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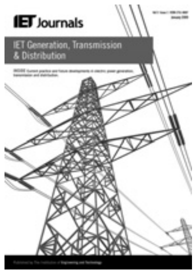

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Combined control of a distribution static synchronous compensator/flywheel energy storage system for wind energy applications

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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 electrical systems. 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 has two control modes. One control mode mitigates the power fluctuations of wind generators, and it is based on fuzzy logic and a special filter. The other control mode contributes to recover the frequency when significant faults arise in the system. Simulation tests on the behaviour of the device are analysed when it works in combination with wind generation in the electrical system. Results show a satisfactory performance of the proposed control techniques along with a high effectiveness to smooth the active power fluctuations of wind generation and to contribute to the recovery of the frequency.

1 Introduction

Wind power generation is considered the most economic viable alternative within the portfolio of renewable energy resources. Among its main advantages are the 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, the lack of controllability over the wind and the type of generation system implemented, different from conventional generators, cause problems within the electrical systems. One of the major problems of wind conversion systems arises by the variations of the output power produced by short-term wind fluctuations, which can affect the power quality or cause frequency deviations. These may lead to system instability, particularly in an island power network or any power system where a high penetration of wind energy exists [1–5]. The mentioned problems are more severe in the case of fixed-speed wind turbines because they use induction generators directly connected to the grid [1, 2]. The advantages of using fixed-speed wind turbines are cost effectiveness and robustness.

On the other hand, the reduced cost of power electronics devices as well as the breakthrough of new technologies in the field of energy storage makes it possible to incorporate them into power systems [6–12]. Such energy storage devices controlled by power electronics allow a dynamic control to be made of both voltage and flows of active and reactive power. Therefore they have a great potential for improving the dynamic operation of power systems. This paper proposes the application of energy storage with electronic control to smooth the output power of wind generators, especially fixed-speed wind turbines and to enable their contribution to ancillary services such as the primary frequency control.

In recent years, studies related to the interaction of wind power generation and energy storage have been reported. The main energy storage technologies considered in these studies are: batteries [13–16], compressed air [17], pumped hydro storage [18], superconducting magnetic energy storage (SMES) [19–22], super-capacitors (SC) [23, 24] and flywheel energy storage systems (FESS) [25–29]. Storage technologies using SMES, SC and FESS are better adapted to mitigate problems introduced by wind power generation owing to short-term wind fluctuations. These three technologies show fast response times, higher electrical efficiencies and longer lifetimes, which are key features for the proposed application where continuous operation is required. Considering these three technologies, FESS stand out for their commercial availability, lower capital costs and greater experience in industrial applications with excellent results [30–32]. 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 flywheel (LS-FESS) and high-speed flywheel (HS-FESS). HS-FESSs represent newer technology providing better speeds of response, cycling characteristics and electric efficiencies than LS-FESS [30–32].

To connect the short-term storage devices to the electrical grid, an interface with power electronics is required. The main power electronics controllers are classified as flexible AC transmission system (FACTS) and custom power for distribution systems [33]. FACTS and custom power controllers based on power electronics devices with gate turn-off capability can exchange active and reactive power with the electrical system if an energy storage system is included within the DC bus. In general, these controllers can be divided into four categories: series, shunt, combined series–series and combined series–shunt. A shunt controller is one of the best alternatives for mitigating voltage problems introduced by wind power generation, because it is much more effective in maintaining a required voltage profile at a substation bus than a series controller, and cheaper than the combined controllers [33]. A distribution static synchronous compensator (DSTATCOM) is one of the main shunt controllers used in distribution systems. A DSTATCOM is a fast-response, solid-state power controller that provides flexible voltage control at the point of connection to the utility distribution feeder for power quality improvements [33]. DSTATCOM or STATCOM for transmission systems has been proposed in the bibliography to be used with wind generation [34–36]. In these papers, the shunt controller was generally used to compensate voltage fluctuations introduced by the wind power generation to improve the power quality of the system.

Many solutions using short-term storage devices with electronic control have been proposed and studied in the bibliography to improve the incorporation of wind generation in power systems related to the smoothing of the wind power fluctuations or providing ancillary services [13, 19, 23–29]. In [13], a control strategy is developed to manage the power flow among wind-turbine generator, energy storage device and the grid, so as the overall wind conversion system is turned into a dispatchable power source. The control strategy ensures the load demand is fully provided regardless of the wind speed variations and load changes for both grid-connected and island situations. In [23], a SC is used with a doubly fed induction generator (DFIG) in order to smooth the fast wind-induced power variations. The SC is used to reinforce the DC bus during transients, thereby enhancing low-voltage ride through capability of the wind generator. Qu [24] proposes a novel two-layer constant power control scheme for a wind farm equipped with DFIG wind turbines, where each wind turbine is equipped with a SC. The control is used to regulate each DFIG wind turbine to generate the desired amount of active power, where the deviations between the available wind energy input and desired active power output are compensated by SC. In [19], the use of an improved SMES controller is proposed for the stabilisation and control of the power flow of hybrid microgrids incorporating wind generation. Cimuca [25] proposes the direct torque control (DTC) as an alternative to the flux-oriented control for an induction machine-based FESS associated to a variable-speed wind generator. In this case, the tasks of the FESS control are: to regulate the DC-link voltage, to regulate the power flow on the grid or on an isolated load and to use a DTC to improve the FESS efficiency. In [26], authors use a FESS connected to the wind generator at the DC bus in order to evaluate its capacity to participate in the ancillary services. 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 because of the random wind speed variations. The control method and the energetic performances of a low-speed FESS with a classical squirrel-cage induction machine in the view of its association to a variable-speed wind generator (VSWG) are investigated in [27]. In this case a fuzzy logic supervisor is used for the FESS with the aim of smoothing the power generated by the VSWG. In [28], a multi-level control of the DSTATCOM/FESS to improve the integration of wind generators (WGs) within a power system was developed and each part of the control was explained in detail. The control to mitigate the wind power fluctuations includes three modes of operation of the DSTATCOM/FESS device, namely, voltage control, power factor correction and active power control. In [29], a novel control strategy for power smoothing of wind generators using a flywheel driven by a sensorless vector-controlled induction machine is proposed. The main control strategy of the FESS addresses the problem of regulating the DC-link voltage of the wind generator against input power surges or sudden changes in load demand. Although the solutions mentioned above offer practical solutions for the power variation problem of wind conversion systems, they focus less to describe an effective method to carry out a combined active power control of the storage device in order to smooth the wind power fluctuation and to contribute to frequency control when faults occur in the electrical system.

To control the active power generated or stored by the storage device coupled with an electronic controller so as to continuously follow and smooth the power fluctuations injected by wind generation requires dealing simultaneously with adverse variables, such as the randomness of wind power fluctuations and the limited storage capacity. This way, it is intended not only to smooth the wind power fluctuations but also to provide a suitable management of the stored energy so as to prevent the storage device from becoming overloaded or running out of charge. On the other hand, the active power control of the storage device coupled with an electronic controller, related to the frequency control, should only happen when significant frequency deviations owing to faults occur in the electrical system.

Based on the above, a DSTATCOM coupled with a HS-FESS (FESS from now on) has been previously proposed by the authors as an auxiliary source of energy for wind conversion systems [28, 37]. The main aim of this paper is to develop a control strategy of a DSTATCOM/FESS both to smooth the wind power fluctuations that wind generators (WGs) inject into a power system and to participate in the frequency control when significant faults arise in the system. For this purpose, the application of a fuzzy inference system (FIS) is proposed, which 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. The diagram of the proposed DSTATCOM/FESS controller is shown in Fig. 1.

The DSTATCOM and the Interface use two-level voltage source inverters (VSIs), and the commutation valves are insulated gate bipolar transistors with anti-parallel diodes. The

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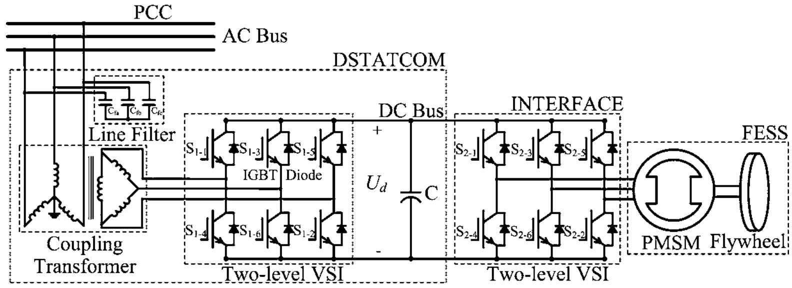

Fig. 1 *Representation of the DSTATCOM/FESS controller*

VSIs are modelled with detailed blocks for 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. This filter is formed by the coupling transformer and the filter capacitors shown in Fig. 1.

The available energy stored by a FESS is computed with

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

where ΔE is the available energy stored by the flywheel, ω is the operation speed, $\omega_{\min}$ the minimum operation speed and J 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's data sheets [31, 32]. The flywheel is modelled as an additional mass coupled to the rotor shaft of the PMSM [38].

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, which are simpler to design [39–41]. Both parts of the multi-level control schemes, 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 [28]. Only general information about the operative function of each control block is presented below in Sections 3.1 and 3.2. On the external level of the DSTATCOM, the active power control (APC) box (bottom, left corner of Fig. 2) for the active power control is the main contribution of this paper and will be explained in detail below in 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 external level control is designed for performing the APC explained in Section 3.3; and the voltage control (VC). The VC consists in controlling the voltage at the point of common coupling (PCC) of the DSTATCOM through the modulation of the reactive component of the output current. To this aim, the instantaneous voltage at the PCC (ud) is

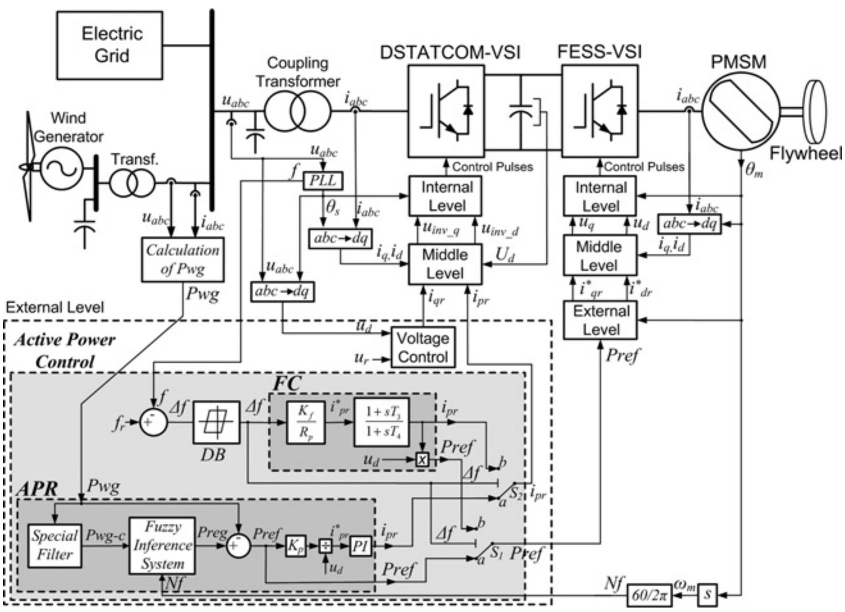

Fig. 2 *Structure of the multi-level control of the DSTATCOM/FESS*

computed by using a synchronous-rotating orthogonal reference frame and is then compared with a reference voltage (*ur*) [28, 42]. The middle level control allows the expected output to dynamically track the reference values set by the external level. This block has two main parts, the current regulator and the DC voltage regulator. For the current regulator, the control is performed with the synchronous-rotating *dq* reference frame with conventional proportional integral (PI) controllers. PI controllers are also used in the DC voltage regulator [28, 42]. The internal level is responsible for generating the switching signals for the valves of the VSI of the DSTATCOM. The internal level is mainly composed of a line synchronisation module and a three-phase pulse-width modulation firing pulses generator [28, 42]. The line synchronisation module consists primarily of a phase locked loop (PLL) [43]. In this work, the PLL model based on the *dq* transformation was used [44].

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 a 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 meet the power requirements demanded by the DSTATCOM. The control is made by using vector control; the main characteristic of this control is the synchronisation of the stator flux with the rotor [28, 43]. The middle and internal levels have practically the same functions as the middle and internal control levels of the DSTATCOM, respectively. The main difference with the DSTATCOM control is that the synchronism angle to make the coordinate transformation is not computed with a PLL. In this case, the angle is obtained by measuring the position angle of the machine and multiplying by the number of pairs of poles [28, 43].

3.3 Active power control

The APC is composed of the active power regulation block (APR) to smooth the wind power fluctuations and the frequency control block (FC) to compensate frequency deviations. The APR mode is activated when switches S_1 and S_2 are in *a*, and the FC mode is activated when switches S_1 and S_2 are in *b*, this is shown in the shaded part of Fig. 2.

3.3.1 Active power regulation: The aim of regulating 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 so as to make the FESS not become overloaded or run out of charge. 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 wind power generation and the rotational speed of the flywheel. 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 FIS [45], to control the active power of the DSTATCOM/FESS to follow the wind power fluctuations. 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. A simple structure of the active power regulator is shown in Fig. 2 (APR block).

The function of the FIS is to calculate the value of a regulation power, P^{reg}, which is the power required to supply the WGs plus DSTATCOM/FESS. The difference between the regulation power, P^{reg}, and the power injected by wind generation, P^{wg}, is the reference power, $P^{ref,}$ which must either be generated or stored by the DSTATCOM/FESS system. The FIS inputs are the corrected value of wind power generation, P^{wgc}, and the rotational speed of the flywheel, N^{f} (charge status) of the storage device. The corrected power of wind generation, P^{wgc}, is calculated from the wind power generation, P^{wg}, after being smoothed by a special filter consisting of a Backlash block and a simple signal filter.

The Backlash [46, 47] 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 be 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.

More detail on the operation of the Backlash block can be found in [46, 47]. The filtering part applies a second-order low-pass filter to make smoother output changes 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 into 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 into the system, and less power is stored.
- If the rotational speed of the flywheel is half, then the system is under normal operation. In this condition, either power generation or storage will be not benefited. The electrical system is fed with wind power, with fluctuations smoothed by the storage device.

For the input variables of the FIS (P^{wgc} and N^{f}), 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 the regulation power, P^{reg}, which is divided into seven linguistic 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 variable. After a thorough selection based on analysing the results of simulations with different membership functions (triangular, trapezoidal and Gaussian), the triangular fuzzy sets have

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been chosen for simplicity. The membership functions of the input and output variables are represented in Fig. 3. The membership functions of the first input (P^{wgc}) and the output (P^{reg}) have been distributed proportionally along the universe of discourse of each variable. The membership function of the second input (N^{f}), which 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 Fig. 3 was chosen since these distributions yielded better results (the compensation of wind power fluctuations, both smoothly and without sudden changes, was achieved).

For the implemented FIS, the fuzzy rules are determined from Table 1. This table is created on the prior mentioned principles: to smooth the wind power fluctuations and to enable a suitable management of the energy stored. In this application, the fuzzy inference system Mamdani type [48] is used. Moreover, the defuzzyfication strategy applied is the fuzzy mean method [49].

3.3.2 Frequency control: The frequency control block is responsible for determining the active power exchange with the electrical system when it is necessary to recover the system frequency after eventual faults of some system components. A simple structure of the frequency control is shown in Fig. 2 (FC block).

This control is in charge of minimising the magnitude and duration of system disturbances by damping power oscillation. The purpose of this is to keep the system frequency above the acceptable minimum level during the transient dynamics. Power oscillation damping can be carried out by the modulation of the active component of the output current.

The input signals of the system are produced by direct frequency measurement of the AC system through the PLL shown in Fig. 2, yielding Δf. The frequency error Δf is proportional to the rate of change of the generator angle $d\delta/dt$ involved, which represents directly the power oscillation of the system. A dead-band block is incorporated into the control loop with the purpose of managing the participation of the DSTATCOM/FESS system in the frequency control of the utility system. The dead-band adjustment allows determining the activation of the controller in case of different severity levels of the disturbances. A proportional gain K_f and a speed-droop R_p (or regulation characteristic) are used to get a stable load division among several generating units operating in parallel. A phase-lag compensator is used to enhance the performance of the frequency control system. The output current signal i_{pr} represents the flow of active current that needs to be injected by the proposed controller for compensating the frequency deviation of the system.

The FC mode is only activated when significant frequency deviations arise. To do this, S_1 and S_2 are switched from position a to b when the frequency deviation exceeds the dead-band value. S_1 manages the active power reference for the FESS and S_2 manages the active current reference of the

Table 1 Inference table to obtain P^{reg}

		N^{f}				
		L	LM	M	HM	H
P^{wgc}	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

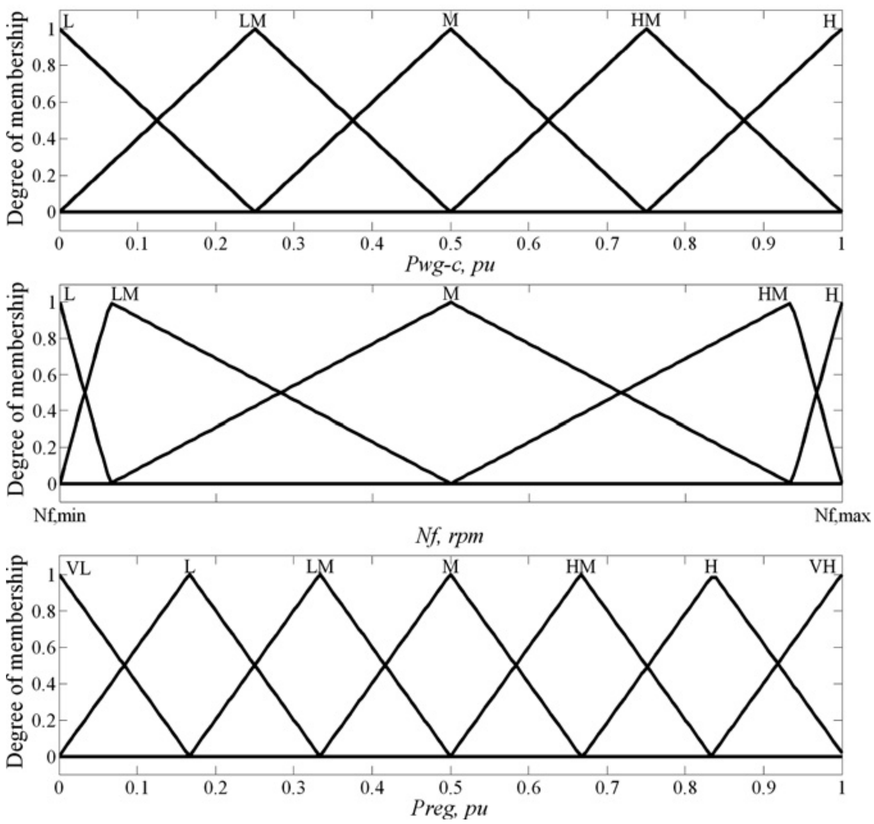

Fig. 3 *Membership functions of the input variables P^{wgc} and N^{f}; and the output variable, P^{reg}*

DSTATCOM. According to the FC mode, the FESS device must be partially charged at a specific rating to allow power to be absorbed or injected from or into the grid at any time. This permits to counteract positive and negative power changes in the utility system. The level of charge of the FESS is controlled by the APR mode that it is in charge of making a suitable management of the stored energy so as to prevent the FESS become overloaded or run out of charge.

4 Test system

The test power system used to study the proposed control strategy of a DSTATCOM/FESS device is shown in Fig. 4 as a single line diagram. This system consists of a subsystem which operates at 13.8 kV/50 Hz and implements a dynamically modelled wind farm (WF), a synchronous generator (SG), a load, and the DSTATCOM/FESS device, all linked through a 90 km transmission line and a 132/13.8 kV transformer to a bulk power system represented by an infinite bus type.

The WF consists of two rows with seven wind turbines each. The distance between two neighbour turbines and between the two rows is 700 m. The rated power of each wind turbine is 750 kW. Therefore the 14-turbine wind farm has 10.5 MW rated power. Each wind turbine uses an induction generator with a squirrel-cage rotor. It is connected to the grid through a transformer with star-triangle winding. The wind generator is modelled with blocks of an induction generator and a wind turbine available in the library of the simulation program. Parameters are taken from the manufacturer's data sheets [50, 51]. The demand of reactive power from the WF is supplied by capacitors so as to reach a close-to-one power factor. The SG (50 MVA rated power) is powered by a multi-stage tandem compound steam turbine which is connected to the network through a $Y-\Delta$ step-up transformer. The controls of the unit include a standard IEEE voltage regulator and a speed governor with power system stabiliser [52, 53]. The SG and the steam turbine are modelled with blocks available in the library of the simulation program. All loads are modelled by constant impedances and are grouped at bus 8 (Ld: 45 MW, 5 Mvar). All lines are modelled by using lumped parameters.

The proposed DSTATCOM/FESS device is connected to Bus 5 (on the same bus of the wind farm). For simplicity, the DSTATCOM/FESS device is represented in Fig. 4 as a single block. However, the FESS consists of four modules with ten flywheel units each (40 flywheel units of 100 kW rated power each). Therefore the 40 flywheel units have a total of 4 MW rated power. The maximum and minimum operational speeds of the flywheel are 15 500 and 31 000 rpm, respectively. The rated storage capacity of the FESS is 30 kWh (27 s to maximum power). 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's data sheets [31, 32]. The major test system data and the DSTATCOM/FESS data are summarised in [28].

The analysis and validation of the control algorithms proposed for the DSTATCOM/FESS controller are carried out through simple events that impose high demands upon the dynamic response of the device. Two cases are considered. The first case study (Case A) discusses the performance of the control algorithm of the device working in the APR mode. For this, a variation of wind speed profile is applied to the WF so that it makes the DSTATCOM/FESS work constantly in both ways, by storing and delivering energy. In the second case study (Case B), a test is made of the device proposed in FC mode. For this, external perturbations are imposed, like a three-phase fault, and the behaviour of the control is observed.

5 Simulation results

5.1 Case study A: DSTATCOM/FESS performance analysis working in APR mode

For this study, the basic test power system shown in Fig. 4 is used. A suitable profile for variation of the wind speed is applied with 10 m/s mean wind speed. Fig. 5*a* shows the active power flow for the system WF plus DSTATCOM/FESS, with Bk3 switched off and on, that is, with the DSTATCOM/FESS device disconnected and connected, respectively. It is noted how the DSTATCOM/FESS device, with the proposed APR control mode, reduces the wind power fluctuations, preventing that these fluctuations be transmitted into the power system.

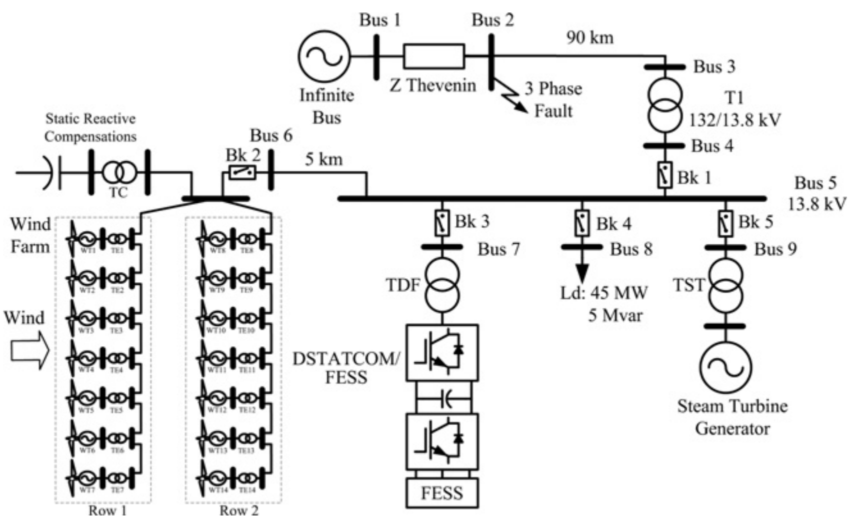

Fig. 4 *Test power system*

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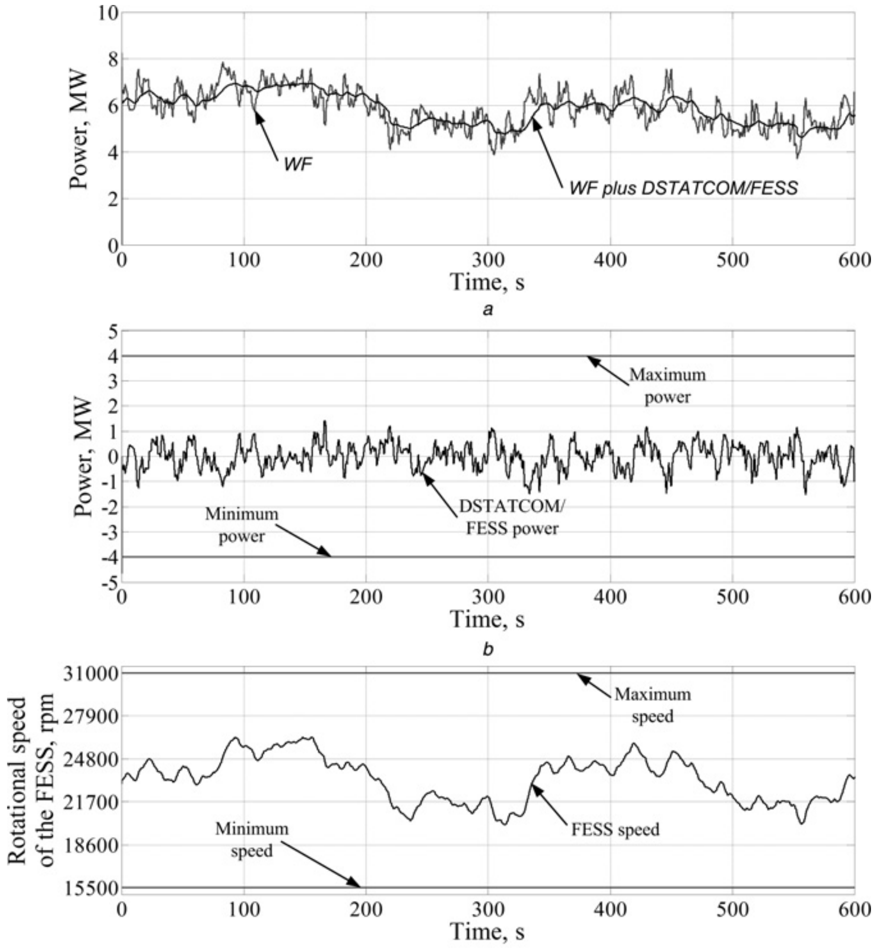

Fig. 5 *Performance of DSTATCOM/FESS working in APR mode*

a Active power flow for the WF with and without the DSTATCOM/FESS device
b Active power injected by the DSTATCOM/FESS
c Rotational speed of the flywheel

The active power injected by the DSTATCOM/FESS is shown in Fig. 5*b*. It can be noted that the active power injected has swift variations, similarly to the wind power, thus achieving that the power injections of the DSTATCOM/FESS device compensate effectively the variations of wind power.

Finally, the performance of the rotational speed for one of the flywheels is shown in Fig. 5*c*. It can be noted that, with the control system implemented, the rotational speed never falls below the minimum speed (no load state) and does not exceed the maximum speed (overloaded state).

5.2 Case study B: DSTATCOM/FESS performance analysis working in FC mode

The performance of the FC mode is studied by using the same system of Fig. 4. In order to perform it, a three-phase-to ground fault is applied at bus 2 in the bulk power system (at $t = 10.1$ s). Five cycles later, that is at $t = 10.2$ s, the fault is cleared by tripping the tie line through the opening of the breaker placed between buses 4 and 5 (Bk1).

For the topology presented in the test case, in the steady state previous to the fault, the small system (SG, WF, load and the DSTATCOM/FESS device) exports about 9.5 MW to the bulk power system. In this state, the system frequency is at its rated value (50 Hz). After the fault, the small system operates in island conditions. In this way, the SG and the WF have to supply all the power required by the load; therefore the speed governor of the SG must automatically recover the system frequency to its rated value. As can be seen from the simulation results of Fig. 6*a*, in the base case (without the DSTATCOM/FESS device), the SG unit is capable of recovering the system frequency.

Now, the connection of a DSTATCOM/FESS with 4 MW rated power and 30 kWh rated storage capacity is considered. The results of Fig. 6*a* clearly show the action of the FESS device and the excellent performance of the controls of the DSTATCOM/FESS. After the fault, when the frequency deviation exceeds the dead-band limits (0.15 Hz for this case), the FESS device with the FC mode is activated. The rapid active power consumption absorbs the sudden generation surplus occurred after the tie line tripping. Thus, the SG is able to find the balance with the load with a lesser frequency deviation. In this case, the system frequency rises to nearly 50.4 against 50.7 Hz in the base case; the effects of the disturbance are totally mitigated in a shorter time than in the base case and the overshoot is decreased. The improvement of the frequency control is obtained by the action of the FESS device, which consumes active power for about 10 s. Furthermore, after the frequency falls down under the limit of the dead-band value, the APR mode is activated again. This causes that power fluctuations of the WF be mitigated and, thus, the minor frequency deviations

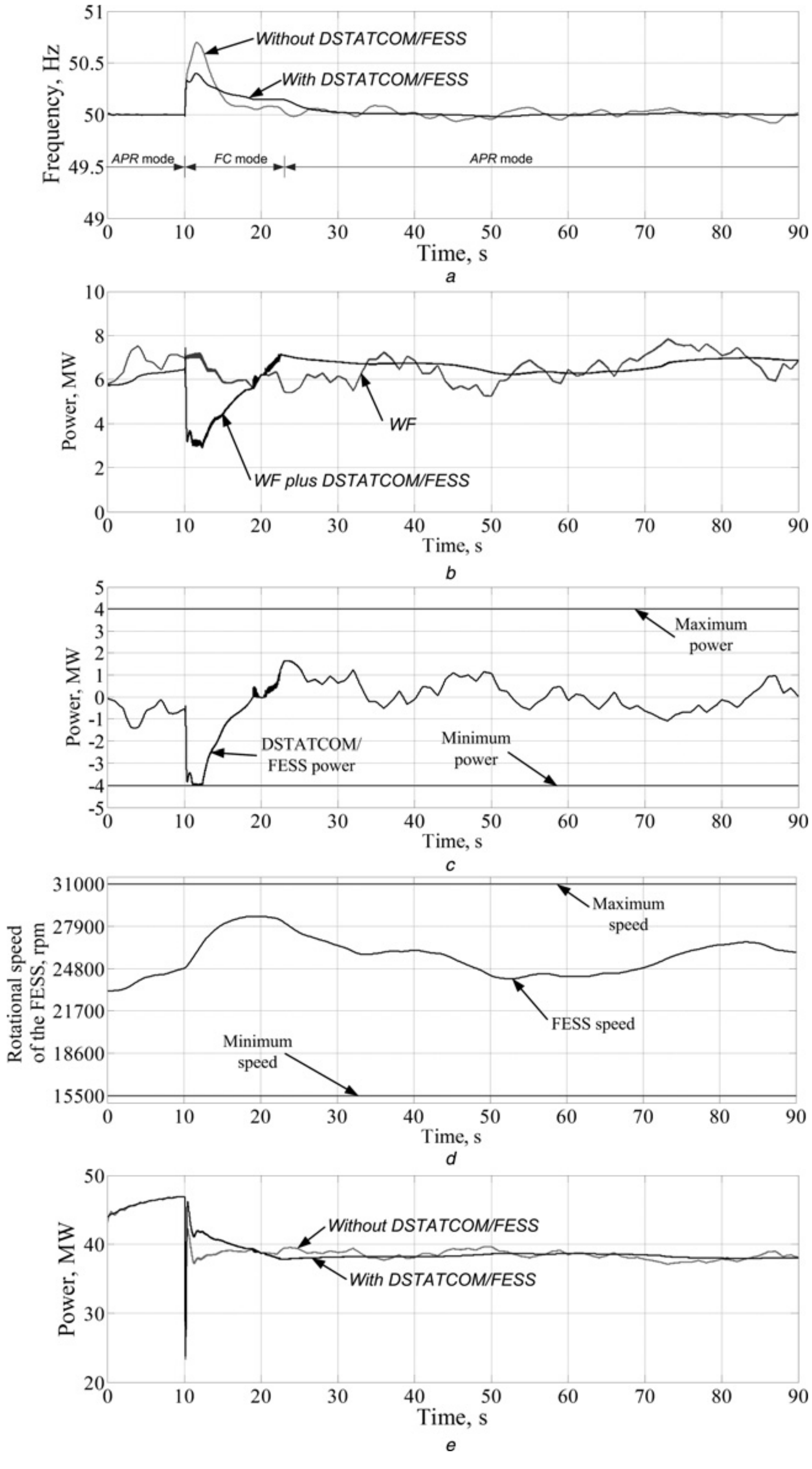

Fig. 6 *Performance of DSTATCOM/FESS working in APR mode*

a System frequency
b Active power flow of the WG with and without the DSTATCOM/FESS device
c Active power injected by the DSTATCOM/FESS
d Rotational speed of the flywheel
e Active power of synchronous generator

be also reduced, as can be noted from Fig. 6*a*. The active power flow for the system WF plus DSTATCOM/FESS, with Bk3 switched off and on, that is, with the DSTATCOM/FESS device disconnected and connected, and the active power injected by the DSTATCOM/FESS are shown in Figs. 6*b* and *c*, respectively. It can be noted that after the fault, the DSTATCOM/FESS stores its maximum power. Hence, the WG with the DSTATCOM/FESS and the proposed control contributes to the recovery of the frequency. The rotational speed for one of the flywheels is shown in Fig. 6*d*. It can be noted a marked increase of speed (or load state) during the fault owing to the energy storage. Finally, the active power

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injected by the synchronous generator with and without the connection of the DSTATCOM/FESS device is shown in Fig. 6*e*. It can be noted from Fig. 6*e* that with the connection of the DSTATCOM/FESS device the operation of the synchronous generator is significantly improved.

6 Conclusions

This paper presents control aspects of an FESS coupled with a DSTATCOM controller to improve the integration of fixed-speed wind turbines into the power system. A proposal is made for the control algorithm of the device using two control modes. One mode uses a FIS together with a special filter to smooth the wind power fluctuations that wind generators inject into a power system. The other control mode is used to contribute to the frequency control when important faults arise in the system.

From the results obtained, it can be concluded that the developed control algorithms work satisfactorily. The DSTATCOM/FESS device effectively compensates the active power fluctuations from a WF. The complete system (WF plus DSTATCOM/FESS) generates a smoother power response than that of the system without the DSTATCOM/FESS. Moreover, the complete system also contributes to the recovery of the frequency when significant faults occur in the system. For the APR control mode, it is concluded that the active power control of the DSTATCOM/FESS using the controller based in fuzzy logic achieves an optimal management of the stored energy, by correcting the wind power fluctuations and making the storage device never fall below no load condition nor, on the contrary, come into maximum overload. With this control mode, the power quality of wind generators is improved and, at the same time, a good use of the energy stored is achieved. For the FC mode, it is concluded that when faults arise in the system so that the frequency falls or rises over a given value; the device changes the control mode from APR to FC and, therefore, successfully contributes to recover the rated system frequency value. With this control mode, the wind power generation in conjunction with the DSTATCOM/FESS controller provides an ancillary service to improve the system security. Therefore the integration of fixed-speed wind turbines in power systems is improved with the compensation provided by the DSTATCOM/FESS controller.

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