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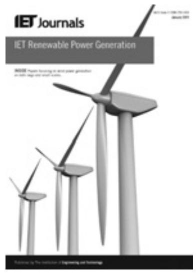

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Active power control of a flywheel energy storage system for wind energy applications

G.O. Suvire P.E. Mercado

CONICET, Instituto de Energía Eléctrica, Universidad Nacional de San Juan, Av. Lib. San Martín 1109 (Oeste), J5400ARL, San Juan, Argentina
E-mail: gsuvire@iee.unsj.edu.ar

Abstract: The integration of wind power generation in power systems is steadily increasing around the world. This incorporation can bring problems onto the dynamics of power systems owing to the lack of controllability over the wind and the type of generation used. In this work, a distribution static synchronous compensator (DSTATCOM) coupled with a flywheel energy storage system (FESS) is used to mitigate problems introduced by wind generation in the electric system. A dynamic model of the DSTATCOM/FESS device is briefly presented and a technique to control the active power exchanged between the device and the power system is proposed. The control technique is based on fuzzy logic and a special filter. Tests of the behaviour of the device are analysed when combined with wind generation in the electric system. Results show an overall satisfactory performance of the proposed control technique along with the high effectiveness of the device used to smooth the active power fluctuations of a wind generator.

1 Introduction

Wind power generation (Pwg) is considered the most economically viable alternative within the portfolio of renewable energy resources. Among its main advantages are a large number of potential sites for plant installation and a rapidly evolving technology, with many suppliers offering from individual turbine sets to turnkey projects. However, owing to the lack of controllability over the wind and the type of generation system used, wind generation introduces problems into the electric systems. Among such problems are those produced by wind-power short-term fluctuations that affect both the power quality and the system dynamics [1–5]. To solve some problems introduced by wind-power short-term fluctuations and after a thorough selection based on analysing the results of previous approaches [6–14], a distribution static synchronous compensator (DSTATCOM) coupled with a flywheel energy storage system (FESS) has been proposed as the most appropriate system [15, 16]. A DSTATCOM is a fast-response, solid-state power controller that provides flexible voltage control at the connection point to the utility distribution feeder for power quality improvements [17]. This device can exchange both active and reactive power if an energy storage system is included into the DC bus. FESSs store kinetic energy in a rotating mass, and they have been used as short-term energy storage devices. FESSs can be classified as low-speed FESS (LS-FESS) and high-speed FESS (HS-FESS). HS-FESS is a newer technology and provides better response speed, cycling characteristics and electric efficiency than LS-FESS [9, 18, 19]. These features allow the HS-FESS (FESS from now on) to work with a DSTATCOM device in order to reduce voltage fluctuations and correct power fluctuations of a wind-power system.

A multi-level control of the DSTATCOM/FESS was developed and each part of the control was explained in detail in [16]. However, the way to carry out the active power control taking into account the load status of the FESS was not studied. To achieve the control of active power of the DSTATCOM/FESS to follow the power fluctuations injected by wind generation is a task that requires dealing simultaneously with adverse variables, such as the randomness of wind-power fluctuations and the limitation of storage capacity of FESS. By controlling the active power generated or stored by the FESS it is intended to smooth the wind power fluctuations and to make a suitable management of the stored energy so as to prevent the FESS from becoming overloaded or running out of charge. Many solutions have been proposed and studied in the bibliography to compensate wind-power fluctuations using a FESS [20–26]. These papers addressing the control issue are focused mainly on the capability of the device to control the voltage and the active or/and reactive power. None of these works have discussed the possible strategies to control the active power following the wind fluctuations and observing the load status of the storage.

Based on the above, the aim of this paper is to propose a control strategy for a DSTATCOM/FESS to smooth the wind power fluctuations that wind generators (WGs) inject into a power-system network, providing a suitable management of the energy stored by the FESS. Given the nature of the problem, namely, the use of continuous variables and the absence of a mathematical model, the application of fuzzy logic is proposed, specifically a fuzzy inference system (FIS) [27], to control the active power of the DSTATCOM/FESS. This FIS is applied in conjunction with a novel filter that allows following the wind-power fluctuations in very short time periods with respect to the storage capacity. The validation of control schemes is achieved through simulations using SimPowerSystems of SIMULINK/MATLAB™.

2 Modelling of the DSTATCOM/FESS

In order to study the dynamic performance of the DSTATCOM/FESS controller, a model of the combined system is proposed, consisting mainly of the DSTATCOM controller, the interface converter and the FESS (Fig. 1).

The DSTATCOM and the interface use two-level voltage source inverters (VSIs), and the commutation valves are insulated gate bipolar transistors (IGBT) with anti-parallel diodes. The VSIs are modelled with detailed blocks of switches and diodes incorporated into the simulation program. The technique of sinusoidal pulse width modulation (SPWM) is used to obtain a sinusoidal voltage waveform. In order to reduce the disturbance caused on the distribution system by the high-frequency switching harmonics generated by the SPWM control, a low-pass sine wave filter is used.

The maximum energy stored by a FESS is computed with (1).

$$\Delta E = J(\omega_{\max}^2 - \omega_{\min}^2)/2 \tag{1}$$

where ΔE is the energy stored by the flywheel, $\omega_{\max}$ and $\omega_{\min}$ are, respectively, the maximum and minimum operation speed of the flywheel, and J is the moment of inertia of the flywheel.

A permanent magnet synchronous machine (PMSM) allows the power exchange between the flywheel and the interface. The PMSM is also modelled with a detailed block included in the simulation program, using the parameters from the manufacturer data sheets [19, 28]. The flywheel is modelled as an additional mass coupled to the rotor shaft of the PMSM [29].

3 DSTATCOM/FESS control

The control proposed for the DSTATCOM/FESS device is divided into two parts: the DSTATCOM control and the FESS control. For each part, a multi-level control scheme is suggested. This scheme has its own control objectives for each level. In this way, a system of complex control is divided into several control levels that are simpler to design [30, 31]. Both parts of the multi-level control scheme, that is the DSTATCOM and the FESS, are divided into three quite distinct levels: external, middle and internal levels, shown in simplified way in Fig. 2. The control algorithm for the DSTATCOM and FESS is fully developed in [16]. Only general information about the operative function of each control block is presented below (Sections 3.1 and 3.2). On the external level of the DSTATCOM, the active power regulation (APR) block (bottom, right corner of

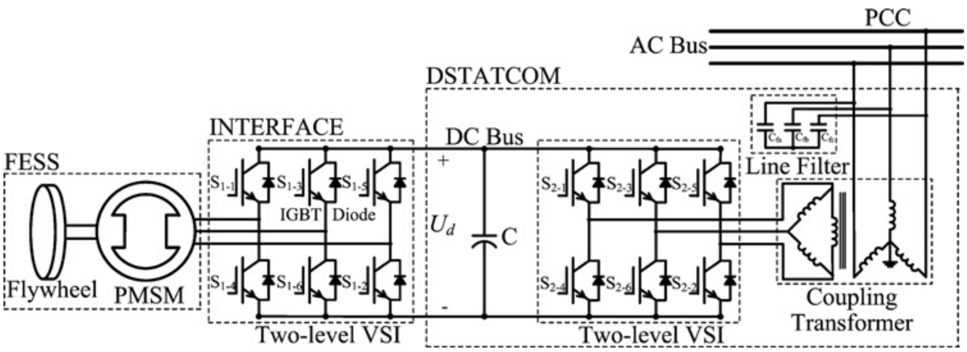

Fig. 1 *Representation of the DSTATCOM/FESS controller*

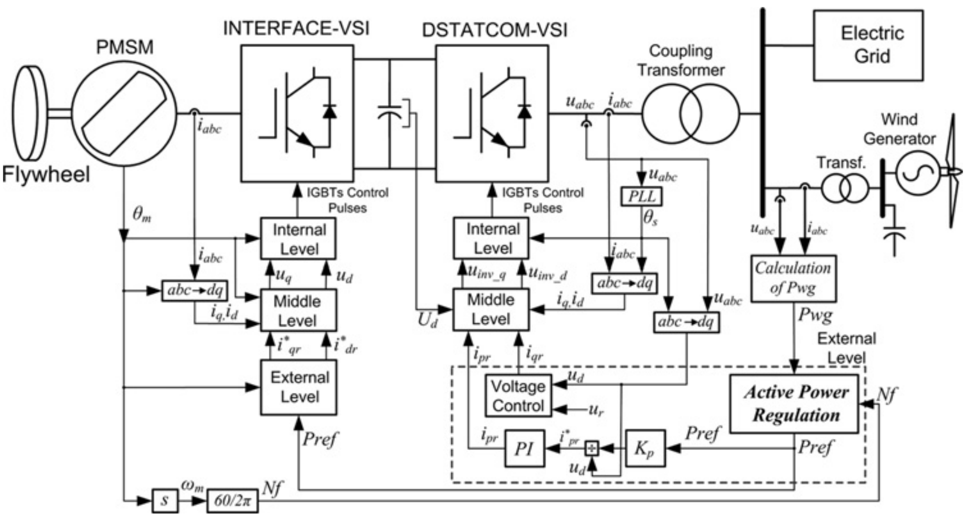

Fig. 2 *Structure of the multi-level control of the DSTATCOM/FESS*

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Fig. 2) for the active power control is the main contribution of this paper and is explained in detail below (Section 3.3).

3.1 DSTATCOM control

Each control level of the DSTATCOM performs certain associated functions. The external level is responsible for determining the active and reactive power exchange between the DSTATCOM and the utility system. The middle-level control allows the expected output to dynamically track the reference values set by the external level. The internal level is responsible for generating the switching signals for the valves of the VSI of the DSTATCOM.

3.2 FESS control

FESS control is achieved by controlling the interface-VSI. By setting via VSI a three-phase voltage of controllable amplitude and phase, the PMSM will be able to work as a motor that stores energy or as generator that supplies energy. Likewise the DSTATCOM control, each control level has to perform certain functions. The external level is responsible for determining the power exchange between the DC bus of the DSTATCOM and the FESS so as to fulfil the power requirements imposed by the DSTATCOM. The middle and internal levels basically have the same functions as the middle and internal control levels of the DSTATCOM, respectively.

3.3 Active power regulation

The aim of controlling the active power generated or stored by the FESS is to smooth the wind-power fluctuations and to make a suitable management of energy stored thereby avoiding the FESS becoming overloaded or run out of charge. As mentioned before, the application of a FIS is proposed to control the active power of the DSTATCOM/FESS. The FIS is applied together with a novel filter that allows following the wind power in very short times with respect to the storage capacity.

The function of the FIS is to calculate the value of a regulation power (Preg), which is the power required to supply the whole system (i.e. WG plus DSTATCOM/FESS). The difference between the Preg and the power injected by wind generation, Pwg, is the reference power, Pref that must either be generated or stored by the DSTATCOM/FESS system.

A simple structure of the active power regulator is shown in Fig. 3. The rotational speed of the flywheel has a finite range of variation; therefore the regulator must adapt the value of regulated power as a function of the Pwg and the rotational speed of the flywheel. The regulator inputs are the corrected value of Pwg (Pwg-c), and the rotational speed of the flywheel, *Nf* (charge status) of the storage device. The Pwg-c is calculated from Pwg after being smoothed by a special filter consisting of a Backlash block and a simple signal filter.

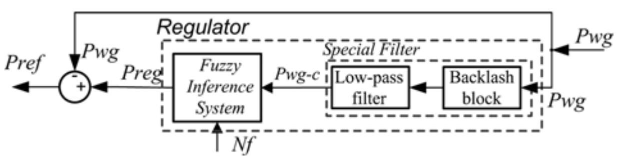

Fig. 3 *Structure of the active power regulation*

The Backlash [32, 33] block implements a system where an input change causes an equal output change. However, when the input changes direction, an initial input change has no effect on the output. The amount of side-to-side play in the system is referred to as the dead-band, and it is centred on the output. A Backlash system can appear in one out of three modes:

- Disengaged: the input does not drive the output and the output remains constant.
- Engaged in a positive direction: the input is increasing (i.e. it has a positive slope) and the output is equal to the input minus half the dead-band width.
- Engaged in a negative direction: the input is decreasing (i.e. it has a negative slope) and the output is equal to the input plus half the dead-band width.

Fig. 4 illustrates the operation of the Backlash system. Fig. 4*a* shows the relationship between the input and the output while the system is disengaged. Fig. 4*b* shows the state of the block when the input has reached the end of the dead-band and engaged the output. The output remains in its previous value. Finally, Fig. 4*c* shows how a change in the input affects the output while the system is engaged. If the input reverses its direction, it disengages from the output. The output remains constant until the input either reaches the opposite end of the dead-band or reverses its direction again and engages at the same end of the dead-band.

The filtering part applies a low-pass filter of second order to make smoother changes of output of the Backlash system.

The fuzzy logic regulator for this application is based on the following principles:

- If the rotational speed of the flywheel is too low, then the storage will be benefited. A larger amount of generated power is used to charge the flywheel and, consequently, less power is supplied to the system.
- If the rotational speed of the flywheel is too high, then the power generation will be benefited. A larger amount of generated power is supplied to the system, less power is stored.
- If the rotational speed of the flywheel is half, then the system is under normal operation. In this condition, neither power generation nor storage is benefited. The electric system is fed with wind power with fluctuations smoothed by the storage device.

The input variables to the FIS are the Pwg-c and the Nf. The first input is in *pu* (per unit) that varies between 0 and

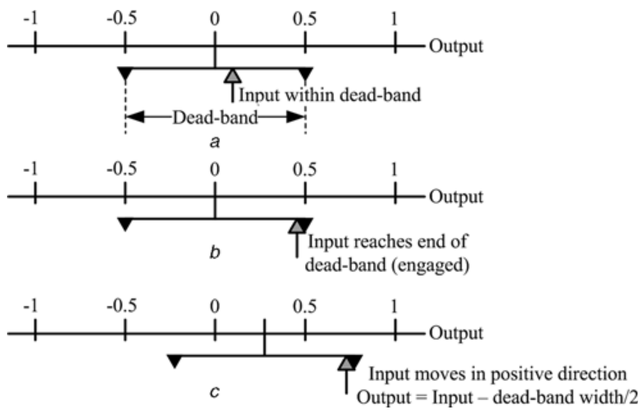

Fig. 4 *Operation of the Backlash system*

a The system is disengaged
b The input has engaged the output
c The output is driven by the input

1, whereas the second input varies between the operative limits of the flywheel speed. For these input variables, five fuzzy sets are considered: low (L), low medium (LM), medium (M), high medium (HM) and high (H). The output variable of the FIS is Preg that is divided into seven values: very low (VL), low (L), low medium (LM), medium (M), high medium (HM), high (H) and very high (VH).

Fuzzy values are mapped via membership functions, both to the input variables and to the output variables. After a thorough selection based on analysing the results of simulations with different membership functions (triangular, trapezoidal and Gaussian), the triangular fuzzy sets have been chosen for simplicity. The membership functions of the input and output variables are represented in Fig. 5. The membership functions of the first input (Pwg-c) and the output (Preg) have been distributed proportionally along the universe of discourse of each variable. The membership function of the second input (Nf) that represents the state of charge of the storage, has been distributed with different forms for the triangles. After testing different distributions for the triangles of this input, the one shown in the Fig. 5 was chosen since these distributions yielded better results (the compensation of wind-power fluctuations, both smoothly and without sudden changes, was achieved).

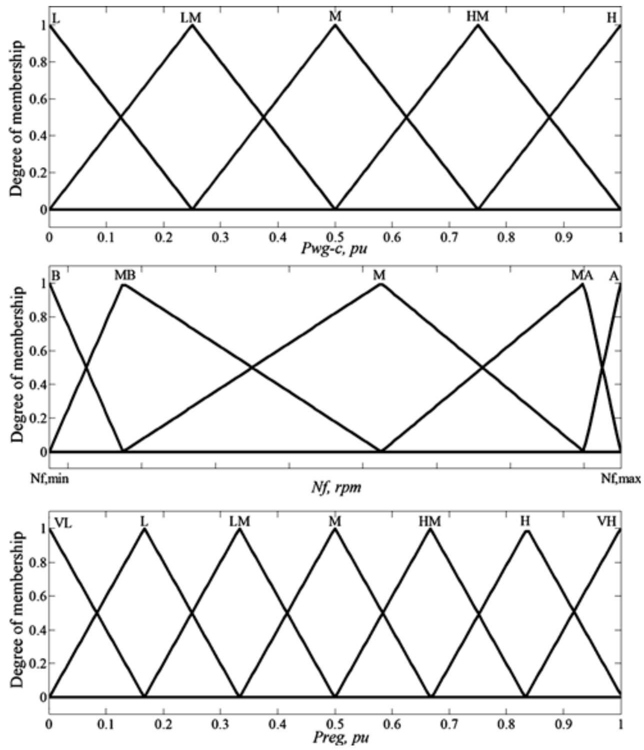

Fig. 5 *Membership functions of the input variables Pwg-c and Nf; and the output variable, Preg*

Table 1 Inference table to obtain Preg

		Nf				
		L	LM	M	HM	H
$P_{wg\text{-}c}$	L	VL	VL	L	LM	M
	LM	VL	L	LM	M	HM
	M	L	LM	M	HM	H
	HM	LM	M	HM	H	VH
	H	M	HM	H	VH	VH

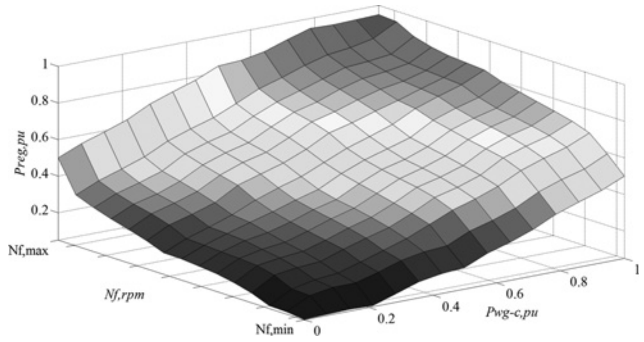

Fig. 6 *Preg against Nf and Pwg-c, obtained with the proposed FIS*

For the implemented FIS, the fuzzy rules are determined from Table 1. This table is created based on the principles mentioned before: to smooth the wind-power fluctuations and to make a suitable management of the energy stored.

In this application, the Mamdani-type FIS [34] is used. Moreover, the defuzzyfication strategy applied is the fuzzy mean method [35]. The output of the FIS ranges from 0 to 1. The evolution of Preg against Nf and Pwg-c is shown in Fig. 6.

4 Test system

The test power system used to study the control strategy proposed of a DSTATCOM/FESS device is shown in Fig. 7 as a single-line diagram. This sub-transmission system operates at 13.8 kV/50 Hz and includes a dynamically modelled WG linked to a bulk power system represented by an infinite bus-type.

The WG (rated power: 750 kW) uses an induction generator with a squirrel-cage rotor. It is connected to the grid through a transformer with star-triangle winding. The demand for reactive power from the WG is supplied by capacitors to reach a close-to-one power factor. The WG is modelled with blocks of an induction generator and a wind turbine available in the library of the simulation program. Parameters are obtained from the manufacturer data sheets [36, 37]. The sub-transmission line is modelled by using lumped parameters. All loads are modelled by constant impedances and are grouped at bus 4 (Ld: 500 kW).

The proposed DSTATCOM/FESS device (maximum rated power: 100 kW and rated storage capacity: 750 Wh) is connected to the main bus (bus 3). The DC voltage of the DSTATCOM is 750 V and the capacitor used has a rated capacitance of 1000 μF. The DSTATCOM-VSI works with a switching frequency of 8 kHz, whereas the interface-VSI works with 20 kHz. The parameters of the FESS (PMSM and flywheel) are obtained from the manufacturer data

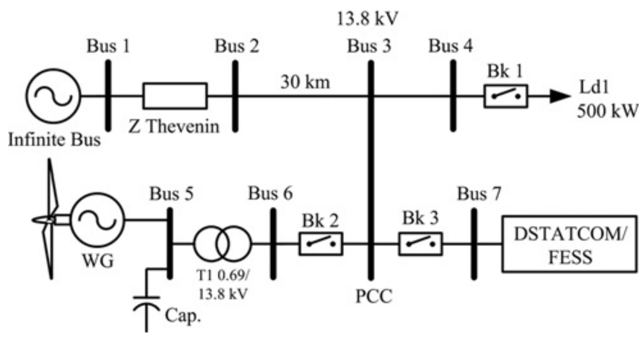

Fig. 7 *Test power system*

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sheets [18, 28]. The major test system and the DSTATCOM/FESS data can be found in previous work [16].

5 Simulation results

The analysis and validation of the control algorithm proposed for the DSTATCOM/FESS controller are carried out through simple events that impose high demands upon the dynamic response of the device. For this study, the basic test-power system shown in Fig. 7 is used. Two cases are considered. The first case study (Case A) discusses the performance of the control algorithm of the device when it is compared with other control algorithms. In the second case study (Case B), tests are made of the control proposed when different storage capacities are considered. In both cases, two suitable profiles for variation of the wind speed are applied, the first one with a constant mean wind speed of 10 m/s, and the second one with a variable mean wind speed so that it makes the WG work near to maximum and minimum power, the profiles are shown in Fig. 8.

The value of the dead-band width for the Backlash block is adjusted based on the maximum variation of wind power around its mean value (that depends on the mean value of the wind speed) and the maximum capacity of the storage device. In this application, the values of the dead-band width for the Backlash block were obtained based on simulations and tests for different mean wind speeds and for different number of storage devices. The tests were performed with four, eight and 16 flywheels (approximately half, same and twice, respectively, the power of the WG used in the case studies). Table 2 shows the values obtained from these tests that are used for the case studies presented below. In operation, the dead-band width adopted is set according to the mean wind speed in three speed ranges (0–4, 5–12 and 13–25 m/s).

5.1 *Case study A: comparison of the control algorithm proposed with other control methods*

In this case, tests are carried out comparing the active power control proposed with two other methods of control [16, 22, 24–26]. In one of these methods, Preg is considered as a constant value, equal to the value of wind power for a given constant wind speed [16, 22]. In the other method Preg is obtained from wind power filtered by a low pass filter [24–26]. Basic schemes of these methods are shown in Fig. 9. Tests are done with the connection of the DSTATCOM/FESS device with eight flywheel units.

Table 2 Dead-band width adopted for different mean wind speeds and number of storage devices

Mean wind speed, m/s	Pwg, mean value, kW	Pwg, Maximum variation, kW	Dead-band width, kW		
			4FW	8FW	16FW
4	15	75	20	35	60
6	100	280	200	350	600
8	250	400			
10	485	450			
12	665	370			
14	720	180	20	35	60
16	725	130			
18	718	40			
20	705	40			
22	700	40			
24	700	40			

5.1.1 Constant mean wind speed: The profile for variation of the wind speed shown in Fig. 8*a* is applied to the WG. The active power injected by the WG, Pwg, for these wind speed variations is shown in Fig. 10*a*. The

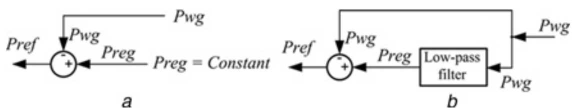

Fig. 9 *Basic schemes of the comparison methods*

a Structure of the control method with Preg equal to a constant
b Structure of the control method with Preg passed through a low pass filter

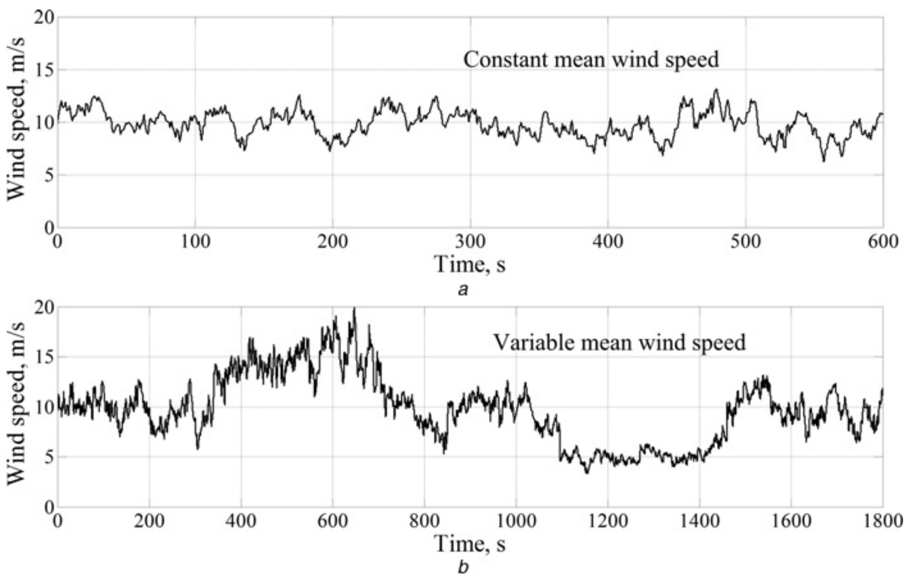

Fig. 8 *Wind speed with mean value*

a Constant ($ws_m = 10$ m/s)
b Variable

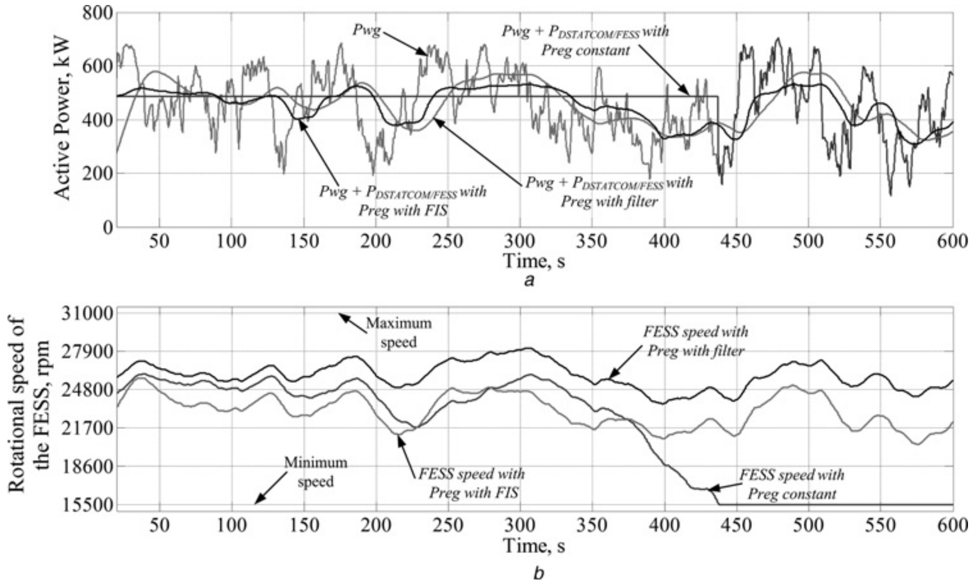

Fig. 10 *Case with constant mean wind speed*

a Active power injected by the WG, Pwg, and by the whole system with Preg with FIS, Preg constant and Preg with filter
b Rotational speed of the flywheel with Preg with FIS, Preg constant and Preg with filter

active power injected by the whole system (i.e. WG plus DSTATCOM/FESS) is also shown in the same figure, with the control method proposed (Preg with FIS) and the other methods (Preg constant and Preg with filter). The performance of the rotational speed (state of charge) for one of the flywheels is shown in Fig. 10*b* for the three control methods.

It can be noted that, with the DSTATCOM/FESS device connected with the control method Preg constant, the output power of the whole system is constant at first, but then at approximately $t = 440$ s, the storage device reaches its lower limit and the controller loses the regulation capacity. With the proposed method and the control with Preg with filter, it can be noted that the output power of the whole system is not constant; however, power fluctuations are significantly reduced, and the rotational speed never falls below the minimum speed (no load state) and does not exceed the maximum speed (overload state).

5.1.2 Variable mean wind speed: The profile for variation of the wind speed shown in Fig. 8*b* is applied to the WG. In this case the storage device is more required. The active power injected by the WG, Pwg and by the whole system with Preg with FIS, Preg constant and Preg with filter, is shown in Fig. 11*a*. The performance of the rotational speed for one of the flywheels is shown in Fig. 11*b* for the three control methods.

It can be noted that the storage device with Preg constant, and also with Preg with filter, reaches its lower and upper limits and the controller loses the regulation capacity. These

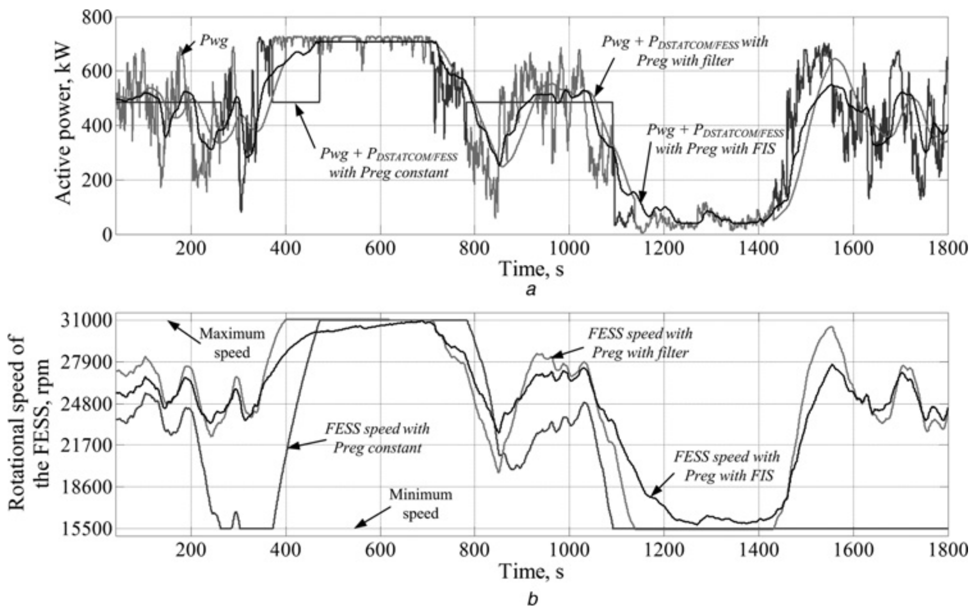

Fig. 11 *Case with variable mean wind speed*

a Active power injected by the WG, Pwg, and by the whole system with Preg with FIS, Preg constant and Preg with filter
b Rotational speed of the flywheel with Preg with FIS, Preg constant and Preg with filter

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methods could operate properly when the storage capacity is rather large. As can be seen, with the same storage capacity, the proposed method smoothes the wind power fluctuations without reaching any limits. Therefore the proposed method could smooth the wind-power fluctuations with less storage capacity than those used by the other two methods.

5.2 Case study B: performance of the control algorithm proposed with different storage capacities

In this case study, the control algorithm proposed is used and tests with four, eight and 16 flywheels (approximately half, same and twice, respectively, the power of the WG) were carried out with constant and variable mean wind speed.

The profile of variation of the wind speed with constant mean value of 10 m/s, shown in Fig. 8*a*, is applied to the WG. The active power injected by the WG, Pwg and by the whole system with four, eight and 16 flywheels for this wind profile is shown in Fig. 12*a*. The performance of the rotational speed (state of charge) for one of the flywheels is shown in Fig. 12*b* for this case.

For the case with variable mean wind speed, the profile for variation of the wind speed shown in Fig. 8*b* is applied to the WG. In this case the storage device is more required. The

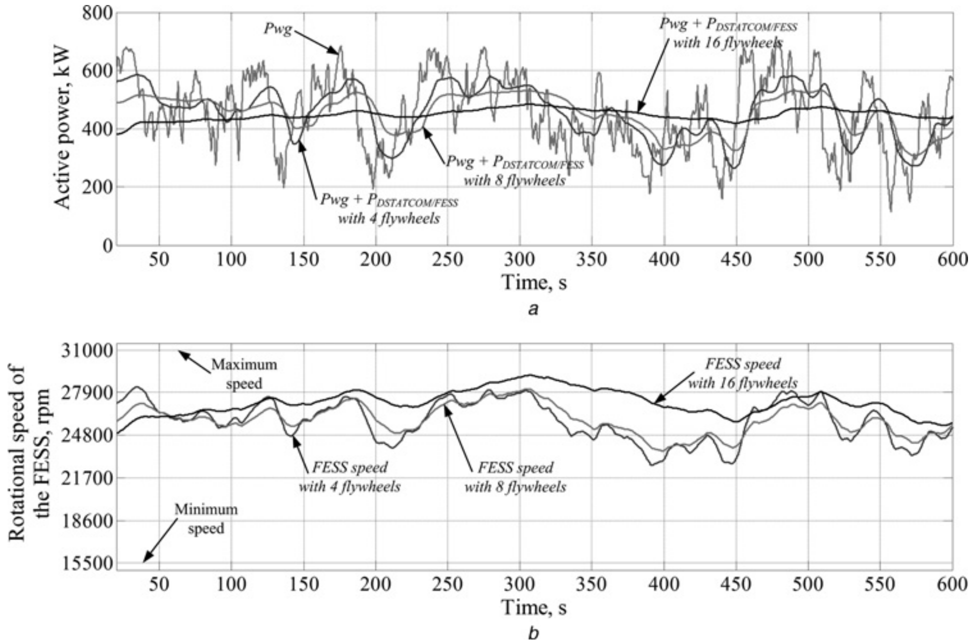

Fig. 12 *Case with constant mean wind speed*

a Active power injected by the WG, Pwg, and by the whole system with 4, 8 and 16 flywheels
b Rotational speed of the FESS with 4, 8 and 16 flywheels

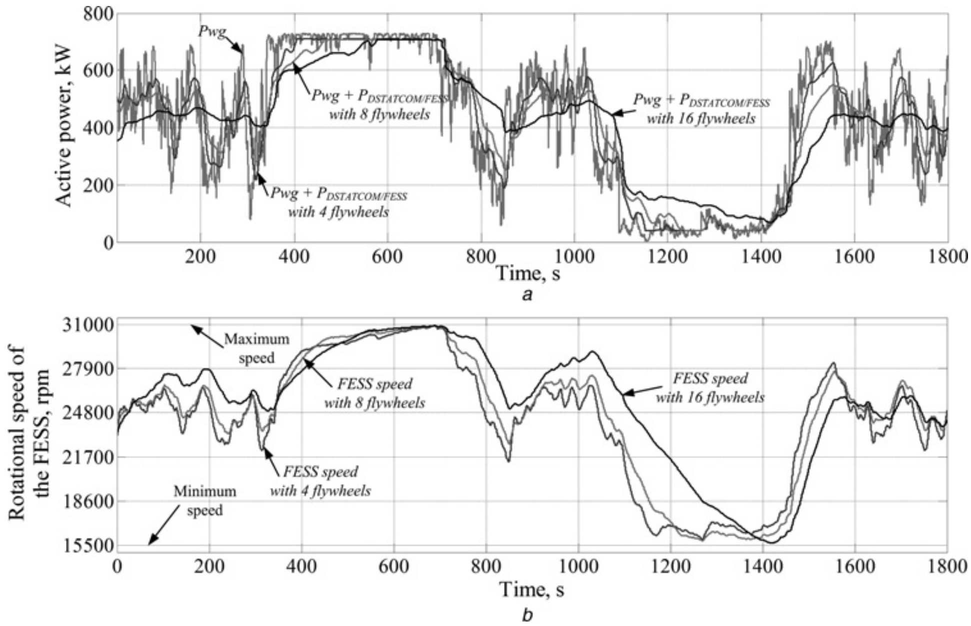

Fig. 13 *Case with variable mean wind speed*

a Active power injected by the WG, Pwg, and by the whole system (i.e. WG plus DSTATCOM/FESS) with 4, 8 and 16 flywheels
b Rotational speed of the FESS with 4, 8 and 16 flywheels

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active power injected by the WG, Pwg and by the whole system with four, eight and 16 flywheels for the variable mean wind speed is shown in Fig. 13*a*. The performance of the rotational speed (state of charge) for one of the flywheels is shown in Fig. 13*b* for this case.

It can be observed from Figs. 12 and 13 that the controller with the proposed control responds effectively reducing the wind-power fluctuations, preventing these large fluctuations impact on the power system. These figures show also that the larger the number of flywheels, the greater the smoothing effect of the output power. Moreover, using the control system implemented, the rotational speed never falls below the minimum speed (no load state) and does not exceed the maximum speed (overload state) in all cases.

6 Conclusions

This paper presents aspects of the active power control of a FESS coupled with a DSTATCOM controller. A proposal is made for the control algorithm of the device using a FIS in conjunction with a special filter to smooth the wind-power fluctuations that WGs inject into a power-system network.

From the results obtained, it can be concluded that the developed control algorithm works satisfactorily. The DSTATCOM/FESS device effectively compensates the active power fluctuations from a WG. The complete system (DSTATCOM/FESS plus WG) generates a smoother power response than that of the system without the DSTATCOM/FESS. This smoothing effect of the output power increases with the number of flywheels. Finally, it is concluded that the active power control proposed for the DSTATCOM/FESS achieves a very good management of the stored energy because the wind-power fluctuations are corrected with the storage device never being discharged or overloaded.

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