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Research Article

Control by Fuzzy Logic Associated with the Flow Oriented Command of the Dual Star Asynchronous Generator Integrated into a Wind Turbine

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Abstract

This paper aims to study and simulate the control of a wind turbine based on a double star asynchronous generator (GASDS); to control the energy production of this conversion chain the mechanical power generated should be optimised. Ensuring maximum power capture with the MPPT strategy (Maximum Power Point Tracking) for different wind speeds. For this purpose a control by fuzzy logic FLC associated with the orientation of the rotor flux FOC of the GASDS has been particularly described in order to improve system performance and better trajectory tracking in the case of the variant wind speed systems.

Keywords: Wind Turbine; GASDS; Flow Oriented Command; MPPT; Fuzzy logic control; MATLAB

Introduction

The wind resource comes from the movement of air masses which is due indirectly to the sunshine of the Earth. By the warming of certain areas of the planet and the other cooling, a pressure difference is created and the air masses are in perpetual displacement, it's the wind; which produces a considerable quantity of energy. It is defined by its direction and speed which varies according to the geographical zones and seasons.

A wind turbine is a chain of devices that transforms some of the kinetic energy of the wind into mechanical energy available on the transmission shaft and with a speed multiplier G the speed of rotation is increased where the generator can debit electricity into the grid by transforming the mechanical energy received on the rotation shaft of the electric generator into electrical energy [1, 3].

The entire conversion chain involves a wide variety of areas and poses aerodynamic, mechanical, electrical and automatic problems [6].

Areas of performance for a wind turbine

The converted power curve of a turbine, generally supplied by the manufacturers, which makes it possible to define four zones of operation for the wind turbine according to the wind speed (figure1).

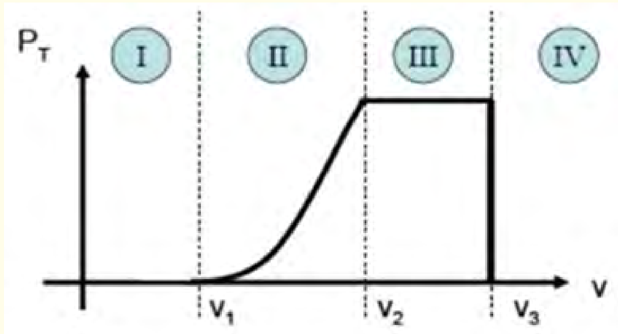

Figure 1: Areas of performance for a wind turbine.

The energy conversion must be maximized in zone II. In fact, two different controllers are requested. One for zone II, maximizing energy production, and one for zone III, keeps the power output constant at the nominal power [2, 3].

Optimization of the energy conversion of a wind turbine by MPPT strategy

Due to the erratic nature of the wind energy, turbine design and control modes must be optimized to extract the maximum power possible from wind energy. Some algorithms have been developed to obtain the optimal operating points of maximum power transfer (MPPT).

The principle of the Maximum Power Point Tracking (MPPT) strategy consists, for a given blade angle, of adjusting, depending on the wind speed V_{wind}, the speed of rotation of the turbine to a value reference Ω^*_{mec} to maintain an optimum relative speed and therefore a maximum power coefficient C_{Pmax},

$$\Omega^*_{mec} = \left(\frac{V_{wind} \cdot \lambda_{opt}}{R}\right)G \quad (1)$$

It is the action on the electromagnetic torque T_{em} (and thus on the power converted by the generator) which will make it possible to obtain Ω^*_{mec} and maximize the power extracted with the retention of C_{Pmax} [1, 7].

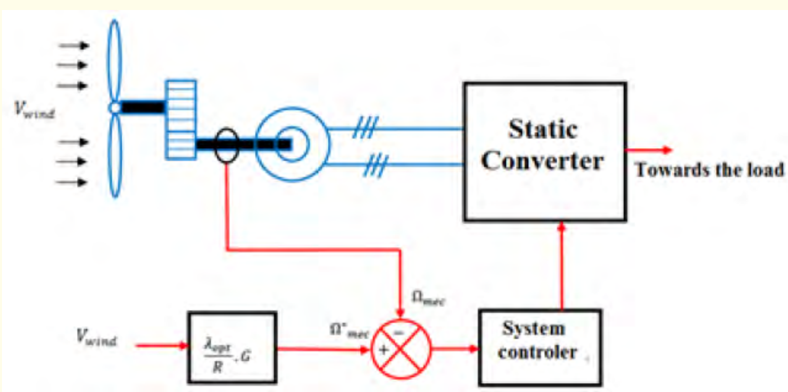

Figure 2: Strategy of the MPPT method.

Wind turbine based on a double star asynchronous generator

The asynchronous dual-star generator (GASDS) is like the asynchronous cage generator, if the rotational speed of the rotor is slightly greater than that of the magnetic field of the stator, then an electromagnetic force similar to that obtained with a Synchronous generator is developed, the machine does not generate its own excitation energy. For this, it will be necessary to provide this energy and stabilize its output voltage and its frequency through capacitors connected to the stator terminal.

The GASDS consists of a stator with two identical three phase windings offset by an electric angle α = 30 and a squirrel cage rotor.

When the rotor rotates at a speed Ω different from ΩS, the rotor cage becomes the seat of a system of three-phase electromotive forces generating themselves rotor induced currents which are manifested by the development of a torque of electromagnetic forces on the rotor to reduce t the speeds difference [4, 6].

Electric equations

The voltage equations of GASDS represent for each winding the sum of the ohmic drop and the inductive drop due to the flux.

For Star 1 $$[v_{s1}] = [R_{s1}][i_{s1}] + \frac{d[\varphi_{s1}]}{dt} \quad (2)$$

For star 2 $$[v_{s2}] = [R_{s2}][i_{s2}] + \frac{d[\varphi_{s2}]}{dt} \quad (3)$$

For rotor $$[v_r] = [R_r][i_r] + \frac{d[\varphi_r]}{dt} \quad (4)$$

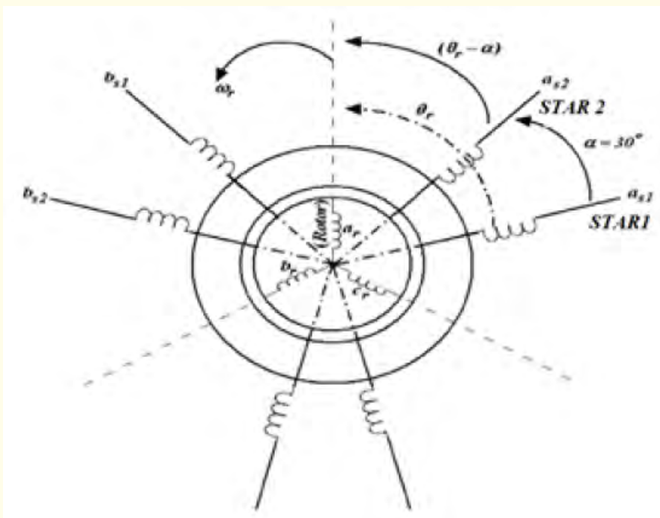

Figure 3: Schematic representation of stator and rotor windings of a GASDS.

Mechanical equation

The fundamental equation of machine motion is given by:

$$J\frac{d\Omega}{dt} = T_{em} - T_r - F_r\Omega \quad (5)$$

Two-phase model of the GASDS

The principle of the Two-phase transformation consists in replacing the magnitudes (current, voltage and flux) of real indices a, b, c by quantities of indices d, q, o (direct, in quadrature and homopolar) with the using Park's matrix.

$$[P(\theta_{s1})] = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta) & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ -\sin(\theta) & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}$$

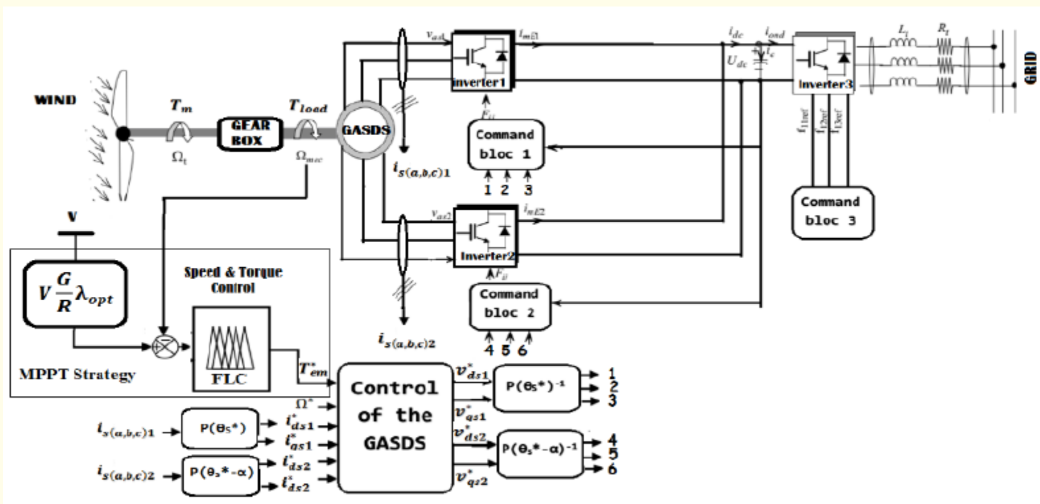

Figure 4: Schematic representation of the fuzzy control of GASDS ensuring the MPPT strategy.

By applying these transformations to voltages as well as to stator flows, we obtain the following classical electric model.

$$g = \frac{\omega_s - \omega_r}{\omega_s}$$

$$\begin{cases} \frac{d}{dt}\varphi_{ds1} = V_{ds1} - a_1\varphi_{ds1} + a_2\varphi_{ds2} + \omega_s\varphi_{qs1} + a_3\varphi_{dr} \\ \frac{d}{dt}\varphi_{ds2} = V_{ds2} - a_1\varphi_{ds2} + a_2\varphi_{ds1} + \omega_s\varphi_{qs2} + a_3\varphi_{dr} \\ \frac{d}{dt}\varphi_{qs1} = V_{qs1} - a_1\varphi_{qs1} + a_2\varphi_{qs2} - \omega_s\varphi_{ds1} + a_3\varphi_{qr} \\ \frac{d}{dt}\varphi_{qs2} = V_{qs2} - a_1\varphi_{qs2} + a_2\varphi_{qs1} - \omega_s\varphi_{ds2} + a_3\varphi_{qr} \\ \frac{d}{dt}\varphi_{dr} = -a_4\varphi_{dr} + a_5\varphi_{ds1} + (\omega_s - \omega_r)\varphi_{qr} + a_5\varphi_{ds2} \\ \frac{d}{dt}\varphi_{qr} = -a_4\varphi_{qr} + a_5\varphi_{qs1} - (\omega_s - \omega_r)\varphi_{dr} + a_5\varphi_{qs2} \\ \frac{d}{dt}\Omega_r = a_6 a_7(\varphi_{qs1}\varphi_{dr} - \varphi_{ds1}\varphi_{qr} + \varphi_{qs2}\varphi_{dr} + \varphi_{ds2}\varphi_{qr}) \\ \qquad -\frac{1}{J}(C_r + k\Omega_r) \end{cases}$$

Where :

$$a_1 = \frac{R_{s1}}{L_{s1}} - \frac{R_r L_a}{L_{s1}^2} \qquad , a_5 = \frac{R_r L_a}{L_r L_s}$$
$$a_2 = \frac{R_{s1} L_a}{L_{s2} L_{s1}} \qquad , a_6 = \frac{1}{L_{s1}} - \frac{L_a}{L_{s1}^2} - \frac{L_a}{L_{s1} L_{s2}}$$
$$a_3 = \frac{R_{s1} L_a}{L_r L_{s1}} \qquad , a_7 = \frac{P L_m}{J(L_m + L_r)}$$
$$a_4 = \frac{R_r}{L_r} - \frac{R_r L_a}{L_r^2}$$

The relation of the electromagnetic torque expressed as a function of the stator currents and rotor flows in the following Park (d, q) reference:

$$T_{em} = P \frac{L_m}{L_m + L_r} \left[\varphi_{rd}(i_{ds1} + i_{ds2}) - \varphi_{rq}\left(i_{qs1} + i_{qs2}\right)\right] \qquad (5)$$

Indirect vector control by orienting the rotor flow of the GASDS

The control of the double star asynchronous machine (GASDS) can be achieved by a vector control law. Those related to flow orientation, providing decoupled control between control variables, are still used in a wide range of industrial applications thanks to the high dynamic performance they provide. The purpose of this command is to assimilate the behavior of the asynchronous machine to that of a DC machine with separate excitation, decoupling the torque control from that of the flux [4, 5].

The decoupling can be achieved by several variants, by orientation of the stator flux, the flux in the gap, or the rotor flow, in our study, we opted for the rotor flow orientation technique.

Considering as reference quantities the rotor flux φ_r^* and the torque T_{em}^*, and ex-pressing that: $\begin{cases}\varphi_{dr} = \varphi_r^* \\ \varphi_{qr} = 0\end{cases}$ after replacing in the system of equations of the stator tensions, we obtain:

$$\begin{cases}
\frac{d}{dt} i_{ds1} = a_1 V_{ds1} - a_1 R_{s1} i_{ds1} + a_3 i_{qs1} + a_2 a_1 \varphi_r \\
\frac{d}{dt} i_{qs1} = a_1 V_{qs1} - a_1 R_{s1} i_{qs1} - a_3 i_{ds1} - a_3 a_1 \varphi_r \\
\frac{d}{dt} i_{ds2} = a_1 V_{ds2} - a_1 R_{s1} i_{ds2} + a_3 i_{qs2} + a_2 a_1 \varphi_r \\
\frac{d}{dt} i_{qs2} = a_1 V_{qs2} - a_1 R_{s1} i_{qs2} - a_3 i_{ds2} - a_3 a_1 \varphi_r \\
\frac{d}{dt} \varphi_r = -\frac{a_4}{L_m} \varphi_r + a_4 (i_{ds2} + i_{ds1}) \\
\frac{d}{dt} \Omega_r = \frac{1}{J} [\, p^2 \frac{a_4}{R_r} \varphi_r (i_{qs1} + i_{qs2}) - p C_r - K_r \Omega_r]
\end{cases}$$

where
$$\begin{cases}
a_1 = \frac{1}{L_{s1}} \\
a_2 = T_r \omega_{gl} \\
a_3 = \omega_s \\
a_4 = \frac{L_m R_r}{L_m + L_r}
\end{cases}$$

and : $\tau_r = \frac{L_r}{R_r} \quad , \omega_{gl} = \omega_s - \omega_r$

And from the torque expression we have:

$$i_{ds1}^* + i_{ds2}^* = \frac{\varphi_r^*}{L_m} \tag{6}$$

$$i_{qs1}^* + i_{qs2}^* = \frac{L_m+L_r}{PL_m\varphi_r^*} T_{em}^* \tag{7}$$

$$\omega_{gl}^* = \frac{R_r L_m}{(L_m+L_r)\varphi_r^*}(i_{qs1}^* + i_{qs2}^*) \tag{8}$$

For perfect decoupling, the control loops of the stator currents (i_{ds1}, i_{qs1}, i_{ds2}, i_{qs2}) are added and the voltages (v_{ds1}, v_{qs1}, v_{ds2}, v_{qs2}) are obtained at their outputs and to ensure a better robustness and functioning towards the internal or external disturbances we'll use the fuzzy logic regulator.

MPPT strategy modeling based on FLC

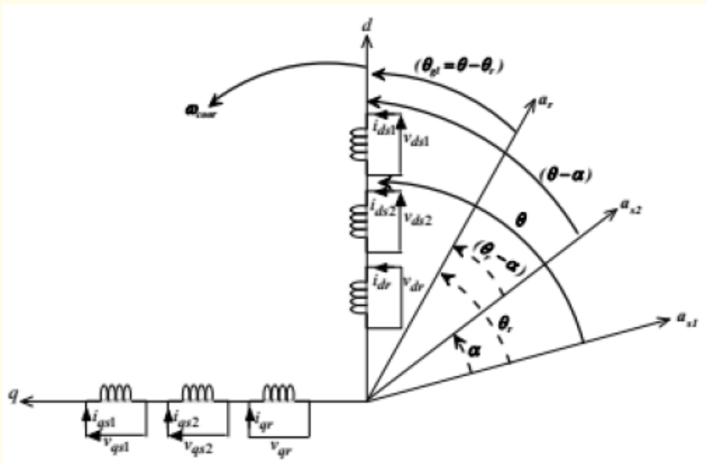

Figure 5: Schematic representation of the generalized model of the GASDS along the (d, q) axis.

Observation of the process shows that the significant quantities for the control are the speed error (e) and the variation of this error (Δe) which we will adopt them for the inputs of the fuzzy corrector, As for its output, it represents the increment of the control signal to be applied to the process to be controlled, which corresponds to the value of the reference torque T_{em}^*. This configuration, analogous to that of a conventional PI, is often referred to as fuzzy PI [3, 7].

Fuzzification

The objective of fuzzification is to transform the input deterministic variables into fuzzy variables, that is to say into linguistic variables, by defining membership functions for these different input variables.

- NB: Negative Big;
- PB: Positive Big.
- NS: Negative Small;
- PS: Positive Small;
- AZ: About Zero;

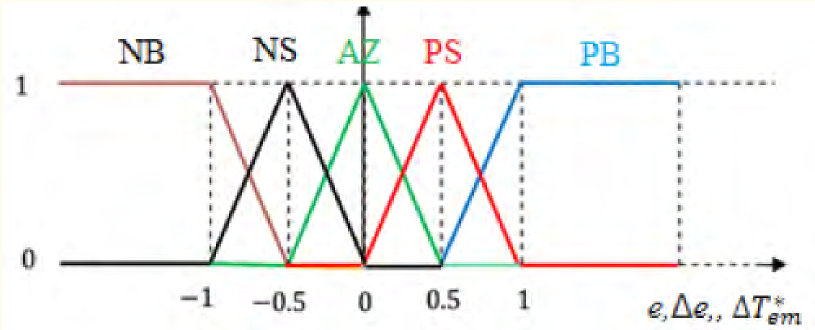

Figure 5: Membership functions of the inputs and the output of the selected fuzzy controller.

Fuzzy inference rules

Inference or decision making is the core of the fuzzy controller systems based on fuzzy logic use human knowledge to make decisions presented in the form of fuzzy rules based on concepts and expertise. They are expressed in the form If Then rules.

If (e) is NS and (Δe) is PB Then T^{*}_{em} is PS. Each of the two language inputs of the fuzzy controller has five fuzzy sets, which gives a set of twenty-five rules. These can be represented by the following inference matrix [3, 6]:

ΔT^{*}_{em}		Δe_n				
		NB	***NS***	***AZ***	***PS***	***PB***
e_n	NB	NB	NB	NS	NS	AZ
	NS	NB	NS	NS	AZ	PS
	AZ	NS	NS	AZ	PS	PS
	PS	NS	AZ	PS	PS	PB
	PB	AZ	PS	PS	PB	PB

Table 1: fuzzy regulator inference matrix.

This inference matrix is established by a logic that takes into account the physics of the system. Indeed, it is quite normal to generate a large positive reference torque variation when the error on the output speed of the MADA with respect to its set point and its variation are positive large (Rule 25), etc.

Defuzzification

The defuzzification consists in deducing a precise numerical value of the output of the regulator 1 from the resultant fuzzy conclusion T^{*}_{em} resulting from the inference operation consists in making a decision, that is to say, obtaining a real order obtained in the form of a fuzzy set. In the case of a reasoning based on the inference of fuzzy rules, several methods exist, the most commonly used is the Center of gravity method which we used in our work to obtain the crisp value of the reference torque [3, 6].

Association of FLC and FOC to the control of the GASDS

This part is devoted to the application of the fuzzy logic to the speed control of the GASDS with oriented rotor flow. It is a continuation of a velocity profile of strong non-linearity, which forces us to control it with a non-linear controller such as the fuzzy logic controller (RLF). In order to obtain a high-performance control system [1].

The principle of this method consists in directly determining the component of the rotor flux from the mechanical rotation speed of the rotor by using a speed sensor, this being achievable by a defluxing block defined by the following nonlinear function:

$$\varphi_r^* = \begin{cases} \varphi_r^* = \varphi_n & if \quad |\Omega| \le \Omega_n \\ \varphi_r^* = \varphi_n \frac{\Omega_n}{|\Omega|} & if \quad |\Omega| > \Omega_n \end{cases} \qquad (9)$$

The command must be limited by a saturation technique defined by:

$$T_{em}^* = \begin{cases} T_{em}^* & if \quad |T_{em}^*| \le T_{em}^{max} \\ T_{em}^{max} & if \quad |T_{em}^*| > T_{em}^{max} \end{cases}$$

For perfect decoupling ,we applied the FLC to the GASDS with FOC based on the method we adopted in MPPT control by introducing the error of the stator currents (i_{ds1}, i_{qs1}, i_{ds2}, i_{qs2}) and their variations as inputs and their voltage v_{ds1}, v_{qs1}, v_{ds2}, v_{qs2}) as outputs for the control loops [1; 3].

The schematic representation of the fuzzy logic control associated with the vector control by GASDS rotor flow orientation dedicated to the variable speed wind turbine system is illustrated in figure (6).

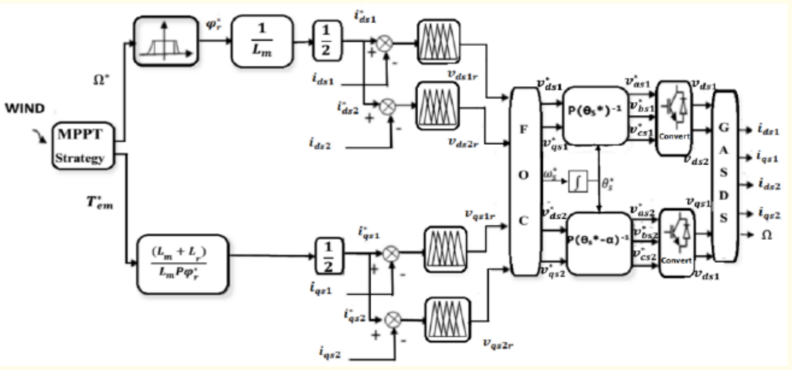

Figure 6: Block diagram of the FLC with orientation of the rotor flux of the GASDS.

Interpretations of the results

The control of the speed and the torque of the GASDS is carried out by simultaneous action on the frequency and on the amplitude of the stator voltage, based on variable frequency voltage inverters. Each star of the GASDS is connected to three-phase static converters (MLI) with controlled switching, the simulations were performed with the Matlab software.

For a variable wind speed according to the shape of the curve shown in Figure 7, the simulation results obtained for the wind are shown in Figures (8, 9, 10 and 11), for wind speeds lower than the nominal speed, the fuzzy MPPT technique optimizes the power captured by the wind turbine. When the wind speed exceeds the nominal speed, the fuzzy logic control loop reacts to maintain the power at its rated value.

Figure 8 shows the pace of the speed. It can be noted that the speed of rotation perfectly follows its reference which is variable according to the imposed wind profile (figure 7). The paces of the reference torque, derived from the MPPT algorithm and the electromagnetic torque of the generator, are illustrated in Figure 9, it shows that the electromagnetic torque reaches its maximum value when the wind speed is maximum, the remark is that the couple follows the couple of reference.

The (Figure 10) represents the stator currents of the two stars, we note that the 2nd star is shifted by an electric angle α = 30 from the 1st star.

The evolution of rotor flux is illustrated in Figure 15. The shape of the components of the rotor flux shows a good orientation of the flow, guaranteeing a well decoupled vector control of the GASDS.

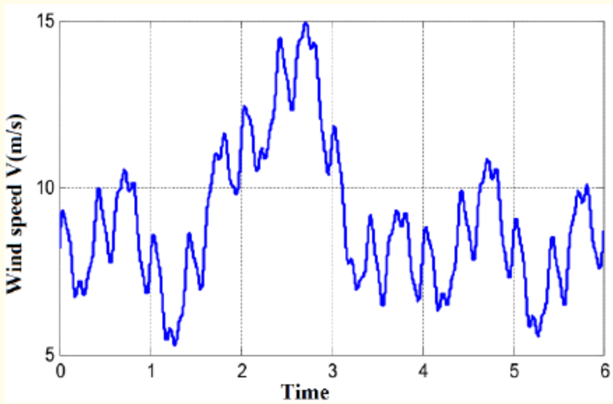

Figure 7: Wind speed.

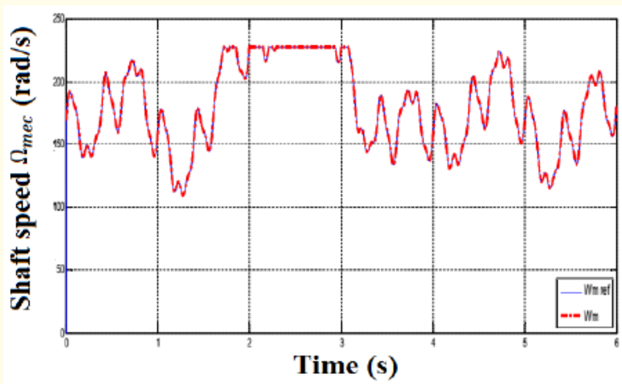

Figure 8: Speed of the GASDS and its reference.

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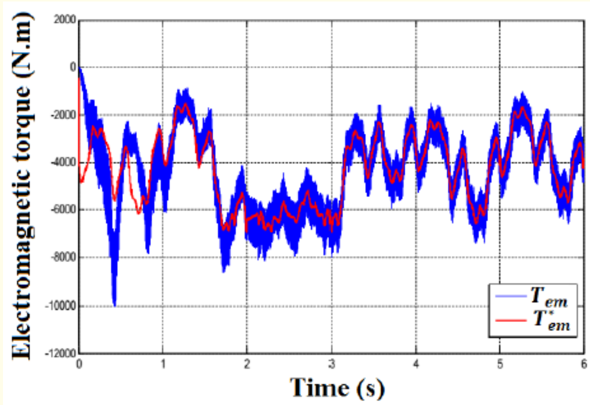

Figure 9: Electromagnetic torque and its reference.

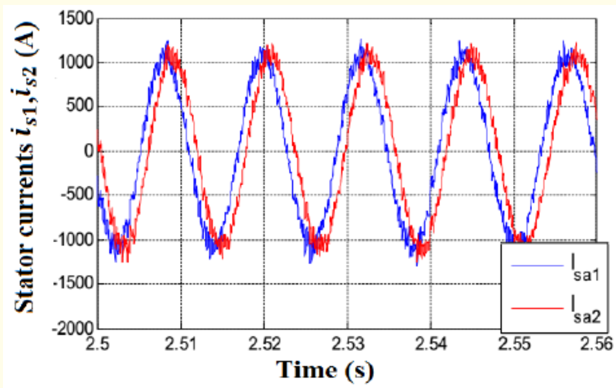

Figure 10: Stator currents.

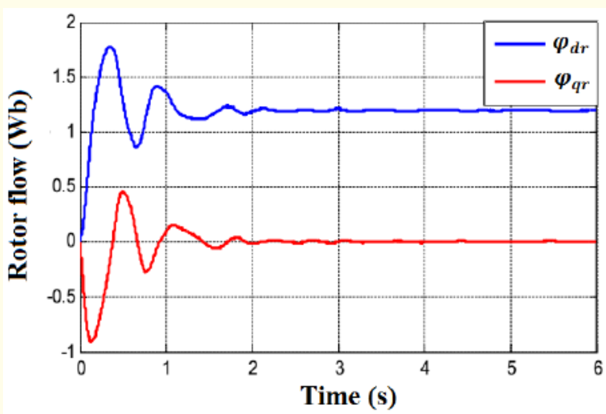

Figure 11: Direct and quadratic rotor flows.

Conclusion

This paper was devoted to the control of a wind turbine connected to the power grid based on the GASDS. The optimization of the wind energy conversion chain is carried out making an application on the control of the asynchronous duel star rotor oriented flow machine, in order to adjust the speed of the studied wind system to its optimal value ensuring the MPPT. The most suitable nonlinear method is the theory of fuzzy logic. In this technique we have used an FLC type regulator, which provides good dynamic and static performance and better trajectory tracking in the case of the time invariant system.

The torque control is applied to the generator using the principle of vector control with FOC which allows the GASDS to be treated in a manner similar to that of the DC machine, which provides an attractive solution to achieve better performance in variable speed wind energy applications which is simulated numerically using the MATLAB tool.

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