Chapter 2
Facts Devices

In recent years technological advances in power electronics have facilitated the development of electronic equipments that offer the ability to handle large amounts of power; consequently, the use and application of this technology into electrical power systems have increased significantly. These electronic devices, called Flexible AC Transmission System (FACTS), are based on electronic power converters and they provide the ability to make quick adjustments and to control the electrical system. FACTS devices can be connected in series, in parallel, or in a combination of both. The benefits they offer to the electrical grid are widely referenced in scientific literature. These benefits include improvement of the stability of the grid, control of the flow of active and reactive power on the grid, loss minimization, and increased grid efficiency.

The installation of FACTS devices (with serial or parallel connections) in a wind farm substation or in the terminals of wind turbines is increasing rapidly owing mainly to the specifications listed in the Transmission System Operators' (TSO) grid codes which require that wind turbines should provide ancillary services similar to those of conventional synchronous generators.

2.1 Static Var Compensator (SVC)

According to the IEEE definition, a Static Var Compensator (SVC) is a shunt-connected static var generator or absorber whose output is adjusted to exchange capacitive or inductive current to maintain or control specific parameters of the electrical power system (typically, the bus voltage) [1].

Typical SVCs can be classified on Thyristor-Controlled Reactor (TCR), Thyristor-Switched Reactor (TSR) or Thyristor-switched capacitors (TSCs). Figure 2.1 shows a TCR single-phase equivalent circuit in which the shunt reactor is dynamically controlled from a minimum value (practically zero) to a maximum value by means of conduction control of the by-directional thyristor valves. By this controlled action the SVC can be seen as a variable shunt reactance established by the parallel connection of

H. Amaris et al., *Reactive Power Management of Power Networks with Wind Generation*, Lecture Notes in Energy 5, DOI 10.1007/978-1-4471-4667-4_2,

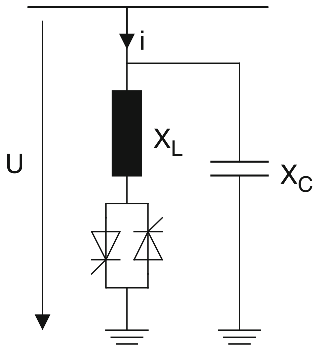

Fig. 2.1 Single-phase equivalent circuit of the shunt SVC (TCR)

the shunt capacitive reactance X_C and the effective inductive reactance X_L controlled by the thyristor switching.

2.1.1 Mode of Operation

The instantaneous current supplied by SVCs is given by:

$$I = \begin{cases} \frac{\mathrm{U}}{\mathrm{X_L}}(\cos\alpha_{svc} - \cos\omega t) & \alpha_{svc} \le \omega t \le \alpha_{svc} + \varepsilon \\ 0 & \alpha_{svc} + \varepsilon \le \omega t \le \alpha_{svc} + \pi \end{cases} \tag{2.1}$$

Where:

U represents the SVC voltage at the Point of Common Coupling (PCC).
$\mathrm{X_L}$ is the SVC total inductance.
α_{svc} is the firing delay angle.
ε is the SVC conduction angle given by

$$\varepsilon = 2(\pi - \alpha_{svc}) \tag{2.2}$$

It can be seen that as the delay angle α_{svc} increases, the conduction angle $\in$ of the valve decreases.

Figures 2.2, 2.3, and 2.4 show different current wave-shapes injected by the TCR for diverse firing delay angles.

The SVC's control of the output current is based on the control of the firing delay of thyristors. Hence, the maximum injected current is obtained by a firing delay of 90° (full conduction). Meanwhile, the firing angle delays between 90° and 180° electrical degrees only indicate a partial current contribution. This fact contributes to enhancing the device's inductance and makes it possible, at the same time, to decrease its contribution of reactive power and current.

The fundamental component of current is obtained by means of a Fourier analysis (2.3) or in a reduced version (2.4):

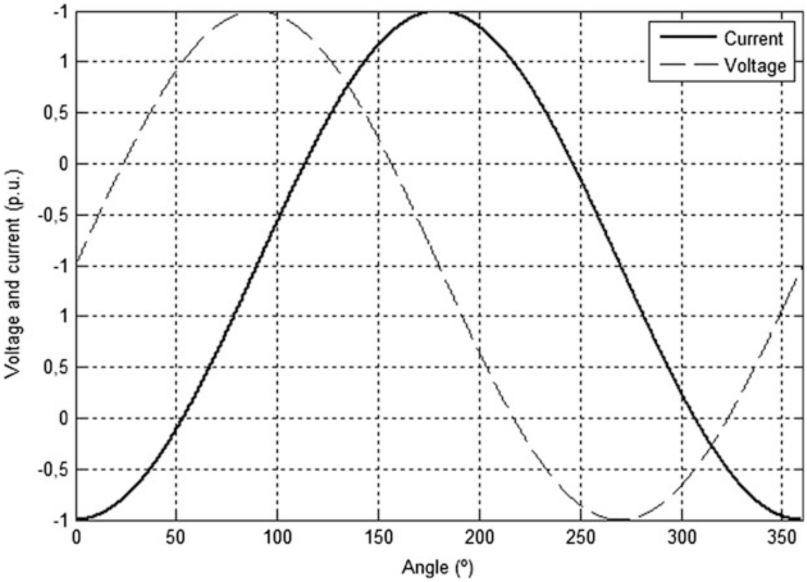

Fig. 2.2 AC current wave shape for $\alpha_{svc} = 90^{\circ}$

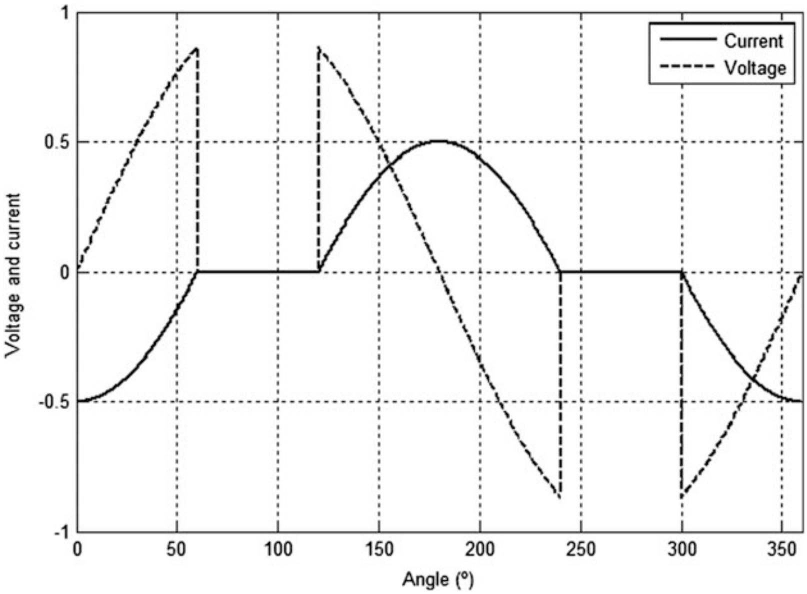

Fig. 2.3 AC current wave shape for $\alpha_{svc} = 120^{\circ}$

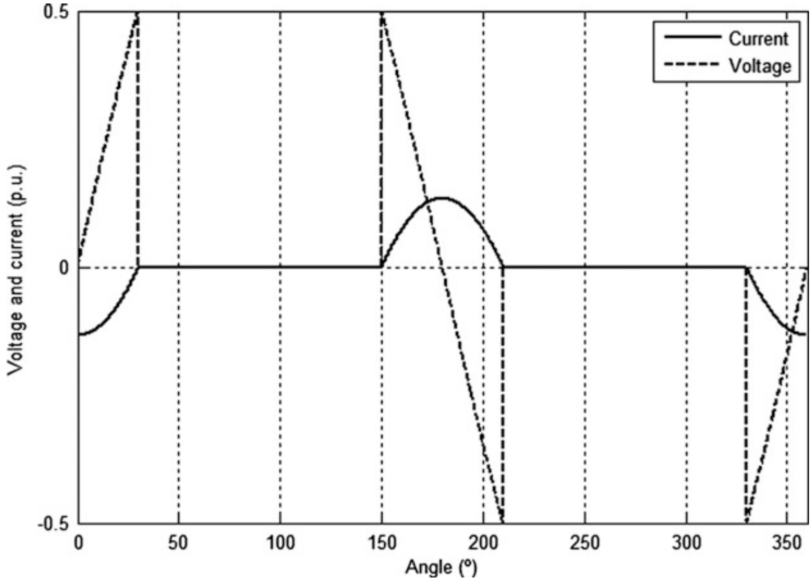

Fig. 2.4 AC current wave shape for $\alpha_{svc} = 150°$

$$I_1 = \frac{2(\pi - \alpha_{SVC}) + \sin 2\alpha_{SVC}}{\pi X_L} U \tag{2.3}$$

Which can be expressed as:

$$I_1 = B_{SVC}(\alpha_{SVC})\mathrm{U} \tag{2.4}$$

Where:

$$B_{SVC}(\alpha_{SVC}) = \frac{2(\pi - \alpha_{SVC}) + \sin 2\alpha_{SVC}}{\pi X_L}$$

The maximum value of B_{svc} is $1/X_L$, which corresponds to a conduction angle of 180° and represents the condition for maximum conduction of the thyristor's group. The lowest value of B_{svc} is 0 and it is obtained from a conduction angle equal to zero or from a firing angle of 180°. Thyristor firing angles lower than 90° are not allowed because they generate an asymmetric current wave with a high component of continuous current.

The slope defined as the ratio between the voltage variation and the variation of the SVC compensating current over the whole control range could be thus expressed via the voltage–current characteristics:

$$U = U_{ref} + X_{SL} I \tag{2.5}$$

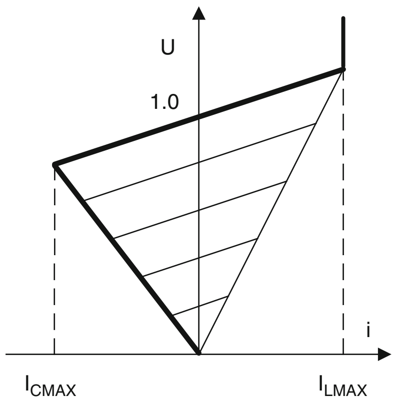

Fig. 2.5 Voltage–current characteristics of the SVC

Typical values of X_{SL} are located within the interval ranging from 0.02 to 0.05 p.u., referring to the SVC's base magnitude. Under limit conditions the SVC will become a fixed reactance. Figure 2.5 shows the characteristic curve of an SVC.

The reactive power supplied by the TCR could thus be calculated using (2.6):

$$Q_{SVC}(\alpha_{SVC}) = \frac{U^2}{X_C} - U^2 B_{SVC}(\alpha_{SVC}) \tag{2.6}$$

From the point of view of power system planning, localization and optimum sizing of FACTS devices are the most important aspects for operating electric networks with high wind power penetration while at the same time maintaining the security and efficiency of the whole electric system.

2.2 Static Synchronous Compensator (STATCOM)

The concept of the STATCOM was proposed by Gyugyi in 1976. According to IEEE a STATCOM can be defined as a static synchronous generator operated as a shunt-connected static var compensator whose capacitive or inductive output current can be controlled independent of the AC system voltage.

A STATCOM is a static compensator that it is connected to the grid in parallel for the compensation of reactive power. It is able to inject or absorb reactive power in a controlled way regardless of the grid voltage [1, 2]. The basic element is the Voltage Source Converter (VSC) which converts an input DC voltage to an AC voltage at the fundamental frequency with a given magnitude and a controllable phase. The AC output voltage is dynamically controlled in order to provide the required reactive power to the network.

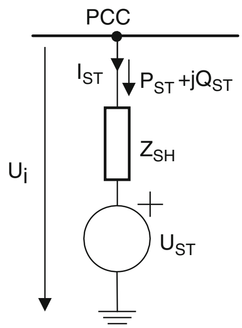

Fig. 2.6 Equivalent circuit of the statcom

2.2.1 Mode of Operation

The VSC generates a voltage at the fundamental frequency $\underset{\to st}{U} = U_{st}\angle\delta_{st}$ with controllable voltage amplitude and phase. The VSC is connected to the grid $\underset{\to i}{U} = U_i\angle\delta_i$ through an inductive impedance, Z_{sh}, that represents the coupling transformer and the connection filters, the equivalent circuit is as shown in Fig. 2.6.

The interchange of active and reactive power with the grid can be expressed as follows:

$$P_{st} = U_i^2.g_{sh} - U_iU_{st}[g_{sh}.\cos(\delta_i - \delta_{st}) + b_{sh}.\sin(\delta_i - \delta_{st})] \tag{2.7}$$

$$Q_{st} = -U_i^2.b_{sh} - U_iU_{st}[g_{sh}.\sin(\delta_i - \delta_{st}) - b_{sh}.\cos(\delta_i - \delta_{st})] \tag{2.8}$$

where $Y_{sh} = \frac{1}{Z_{sh}} = g_{sh} + jb_{sh}$.

The capacity for injecting reactive power into the grid is limited by the maximum voltage and the maximum current allowed by the semiconductors, as shown in Fig. 2.7.

The principle of operation of the VSC-based STATCOM depends on the control strategy for regulating the interchange of power between the converter and the grid and it depends also on the output AC voltage of the converter. If the magnitude of the voltage of the converter is equal to the voltage of the grid, $U_{st} = U_i$, the interchange of reactive power between the STATCOM and the grid is equal to zero.

In contrast, if the voltage of the converter is less that the grid voltage at the PCC, $U_{st} < U_i$, the STATCOM absorbs reactive power (draws lagging current). However, if the STATCOM is controlled in such a way that the output voltage of the converter is higher than the PCC voltage, reactive power is injected into the grid [3].

In practice, it is also necessary to control the active power exchange of the STATCOM by regulating the phase angle $\delta_{i\_st} = \delta_i - \delta_{st}$ between the voltage at the VSC ($\underset{\to st}{U} = U_{st}\angle\delta_{st}$) and the voltage at the PCC ($\underset{\to i}{U} = U_i\angle\delta_i$) so that the VSC absorbs active power from the grid to maintain a constant voltage for the DC-link.

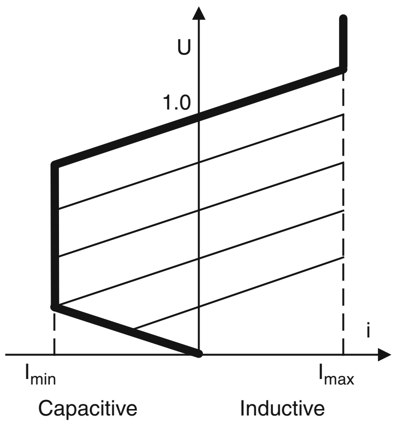

Fig. 2.7 Voltage–current characteristics of the STATCOM

2.2.2 *Control Techniques*

There are various control techniques, as detailed in [4] where the two listed below are the most typical:

- Voltage local control at the PCC voltage: In this control strategy, the purpose is to regulate the PCC voltage, U_i, so that it is maintained constant at its reference value ${U_i}^{ref}$. Mathematically, this condition is expressed as a restriction of operation:

$$U_i - {U_i}^{ref} = 0 \tag{2.9}$$

- Reactive Power control at the PCC: In many situations, the STATCOM is required to inject reactive power into the grid according to the specifications of the TSO. This form of control can be applied, for example, when a coordinated control is required for FACTS devices and wind farms performing reactive power delivery to the entire grid [5]. When this mode of operation is desired, it must be expressed as a restriction of operation as follows:

$$Q_{st} - {Q_{st}}^{ref} = 0 \tag{2.10}$$

2.2.3 *Restrictions of Operation*

In a STATCOM the maximum reactive power that can be supplied to the grid depends on the maximum voltages and currents permitted by the power semiconductors, so it is necessary to include the following internal restrictions:

- The VSC output voltage must fall within the allowed limits of operation:

$$U_{st,\min} \leq U_{st} \leq U_{st,\max} \tag{2.11}$$

where $U_{st,\min}$ and $U_{st,\max}$ are the limiting values of the minimum and maximum voltages allowed by the semiconductors, respectively.

- The current injected by the STATCOM, I_{st}, must be less than the maximum current allowed by the semiconductors, $I_{st,\max}$:

$$I_{st} \leq I_{st,\max} \tag{2.12}$$

Where:

$$I_{st} = \left| \frac{\underset{\rightarrow i}{U} - \underset{\rightarrow st}{U}}{Z_{st}} \right| \tag{2.13}$$

- In contrast, it is necessary to include external restrictions of the grid voltage at the PCC. According to the specific regulations of the grid operator the grid voltage at the PCC must be maintained within certain allowed limits:

$$U_{i,\min} \leq U_i \leq U_{i,\max} \tag{2.14}$$

2.2.4 Application of the STATCOM in Wind Farms

The first studies that analyzed the incorporation of STATCOMs in wind farms were initiated at the end of the 1990s with the aim of improving the flicker and power quality of fixed-speed wind turbines (Fig. 2.8). In these situations, the converter was controlled with a unitary power factor so that there was not any interchange of reactive power between the wind farm and the grid. This strategy has been followed in [6] which demonstrated that by injecting reactive power it was possible to improve the stability and the dynamic operation at the wind farm substation (wind turbines and statcom).

At the Rejsby Hédé wind farm in Denmark a STATCOM was installed in 1998 with a rated power of 8 Mvar for compensating the reactive power of the wind farm. The wind farm consisted of 40 turbines of 600 kW each with a total capacity of 24 MW [7]. The main objective was to improve power quality and to supply the reactive power needed to operate the wind farm. It was noted that it was possible to operate the wind farm with a unitary power factor (instead of regulating the reactive power interchange between the wind farm and the grid) provided that the reactive power demand of the wind farm were inferior to the maximum capacity of the STATCOM; However, above 8 Mvar it was necessary to absorb reactive power from the grid.

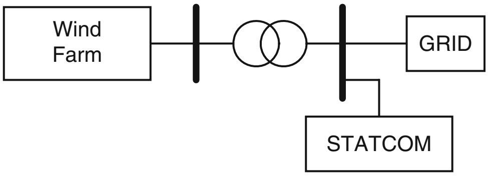

Fig. 2.8 Statcom installed at the wind farm substation

In recent years the new grid code specifications which refer to the regulation of reactive power and Low-Voltage Ride-Through capability (LVRT) have again generated interest in implementing SVCs or STATCOMs in wind farms. In [8] the application of STATCOMs to improve voltage fluctuations is discussed and [9] contains an analysis of how to improve the LVRT capability in fixed-speed wind turbines if STATCOM devices are installed at the wind farm PCC instead of an SVC. This last reference highlights the fact that STATCOMs have an inherent ability to increase the transient stability margin by injecting an adjustable reactive current to the grid regardless of the level of voltage supply; consequently, they are ideal devices for offering LVRT capabilities against voltage dips.

In [10] the possibility of controlling the injection of reactive power of a STATCOM in coordination with DFIG variable-speed wind turbines is analyzed. The main purpose of the STATCOM is to inject reactive power in the PCC in order to reduce the depth of the voltage dip at the wind farm terminal allowing DFIG wind turbines to remain connected during voltage dip situations.

2.3 STATCOM Versus SVC

The main difference between a STATCOM and an SVC is the way they operate: a STATCOM works as a controllable voltage source while an SVC works as a dynamically controllable reactance connected in parallel.

Compared with an SVC, a STATCOM offers the possibility of feeding the grid with the maximum available reactive current even at low voltage levels, this is possible because in every equilibrium condition the injected reactive power varies linearly with the voltage at the Point of Common Coupling (PCC) [11]. In contrast, for an SVC there is a quadratic dependence of the reactive power on the voltage at the PCC which means that to inject the same reactive power it is necessary to install an SVC with a nominal capacity higher than that of a STATCOM.

With regard to the maximum transient capacitive current it is observed that in an SVC the capacitive current is limited by the size of the capacitor and by the magnitude of the AC voltage. In the case of a STATCOM the maximum capacitive current that can be injected is limited by the maximum current capacity of the semiconductors used [12] and is independent of the voltage level at the PCC.

Another feature of a STATCOM is that the DC-link capacitor serves as storage for active power. Therefore in certain situations, depending on the capacitor size, it is possible to regulate the interchange of active power with the grid also.

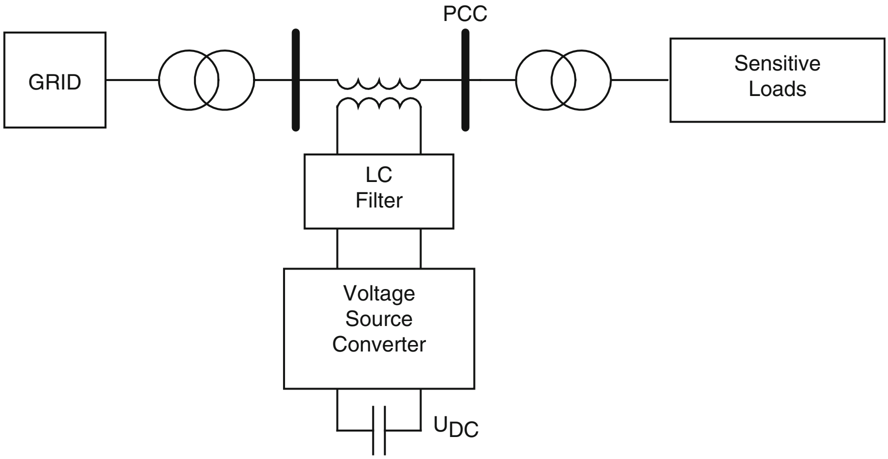

Fig. 2.9 Equivalent circuit of a DVR connected to the grid

STATCOM devices are capable of much faster dynamic reaction (1/4-1 cycle) than an SVC. In a STATCOM the speed of response is limited by the commutation frequency of the IGBT's (normally 1 kHz) [13].

2.4 Dynamic Voltage Restorer (DVR)

A DVR is composed of a Voltage Source Converter (VSC) that has an energy storage connected to the DC link. The VSC is connected in series with the power network by means of a series-connected injection transformer and coupling filters. A DVR may be formed by three VSCs [14] where each one is connected to the network through an LC filter (L_f, C_f) and a transformer. The capacitor filter is connected across the secondary winding of the coupling transformer as shown in Fig. 2.9.

The DVR is normally used to protect critical loads or sensitive installations from the effects of faults at the point of common coupling. During a voltage dip the DVR is able to inject the required voltage to reestablish the load supply voltages.

The typical DVR is based on IGBT solid-state power electronic switching devices in a PWM converter structure and it is capable of independently generating or absorbing controllable real and reactive power at its AC output terminals. For line currents exceeding the inverter rating a bypass scheme can be incorporated to protect the power electronic converter.

DVRs are installed at wind farms mainly for providing low-voltage ride-through capability [14], as is shown in Fig. 2.10.

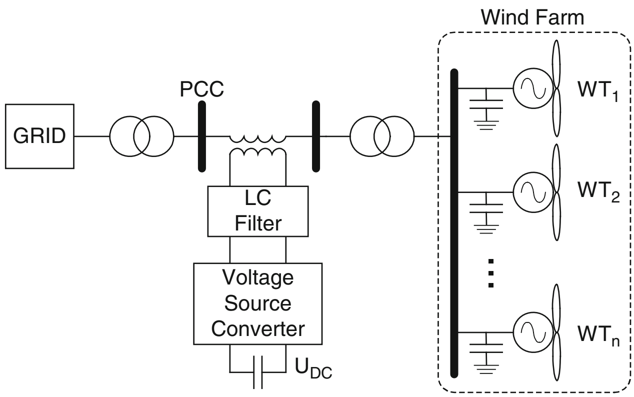

Fig. 2.10 Scheme of a DVR connected at wind farm substation

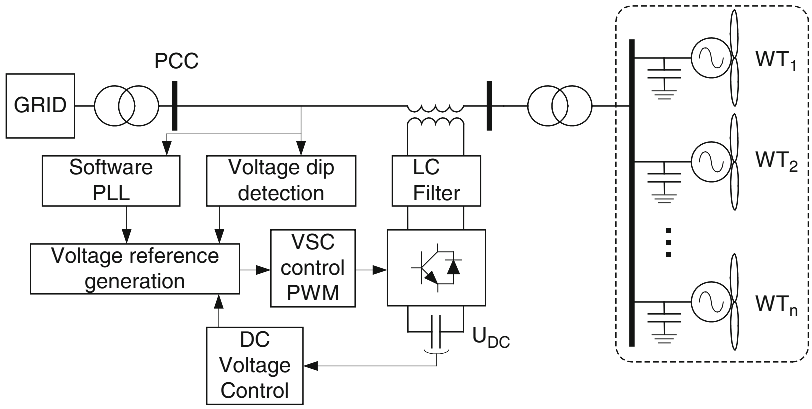

Fig. 2.11 Control blocks at a DVR

2.4.1 DVR Control

The control structure of the DVR includes the following stages (Fig. 2.11): the measured phase voltage before the DVR transformer is fed to the Phase-Locked-Loop (*PLL*) to detect the phase angles and to generate synchronizing signals, U_{ref}. Additionally, the voltage before the DVR transformer is measured to detect and estimate voltage dips. That information is sent to the Voltage reference generation block where it is processed. The result is driven to the VSC Control – PWM, where the switching signals for firing the IGBTs are obtained. The DC voltage is measured for feeding back the Voltage reference generation Control [15].

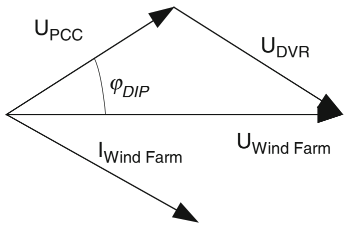

Fig. 2.12 Pre-dip compensation strategy at the DVR

2.4.1.1 VSC Control

The technique usually used to control the AC output voltage is Pulse Width Modulation using the Park transformation [16].

2.4.1.2 Voltage Dip Detection

The objective of this task is to detect the start and finish of the voltage dip at the PCC as soon as possible. This process can be very sensitive to disturbances and noise signals. For this reason, the voltage dip detection block is required to be reliable, generating a minimum number of false operations. Several methods have been applied to detect the instant of time in which the voltage dip appears, such as Kalman filters or wavelets [17].

2.4.1.3 Voltage Reference Generation

This block is responsible for computing the voltage reference signal for the VSC control. Its performance depends on the chosen compensation strategy. The basic strategies are as follows [18]:

- Pre-dip compensation: The simplest solution is to reestablish the exact voltage before the sag (magnitude and phase), see Fig. 2.12. The voltage at the PCC is continuously tracked (U_{PCC}), and with this information, the voltage injected by the DVR (U_{DVR}) is computed to maintain the voltage at the wind farm terminals fixed to the pre-dip situation ($U_{Wind\ Farm}$).

$$U_{DVR} = U_{WindFarm} - U_{PCC} \tag{2.15}$$

- In-phase compensation: This approach relies on compensating the voltage in phase to the grid voltage after the voltage dip. It should be noted that using this compensation strategy makes it possible to minimize the voltage magnitude but the phase jump is not compensated.
- Energy-optimized compensation: This strategy consists of injecting the maximum reactive power by drawing as much active power from the grid as possible. By using this compensation strategy it is possible to restore the voltage but a

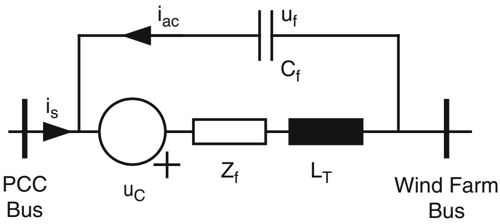

Fig. 2.13 Single-phase equivalent circuit of the DVR

phase jump occurs. This compensation strategy only works properly with small voltage depths.

The single-phase equivalent circuit of the DVR is shown in Fig. 2.13, in which the following parameters are considered:

- u_c corresponds to the switching voltage generated at the AC converter terminals.
- L_T represents the leakage inductance of the series transformer.
- The LC filter is composed of a filter inductance L_f and a capacitor filter C_f. The voltage across the capacitor filter is denoted as u_f.
- The impedance $Z_f = R_{in} + j\omega L_f$ is composed of both the resistance R_{in} which represents the switching losses of the converter and the filter inductance L_f.

From the single-phase equivalent circuit the differential equations of the controller using the state space methodology may be obtained:

$$\dot{x} = \begin{bmatrix} 0 & 1/C_f \\ -1/L_T & -R_{in}/L_T \end{bmatrix} x + \begin{bmatrix} 0 & -1/C_f \\ U_{dc}/L_f & 0 \end{bmatrix} \cdot \begin{bmatrix} u_c \\ i_s \end{bmatrix} \tag{2.16}$$

where the state vector is:

$$x = \begin{bmatrix} u_f \\ i_{ac} \end{bmatrix} \tag{2.17}$$

Equation 2.16 is used to obtain the control law for the series compensator. The controller determines the voltage that has to be injected into the grid to compensate for the voltage dips.

2.4.2 Numerical Results

In this section different simulations are carried out in a wind farm of 20 MVA at a nominal voltage of 11 kV that is composed of fixed-speed wind turbines. Each electrical machine consists of an induction generator of 690 V and 750 kW. Induction generators are provided with bank capacitors for reactive power compensation. The distribution line is represented by its π equivalent circuit and a series

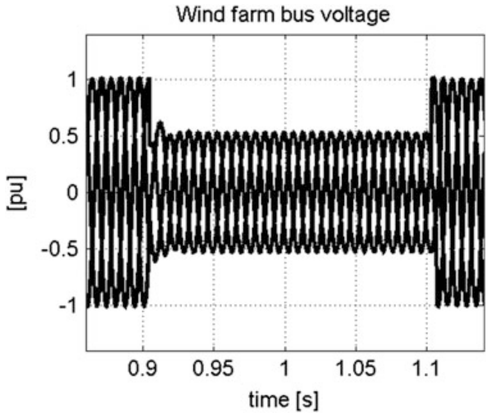

Fig. 2.14 Voltage evolution under fault conditions without DVR

DVR is installed at the wind terminals. Its performance is tested under symmetrical three-faults and unbalanced faults.

The wind farm is assumed to be formed by n generators in parallel all of them with similar characteristics. All the simulations were performed assuming that the whole wind farm is operating at 0.99 leading power factor. For simplicity it has been assumed that each of the turbines experiences the same wind speed, therefore, the whole farm may be represented by its equivalent induction generator.

2.4.2.1 Wind Turbine Performance Under Fault Conditions Without DVR

In this first simulation the DVR is not connected at the wind farm bus. Consequently when a three-phase fault appears at the wind farm terminals (Fig. 2.14) the fixed-speed wind farm is not able to withstand the voltage dip and the angular velocity of the rotor under fault conditions starts to increase, increasing the probability of stability problems, as is depicted in Fig. 2.15.

2.4.2.2 Wind Turbine Performance Under a Three-Phase Fault with DVR

In this scenario the DVR is connected at the wind farm bus. A symmetrical three-phase fault is simulated at the wind terminals with a voltage depth of 50 % and a phase jump of 20° at the beginning of the voltage dip. The voltage dip at the PCC lasts from instant of time t = 0.9 ms to t = 1.1 ms.

In Fig. 2.16 it can be noted that the DVR detects the voltage dip efficiently and injects the required voltage to restore the voltage seen by the wind farm.

It should be highlighted that by using the pre-dip compensation strategy the wind farm's active and reactive power injected to the network is not affected by the voltage dip (Fig. 2.17) and remains almost fixed at the reference values. The angular velocity and the electromagnetic torque of the equivalent wind turbine (Fig. 2.18) recover nominal values after the voltage dip.

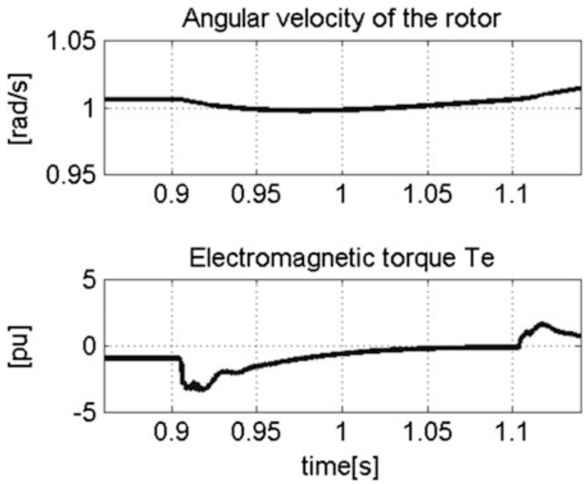

Fig. 2.15 Angular velocity and electromagnetic torque evolution under fault conditions without DVR

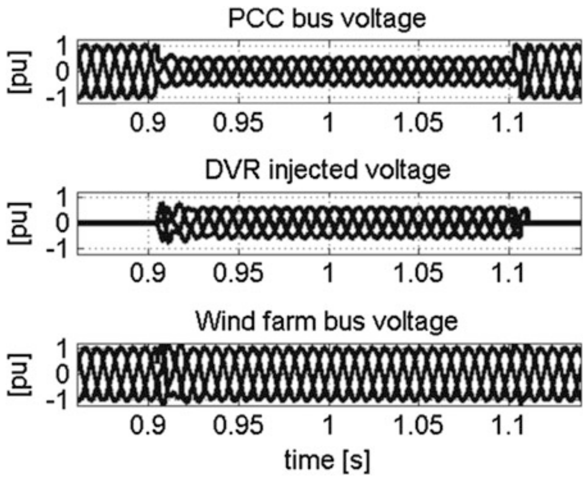

Fig. 2.16 Voltage evolution under a three-phase fault with DVR

2.4.2.3 Wind Turbine Performance Under a Single-Phase to Ground Fault with DVR

In this last case the performance of the DVR has been tested under unbalanced fault conditions in which a single-phase to ground fault has been simulated at the wind terminals. As seen at the PCC voltage (Fig. 2.19) the DVR detects the beginning of the voltage dip, the voltage depth and the phase that is affected. Consequently, it only injects the required compensation voltage in the affected phases.

Both the wind farm injected power and the angular velocity of the equivalent turbine are shown in Figs. 2.20 and 2.21, respectively. Notably, the stability of the wind farm is not affected by the voltage dip.

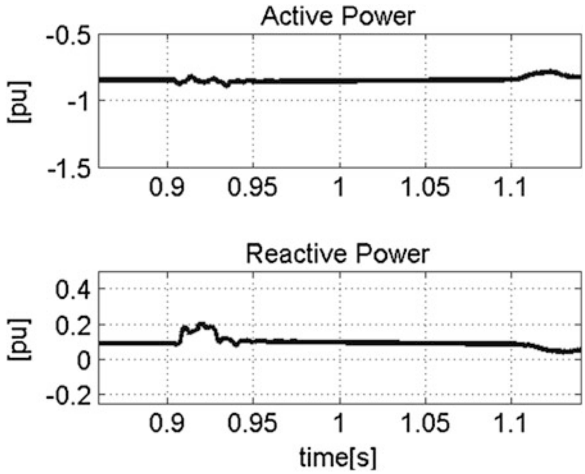

Fig. 2.17 Active and reactive power evolution at the PCC under a three-phase fault with DVR

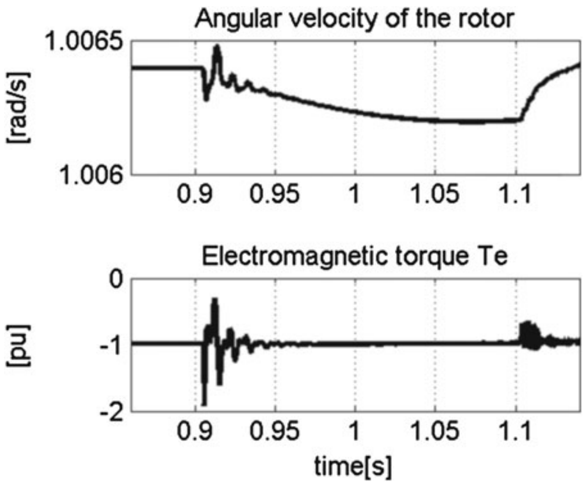

Fig. 2.18 Angular velocity and electromagnetic torque evolution under a three-phase fault with DVR

These two examples show how the installation of a serial DVR at wind farms can efficiently improve the LVRT capability of fixed-speed wind farms under fault situations.

2.4.3 Reactive Power Support Under Voltage Dips in Fixed-Speed Wind Farms

Most utilities establish codes for their national grid that state that wind farms shall offer reactive power support to the grid during faults. Consequently during the

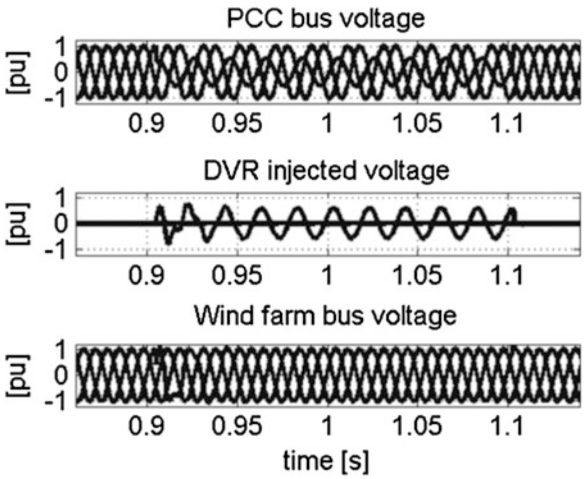

Fig. 2.19 Voltage evolution under a single-phase to ground fault with DVR

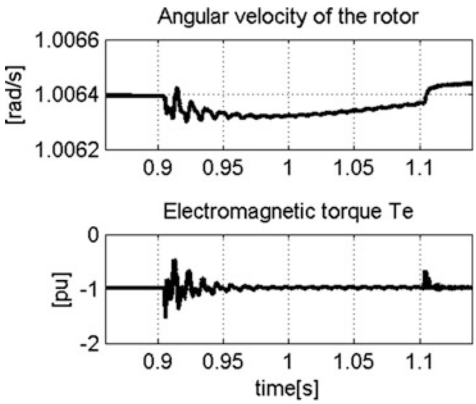

Fig. 2.20 Angular velocity and electromagnetic torque evolution under a single-phase to ground fault with DVR

occurrence of a voltage dip they are required to stay connected and to inject reactive power during both the fault and post-fault periods.

The Spanish grid code for wind turbines [19] establishes the active and reactive power requirements with which the wind turbine must comply during voltage dips (see Figs. 2.22 and 2.23).

Because fixed-speed wind farms do not offer LVRT capabilities by themselves a serial DVR is proposed to offer voltage support at the PCC and to inject the required reactive power during voltage dips.

The operation conditions of the DVR depend on the working conditions of the wind farm. The wind farm working conditions are established by the apparent power $S_{WindFarm}$ generated by the wind farm, as expressed in (2.18). This power will develop a certain current flowing from the wind farm to the DVR series transformer.

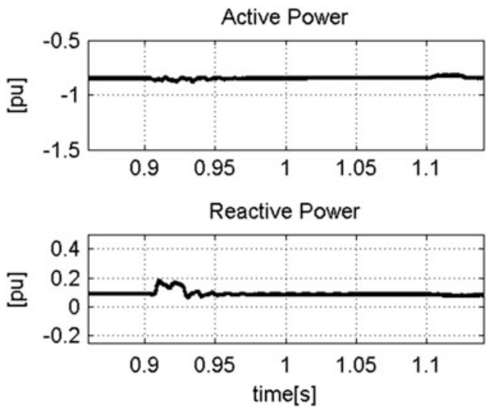

Fig. 2.21 Active and reactive power evolution at the PCC under a single-phase to ground fault with DVR

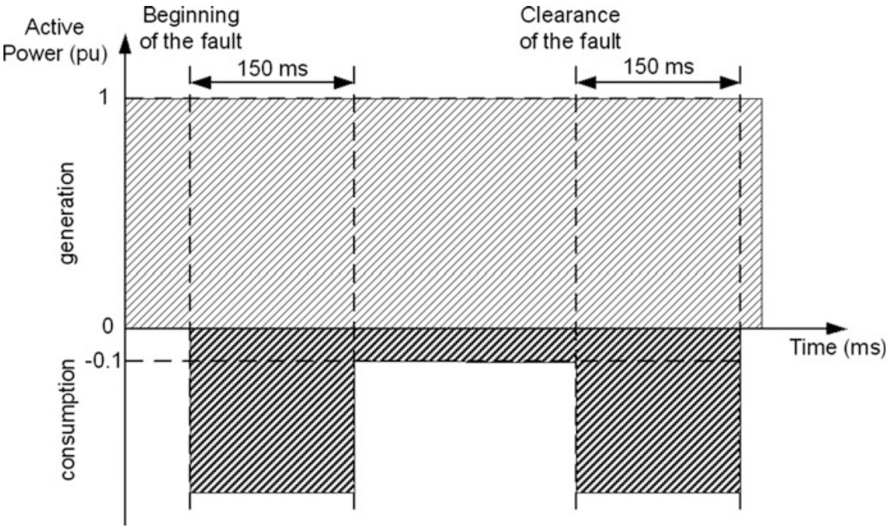

Fig. 2.22 Active power requirements at wind farm substation during voltage dips [19]

$$\underset{\rightarrow}{S}_{WindFarm} = S_{WindFarm} \angle \varphi_{WindFarm} = P + jQ \quad (2.18)$$

The results of the simulation are shown in Figs. 2.24 and 2.25. In Fig. 2.24 the voltage profile at the PCC, the voltage at the wind farm terminals and the voltage injected by the DVR is depicted, in this figure it can be noted how the voltage at the wind farm holds in a range of voltages around the reference value (1.0 p.u). Figure 2.25 shows how the active power injected by the fixed speed wind farm oscillates during the voltage dip in order to comply with the grid code requirements. The grid code establishes that the active and reactive power at the PCC could be

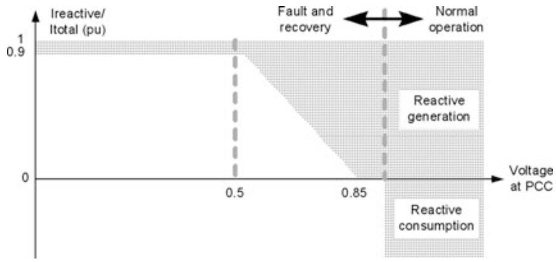

Fig. 2.23 Reactive power requirements at wind farm substation during voltage dips [19]

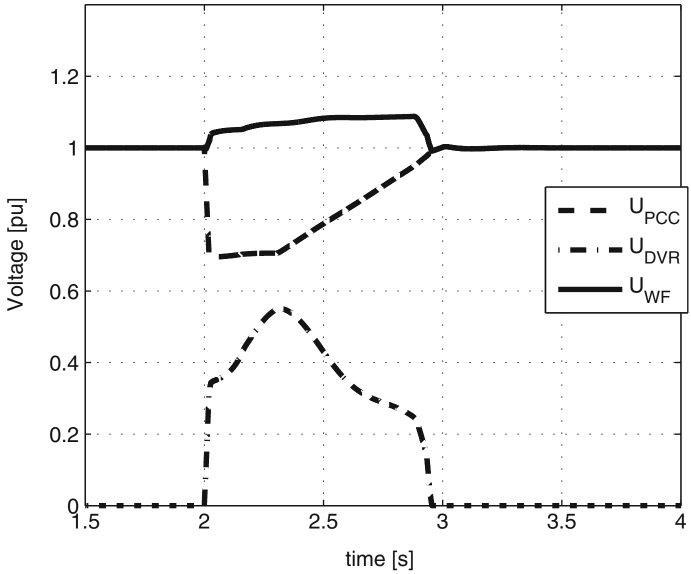

Fig. 2.24 Voltage at the PCC (*dashed line*), voltage injected by the DVR (*dash-dot line*) and voltage at the wind farm substation (*solid line*)

consumed or generated for a short period of time that was determined to be 150 ms [19]. For the rest of the fault both active and reactive power will be generated.

It must be noted that the wind farm does not provide reactive power to the grid, Fig. 2.26 shows the reactive current injected to the grid by the DVR in order to comply with the reactive power requirements (Fig. 2.23).

Previous results plotted in Figs. 2.24, 2.25, and 2.26 show the good performance of the DVR according to the LVRT requirements in the grid code [19].

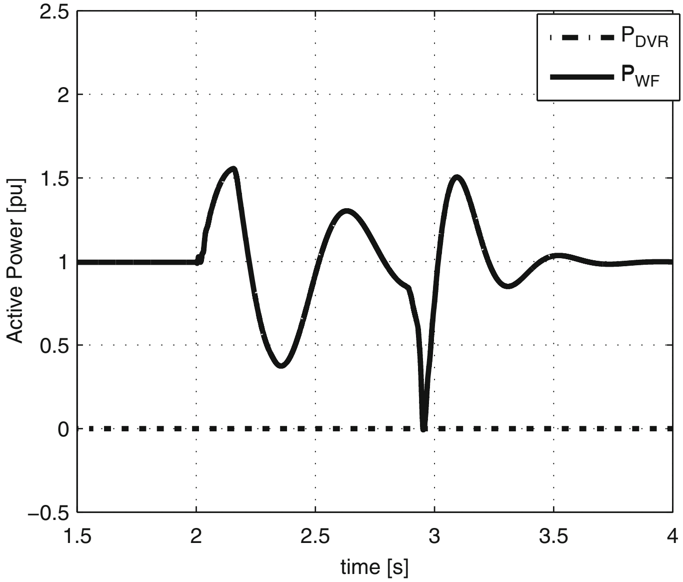

Fig. 2.25 Active power injected by the wind farm (*solid line*) and by the DVR (*dash line*)

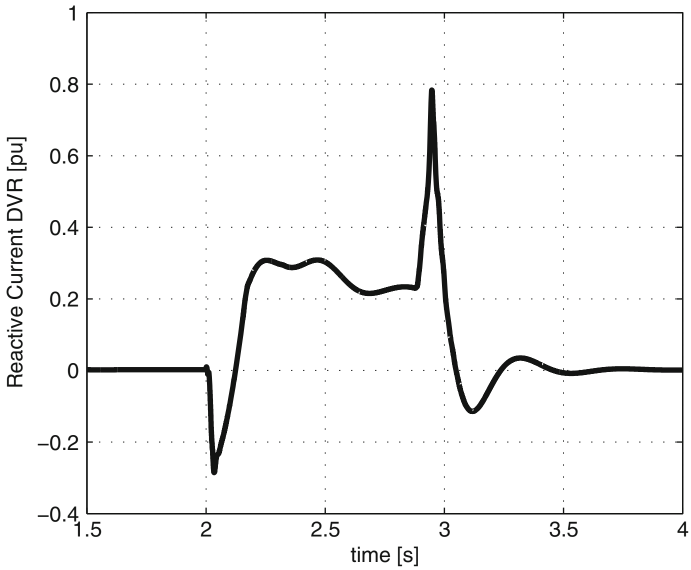

Fig. 2.26 Reactive current injected by the DVR

References

1. Hingorani NG, Gyugyi L (1999) Undestanding FACTS. IEEE Press, New York
2. Mithulananthan N, Canizares CA, Reeve J, Rogers GJ (2003) Comparison of PSS, SVC, and STATCOM controllers for damping power system oscillations. IEEE Trans Power Syst 18 (2):786–792
3. Moore P, Ashmole P (1998) Flexible AC transmission systems. 4. Advanced FACTS controllers. Power Eng J 12(2):95–100
4. Zhang X-P, Rehtanz C, Pal B (2006) Flexible AC transmission systems: modelling and control. Springer, Berlin
5. Amaris H, Alonso M (2011) Coordinated reactive power management in power networks with wind turbines and FACTS devices. Energ Convers Manage 52(7):2575–2586
6. Saad-Saoud Z, Lisboa ML, Ekanayake JB, Jenkins N, Strbac G (1998) Application of STATCOM's to wind farms. IEE Proc Gener Trans Distrib 145(5):511–516
7. Sobtink KH, Renz KW, Tyll H (1998) Operational experience and field tests of the SVG at Rejsby Hede. In: International conference on power system technology proceedings, POWERCON'98, vol 1, Zhejiang, pp 318–322
8. Han C, Huang AQ, Baran ME, Bhattacharya S, Litzenberger W, Anderson L, Johnson AL, Edris A (2008) STATCOM impact study on the integration of a large wind farm into a weak loop power system. IEEE Trans Energ Convers 23(1):1266–1272
9. Molinas M, Are Suul J, Undeland T (2008) Low voltage ride through of wind farms with cage generators: STATCOM versus SVC. IEEE Trans Power Electron 23(3):1104–1117
10. Qiao W, Harley RG, Venayagamoorthy GK (2009) Coordinated reactive power control of a large wind farm and a STATCOM using heuristic dynamic programming. IEEE Trans Energ Convers 24(2):493–503
11. Molinas M, Vazquez S, Takaku T, Carrasco JM, Shimada R, Undeland T (2005) Improvement of transient stability margin in power systems with integrated wind generation using a STATCOM: an experimental verification. In: International conference on future power systems, vol 1, pp 1–6
12. Zhang W (2007) Optimal sizing and location of static and dynamic reactive power compensation. PhD thesis, University of Tennessee, Knoxville
13. Han C, Yang Z, Chen B, Song W, Huang AQ, Edris A, Ingram M, Atcitty S (2005) System integration and demonstration of a 4.5 MVA STATCOM based on emitter turn-off (ETO) thyristor and cascade multilevel converter. In: 31st annual conference of IEEE Industrial Electronics Society, IECON 2005, Raleigh, pp 1329–1334
14. Lam C-S, Wong M-C, Han Y-D (2004) Stability study on dynamic voltage restorer (DVR). In: Proceedings of the first international conference on power electronics systems and applications, Hong Kong, China, pp 66–71
15. Alvarez C, Amaris H (2006) Voltage dips compensation in wind farms using dynamic voltage restorer. In: Proceedings of the 5th international Nordic workshop on power and industrial electronics, NORPIE 2006, Aalborg
16. Nielsen JG, Newman M, Nielsen H, Blaabjerg F (2004) Control and testing of a dynamic voltage restorer (DVR) at medium voltage level. IEEE Trans Power Electron 19(3):806–813
17. Lobos T, Rezmer J, Janik P, Amaris H, Alonso M, Alvarez C (2009) Application of wavelets and prony method for disturbance detection in fixed speed wind farms. Int J Electron Power Energ Syst 31:429–436
18. Meyer C, De Doncker RW, Wei Li Y, Blaabjerg F (2008) Optimized control strategy for a medium-voltage DVR – theoretical investigations and experimental results. IEEE Trans Power Electron 23(6):2746–2754
19. P.O. 12.3. Requisitos de Respuesta frente a Huecos de Tensión de las Instalaciones Eólicas, Resolución del Ministerio de Industria, Oct 2006. (In Spanish)

http://www.springer.com/978-1-4471-4666-7

Reactive Power Management of Power Networks with
Wind Generation
Amaris, H.; Alonso, M.; Alvarez Ortega, C.
2013, X, 126 p., Hardcover
ISBN: 978-1-4471-4666-7