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A fuzzy logic supervisor for active and reactive power control of a variable speed wind energy conversion system associated to a flywheel storage system

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ABSTRACT

In this paper, we propose a Wind Energy Conversion System (WECS) at variable speed using a Doubly Fed Induction Generator (DFIG) controlled on the rotor side through converters. A Flywheel Energy Storage System (FESS) is connected to the studied wind generator at the DC bus in order to evaluate its capacity to participate to the ancillary services. We study the improvement of the active and reactive power quality produced by the wind generator and its effect on the load voltage regulation connected to the wind generator. For that, a fuzzy logic supervisor is established to control the FESS operation and the DC bus voltage in order to smooth the active power fluctuations due to the random wind speed variations. A control law is also described to smooth the reactive power at the connection node to the grid.

1. Introduction

In order to increase the penetration rate of the wind generators in the power electric system dispatching, it is necessary to incorporate them in the ancillary services such as voltage or frequency control and reactive power compensation. The association of an Energy Storage System (ESS) to these renewable sources has a significant role in the power system stability. In fact, an ESS can contribute to the energy balance between the production and the consumption. It provides the energy in case of consumption deficiency and accumulates it at high wind speeds for which the energy request is reduced. An ESS offers also the possibility of the power regulation supplied as well as the load voltage control connected to the wind generator.

Barton and Infield [1] have developed probabilistic methods to evaluate the energy storage capacity to increase the penetration of the intermittent embedded renewable generation (ERG) on the power system. The interest was concerted to the wind generator connections to the locations where the ERG level is limited by the voltage rise. Various storage technologies associated with their principal applications are then developed [1,2]. Therefore, a comparative study permits to classify them according to their time scales and their storage capacities. The FESS can be adopted for this production type which requires a storage capacity of a few minutes [3–5]. This is due to its important characteristics to ensure a high dynamic, a long lifespan and a good efficiency.

In Ref. [6], a variable speed WECS using a permanent magnet synchronous generator was adopted. A FESS is associated to the wind generator to smooth the fluctuated powers injected to grid. Different control laws and fuzzy supervision were elaborated in order to control the FESS operation, to regulate the DC bus voltage and to improve the powers quality provided for an operated mode coupled to the power electric system or to an isolated load.

Others [7,8] propose also an energy conversion structure with a variable speed generator based on a DFIG associated to a super capacitor. This storage element has the capability to compensate enough real power to the system for smoothing instantaneous wind fluctuations. It also ensures the system transient stability and improves the voltage quality supplied on the generator level.

In this paper, a method has been developed to reduce output power fluctuations of a DFIG with an energy storage system using a FESS. We are interesting on the study of the power quality improvement produced by the wind generator due to random wind speed variations and its effect on the load voltage control connected to the wind generator. A supervisor based on a fuzzy logic was elaborated to control the FESS operation in order to smooth the active power fluctuating. A control laws were also applied allowing the regulation of the DC bus voltage as well as the reactive power enhancement satisfying the load flow.

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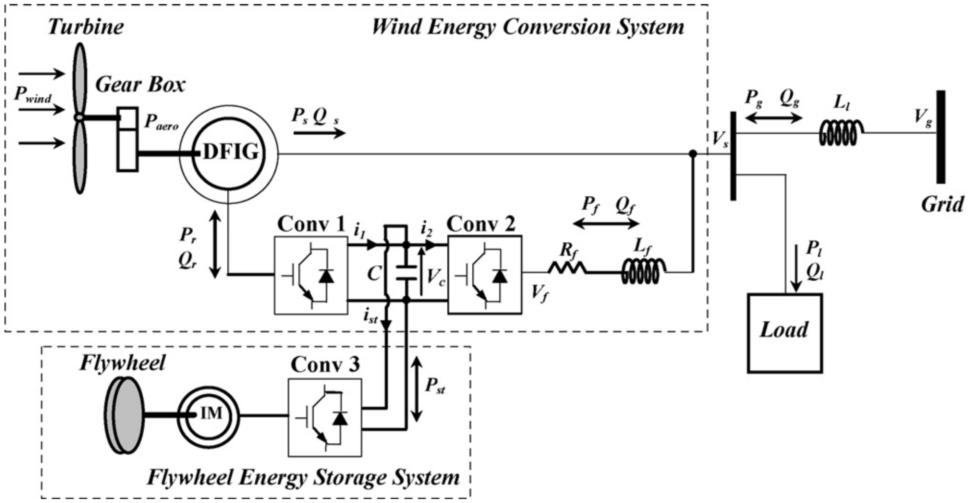

Fig. 1. WECS under consideration.

2. Desription of the studied WECS

The WECS adopted here is shown in Fig. 1. It consists of a DFIG driven by a wind turbine and controlled on the rotor side through the power converters which ensuring a variable speed operating. The stator is connected to the power electric system through a transmission line and supplying a load. The FESS coupled to DC bus, is constituted of an induction machine. The main purpose is the control of the active and reactive power transit in the system and its effect on the load voltage regulation.

3. DFIG control

To obtain the state model of the DFIG, we adopt the hypotheses of the oriented constant stator flux and we neglect the stator resistor, then we have:

$$\phi_{sq} = 0, \quad \frac{d}{dt}\phi_{sd} = 0, \quad v_{sd} = 0 \text{ and } v_{sq} = -V_s \tag{1}$$

where V_s is the stator voltage magnitude.

We deduce the following reduced state model as:

$$\begin{cases} v_{rd} = \sigma L_r \dfrac{d}{dt} i_{rd} + r_r i_{rd} - (\omega_s - \Omega_{mec})\, \sigma L_r i_{rq} \\ v_{rq} = \sigma L_r \dfrac{d}{dt} i_{rq} + r_r i_{rq} + (\omega_s - \Omega_{mec})\, \sigma L_r i_{rd} + \dfrac{M}{L_s}\phi_{sd}(\omega_s - \Omega_{mec}) \end{cases} \tag{2}$$

where v_{rd} and v_{rq} are the d and q components of the rotor voltage, respectively; v_{sd} and v_{sq} are the d and q components of the stator voltage, respectively; i_{rd} and i_{rq} are the d and q components of the rotor current, respectively; ϕ_{sd} and ϕ_{sq} are the d and q components of the stator flux, respectively; ω_s and Ω_{mec} are the synchronous pulsation and the aero generator speed, respectively; r_r is the rotor resistor; L_s, L_r and M are the stator, the rotor and the mutual inductance, respectively; σ is a leakage parameter such as $\sigma = 1 - (M^2/L_s L_r)$.

Usually, the DFIG control is ensured by a vector control of the rotor currents [9–11]. The maximum power point tracking (MPPT) is ensured by the converter 1 (Conv1) in the rotor side. The MPPT, which depends on the aerodynamic power and the wind speed turbine, is carried out in some work by using fuzzy rules [12] or by an artificial neuronal network [13].

4. DC bus voltage control

The converter 2 (Conv2) in the grid side ensures the DC bus voltage control as well as the exchanged active and reactive powers between the generator, the load, the power system and the FESS. Each converter exerts its influence on the DC bus by his injected current.

In power terms, and by neglecting the converter losses, the DC bus equation can be written as following:

$$\frac{d}{dt}V_C^2 = \frac{2}{C}(P_r - P_f - P_{st}) \tag{3}$$

where P_r is the active power in the rotor side, P_f is the P_r one transmitted through the filter and P_{st} is the FESS power (stored/restored).

The filter is used to attenuate the generated harmonics by the Conv2. By neglecting the filter resistor and tacking into account the hypothesis defined in Eq. (1), we obtain [14]:

$$v_{fd} = -L_f \omega_s i_{fq} \tag{4}$$

$$v_{fq} = L_f\, \omega_s i_{fd} - V_s \tag{5}$$

where i_{fd} and i_{fq} are the d and q components of the filter current, respectively; v_{fd} and v_{fq} are the d and q components of the modulated average voltage in the filter side, respectively.

The active and reactive powers transmitted into the grid through the filter are given by:

$$P_f = \frac{V_s}{L_f \omega_s} v_{fd} \tag{6}$$

and

$$Q_f = -\frac{V_s}{L_f \omega_s}(v_{fq} + V_s) \tag{7}$$

The two expressions (6) and (7) show that the powers P_f and Q_f can be separately controlled by v_{fd} and v_{fq}, respectively. Consequently, it would be possible to regulate the DC bus voltage by v_{fd}. The control diagram of the DC bus voltage V_C is shown in Fig. 2. The proportional integral regulator PI was introduced into the regulation loop to make null the regulation error and to eliminate the P_r and P_{st} effect considered as perturbations.

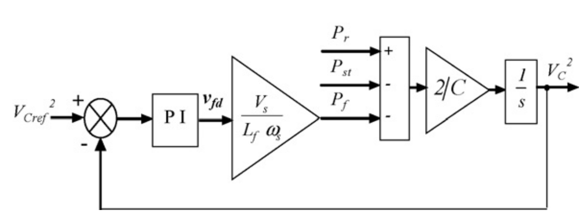

Fig. 2. Control of the DC bus voltage.

5. Power assessment

The active and reactive power assessment in the load connection node to the wind generator is given by:

$$P_g = P_s + P_f - P_l = P_m - P_l \tag{8}$$

$$Q_g = Q_s + Q_f - Q_l = Q_m - Q_l \tag{9}$$

where P_s and Q_s are the active and reactive powers provided by the wind generator in the stator side, respectively; P_f and Q_f are the active and reactive powers in the filter side, respectively; P_l and Q_l are the active and reactive powers of the load, respectively; P_m and Q_m are the active and reactive powers of the wind generator at the connection node, respectively.

The DFIG is coupled to the power system through a transmission line in the stator side. Thus, by neglecting the line resistor, we can write in steady state the following equations:

$$\begin{cases} V_{gd} - L_l\,\omega_s\, i_{gq} = 0 \\ V_{gq} + V_s + L_l\,\omega_s\, i_{gd} = 0 \end{cases} \tag{10}$$

with i_{gd} and i_{gq} are the d and q components of the transmission line current, respectively; V_{gd} and V_{gq} are the d and q components of the grid voltage, respectively; L_l is the line inductance.

Eq. (10) permit to deduce the P_g and Q_g expressions, which are given by:

$$P_g = -\frac{V_s V_{gd}}{L_l \omega_s} \tag{11}$$

and

$$Q_g = \frac{V_s}{L_l \omega_s}(V_{gq} + V_s) \tag{12}$$

In the same way, the computation of the stator voltage variations ΔV_s gives:

$$\Delta V_s^2 = \frac{2L_l\,\omega_s\,(V_s^2 - L_l\,\omega_s\,Q_g)}{2V_s^2 - 2L_l\omega_s Q_g - 1}\,\Delta Q_m - \frac{2L_l{}^2\,\omega_s^2 P_g}{2V_s^2 - 2L_l\omega_s Q_g - 1}\,\Delta P_m \tag{13}$$

Eq. (13) shows the relation between the stator voltage variations ΔV_s according to the active and reactive powers of the wind generator in the connection node.

Since the aerodynamic power is proportional to the cube of the wind speed [13], its random variations have a great influence on the powers quality of the DFIG and consequently on the quality of the whole electric parameters at the grid node. Therefore, in order to ensure a constant and smooth voltage V_s, it is preferred to impose a null reactive power Q_g injected into the grid ensuring a unit power factor. It is also necessary to approve a perfect P_m and Q_m powers smoothing. The DFIG presents the main advantage to produce the reactive power which can be controlled in order to impose $Q_m = Q_l$. This will be ensured by the converter 2 (Conv2) in the grid side. The active power smoothing will be ensured by the FESS, which according to the DC bus voltage control, allows to compensate its variations compared to the desired values.

6. Smoothing of the reactive power Q_m produced by the wind generator

To have a null reactive power injected into the grid, we must compensate the Q_s fluctuations by the converter 2 (Conv2) to guarantee the reactive assessment balance given by expression (9).

The regulation loop of the filter reactive power Q_f is showing in Fig. 3. This control loop permits to achieve the reference value choosing in order to satisfy the reactive power production and consumption at the load node, such as:

$$Q_{f\_ref} = Q_l - Q_s \tag{14}$$

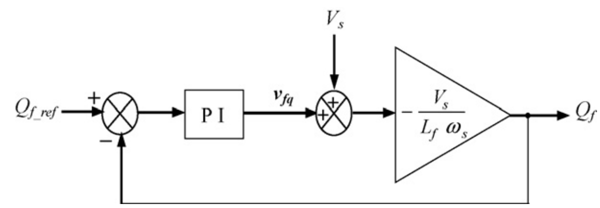

Fig. 3. Regulation loop of the filter reactive power Q_f.

Therefore, the reactive power smoothing permits to minimize the voltage variations ΔV_s, but it is insufficient to make it constant. For this reason, it is also indispensable to smooth the active power in order to improve the voltage quality.

7. FESS control

In this study, we assume that the load connected to the wind generator requires an active power P_l = 1.2 pu and a reactive power Q_l = 0.2 pu. In order to satisfy these two conditions and to ensure the balance between production and consumption as it is described by Eqs. (8) and (9), the use of the FESS is necessary [15]. Its importance appears mainly on its long duration capacity to store and restore the energy for various wind speed.

The FESS is connected to the wind energy conversion system through the DC bus. It permits to store the electric power in overproduction and to restore it in underproduction [16,17]. So, it contributes to the power regulation provided by the wind generator. This leads to improve the fluctuate active power quality satisfying the load consumption as well as its voltage regulation.

As it is defined previously, if P_m is the active power in the connection node, which corresponds to the aerodynamic power P_{aero} decreased by the machine losses, P_{reg} is the desired one injected to the grid, then the reference power of the FESS control P_{st} is determined by:

$$P_{st} = P_{reg} - P_m \tag{15}$$

The reference value P_{st} is added to the DC bus controller output. The integration of this expression gives the total power E_{fw} stored in the flywheel, so we have:

$$E_{fw} = E_{fw0} + \int P_{st}\; dt \tag{16}$$

where E_{fw0} is the initially flywheel stored energy.

While this energy depends on the flywheel speed Ω_{fw} by:

$$E_{fw} = \frac{1}{2} J_{fw}\; \Omega_{fw}^2 \tag{17}$$

then, we deduce the flywheel speed as following:

$$\Omega_{fw} = \sqrt{\frac{2E_{fw}}{J_{fw}}} \tag{18}$$

where J_{fw} is the flywheel inertia.

With this control law, the FESS does not contribute to the DC bus voltage control, which is ensured by the converter 2 (Conv2) in the grid side. If the wind generator will be coupled to the isolated load, the FESS control strategy must be modified. In fact, a new term will be added in Eq. (15) so that [6]:

$$P_{st} = P_{reg} - P_m - \Delta P \tag{19}$$

with ΔP is the needed power to control the DC bus.

This term permits to regulate the DC bus voltage through a PI regulator and it is incorporated in the speed control loop of the FESS certified by the converter 3 (Conv3). Consequently, the converter 2

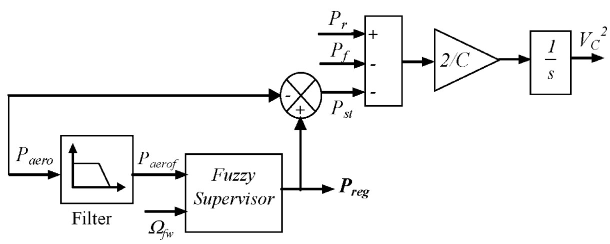

Fig. 4. Scheme of the fuzzy supervisor.

(Conv2) will ensure the frequency and voltage regulation applied to the isolated load.

8. FESS fuzzy supervisor

The power desired from the coupling flywheel-wind generator P_{reg} depends really on two parameters. The first one is the flywheel speed, which must be always preserved between the operation limits. The second one is the wind power accessibility associated to the weather conditions. For that, a fuzzy logic supervisor is established [18] to generate the adequate regulation power value P_{reg} according to the flywheel speed Ω_{fw} and the filtered wind power generated P_{aerof} as it is shown in Fig. 4.

The fuzzy system consists of Ω_{fw} and P_{aerof} inputs. Thus, three membership functions are proposed for each one defined as following: small (S), medium (M) and large (L) shown in Fig. 5.

According to the flywheel state and the wind speed evolution, the FESS must store or restore electrical power compared to the reference value. So, if the flywheel speed is too small, storage is favoured. Most of the generated power is so used to flywheel charge. If this speed becomes too high, the restitution is selected. Then, if the speed is middling, the system operates normally. Nine fuzzy rules are then defined which consequences are summarized in Table 1.

By adopting a Sugeno fuzzy inference system of 0 order, which not requiring a defuzzification stage, the fuzzy supervisor output is calculated as following:

$$P_{reg} = \frac{\sum_{i=1}^{9} \alpha_i\, y_i}{\sum_{i=1}^{9} \alpha_i} \qquad (20)$$

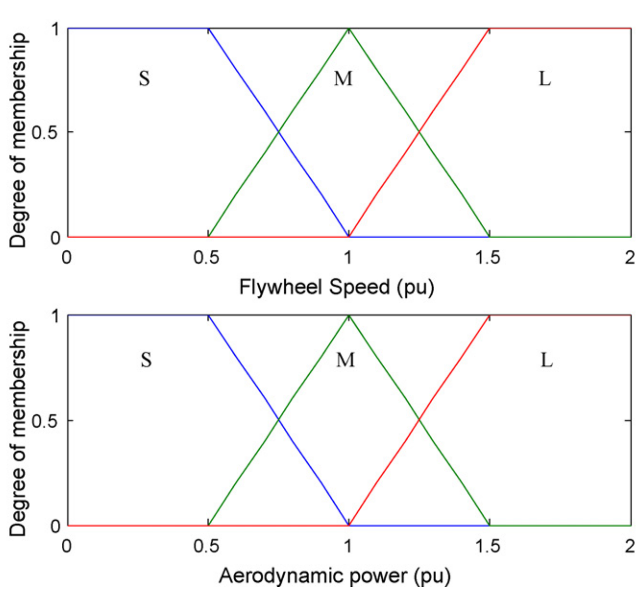

Fig. 5. Membership functions of input variables.

Table 1
Fuzzy inference table.

Ω_{fw} (pu)	P_{aerof} (pu) Small	Medium	Large
Small	VS	SM	BM
Medium	S	M	B
Large	SM	BM	VB

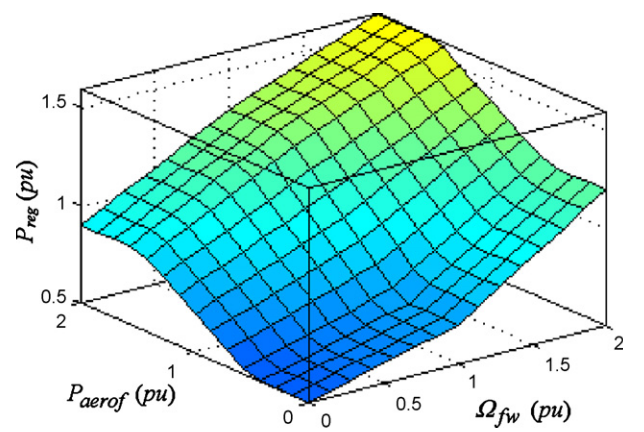

Fig. 6. Regulation power P_{reg} according to the flywheel speed Ω_{fw} and the filtered aerodynamic power P_{aerof}.

where y_i is the consequence of the fuzzy rule i which represents the smoothed desired power value.

α_i is such as:

$$\alpha_i = \prod_{j=1}^{3} \mu_j(\Omega_{fw})\mu_j(P_{aerof}), \quad i = 1\ldots 9 \qquad (21)$$

with $\mu_j(\Omega_{fw})$, $\mu_j(P_{aerof})$ are the membership degree of the variables Ω_{fw} and P_{areof}, respectively.

Fig. 6 shows the evolution of the desired regulation power delivered by the fuzzy supervisor P_{reg} according to the flywheel speed Ω_{fw} and the filtered aerodynamic power P_{aerof}.

9. Simulation results and interpretations

All simulations are run with the 300 s duration with the same wind variation shown in Fig. 7. Wind speed model varies within

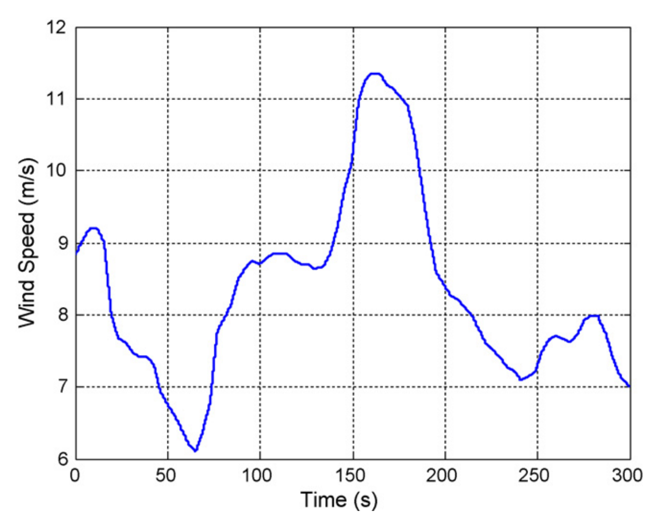

Fig. 7. Profile of wind speed.

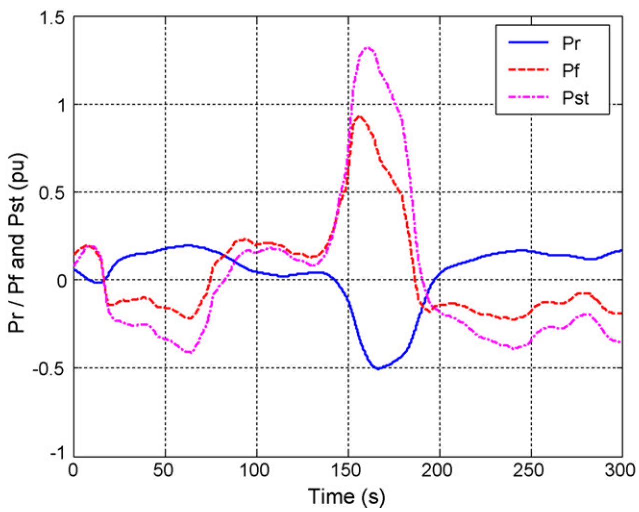

Fig. 8. Power curves P_r, P_f and P_{st}.

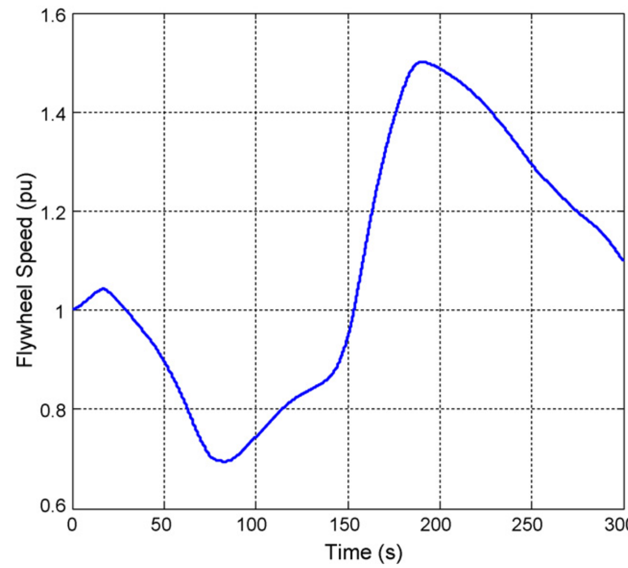

Fig. 10. Flywheel speed Ω_{fw}.

the 6–12 m/s speed range. Fig. 8 shows the power curves forwarded into DC bus. The flywheel reference power P_{st} is positive where it is stored and negative if it is generated by the FESS. The powers P_r and P_f change sign according to the sub or super synchronous operating showing the bidirectional power transfer between rotor and power system. The curve given by Fig. 9 shows the effectiveness of the control law elaborated to stabilise the DC link voltage significantly relating to the reference value chosen here equal to 1 pu. We notice that the flywheel rotational speed remains between the acceptable limits fixed on the membership functions as it is shown in Fig. 10.

In the system without any storage, Fig. 11 shows the P_m power fluctuating following the wind speed variations. Thus, the storage system permits to enhance the power quality by reducing the fluctuations. It is seen that the variations of the active power is comparatively smoother than the system without storage arrangement. This makes it possible to provide a smooth active power to the load which consumes an active power $P_l = 1.2$ pu.

Fig. 12 shows the reactive power curves produced by the wind generator. The power smoothing is carried out around 0.2 pu which corresponding to the load consumption $Q_l = 0.2$ pu. Consequently, the reactive power injected into the grid will be null ensuring a unit power factor at the connection node.

Expression (13) shows the relation between the load voltage variations and the active and reactive powers produced by the wind

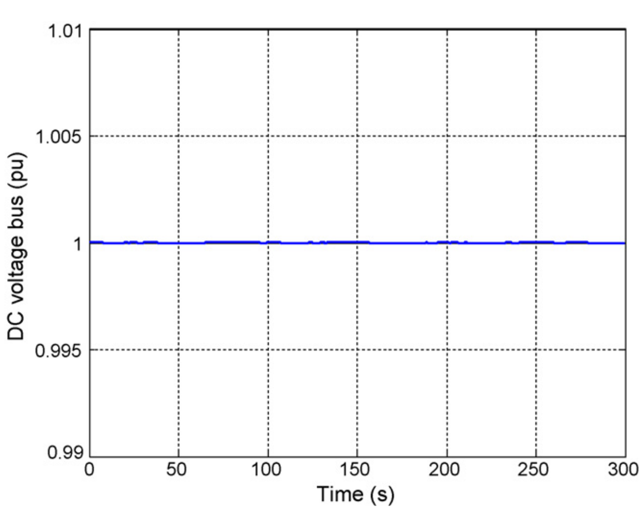

Fig. 9. DC bus voltage curve.

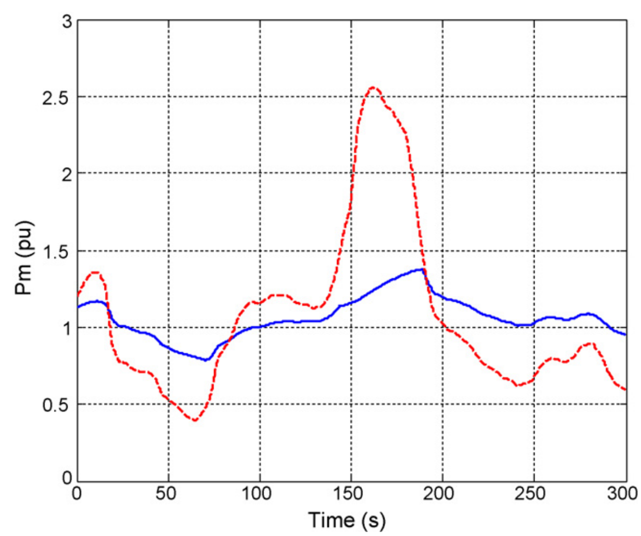

Fig. 11. Active powers generated by the wind generator P_m at the connection node (solid line—with storage, dotted line—without storage).

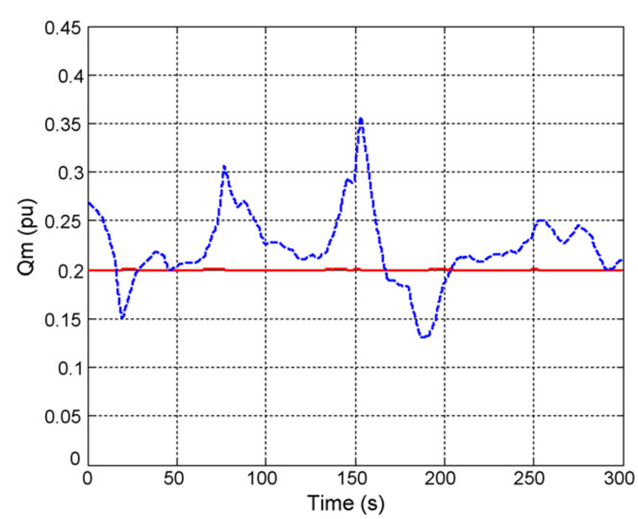

Fig. 12. Reactive powers generated by the wind generator Q_m at the connection node ($Q_l = 0.2$ pu).
(solid line—with smoothing, dotted line—without smoothing).

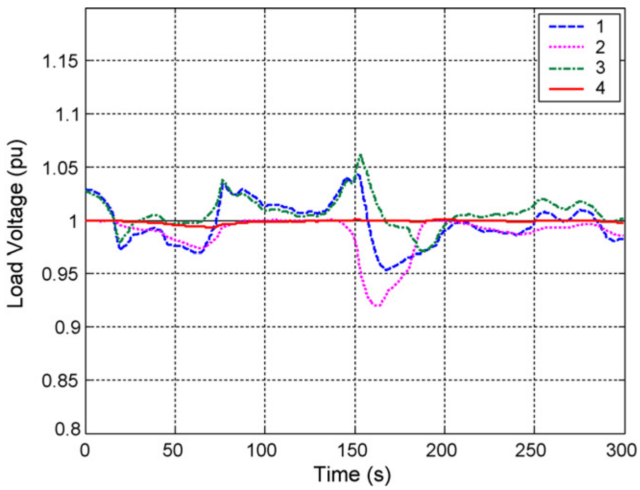

Fig. 13. Curves of the load voltage V_s. (1) P_m non-smoothing and Q_m non-smoothing. (2) P_m non-smoothing et Q_m smoothing. (3) P_m smoothing et Q_m non-smoothing. (4) P_m smoothing and Q_m smoothing.

generator. For that, the powers quality affects greatly the voltage level on the connection node. The curves of the load voltage are shown in Fig. 13. It is noticed that the load voltage variations are reduced for an important active and reactive power smoothing. This shows the significant improvement related to the powers quality and their effect on the load voltage connected to the wind generator.

The wind profile shown at Fig. 7 reveals three zones: weak wind lower than 8 m/s, middling wind around 8 m/s corresponding to the nominal operating of the wind generator and high wind superior than 8 m/s. The active power in the rotor side P_r is proportional to the rotor slip pulsation, thus it is positive in the under synchronised operation for which the wind speed is less than 8 m/s as it is shown in Fig. 8. It becomes negative if the wind speed increases and the mechanical speed will be greater than the synchronous one. The active power through the filters P_f changes also according to the wind speed. The FESS power P_{st} is stored in the flywheel for the high wind which involves acceleration in the flywheel speed illustrated in Fig. 10. The flywheel is then slowed if the wind speed decreases what proves that P_{st} will be restored as shown in Fig. 8. In consequence, the FESS has an important purpose to provide an extra power supply available according to the wind speed variations.

10. Conclusion

In this paper, powers smoothing capability of the DFIG associated to a FESS in the DC bus link is investigated. The FESS control based on a fuzzy logic supervisor is able to reduce the active power fluctuations due to the random wind speed variations and to produce more clean power to the grid. Reactive power control is ensured to provide a smooth reactive power to the load supplied by the wind generator. The results show the enhancement of the powers quality and its contribution to improve and to reduce the load voltage variations in the connection node.

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Appendix A

All the parameters are given in pert unit (pu)

A	DFIG
	Nominal power 100 kW Base voltage 600 V Stator resistor $r_s = 0$ Rotor resistor $r_r = 0.0043$ Stator inductance $L_s = 1.59$ Rotor inductance $L_r = 1.317$ Mutual inductance $M = 1.159$ Inertia $J_{DFIG} = 1000$
B	Wind turbine
	Gear box $\eta = 70$ Number of blades 3 Blade radius 12 m
C	FESS
	Inertia $J_{fw} = 3000$
D	DC bus
	$C = 400$
E	Filter
	Filter inductance $L_f = 0.2$ Filter resistor $R_f = 0$
F	Line
	Line inductance $L_l = 0.2$ Line resistor $R_l = 0$
G	Grid
	Grid voltage $V_g = 1$ Synchronous speed ω = 1

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