J Electr Eng Technol Vol. 9, No. 4: 1258-1268, 2014
http://dx.doi.org/10.5370/JEET.2014.9.4.1258

ISSN(Print) 1975-0102
ISSN(Online) 2093-7423

Comparative Study of the Behavior of a Wind Farm Integrating Three Different FACTS Devices

Raúl Sarrias*, Carlos González, Luis M. Fernández†, Carlos Andrés García* and Francisco Jurado*****

Abstract – Improving grid connection of wind farms is a relevant issue to be addressed, especially for fixed-speed wind turbines. Certain elements, such as FACTS (Flexible AC Transmission Systems), are able to perform voltage and reactive power regulation in order to support voltage stability of wind farms, and compensate reactive power consumption from the grid. Several devices are grouped under the name of FACTS, which embrace different technologies and operating principles. Here, three of them are evaluated and compared, namely STATCOM (Static Synchronous Compensator), SVC (Static Var Compensator) and SSSC (Static Synchronous Series Compensator). They have been modeled in MATLAB / Simulink, and simulated under various scenarios, regarding both normal operation and grid fault conditions. Their response is studied together with the case when no FACTS are implemented. Results show that SSSC improves the voltage stability of the wind farm, whereas STATCOM and SVC provide additional reactive power.

Keywords: SSSC (Static Synchronous Series Compensator), STATCOM (Static Synchronous Compensator), SVC (Static Var Compensator), Wind farm, Wind turbine

1. Introduction

Increasing penetration of renewable energy generation systems into the electric power systems all over the world has been noticeable for the last decades. In many countries, there has been a remarkable support of these natural resources in an attempt to progressively substitute the traditional power plants, mainly based on the consumption of fossil fuels, with a cleaner alternative. In this regard, among the different available technologies, wind power has gained the most relevant position towards electricity generation in large power systems. Nonetheless, the massive use of an intermittent and unpredictable source, such as wind, possesses stability and reliability challenges into the power grid that must be properly addressed. Several studies have been carried out evaluating the impact of large amount of wind energy into power systems [1-5]. In order to maintain a proper quality in the electric power supply to loads, voltage and frequency regulation is the key factor to be taken into account; whereas balanced active and reactive power flow between generation and demand must be guaranteed not to threaten the stability of the power system.

In the early stages of wind power, fixed-speed wind turbines equipped with squirrel cage induction generator (SCIG) dominated the market. Currently, even though new and improved technologies for wind turbines have arisen, such as doubly-fed induction generator (DFIG) [6] and permanent magnet synchronous generator (PMSG) [7], the SCIG still remains as an important fraction of the globally installed wind park.

Nonetheless, several drawbacks must be faced when using this technology. The SCIG presents a simple scheme in which the stator windings are directly connected to grid, while the rotor windings are short-circuited and not electrically accessible. This arrangement does not require any power converter or additional equipment that allows active or reactive power control in the generator itself. Besides, since the stator currents must adapt to the frequency imposed by the grid, only a very narrow margin of variability can be accomplished in the rotating speed of the wind turbine [8].

Due to its structure, the SCIG consumes a certain amount of reactive power to create the magnetic field in the stator windings. This consumption is usually reduced by using compensating capacitors when the generator operates in steady-state conditions. These capacitors are usually connected or disconnected in modules to adapt to different power ratings. Nevertheless, this solution does not provide an optimal dynamic response under variable generation conditions. This performance becomes even less adequate when a grid fault occurs. Under voltage sags, active power output of the wind turbine drops rapidly, while reactive power support from the grid to the generator is still necessary. This worsens the effects of the fault on the

† Corresponding Author: Dept. of Electrical Engineering, University of Cádiz, EPS Algeciras, Spain. (luis.fernandez@uca.es)
* Dept. of Electrical Engineering, University of Cádiz, EPS Algeciras, Spain. (raul.sarrias@uca.es, carlosandres.garcia@uca.es)
** University of Cádiz, EPS Algeciras, Spain. (carlosgonzalezroca@gmail.com)
*** Dept. of Electrical Engineering, University of Jaén, EPS Linares, Spain. (fjurado@ujaen.es)
Received: November 30, 2012; Accepted: January 22, 2014

voltage, usually causing the fixed-speed wind turbines to trip either due to overspeed or undervoltage [1]. This helps recovering voltage stability; however, it reduces active power supply to load and jeopardizes power balance in the grid.

Subsequently, newly developed grid codes in countries with high penetration of wind power are becoming more demanding towards the operation of this source [9-11], setting the low voltage ride through (LVRT) capabilities that force the wind turbines to remain connected during voltage sags of specified characteristics, and to provide certain amount of reactive power in order to support voltage recovery. Nonetheless, this feature cannot be accomplished by the SCIG on its own. Therefore, additional equipment is needed in order to allow this technology satisfy the imposed requirements. Here, Flexible AC Transmission Systems (FACTS) play an important role.

Several distinctive devices can be classified under the name of FACTS [12-14]. Among others, Static Synchronous Compensator (STATCOM), Static Var Compensator (SVC) and Static Synchronous Series Compensator (SSSC), appear as an adequate solution to the reactive power and voltage regulation conflicts of fixed-speed wind turbines. These devices are able to interact with the system so as to improve the quality of the energy delivered to grid by the wind turbines and provide the LVRT capabilities demanded by grid codes [15-23]. According to their implementation, STATCOM and SVC can be defined as shunt-connected devices, whereas SSSC is connected in series with the SCIG output terminals.Application of STATCOM, SVC and SSSC to wind farms has been addressed in the literature. Special attention has been drawn on LVRT enhancement of fixed-speed wind turbines using STATCOM [16, 19, 24, 25] and their ability to accomplish grid code requirements [26, 27]. Furthermore, an improved configuration is presented in [28, 29], where an energy storage system is added to the STATCOM topology to allow active power flow regulation, and improve primary frequency control of power systems [30]. The use of SVC for voltage stability applications is studied in [21, 31, 32], and the behavior of SSSC within electric power systems is evaluated in [33] and [34].

Since they present different characteristics regarding their structure and controllability, dissimilar behavior of these devices is expected under the same operating conditions. Nonetheless, no relevant references exist in which comparison between these three technologies is carried out. Hence, this aspect is considered here, focused mainly on their performance together with grid connected fixed-speed wind farms.

This paper evaluates the dynamic response to grid faults of a wind farm equipped with SCIG and FACTS.A 12 MW fixed-speed wind farmhas been modeled using MATLAB/Simulink software. The wind farm is connected to grid using FACTS that compensates the reactive power consumption of induction generators, and improves voltage stability when grid faults occur. Therefore, three different configurations have been obtained according to the FACTS implemented, i.e. STATCOM, SVC and SSSC. Transient stability simulations under various operating conditions have been carried out in MATLAB/Simulink to evaluate the dynamic response of the models to grid disturbances. The results are observed, and a comparative study is done between the proposed configurations. Finally, the most relevant aspects of the analysis are highlighted. The paper is organized as follows. Section 2 presents a brief description of the wind farm. The FACTS models are detailed in Section 3. Simulations are illustrated and discussed in Section 4. Finally, Section 5 states the conclusions drawn from the analysis.

2. Wind Farm Description

The evaluation carried out herein is developed on a wind farm chosen as a reference. This wind farm is modeled in MATLAB/Simulink, and has been modified in order to analyze its performance with different FACTS.

The wind farm consists of four identical branches connected to a common node, which is considered to be the output terminal of the wind farm. Moreover, each branch comprises two fixed-speed wind turbines equipped with SCIG. The rated power of the induction generators is 1.5 MW. Hence, a total wind farm rated power of 12 MW is obtained from the sum of four branches of 3 MW each. Besides, every couple of wind turbines connected to the same branch present a compensating capacitor of 400 kVAr reactive power at its output. A scheme of the wind farm is shown in Fig. 1, where two of the branches have been omitted for the sake of clarity in the representation.

A voltage transformer is also required in order to boost the 575 V SCIG output to 25 kV, which is the voltage used within the wind farm network. Therefore, four of these 575 V/25 kV transformers of 4 MVA rated power are implemented among the four branches of the wind farm.

In addition, a 1 km long transmission line has been implemented using the pi-model to account for the power losses occurred from the transformer output to the common node.

This structure is repeated in each of the four branches. In the cases when FACTS are implemented, the common node also serves as the connecting port of these devices. Here, it is essential to make the difference between the shunt-connected elements, such as STATCOM and SVC, and the series compensator, namely SSSC. For STATCOM and SVC, an additional branch with one of the previous devices is connected in parallel at the common node of the wind farm, whereas the SSSC is connected in series between this node and the rest of the transmission line to the Point of Common Coupling (PCC). Accordingly, when no FACTS are considered, this element must be removed

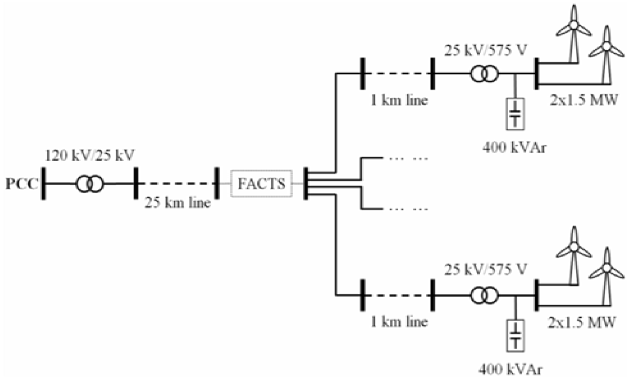

Fig. 1. Wind farm scheme

and both nodes connected in the scheme presented in Fig. 1.

Following the FACTS, the pi-model of a 25 km long transmission line connects the wind farm with a voltage transformer, which elevates voltage from 25 kV to the 120 kV required at the PCC to grid with a rated power of 47 MVA.

Finally, the grid is implemented using an ideal three-phase AC source, which introduces a constant amplitude and frequency AC signal at the PCC.

2.1 Wind turbine and SCIG modeling

The wind turbine and the SCIG have been modeled by well-known and broadly used models for these purposes [35]. First, the blades and rotor of the wind turbine are implemented by using the actuator disk theory, which defines the mechanical torque of the wind turbine, T_m, as follows.

$$T_m = \frac{P_m}{\omega_r} = \frac{1}{\omega_r}\left(\frac{1}{2}\cdot\rho\cdot A\cdot C_p(\lambda,\theta)\cdot u^3\right) \quad (1)$$

where P_m, A and ω_r stand for the mechanical power, area and electrical angular speed of the rotor respectively. C_p is the power coefficient of the wind turbine, which is a function of the tip speed ratio (λ) and the blade pitch angle (θ); u is the wind speed and ρ is the air density.

The electrical behavior of the SCIG is represented by a fourth-order model, which presents the stator and rotor voltages in a direct (d)-quadrature (q) reference frame through the Park transformation, as given by

$$\begin{aligned} V_{ds} &= R_s\cdot i_{ds} + \frac{d\varphi_{ds}}{dt} - \omega\cdot\varphi_{qs} \\ V_{qs} &= R_s\cdot i_{qs} + \frac{d\varphi_{qs}}{dt} + \omega\cdot\varphi_{ds} \end{aligned} \quad (2)$$

$$\begin{aligned} V'_{dr} &= R'_r\cdot i'_{dr} + \frac{d\varphi'_{dr}}{dt} - (\omega-\omega_r)\cdot\varphi'_{qr} = 0 \\ V'_{qr} &= R'_r\cdot i'_{qr} + \frac{d\varphi'_{qr}}{dt} + (\omega-\omega_r)\cdot\varphi'_{dr} = 0 \end{aligned} \quad (3)$$

where subindexes s and r stand for stator and rotor; flux linkages are given by φ; V, R and i are used for voltages, electrical resistances and currents respectively; and ω is the synchronous speed. The prime sign (ʻ) indicates that the rotor variables are referred to the stator. Moreover, the d-q components of the stator and rotor flux linkages are given by,

$$\begin{aligned} \varphi_{ds} &= L_s\cdot i_{ds} + L_m\cdot i'_{dr} \qquad \varphi'_{dr} = L'_r\cdot i'_{dr} + L_m\cdot i_{ds} \\ \varphi_{qs} &= L_s\cdot i_{qs} + L_m\cdot i'_{qr} \qquad \varphi'_{qr} = L'_r\cdot i'_{qr} + L_m\cdot i_{qs} \end{aligned} \quad (4)$$

where L denotes inductance and subindex m stands for mutual.

Furthermore, the electromagnetic torque (T_e) of the SCIG can be calculated by

$$T_e = 1.5\cdot p\cdot(\varphi_{ds}\cdot i_{qs} - \varphi_{qs}\cdot i_{ds}) \quad (5)$$

where p is the pair of poles in the generator.

On the other hand, a second order model characterizes the mechanical behavior of the SCIG, as given by

$$\frac{d\omega_{mec}}{dt} = \frac{1}{2\cdot H}(T_e - F\cdot\omega_{mec} - T_m) \quad (6)$$

where ω_{mec} is the mechanical rotating speed of the rotor; H is the rotor inertia constant; and F is the viscous friction coefficient of the SCIG.

Eqs. (1-6) are implemented in Simulink to model the electric and mechanical performance of a fixed-speed wind turbine generator. The SCIG driven wind turbine is completed with a pitch angle controller that limits the mechanical power capture in order to avoid potentially dangerous operation under high wind speeds.

3. FACTS Models Description

Several devices comprise the family of FACTS, showing different operating principles and configurations. Here, three of them have been considered, i.e. STATCOM, SVC and SSSC, in order to enhance grid-connection capabilities of a wind farm. Their modeling is described in this section.

3.1 Static Synchronous Compensator (STATCOM)

The STATCOM is a switching converter-based, shunt-connected device used to regulate voltage and power flow on electric power systems by means of reactive power injection or absorption [36]. This device consists of a voltage-sourced converter (VSC), which generates a controlled AC voltage at its output, with the use of a coupling transformer, DC capacitor and power electronics.

It is modeled as a voltage-controlled current source, whose value is calculated as a function of the primary and

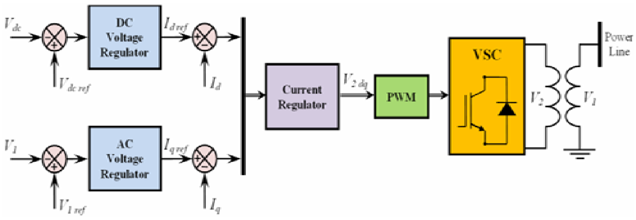

Fig. 2. STATCOM control scheme

secondary voltages of the coupling transformer. The primary voltage is directly measured at the connection port of the STATCOM, whereas the secondary voltage is computed indirectly.

In the control system implemented (Fig. 2), the quadrature component of the converter current (in a *d-q* reference frame) controls the primary voltage of the transformer to its reference, and therefore the reactive power exchange with the system, by using a PI-controller and taking into consideration the droop characteristic of the device.

On the other hand, the direct component of the converter current is used to regulate the DC voltage at the capacitor side of the converter through a PI-controller, and subsequently the active power flow in the converter. Then, with both current references, a current regulator implements the secondary voltage *d-q* components, which are sent to a PWM that generates the switching signals for the converter power electronic devices.

3.2 Static Var Compensator (SVC)

The SVC is a shunt-connected FACTS implemented in power systems to improve voltage stability and regulate power flow. Similarly to the STATCOM, this device allows reactive power exchange with the electric system where it is connected. Nonetheless, it is based on a different operating principle. In the case of SVC, the reactive power generation or absorption is accomplished by means of a variable admittance, which can shift from capacitive to inductive according to the necessities of the controller [36]. This performance can be achieved with thyristor-switched/controlled capacitors and reactors.

The control system applied to this device is a single-loop PI-based controller, where the error signal between the measured voltage at the SVC terminals and its reference is used as input, and the variable susceptance is dynamically calculated and outputted, as shown in Fig. 3. This susceptance is then multiplied by the measured voltage and converted to line currents. Therefore, these currents are calculated so as to compensate the voltage deviation through the variable susceptance, and are injected to the power system regulated by the SVC. Here, the reactive power compensation limits of this device are imposed by the maximum capacitive and inductive limits of the susceptance.

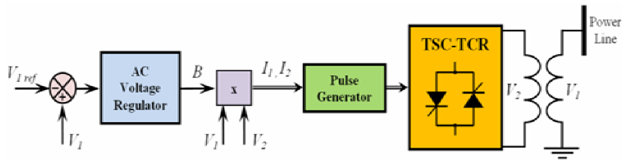

Fig. 3. SVC control scheme

3.3 Static Synchronous Series Compensator (SSSC)

In the family of FACTS, the SSSC corresponds to a different concept compared to the previously detailed devices, since it is connected in series. Nonetheless, they all have the common purpose of improving power flow and voltage stability in electric power systems. Hence, the SSSC is a switching-converter series compensator, based on VSC. Its operating principle lays on the injection of a component voltage in quadrature with the line current, in order to increase the voltage across the series impedance of the line, and subsequently the transmitted power [36].

The control system (Fig. 4) implements a PWM that generates the switching signals for the VSC from the calculated *d* and *q* components of the converter voltage. Since it is connected in series, it is necessary to make a distinction between voltages at both sides of the SSSC. Hence, the actual injected quadrature voltage is calculated as the difference between the *q*-component of the right-hand side voltage (V_{2q}) and the same component of the left-hand side voltage (V_{1q}). For the models developed in this paper, the right-hand side corresponds to the wind farm side, whereas the left-hand side is the grid side. The measured quadrature voltage is compared to its reference, which is externally calculated using a PI-controller that regulates the wind farm output voltage to its reference. Then, the quadrature voltages error signal is inputted to a PI-controller with a feed-forward term of the direct line current, thus obtaining the quadrature voltage needed in the converter. On the other hand, the direct component of the converter voltage is obtained through a single PI-based control loop from the capacitor voltage measurement and its fixed reference.Once the *d* and *q* components of the converter voltage are determined, the PWM defines the switching signals that drive the power converter.

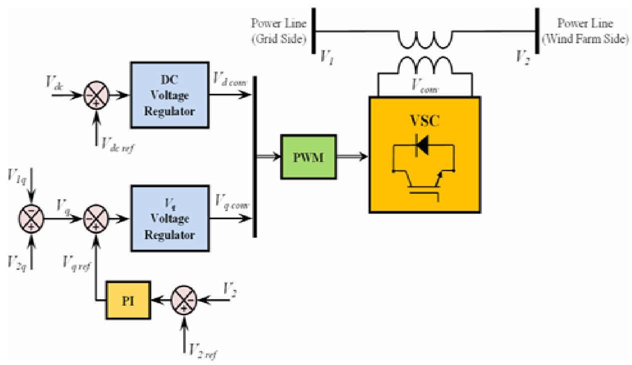

Fig. 4. SSSC control scheme

4. Simulation Results and Discussion

Different simulations have been performed, in which both normal operation and grid faults are evaluated in order to compare the response of the described models under multiple operating conditions.

For the voltage sags and overvoltage situations illustrated in cases study 2-4, the main purpose was to analyze the ability of FACTS to overcome these faults and improve the performance of the wind farm when facing grid perturbations. Therefore, they have been implemented by introducing a transient perturbation on the AC source that models the strong grid where the wind farm is connected. This allows simulating a temporary fault on the PCC due to grid disturbances, monitoring the influence on the wind farm, and showing the improvements achieved with the incorporation of FACTS as desired. Therefore, since these faults are considered to appear in the grid, the PCC is the location chosen to introduce the perturbation.

On the other hand, the single-phase fault to ground presented in case study 5 occurs at the common node between the FACTS and the 25 km transmission line (Fig. 1). This location has been chosen due to its proximity to the FACTS device, with the purpose of clearly appreciating the influence of FACTS on the performance of the whole system. If a further placement of the fault was chosen, the compensating effects of the FACTS might have been mitigated by the transmission line and grid elements, thus hampering the proper interpretation of the results obtained.

4.1 Case Study 1: Normal Operation

In this simulation, the steady state operation of the wind power systems under variable wind speed is analyzed during 240 s. Fig. 5 shows the four different time series of incoming wind speed, one for each of the aggregated branches of the park, considered in this simulation.

One of the most relevant parameters in a fixed-speed wind farm is the output voltage, which is represented in Fig. 6. As can be seen, the wind farm without FACTS is not able to remain connected to grid throughout the simulation, since at the approximate time of 155 s, the voltage drops below the operating limits. No recovery can be observed, and reconnection would be necessary. Therefore, it can be appreciated how the inclusion of FACTS improves the grid connection of wind farms by reducing the voltage fluctuation. Moreover, even though SSSC provides an adequate performance, it is with the STATCOM and SVC that the voltage remains more stable along the simulation, showing no relevant differences between both devices.

The active power generation of the wind farm has also been registered, as illustrated in Fig. 7. As seen, the response of the STATCOM and SVC models does not differ notably. Nonetheless, the SSSC active power output remains slightly lower that the STATCOM and SVC generation during the entire simulation. This is due to the minor active power losses accounted in the SSSC itself. Besides, the simulation indicates that the decrease of wind farm voltage occurred at 155 s in the configuration without FACTS provokes a drastic fall on the active power supply to grid, which forces the wind turbines to disconnect from the grid.

Due to the characteristics of the induction generators

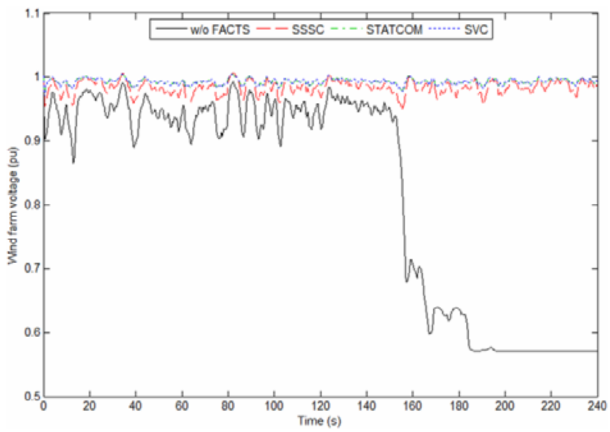

Fig. 6. Wind farm voltage (Case Study 1)

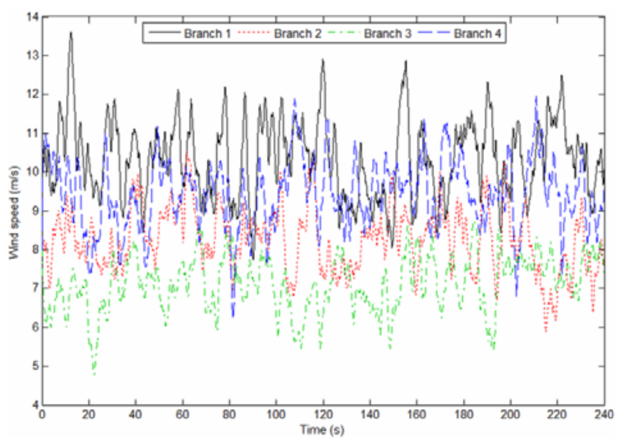

Fig. 5. Incoming wind speed for each aggregated branch

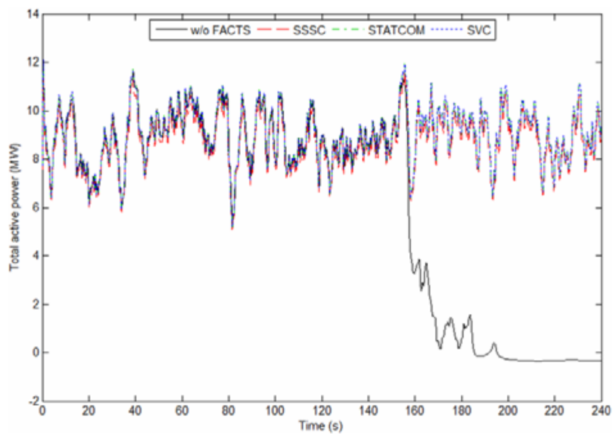

Fig. 7. Total active power generation (Case Study 1)

used in the wind turbines, reactive power consumption from the grid occurs. As seen in Fig. 8, this reactive power consumption is reduced when the wind farm is equipped with FACTS, especially in the cases of STATCOM and SVC. These two devices show identic reactive power response in this simulation, varying between 1 and 2 MVAr reactive power consumption according to the wind speed fluctuations. On the other hand, when using SSSC, the total reactive power input to the wind farm increases notably, reaching values superior to 4.5 MVAr in some instants. Furthermore, the absence of FACTS implies a higher reactive power supply from the grid, and thus increasing the risk of contingencies, which eventually appear when the wind farm without FACTS requires disconnection at 155 s.

Regarding the results in Fig. 8, the use of FACTS leads to a decrease in the reactive power consumption from the grid. This is due to the extra injection provided by these devices, which is presented in Fig. 9. It can be observed that STATCOM and SVC provide higher reactive power compared to SSSC. The former devices output an average value of approximately 1.6 MVAr with a standard deviation of 0.44 MVAr throughout the simulation, whereas the latter presents an average value close to 0.1 MVAr for the studied period, and a standard deviation of 0.07 MVAr. This results show that SSSC, compared to STATCOM and SVC, is able to perform an adequate control on the wind farm voltage with a much lower reactive power injection when operating in steady state conditions with variable wind speed.

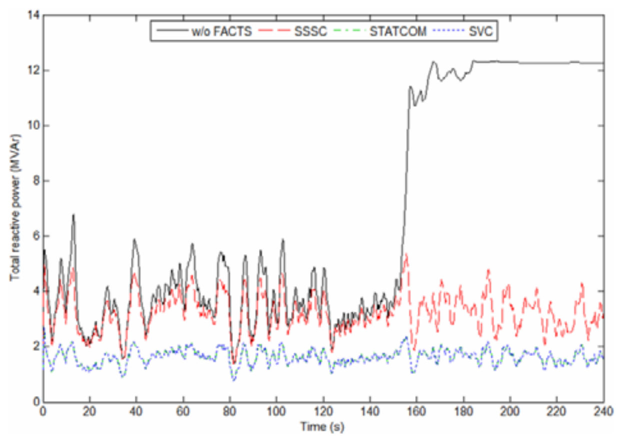

Fig. 8. Total reactive power consumption (Case Study 1)

4.2 Case Study 2: Mild Voltage Sag (0.8 pu during 1 s)

Transient behavior of the models under grid fault conditions has also been studied. Here, a mild voltage sag of 0.8 pu and 1 s duration is considered at the PCC. This disturbance requires the FACTS to support voltage at the wind farm output in order to avoid disconnection of the wind turbines or equipment damage.

This experience uses constant wind speed of 8 m/s as input to the wind turbines, in order to clearly differentiate the mechanical torque variations due to fluctuations in wind, from the electric transients, which are much faster than the former.

Fig. 10 illustrates some of the improvements achieved with the inclusion of FACTS. As seen, at the beginning of the simulation, those wind farms equipped with such devices present a voltage of 1 pu, which is the specified rated value. Nonetheless, in the wind farm without FACTS, a value of 0.98 pu is measured. Moreover, all wind farms experience a sharp decrease in voltage when the voltage sag occurs at 0.5 s. Nevertheless, this diminution continues during the voltage sag for the wind farm without FACTS, reaching a minimum value of 0.75 pu at 1.5 s, when the fault is cleared; whereas the wind farms with SSSC, STATCOM and SVC perform dissimilarly. In the cases of STATCOM and SVC, voltage decreases progressively and registers minimum values of 0.82 and 0.81 pu respectively, which are notably higher than that of the wind farm without FACTS. On the other hand, the SSSC is able to mitigate voltage drop during the sag, remaining close to 0.85 pu most of the fault interval, even though the initial fall is more pronounced for this device.

After the fault clearance, all models are able to restore

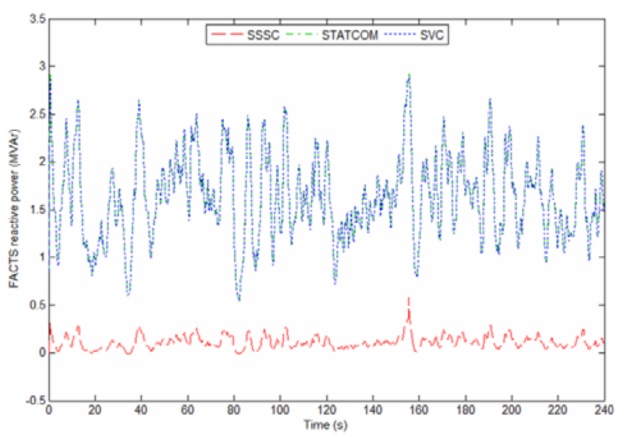

Fig. 9. FACTS reactive power generation (Case Study 1)

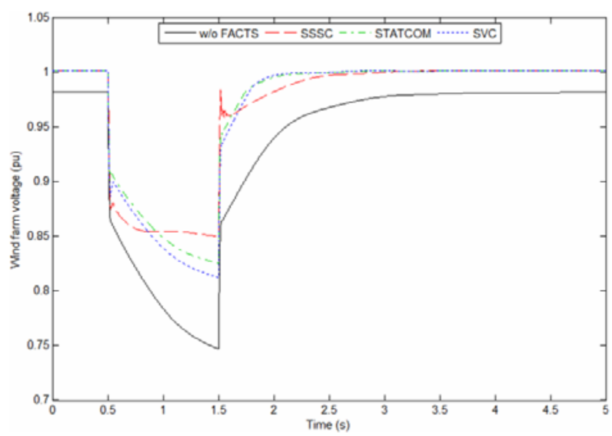

Fig. 10. Wind farm voltage (Case Study 2)

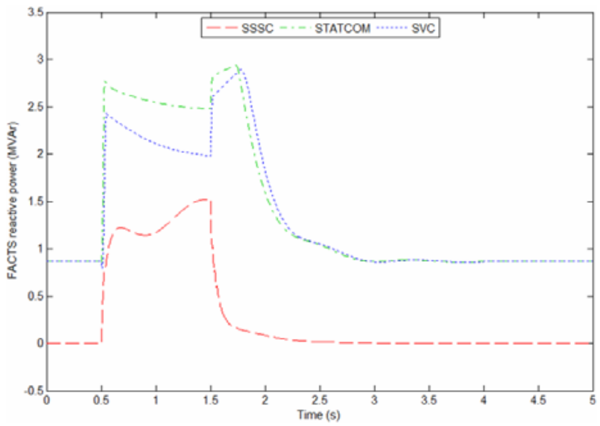

Fig. 11. FACTS reactive power generation (Case Study 2)

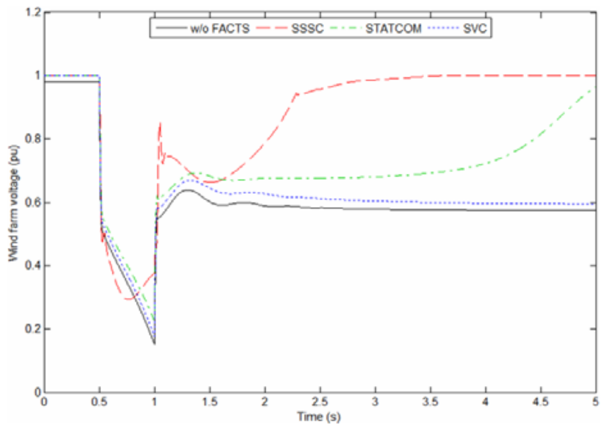

Fig. 12. Wind farm voltage (Case Study 3)

their nominal voltage. STATCOM and SVC are the quickest alternatives with a recovery time of 0.5 s, whereas SSSC and the wind farm without FACTS take approximately 1.5 s to reach their previous condition.

Reactive power injection of FACTS during the voltage sag is also of interest. Fig. 11 represents this response. As seen, both the STATCOM and SVC inject 0.86 MVAr before the fault. When the voltage sag occurs, their reactive power generation increases. STATCOM achieves a higher value than SVC, 2.5 MVAr versus the 2 MVAr provided by the SVC. Moreover, a second boost of reactive power, close to 3 MVAr, appears once the fault is cleared at 1.5 s, in order to support the wind farm voltage recovery. On the other hand, a substantial injection of reactive power is not needed in the case of SSSC. This device is not demanded to provide reactive energy during normal operation. Nonetheless, it is able to supply the grid during the voltage sag with an amount that varies between 1.2 and 1.5 MVAr. This injection soon decreases after the fault clearance.

Therefore, as observed from the results obtained, the SSSC achieves a better performance in voltage support and recovery during the voltage sag with minor requirements of reactive power, compared to STATCOM and SVC. Nonetheless, STATCOM and SVC are still valid, and achieve interesting improvements in voltage support compared to the alternative without FACTS.

4.3 Case Study 3: Severe Voltage Sag (0.2 pu during 0.5 s)

This simulation evaluates the performance of the models under a severe voltage sag of 0.2 pu at the PCC during 0.5 s. These conditions correspond to the most demanding disturbance that wind farms must be able to ride-through according to the current Spanish regulation [37]. Besides, similarly to the previous simulation, the incoming wind speed is fixed at 8 m/s.

The wind farm voltage profile under the indicated operating conditions is shown in Fig. 12. As seen, the systems experience a rapid voltage drop when the fault

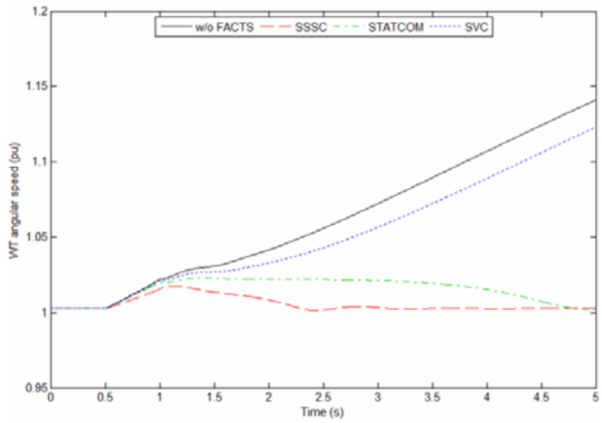

Fig. 13. Rotating speed of wind turbines (Case Study 3)

happens. This decrease is more pronounced in the wind farm without FACTS, with a minimum value of 0.15 pu at 1 s. The wind farms with STATCOM and SVC show a similar performance, since the voltage decreases consistently during the fault, reaching minimum values of 0.23 and 0.18 pu respectively. On the other hand, the SSSC partially raises voltage during a fraction of the voltage sag, after a marked decline at the beginning. Therefore, a final record of 0.38 pu is measured by the time the fault is cleared.

In addition to the final voltage during the sag, the recovery of this parameter after the fault clearance is also of crucial importance. In this regard, it is the SSSC that shows the best performance. According to the results, the wind farm with SSSC recovers 95% of the rated voltage by 2.4 s, whereas the wind farm with STATCOM reaches this boundary by 4.95 s, which is nearly 4 s after the fault is cleared. As can be seen, the wind farm without FACTS and the one with SVC are not able to recover nominal voltage after the voltage drop, as shown in Fig. 12. Therefore, in these two cases the wind farm does not adequately ride-through this voltage sag.

This deficient performance of the SVC and wind farm without FACTS can also be observed in the rotating speed response of the wind turbines, shown in Fig. 13. Due to the incoming versus output power imbalance, the rotor accelerates during the voltage sag. This acceleration is less pronounced for the SSSC, since it is able to release more active power, thus reducing the power imbalance. Nevertheless, once the voltage sag is cleared, the wind turbines of the wind farms with SSSC and STATCOM are able to recover the rated speed. On the other hand, the proper control of the rotating speed is lost during the voltage sag in the wind farms with SVC and without FACTS. As seen in Fig. 13, in both cases, this parameter still increases after the fault is cleared, thus preventing the recovery of wind turbines to nominal values, as previously stated.

4.4 Case Study 4: Overvoltage

Overvoltage has also been considered to happen at the PCC. It consists in a burst of 1.2 pu during 0.5 s that the wind farm must be able to overcome. Regarding the wind farm voltage profile of the models in Fig. 14, it shows that the implementation of FACTS improves the response of the wind turbines to this fault. As seen, the lowest rise in voltage has been recorded for the SSSC, with a mean value of approximately 1.07 pu during the fault. On the other hand, when the wind farm is not equipped with any FACTS, the voltage increases invariably up to 1.17 pu by the end of the fault. The wind farms with STATCOM and SVC devices register a similar performance. They are able to restrain the increase in voltage during the fault, reaching final values close to 1.11 pu in both cases. Moreover, all models recover their nominal voltage and steady state operation once the fault is cleared. The wind farm without FACTS takes 2 s to achieve its previous voltage, and a recovery time of 1 s has been recorded for the SSSC. On the other hand, STATCOM and SVC reach their references within 0.5 s.

The reactive power response of the FACTS is also of interest to evaluate the performance of these devices. It is illustrated in Fig. 15. As can be observed, all the FACTS are required to absorb reactive power in order to reduce

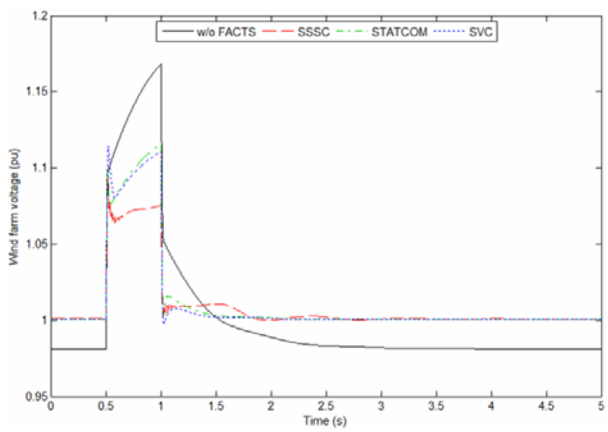

Fig. 14. Wind farm voltage (Case Study 4)

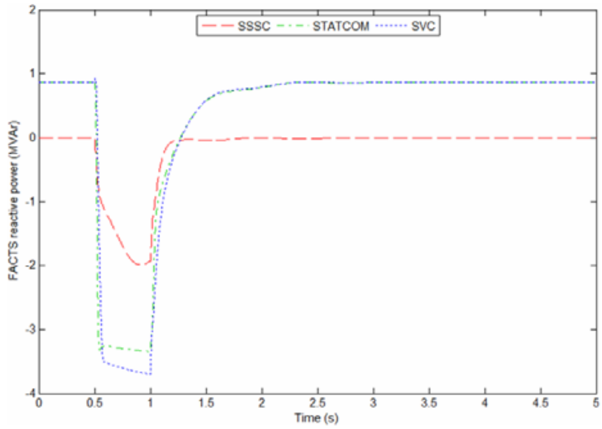

Fig. 15. FACTS reactive power generation (Case Study 4)

voltage during the fault. Nonetheless, the SSSC reaches a maximum consumption of 2 MVAr at 0.9 s, whereas the STATCOM and SVC register their peak values at 3.3 and 3.7 MVAr by the end of the voltage fault. Besides, these two devices also inject reactive power during steady state operation of the wind farm. Therefore, a major advantage of SSSC over STATCOM and SVC can be observed here, since the former achieves a better voltage profile with inferior reactive power exchange.

4.5 Case Study 5: Single-phase fault to ground

Faults to ground are other type of abnormal situations that grid-connected wind farms may have to deal with. In this simulation, a single-phase fault to ground has been considered at the wind farm output terminals from 0.5 s to 0.7 s. In the cases when the wind farm is equipped with FACTS, the fault occurs on the common node between the FACTS and the 25 km transmission line, i.e. the connection between the wind turbines and the FACTS remains untroubled. Moreover, similarly to the preceding experiences, a constant wind speed of 8 m/s is used as input for the wind turbines.

Due to the fault to ground, the voltage at the wind farm output drops abruptly, as shown in Fig. 16. This drop affects all the models. Nonetheless, the FACTS are able to mitigate the sudden decrease in voltage when connected to the wind farm output terminals. Hence, a minimum value of 0.826 pu is observed for the wind farm without FACTS, whereas 0.864 pu is recorded for SSSC and SVC, and 0.869 pu for STATCOM. Moreover, in all cases the wind farm voltage recovers to steady state, in approximately 1.5 s for SSSC and wind farm without FACTS and 1 s for STATCOM and SVC, after the faulty conditions disappear. These results prove a noticeable improvement on the voltage response accomplished with the implementation of FACTS. Besides, they show no remarkable differences between the different FACTS considered.

Regarding reactive power generation of the FACTS, a similar performance to that stated in previous simulations

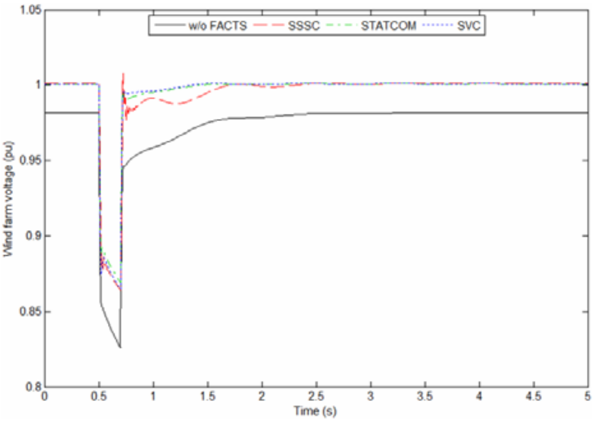

Fig. 16. Wind farm voltage (Case Study 5)

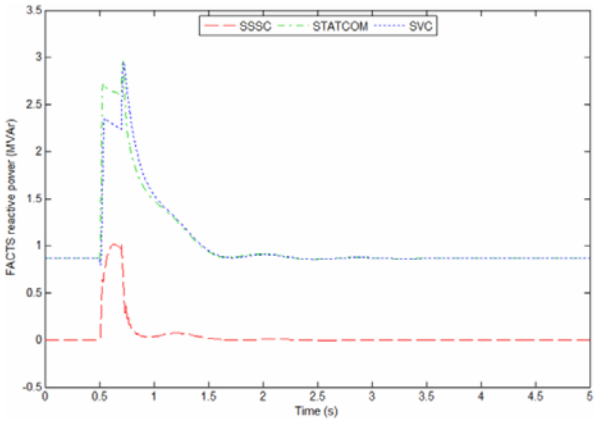

Fig. 17. FACTS reactive power generation (Case Study 5)

can be observed in Fig. 17. As seen, SSSC does not need toprovide a high reactive power injection in order to support the wind farm voltage. In this case, the SSSC reactive power generation reaches 1 MVAr as maximum. On the other hand, STATCOM and SVC achieve higher reactive power generation both during and after the fault clearance. Thus, mean values of 2.65 and 2.3 MVAr have been registered for STATCOM and SVC respectively during the fault to ground, whereas a maximum generation peak close to 3 MVAr occurs shortly after the fault is cleared. Therefore, this simulation reveals that a similar response on voltage profile has been obtained with minor reactive power exchange in the case of SSSC compared to STATCOM and SVC.

5. Conclusion

This paper focuses on the improvement of connection to grid of fixed-speed wind farms by implementing FACTS. The wind farm under study consists of four identical branches with two 1.5 MW SCIG connected on each of them, and a 400 kVAr compensating capacitor for every couple of wind turbines. Three alternative FACTS have been considered, i.e. STATCOM, SVC and SSSC, which are connected at the wind farm output terminals. Five different simulations have been carried out, which include normal operation under variable wind speed, and several grid fault conditions. The performance of the three FACTS presented has been evaluated and compared with that of the wind farm without any compensating device.

Results show that all the FACTS considered here are able to improve the voltage stability and response to transient grid faults of fixed-speed wind farms, compared to the case when no FACTS are implemented. Particularly, SSSC has proved the best voltage regulation performance during grid fault simulations, and adequate behavior under variable wind speed. On the other hand, STATCOM and SVC achieve better voltage stability at the wind farm output terminals against wind speed fluctuations. Nonetheless, they seem to be less able than SSSC to overcome various grid fault conditions.

It is also noticeable the reactive power generation provided by STATCOM and SVC. This additional injection allows reducing the reactive power consumption from the grid in steady state conditions. This reduction is not viable with SSSC, since the operating principle of this device is based on voltage regulation instead of reactive power exchange.

Therefore, the SSSC has shown to perform a proper control on the wind farm voltage under both normal operation and grid disturbances without the necessity of a considerable reactive power generation. On the other hand, in order to reduce the amount of reactive power required from the grid by the wind farm, a shunt-connected device, such as STATCOM or SVC, is needed, even though under certain circumstances these will not be able to properly support wind farm voltage.

Acknowledgements

This work has been supported by the University of Cadiz under the Grant FPI 2012-036, by the Spanish Ministry of Science and Innovation under Grant ENE2010-19744/ALT, and by the Foundation Technological Campus of Algeciras.

References

[1] J. L. Rodríguez, J. Fernández, D. Beato, R. Iturbe, J. Usaola, P. Ledesma and J. Wilhelmi, “Incidence on power system dynamics of high penetration of fixed speed and doubly fed wind energy systems: Study of the Spanish case,” *IEEE Trans Power Syst.*, vol. 17, no. 4, pp. 1089-1095, Nov. 2002.

[2] M. P. Pálsson, T. Toftevaag, K. Uhlen and J. O. G. Tande, “Large-scale wind power integration and voltage stability limits in regional networks,” *in Proc. IEEE-PES Summer Meeting*, 2002, vol. 2, pp. 762-

769.
[3] J. Rodríguez-García, T. Domínguez, J. F. Alonso and L. Imaz, "Large integration of wind power: the Spanish experience," *in Proc. IEEE-PES General Meeting*, 2007, pp. 1-5.
[4] P. S. Georgilakis, "Technical challenges associated with the integration of wind power into power systems," *Renew Sustain Energy Rev.*, vol. 12, no. 3, pp. 852-863, Apr. 2008.
[5] V. Akhmatov and H. Knudsen, "Large penetration of wind and dispersed generation into Danish power grid," *Electr Power Syst Res.*, vol. 77, no. 9, pp. 1228-1238, Jul. 2007.
[6] G. Byeon, I. K. Park and G. Jang, "Modeling and control of a doubly-fed induction generator (DFIG) wind power generation system for real-time simulations," *J Electr Eng & Technol.*, vol. 5, no. 1, pp. 61-69, Mar. 2010.
[7] Y. D. Choy, B. M. Han, J. Y. Lee and G. Jang, "Real-time hardware simulator for grid-tied PMSG wind power system,"*J Electr Eng & Technol.*, vol. 6, no. 3, pp. 375-383, Mar. 2011.
[8] L.M. Fernández, J.R. Saenz and F. Jurado, "Dynamic models of wind farms with fixed speed wind turbines," *Renew Energy*, vol. 31, no. 8, pp. 1203-1230, Jul. 2206.
[9] M. Tsili and S. Papathanassiou, "A review of grid code technical requirements for wind farms," *IET Renew Power Gener.*, vol. 3, no. 3, pp. 308-332, Sep. 2009.
[10] B. Singh and S. N. Singh, "Development of grid connection requirements for wind power generators in India," *Renew Sustain Energy Rev.*, vol. 15, no. 3, pp. 1669-1674, Apr. 2011.
[11] M. Mohseni and S. M. Islam, "Review of international grid codes for wind power integration: Diversity, technology and a case for global standard," *Renew Sustain Energy Rev.*, vol. 16, no. 6, pp. 3876-3890, Aug. 2012.
[12] X. P. Zhang, C. Rehtanz and B. Pal, Flexible AC Transmission Systems: Modelling and Control. *Ed. Springer*, 2012.
[13] E. H. Watanabe, M. Aredes, P. G. Barbosa, G. Santos Jr, F. K. de Araújo and R. F. da Silva, "Flexible AC Transmission Systems," *in Power Electronics Handbook*, Ed. Elsevier, 2006, pp. 797-822.
[14] H. Kim and S. H. Kwon, "The study of FACTS impacts for probabilistic transient stability," *J Electr Eng & Technol.*, vol. 1, no. 2, pp. 129-136, Jun. 2006.
[15] S. G. B. Dasan, S. Ravichandran, Kamesh and R. P. K. Devi, "Steady-state analysis of grid connected WECS using FACTS controller," *in Proc. ICETECT*, 2011, pp. 127-137.
[16] M. J. Hossain, H. R. Pota and R. A. Ramos, "Robust STATCOM control for the stabilisation of fixed-speed wind turbines during low voltages," *Renew Energy*, vol. 36, no. 11, pp. 2897-2905, Nov. 2011.
[17] M. K. Döşoğlu and A. Öztürk, "Investigation of different load changes in wind farm by using FACTS devices," *Adv Eng Software*, vol. 45, no. 1, pp. 292-300, Mar. 2012.
[18] N. S. Kumar and J. Gokulakrishnan, "Impact of FACTS controllers on the stability of power systems connected with doubly fed induction generators," *Int J Electr Power Energy Syst.*, vol. 33, no. 5, pp. 1172-1184, Jun. 2011.
[19] H. Gaztañaga, I. Etxeberria-Otadui, D. Ocnasu and S. Bacha, "Real-time analysis of the transient response improvement of fixed-speed wind farms by using a reduced-scale STATCOM prototype," *IEEE Trans Power Syst.*, vol. 22, no. 2, pp. 658-666, May. 2007.
[20] Z. Saad-Saoud, M. L. Lisboa, J. B. Ekanayake, N. Jenkins and G. Strbac, "Application of STATCOMs to wind farms,"*IEE Proc. Gener Transm Distrib.*, vol. 145, no. 5, pp. 511-516, Sep. 1998.
[21] N. A. Lahaçani, D. Aouzellag and B. Mendil, "Contribution to the improvement of voltage profile in electrical network with wind generator using SVC device," *Renew Energy*, vol. 35, no. 1, pp. 243-248, Jan. 2010.
[22] K. K. Sen, "SSSC - Static Synchronous Series Compensator: Theory, modeling and application," *IEEE Trans Power Delivery*, vol. 13, no. 1, pp. 241-246, Jan. 1998.
[23] W. Qiao, R. G. Harley and G. K. Venayagamoorthy, "Effects of FACTS devices on a power system which includes a large wind farm," *in Proc. IEEE PSCE*, 2006, pp. 2070-2076.
[24] Z. Chen, Y. Hu and F. Blaabjerg, "Stability improvement of induction generator-based wind turbine systems," *IET Renew Power Gener.*, vol. 1, no. 1, pp. 81-93, Mar. 2007.
[25] M. J. Hossain, H. R. Pota, V. A. Ugrinovskii and R. A. Ramos, "Simultaneous STATCOM and pitch angle control for improved LVRT capability of fixed-speed wind turbines," *IEEE Trans Sustainable Energy*, vol. 1, no. 3, pp. 142-151, Oct. 2010.
[26] H. M. El-Helw and S. B. Tennakoon, "Evaluation of the suitability of a fixed speed wind turbine for large scale wind farms considering the new UK grid code," *Renew Energy*, vol. 33, no. 1, pp. 1-12, Jan. 2008.
[27] D. Ramirez, S. Martinez, F. Blazquez and C. Carrero, "Use of STATCOM in wind farms with fixed-speed generators for grid code compliance," *Renew Energy*, vol. 37, no. 1, pp. 202-212, Jan. 2012.
[28] S.M. Muyeen, M.H. Ali, R. Takahashi, T. Murata and J. Tamura, "Wind generator output power smoothing and terminal voltage regulation by using STATCOM/ESS," *in Proc. IEEE PowerTech*, 2007, pp. 1232-1237.
[29] A. Arulampalam, M. Barnes, N. Jenkins and J. B. Ekanayake, "Power quality and stability improvement of a wind farm using STATCOM supported with hybrid battery energy storage," *IEE Proc. Gener Transm Distrib.*, vol. 153, no. 6, pp. 701-710, Nov. 2006.

[30] M. G. Molina and P. E. Mercado, "Modeling and control of integrated STATCOM-SMES system to improve power system oscillations damping," *J Electr Eng & Technol.*, vol. 3, no.4, pp. 528-537, Dic. 2008.
[31] V. K. Polisetty, S. R. Jetti, G. K. Venayagamoorthy and R. G. Harley, "Intelligent integration of a wind farm to an utility power network with improved voltage stability," *in IEEE Industry Applications Conference*, 2006, pp. 1128-1133.
[32] M. Alonso, H. Amaris and C. Alvarez-Ortega, "A multiobjective approach for reactive power planning in networks with wind power generation," *Renew Energy*, vol. 37, no. 1, pp. 180-191, Jan. 2012.
[33] M. A. Kamarposhti and H. Lesani, "Effects of STATCOM, TCSC, SSSC and UPFC on static voltage stability," *Electr Eng.*, vol. 93, no. 1, pp. 33-42, Mar. 2011.
[34] G. Radman and R. S. Raje, "Dynamic model for power systems with multiple FACTS controllers," *Electr Power Syst Res.*, vol. 78, no. 3, pp. 361-371, Mar. 2008.
[35] S. Heier, Grid Integration of Wind Energy Conversion Systems. *John Wiley & Sons*, 1998.
[36] N. G. Hingorani and L. Gyugyi, Understanding FACTS. Concepts and Technology of Flexible AC Transmission Systems. Piscataway, NJ: *IEEE Press, Wiley – Interscience*, 2000.
[37] Spanish TSO, Red Eléctrica de España, "Requirements of response against voltage sags in wind power generation facilities (P.O. 12.3)," available from: http://www.ree.es/operacion/pdf/po/PO_resol_12.3_ Respuesta_huecos_eolica.pdf, accessed October 2012.

Raúl Sarrias He received the M.Sc. degree in Computational Modeling in Engineering from the University of Cadiz in 2012. Currently he pursues the Ph.D. degree under a grant in the Department of Electrical Engineering at the University of Cadiz. His research focuses on electric power systems modeling and renewable energies.

Carlos González He received the M.Sc. degree in Computational Modeling in Engineering from the University of Cadiz in 2012. His research interests are renewable energies and power systems modeling.

Luis M. Fernández He received the M.Sc. degree in electrical engineering from the University of Seville, Seville, Spain, in 1997 and the Ph.D. degree from the University of Cadiz, Cadiz, Spain, in 2004.From 1997 to 2000, he was with the Department of Development and Research, Desarrollos Eolicos S. A. In 2000, he joined the University of Cadiz, Spain, where he is currently an Associate Professor in the Department of Electrical Engineering. His current research interests include renewable energy sources and fuel cell systems.

Carlos Andrés García He received the M.Sc. degree in engineering and Ph.D. degree from the University of Cadiz, Cadiz, Spain, in 2004 and 2009, respectively. Since 1988, he has been an Associate Professor with the Department of Electrical Engineering, University of Cadiz. His research interest focuses on electric machines and renewable energy.

Francisco Jurado He received the M.Sc. and Dr. Ing. degrees from the National University of Distance Education, Madrid, Spain, in 1995 and 1999, respectively. Since 1985, he is a Professor with the Department of Electrical Engineering, University of Jaen, Linares, Spain. His research activities have been devoted to several topics, e.g., power systems, modeling, and renewable energy.