aspects of the sliding

mode and super-twisting control. The super-twisting application to speed and flux control is demonstrated in Section 5. The simulation results, analysis, and discussion are covered in Section 6

II. WIND TURBINE MODEL

The power captured by the wind turbine blades given by the Betz theory is expressed as [12].

$$P_a = \frac{1}{2} C_p(\lambda) \rho S V^3 \quad (01)$$

A wind turbine can only convert a portion of the collected wind power. This proportion is denoted by $C_p(\lambda)$. The tip speed ratio is defined as [17]:

$$\lambda = \frac{R\Omega_t}{V} \quad (02)$$

The aerodynamic torque is also defined by:

$$T_a = \frac{P_a}{\Omega} \quad (03)$$

To increase the speed of the generator, a gearbox is placed between the turbine and the generator. If we neglect the transmission losses this speed is increased by a factor of G according to the following relationship:

$$\Omega_m = G\Omega_t \quad (04)$$

According to equation (1), (2) and figure (2) the optimal turbine speed is directly proportional to the wind speed with a well value of λ and β . To guarantee the MPPT, the generator rotation speed regulation is necessary.

III. MODELLING OF SELF-EXCITED DOUBLE-STAR INDUCTION GENERATOR

The machine is made up of two non-identical stators windings shifted by an angle of 30 electrical degrees. For reasons of simplification, we consider that the rotor is composed of a three-phase balanced winding, and in order to apply the RFOC control, the dq model is employed [18].

The electrical equations in dq reference frame are given as [12], [19]:

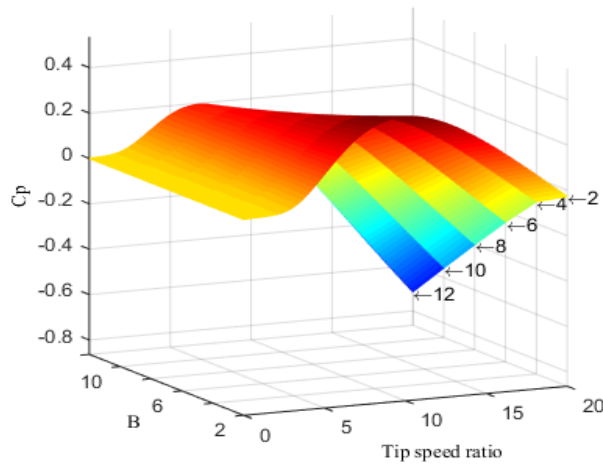


Fig 2. Power coefficient curve of wind turbine

$$\begin{cases} v_{d1} = r_{s1}i_{d1} + \dot{\varphi}_{d1} - \omega_e \varphi_{q1} \\ v_{q1} = r_{s1}i_{q1} + \dot{\varphi}_{q1} + \omega_e \varphi_{d1} \\ v_{d2} = r_{s2}i_{d2} + \dot{\varphi}_{d2} - \omega_e \varphi_{q2} \\ v_{q2} = r_{s2}i_{q2} + \dot{\varphi}_{q2} + \omega_e \varphi_{d2} \\ v_{dr} = r_r i_{dr} + \dot{\varphi}_{dr} - (\omega_e - \omega_r) \varphi_{qr} = 0 \\ v_{qr} = r_r i_{qr} + \dot{\varphi}_{qr} + (\omega_e - \omega_r) \varphi_{dr} = 0 \end{cases} \quad (05)$$

Where r_{sx} ($x = 1,2$) is the stator resistance; r_r rotor resistance; ω_e synchronous reference frame speed; ω_r machine rotation speed; all the other symbols stand for their usual meanings.

The stator, rotor flux linkages are expressed as follows [19]:

With

$$\begin{cases} \varphi_{d1} = L_{ls1}i_{d1} + L_{lm}(i_{d1} + i_{d2}) + L_{md}(i_{d1} + i_{d2} + i_{dr}) \\ \varphi_{q1} = L_{ls1}i_{q1} + L_{lm}(i_{q1} + i_{q2}) + L_{mq}(i_{q1} + i_{q2} + i_{qr}) \\ \varphi_{d2} = L_{ls2}i_{d2} + L_{lm}(i_{d1} + i_{d2}) + L_{md}(i_{d1} + i_{d2} + i_{dr}) \\ \varphi_{q2} = L_{ls2}i_{q2} + L_{lm}(i_{q1} + i_{q2}) + L_{mq}(i_{q1} + i_{q2} + i_{qr}) \\ \varphi_{dr} = L_{lr}i_{dr} + L_{md}(i_{d1} + i_{d2} + i_{dr}) \\ \varphi_{qr} = L_{lr}i_{qr} + L_{mq}(i_{q1} + i_{q2} + i_{qr}) \end{cases} \quad (06)$$

Where L_{lx} ($x = s, r$) is the stator (respectively rotor) leakage inductance; L_{lm} stator mutual leakage inductance; L_m magnetizing inductance.

In the linear magnetic conditions [19], [20]: $L_{md} = L_{mq} = L_m$, $L_{rd} = L_{rq}$. and both armatures (stator and rotor) are smooth poles

The magnetization inductance L_m as a function of the magnetizing current i_m is approximated by the polynomial of interpolation as follows [19].

$$L_m = 0.1406 + 0.0014i_m - 0.0012i_m^2 + 0.00005i_m^3 \quad (07)$$

The expression of the magnetizing current is given by [21]:

$$i_m = \sqrt{(i_d + i_{dr})^2 + (i_q + i_{qr})^2} \quad (08)$$

With:

$$i_d = i_{d1} + i_{d2} \quad (09)$$

$$i_q = i_{q1} + i_{q2} \quad (10)$$

The electromagnetic torque is given as:

$$T_{em} = P \frac{L_m}{L_{lr} + L_m} [i_q \varphi_{dr} - i_d \varphi_{qr}] \quad (11)$$

The machine's mechanical equation is as follows:

$$T_{em} - T_g = J\dot{\Omega} + f\Omega \quad (12)$$

IV. SUPER TWISTING CONTROL

SMC control is a strong non-linear control method that has been studied by numerous experts.

The SMC controller is separated into two major sections: the equivalent control Y_{eq} , and the switching control signal Y_n [5], [18].

$$Y = Y_n + Y_{eq} \quad (13)$$

we consider the sliding surface "S" where

$$S(X) = e \left(\frac{d}{dx} + \lambda \right)^{n-1} \quad (14)$$

In our case, we have

$$S(X) = e \quad (15)$$

The principal objective of this technic is to maintain $e = 0$ and $\dot{e} = 0$, thus, the condition to reach this objective is $e\dot{e} \leq 0$.

Second-order SMC algorithms maintain all of the attributes of classical SMC and reduce chattering in the system [22, 24]. The usual second-order algorithms published are twisting and super-twisting. Second-order SMC ensures the discontinuous term in the switching function's second-order differentiation.

The super twisting sliding mode controller for perturbation rejection and chattering elimination is Composed of two segments: a discontinuous part U_1 , and a continuous part U_2 [4], [11], [25] :

$$U = U_1(t) + U_2(t) \quad (16)$$

Where

$$U_1 = \begin{cases} -K_1 |S_0|^r \text{sign}(S) & \text{if } |U| > S_0 \\ -K_1 |S|^r \text{sign}(S) & \text{if not} \end{cases} \quad (17)$$

$$\dot{U}_1 = \begin{cases} -U & \text{if } |U| > U_M \\ -K_2 \text{sign}(S) & \text{if not} \end{cases}$$

Where

$$\begin{cases} K_2 > \frac{C_0}{K_m} & \text{if } 0 < r < 0.5 \\ K_1^2 > \frac{4C_0 K_m (k_2 + C_0)}{K_m^2 K_m (k_2 - C_0)} & \text{if } r = 0.5 \end{cases}$$

With: S_0 , C_0 , K_M and K_m are constants.

And if $S_0 = \infty$ this algorithm becomes:

$$\begin{cases} u = -K_1 |S|^r \text{sign}(S) + u_1 \\ \dot{u}_1 = K_2 \text{sign}(S) \end{cases} \quad (18)$$

V. APPLICATION OF SUPER-TWISTING ALGORITHM ON THE SPEED AND FLUX CONTROL

The mechanical equation of the machine is provided by equation (12):

$$J\dot{\Omega} = T_{em} - T_g - f\Omega \quad (19)$$

$$\dot{\Omega} = \frac{T_{em}}{J} - \frac{T_g}{J} - d_1 \quad (20)$$

If we consider that the sliding surface is equal to the error, we have:

$$S_\Omega = \Omega - \Omega^* \quad (21)$$

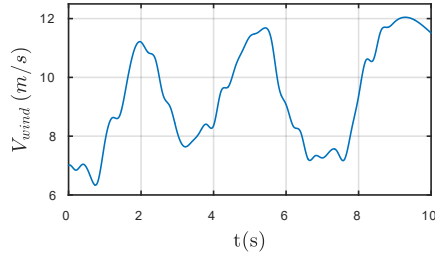


Fig 4. Wind speed profile

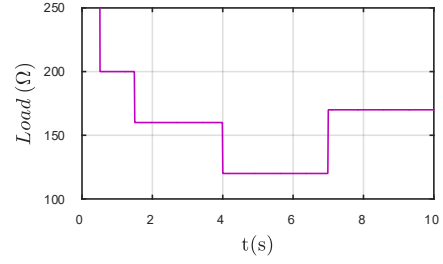


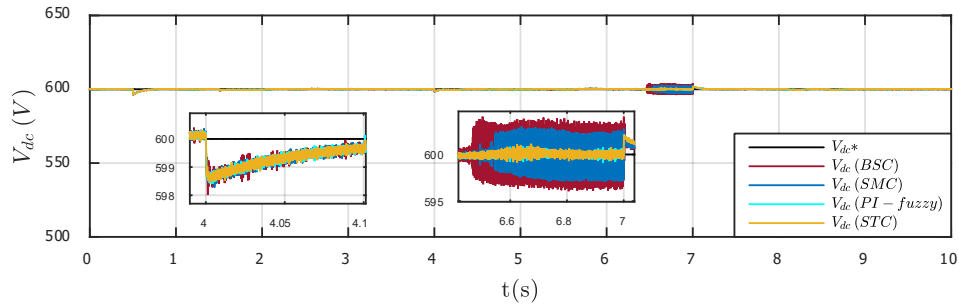
Fig 5. Variable resistive load

In (a) without saturation, all controllers are equal in terms of precision and rapidity. Except from $t=6.5$ to $t=7$ s, in low wind speed and high load, we can say that BC and SMC controllers take more harmonics compared to STC and fuzzy-PI which are still doing well.

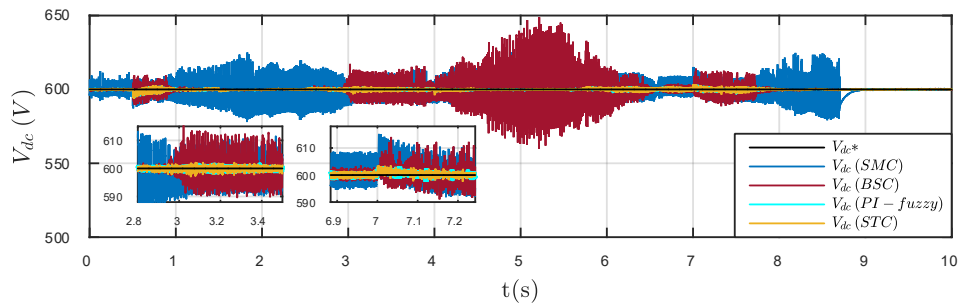
In (b) with magnetic circuit saturation, we notice that the BC and SMC present important disturbances, caused by the high variation of the magnetizing inductance. On the other hand, the STC and fuzzy-PI keep good performance.

Based on the above comments, it is evident that the STC is the best option for this application. This controller allows having similar performances to the fuzzy-PI controller with a simpler structure and low computation.

The next part of this article will be dedicated to the other results obtained with the super twisting controller. Figures 7 and 8 show the actual power coefficient of the turbine; and the DSIG rotation speed, respectively. The turbine rotation speed follows the profile of the optimal speed. Which is reflected by the good power coefficient. Knowing that the turbine's max coefficient $C_{pmax} = 0.43815$. Which verifies that the controller has assured the MPPT control of the system.



(a)



(b)

Fig 6. DC link voltage, (a) without magnetic circuit saturation, (b) with magnetic circuit saturation

Figures 9-11 illustrate respectively, the active power consumed by the resistive load; the power stored or delivered by the battery; and the battery's SOC. We can see that the load receives enough power in spite of the wind speed and the load variation. This is thanks to the storage system, which allows completing the

active power requested by the load in the case where the energy generated by the DSIG is lower than the demand and storage of the surplus.

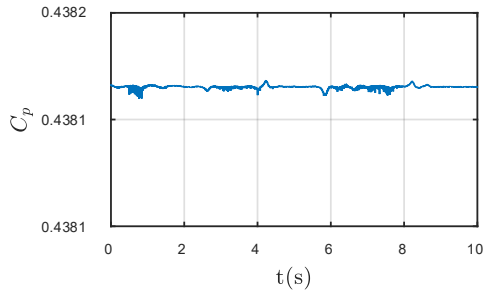


Fig 7. Actual power coefficients

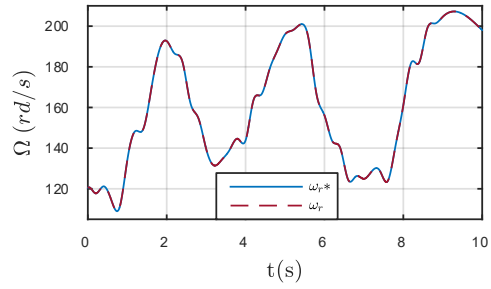


Fig 8. DSIG rotor speed

Figure 12 shows that the electromagnetic torque is always negative (generator mode). Even when the storage winding produces energy if the amount generated by the machine is insufficient. This is explained by the fact that energy is transmitted between the two stator windings (similar to a transformer). Because the frequency of the stator signals is lower than the machine rotation speed, no rotor intervention is required. This allows us to prevent further rotor loss.

Figures 13-15 show respectively the storage winding currents, the power winding currents, and the rotor winding currents. We notice that these currents are sinusoidal and do not contain many harmonics.

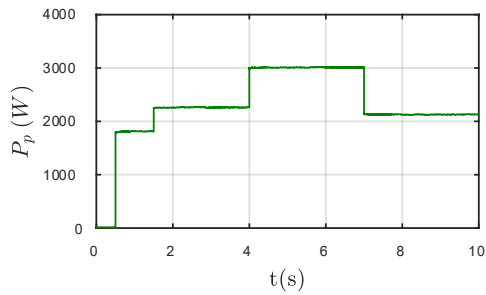


Fig 9. Output power of power winding

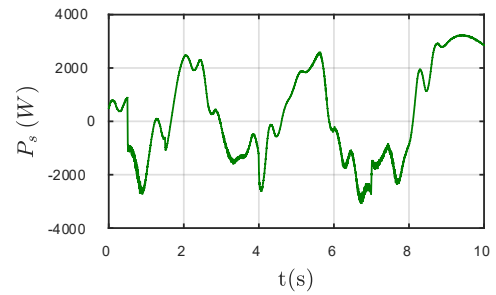


Fig 10. Output power of storage winding

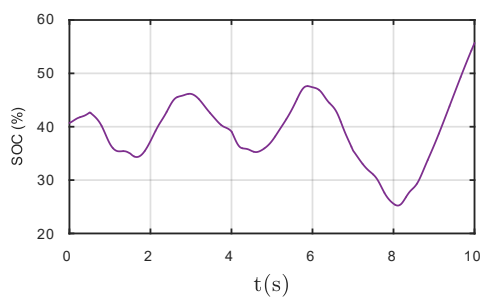


Fig 11. Battery state of charge

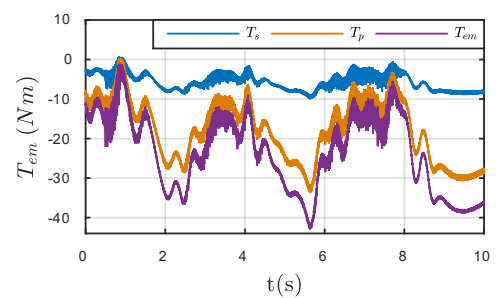
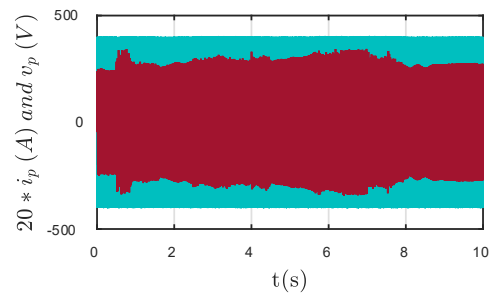
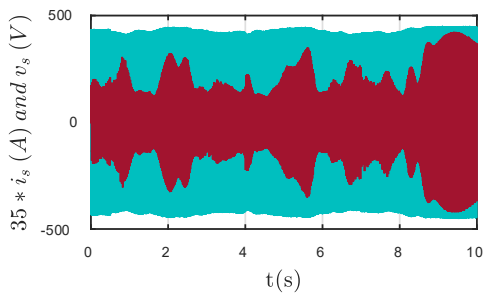


Fig 12. Electromagnetic torque of the two stator windings



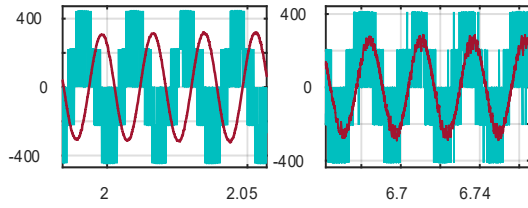


Fig 13. Currents and voltages of storage winding

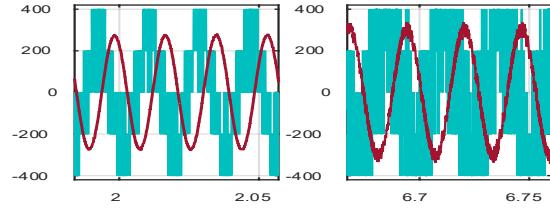


Fig 14. Currents and voltages of power winding

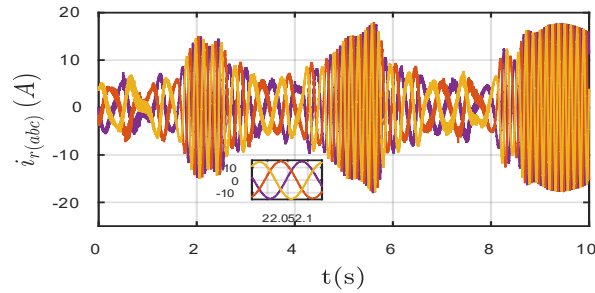


Fig 15. Rotor currents

VII. CONCLUSION

This article is dedicated to the control improvement of a new autonomous wind power system based on the DSIG using the STC controller. In order to adapt to the parametric variation (magnetic inductance variation). For this purpose, this robust controller is applied to the machine rotation speed regulation, and the rotor flux regulation. From the results, we found that the STC controller allows both to keep the advantage of nonlinear controllers (to maintain the system controllability despite the parametric variation); to reduce the chattering phenomenon (8% compared with BSC and 4% compared with SMC); and to have the same performance as the fuzzy-PI controller, with a simpler structure and less expensive in terms of calculations.

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APPENDIX

Tab 1. Wind turbine parameters [25]

SYMBOL	QUANTITY	VALUE
R	Rotor radius	2.325 m
J_t	Inertia	0.04 kg m²
P_w	Rated power	12.7kW
ω_w	Rated rotating speed	300 rpm
V_w	Rated wind speed	12.2m/s
ω_{max}	Maximum rotating speed	500rpm
V_s	Startup wind speed	3m/s
V_{IN}	Cut in wind speed	3 m/s

V_{OFF}	Cut off wind speed	20 m/s
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Tab 2. DSIG parameters

SYMBOL	QUANTITY	VALUE
P_n	Nominal power	8 KW
r_{s1}	Storage winding resistance	3.8 Ω
r_{s2}	Power winding resistance	1.27 Ω
r_r	Rotor resistance	2.1 Ω
L_{ls1}	Storage winding inductance	0.0264H
L_{ls2}	Power winding inductance	0.0088H
L_{lr}	Rotor inductance	0.0132H
L_{lm}	Stator mutual leakage inductance	0.011H
J	Moment of inertia	0.034 kg m ²
f	Viscous friction	0.001 Nm s/rd
$2P$	Number of poles	4

AUTHOR CONTRIBUTIONS

Y.H, S.B developed the theoretical formalism, writing original draft preparation, software. Both H.A, M.A and D.A. authors contributed to the final text version. H.A. supervised the project.

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