Modelling and Control of Wind Parks

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Abstract Wind parks have experienced a great increase over the last years, from small wind parks with a few wind turbines connected to utility distribution systems, to large wind parks connected to transmission networks that may be considered, from the network system operators point of view, as a single wind power plant with operational capabilities similar to a conventional power plant. In this chapter, three main aspects concern to wind park grid integration are considered: the necessity of suitable wind park models for transient stability studies; the wind park control to fulfill system requirements and the application of special devices to enhance grid integration capabilities.

1 Introduction

Wind turbines can be grouped in a wind park to produce electric power as a conventional power plant. A wind park consists of a few to several hundred wind turbines over an extended area and integrated in an internal network composed by medium voltage lines and connected to grid through a common substation and feeder line.

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P. M. Pardalos et al. (eds.), *Handbook of Wind Power Systems*, Energy Systems,
DOI: 10.1007/978-3-642-41080-2_15,

Wind parks have experienced a great increase over the last years, from small wind parks with a few wind turbines connected to utility distribution systems, to large wind parks connected to transmission networks that may be considered, from the network system operators point of view, as a single wind power plant with operational capabilities similar to a conventional power plant.

But, what does ‘operating with the same requirements as a conventional power plant’ mean? To answer this question, are at least necessary three points of view:

- For system operators and utility companies, wind parks have to be integrated in software packages for power system stability studies (dynamic studies). Thus, suitable models are needed to evaluate wind parks at the same level as conventional power plants. Nevertheless, the complexity of models is greater than in case of conventional power plant models, because those are composed of a high number of wind power generators, which require a particular study.
- System requirements are doing that wind parks operate at the same level than conventional power plants, covering production demands or ensuring the stability and reliability of the system. For that reason, the main objective of the wind park controller is to reach the power production setting in a similar way of a conventional power plant and, in some cases, to provide advanced grid support. That is, active power and voltage regulation and reactive power and frequency control. Hence, the wind park controller must to operate inside the park, fulfilling the grid demands by appropriate generation strategies at wind turbine level.
- To improve the wind park production and control capabilities, special devices can be used to enhance wind turbine capabilities and smooth the output power fluctuations caused by the wind speed variability, and thus enhance wind park performance.

Under this scenario, this chapter gives an overall description of modelling and control of wind parks from the point of view of their grid integration as a wind power plant.

Section 2 presents a wide description of the wind parks models studied in the literature, with the main focus on transitory stability studies. The wind park models accuracy relies on detailed modelling of the applied wind turbine technology, considered in a previous chapter. They allow a suitable simulation of the wind parks behaviour under wind speed fluctuations and grid faults. The clearest model (detailed model) represents all the wind turbines, with the necessary detail level of the scope of study, and the model of the internal grid of the park. Its main problem is related to the high order model if the wind park has a high number of wind turbines. Additional wind park models can reduce the complexity of detailed models based on the aggregation of the wind turbines in different ways: (1) a single equivalent model, in which the entire wind turbines are represented by a single unit; (2) a cluster equivalent model, in which the wind turbines with the same characteristics and similar incoming winds are grouped in clusters; and (3) a compound equivalent model, in which only the generation system of each wind turbine is aggregated in an equivalent one, while representing the mechanical systems of all the individual wind turbines.

As wind power plants are today required to participate actively in the power system operation, the grid connection requirements have been revised, demanding an operational behaviour similar to those of conventional power plants. Thus, in Sec 3, it is detailed some of these requirements: (1) Active power regulation and frequency control, and (2) reactive power control and voltage regulation, as previous issue to the description of the control structure of wind parks. Following, an overview of wind parks control structure is performed in this section, considering the main controller as the leading component of the structure, assuring the wind park production in a similar way as a conventional power plant. In addition, dispatch control must define the power references of the wind turbines within the wind park. Finally, an evolution of the main controller, the cluster management system, is illustrated for controlling a group of wind parks connected to a certain grid node.

One of the main issues is that wind power plants are becoming required to help the power system quality, stability and reliability, and these requirements are related to the availability of the wind and the technologies of the wind turbines. Section 4 describes some special power electronics-based system such as Flexible AC Transmission Systems (FACTS), which can be used in wind parks to improve power and voltage control capabilities and in some cases, enhancing power quality. Another way of improving wind power capabilities is to use an energy storage system integrated in wind turbine.

2 Wind Park Modelling

Dynamic studies of wind parks, in which the main focus is to study their influence on the electrical power system, are commonly called transitory stability studies. These studies use time constants between 0.1 and thousands seconds and voltages and powers as main variables. Their principal characteristic is that electrical network transient can be neglected, though network model is typically represented by fundamental frequency model. This consideration reduces the number of differential equations of the model, increases integration time step and allows using load flow algorithms.

As a result of the increase of wind capacity connected directly to transmission systems, development of wind parks models and their integration into software packages for power system stability has been stimulated. Some examples are PSS/E (PTI), PowerFactory (DigSILENT), Netomac (SIEMENS) or Simpow (ABB). Additionally, general-purpose software like MATLAB/Simulink (The Mathworks) is regularly used for transient stabilities studies when dedicated software presents restrictions in simulations [54]. The relevance of the restriction depends on the scope of the investigation and on the characteristics of the component models. Research institutes, universities, commercial entities and network operators have contributed to the development of accurate dynamic models adapted to their needs. Hence, model validation is a key issue that taken up by International Energy Agency (IEA) Wind Task 21. This international working group includes participants from nine countries, and has developed, from 2002 to 2006, a systematic approach for model benchmark testing. The rationale for the proposed benchmark testing is that dynamic wind generation models are being applied for assessing grid connection of large wind parks, even though model accuracy is not always known. This, at best, leads to uncertainty in the market, and, at worst, to an erroneous design jeopardizing power system stability. The challenge is twofold. First, the technology in modern wind parks is fairly complex, and their dynamic behaviour may differ significantly depending on the wind turbine type and manufacturer's specific technical solutions. Thus, it is not trivial to develop accurate wind generation models. Second, model validation must be transparent and adequate for providing confidence. In this respect, IEA Wind Task 21 has contributed by describing a benchmark procedure and applying this procedure for testing numerical wind generation models [26].

The wind park model has to allow the representation of the behaviour of all the wind turbines within the wind park under normal conditions (wind fluctuations) and abnormal conditions (grid faults). Accurate simulations of wind parks rely on detailed modelling of the applied wind turbines, not only the type of technology but specific variations in the same type. The benchmark test procedures suggested by IEA Wind Task 21 consider operation during normal condition and response to a voltage dip, and may include both validation against measurements and model-to-model comparisons:

- *Dynamic operation during normal conditions* Model capability to simulate wind parks characteristics power fluctuations with,
  - *Input:* Wind speed time series (optionally voltage time series).
  - *Output:* Powers and voltage (optionally) time series; power spectral density of active power and short-term flicker emission.
- Dynamic operation during abnormal conditions (*response to voltage dip*) Model capability to simulate wind parks response to voltage dip,
  - *Input* Voltage time series and constant aerodynamic torque (optionally wind speed time series).
  - *Output* Powers and voltage time series.

2.1 Detailed Wind Park Models

Wind park models may be built to various level details depending on the scope of the simulations. The clearest model is the detailed (complete) model, a one-to-one approach that consists in representing all the wind turbines and the internal grid of the park. In [49], a dynamic model of the Hagesholm wind park was implemented in power system simulation program DigSILENT, and verified against measurements to assess the ability of the simulation models to predict the influence of the park on the power quality characteristics of wind turbines specified in IEC61400-21.

In other cases, detailed models are necessary because the focus of the studies is to evaluate the internal evolution of the wind park. Akhmatov [4] presents a large offshore wind park model with eighty wind turbines to investigate how short-term voltage stability can be affected by parameters fluctuation and controllability of wind turbines in terms of dynamic stability limits. These studies include:

- In case of fixed-speed wind turbines, the necessity of dynamic compensation units, like Static Var Compensator (SVC) or STATic Synchronous COMpensator (STATCOM), adequate construction parameters or controllability of wind turbine blade angle in case of grid faults to prevent fatal over-speeding.
- In case of wind turbines with double-outage induction generator and variable rotor resistance, protection of the power electronics of the rotor converter shall be taken in account, blocking power converter and establishing power reserves.
- In case of variable speed wind turbines equipped with DFIG and partial-load frequency converters, the main challenge is to maintain interrupted operation of wind turbines without use of dynamic reactive compensation when the control feature with use of fast re-start of the rotor converters is applied.
- In case of variable speed wind turbines equipped direct-driven synchronous generators connected to the grid through frequency converters, an accurate and sufficiently detailed representation of the converter, its control and protective sequences will be absolutely recommended for investigations of transient voltage stability, because it determines the wind turbine operation during and after the transient event in the power system.

When the scope of the studies is the internal grid of the wind park, detail models are also necessary, like in [35], where a wind park with an internal DC collection grid and the same layout as the wind park in Lillgrund (Sweden), with 48 wind turbines of 2.3 MW, located in 5 radial connected to an offshore platform, is modelled in PSCAD/EMTDC to investigate dynamic operation both for normal operation and for different faults conditions. In this case, the main key is the suitable design of the DC/DC converters and DC bus, whose dynamics are much faster than those of the wind turbine, which can be neglected, and its model can be simplified with a current source connected to the DC/DC converter in the wind turbine.

Another important aspect to consider in studies with detail models is to validate them against measurements. With this consideration, project Erao-3 [42] intends to find measurement of wind turbines and wind parks in the Netherlands for model validation, under the area of IEA Annex XXI. These models can be used in wind parks and local grid studies as well as for the development of more simple, reduced order o aggregate models. In this project, Alsvik Wind Park was considered for constant speed stall wind park dynamic model validation. Comparison of measurements with simulations results showed that:

- The frequency response results of the electrical variables are good if the measured voltage is used as input instead of using a grid model;
- The frequency response results of mechanical variables are less good, which may partly be caused by grid voltage variation, which could not be used as input because it was not measured;
- The results for the voltage dip were quite good, with some mismatch in the damping.

Detailed models are also interesting when the scope of researches is the wind parks integration in the network system. In this case, the different wind power technologies establish the characteristics and control possibilities of wind parks. Gjengedal [20] evaluates the dynamic performance of three technologies, and performs a transient stability study in order to illustrate the differences between fixed speed wind turbines—Danish concept—and variable speed wind turbines (DFIG induction generator or PMSG with full converter). In order to compare the wind generator technologies, dynamic simulations were performed for a wind park with 75 wind turbines of 2 MW divided in clusters, and connected to a typical 132 kV rural grid in Norway. From the five requirements discussed (active and reactive power control, frequency control, transient voltage control and three-phase fault ride-through), fixed speed wind turbines have clearly less control possibilities than variable speed wind turbine; all the technologies have difficulties to ride-through faults that may imply additional costs; and alternative solution may be to disconnect during a fault and reconnect shortly after the fault is cleared.

In the same scope, Cartwright et al. [9] present a voltage and reactive control strategy for a variable speed wind park with 30 DFIG wind turbines of 2 MW. Dynamic models of the wind turbines and converters are developed and simulation results presented confirm the effectiveness of the control strategies within transmission and distribution system implementations.

With the same philosophy, Tapia et al. [55] developed a complete model of a wind park located in Navarra (north of Spain), composed of 33 DFIG wind turbines of 660 KW. Simulations results of the model performance were obtained and compared to the real performance of the wind park, only in case of wind fluctuations, but not in case of abnormal conditions. The wind park model developed is used for the wind park reactive power control.

The response obtained from complete wind park models is commonly used as reference for validating aggregated models. Slootweg [47] investigates an aggregation approach to be used for both fixed and variable speed wind parks, by comparing the simulation response of a detailed and an aggregated wind park models for different operating conditions. It is concluded from this study that in normal operating conditions, in which only wind speed changes occur, as well as during faults, simulation results of the detailed and the aggregated models are rather close. The same conclusion can be found in [15] and [16], where the authors present aggregated models of wind parks with SCIG and DFIG wind turbines, which are validated by means of comparison with the complete wind park models.

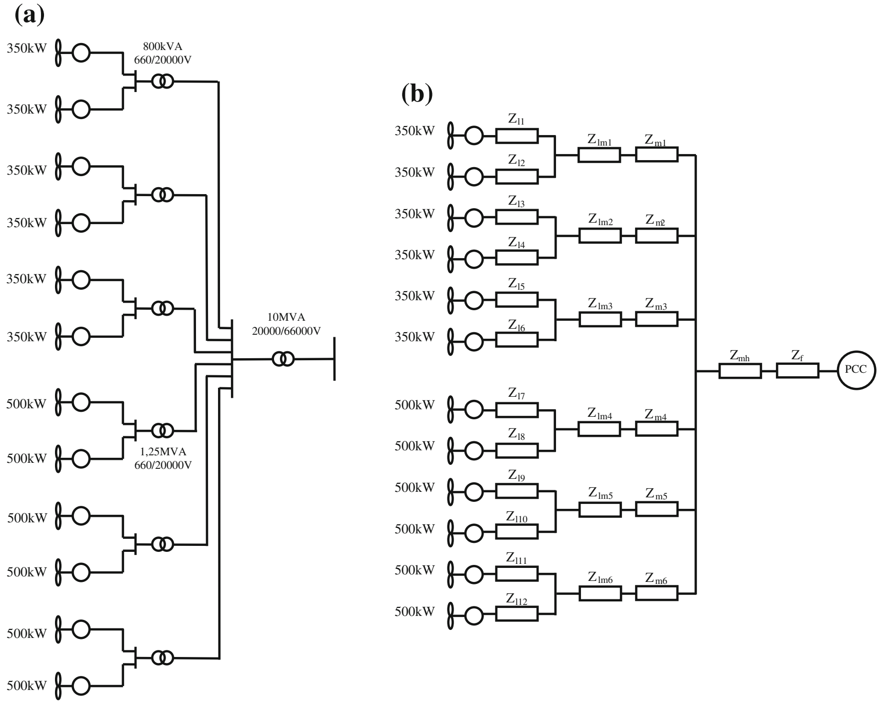

Fig. 1 Fixed speed wind park: **a** structure; **b** equivalent circuit of the internal network

Complete wind park model is always composed of all the wind turbine models of the park, with the necessary detail level of the scope of study, and the model of the internal grid of the wind park. Wind turbine models, as usual in dynamic studies, can be divided in two systems:

- The mechanical system, composed of the rotor (modelled as an ideal rotor disk) and the drive train (modelled, at least, by the two-mass model).
- The generation system, composed of the generator (SCIG, DFIG or PMSG), modelled with the first, third or fifth order model, depending on the scope of the studies. And, depending on the generation system, electronic power converters composed of two converters linked by a DC bus, modelled, in some cases, by neglecting converter dynamics.

Internal grid of the park has to be modelled including low voltage lines between wind turbines and transformers, medium voltage lines to internal substation and line feeder to the point of common couple (PCC). As usual in power systems simulation, electromagnetic transient are neglected, and all the elements of the grid are represented by constant impedances [55].

As example, a fixed-speed wind park structure is considered, as seen in Fig. 1. The park has a radial structure with twelve wind turbines in two clusters. The first one is composed of six 350 kW turbines and the other has six 500 kW wind turbines. Every pair of turbines has a common low voltage-medium voltage transformer to the medium voltage internal lines of the grid. These lines are connected to a medium voltage-high voltage transformer (substation of the park), and a line feeder connect them to the grid at the PCC. Fig. 1a shows the radial structure of the wind park, while Fig. 1b represents the impedances of the equivalent circuit of the internal network.

In this figure, Z_{li} is the low voltage line impedance of wind turbine i; Z_{lmj} is short-circuit impedance of the low/medium voltage transformer j; Z_{mj} is the medium voltage line impedance of the j line; Z_{mh} is the short-circuit impedance of the medium/high transformer and Z_f is the feeder impedance of the wind park.

In addition, the model of the wind park must include all the necessary devices to control generated power, the voltage and the frequency at the point of common coupling, or enhance generated power quality.

2.2 Equivalent Models of Wind Parks

Nevertheless, detailed model presents a main problem, they are high order models if the wind park has high number of wind turbines, and therefore the simulation time is long, because of the excessive number of equations to be computed. The complexity of the wind park model and the simulation time can be reduced by using equivalent models instead of detail models. These equivalent models result from the aggregation of the individual wind turbines into an aggregated model, whose characteristics depend on the input signals and the elements of the wind park. Thus, the models can be qualified in several groups depending on the wind speed that receive every wind turbine and the types and rated values of the machines that compose the park.

The most simply aggregation method is described in [4, 19, 41]. It consists in considering the same incoming wind to all the wind turbines of the wind park (wind speed differences are small in every location) and identical wind turbines (same mechanical and generation model). Thus, the aggregation model can be represented as one equivalent wind turbine with the same mechanical and generation models (identical parameters in per unit) as the individual ones, but with a rated power given as:

$$S_{eq} = \sum_{i=1}^{n} S_i \tag{1}$$

where S_i is rated power of the wind turbine i and n is the number of machines in the park [41].

Nevertheless, these ideal conditions are not the usual in case of large wind park with a great number of wind turbines (wind speed differences cannot be neglected), or if the wind parks are composed of different types of wind turbines or if they have different rated powers [37]. In these cases, the whole wind park is

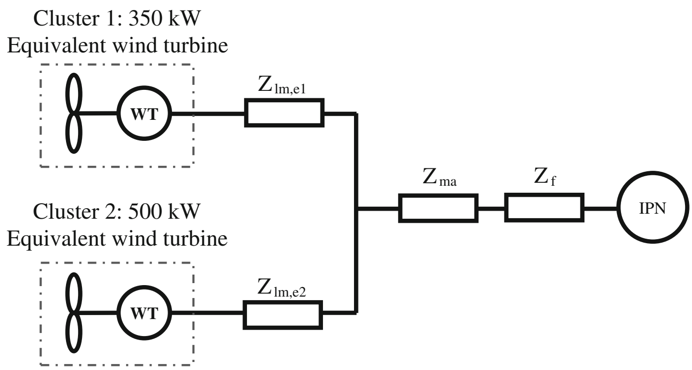

Fig. 2 Cluster representation of the aggregated model of the fixed speed wind park shown in Fig. 1a

represented by a variable number of equivalent wind turbines obtained from a simple aggregation method that consists in representing as much single equivalent wind turbines as groups (clusters) of identical wind turbines that experiencing similar incoming wind speeds are in the park.

Figure 2 shows an aggregated model of the wind park proposed in Fig. 1, considering that the six 350 kW wind turbines experience the same incoming wind and the six 500 kW wind turbines operates under similar wind speeds (with small differences).

As can be seen in Fig. 2, the first group of six 350 kW wind turbines (cluster 1) is replaced by an equivalent wind turbine that receive the same incoming wind as the individual wind turbines and has a rated power given by Eq. (1). The second group of six 500 kW wind turbines (cluster 2) experience similar incoming winds, but not identical. In this case, as illustrated in [16], an equivalent of the winds incident on the aggregated wind turbines can be used as wind incident on the equivalent wind turbine of 3 MW rated power, obtained from Eq. (1). This equivalent wind is obtained from the average of the incoming winds that experience every unit of the cluster. It is useful for wind parks located on topographically simple terrains (e.g. smooth land or off-shore) with wind turbines organized in rows at right angles to the prevailing wind direction. The wind turbines belonging to the same rows usually present similar winds, whereas the winds incident on each row are different because of shadowing between wind turbines (park effect). Akhmatov and Knudsen [5] consider this distribution pattern in the aggregated model of a large offshore wind park composed of seventy-two fixed-speed wind turbines of 2 MW rated power, whose internal network is organized in six rows with twelve wind turbines in each one. In this case, every row of wind turbines operates at the same wind conditions (same operational point). Thus, the whole wind park can be separated in six groups, composing each one of twelve wind turbines, that can be represented by one equivalent wind turbine with a rated power twelve times higher than that of the individuals.

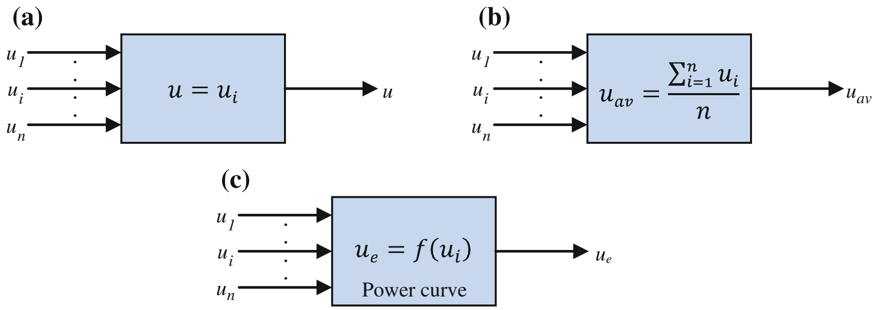

Fig. 3 Wind speed models: **a** constant wind speed model, **b** average wind speed model, **c** equivalent wind speed model

Following this assumption, a step further is presented in [14], where it is considered a new equivalent wind model in case of different incoming winds. This equivalent wind is derived from the power curve of the wind turbines in order to obtain an approximation of the power generated by the wind park as sum of the individual powers that generates each one according to its incoming wind. This equivalent wind is used as wind incident on a re-scaled wind turbine that aggregates the identical wind turbines of the wind park. The resulting model was compared with a clustering aggregated model, formed by groups of wind turbines that experience similar incoming winds, whose equivalent model receives the average of the incident winds of the group. The results analysis shows that the equivalent wind turbine with average incoming wind must be only used for units that experience similar winds (differences less than 2 m/s), while, in case of different winds, the equivalent model with the equivalent incoming wind enables the aggregation of all the wind turbines of a wind park into a single equivalent one.

Figure 3 shows the wind models considered in the literature in case of aggregated wind park models represented by a re-scaled individual wind turbine. Figure 3a presents the simplest wind model, where every wind turbine experiences the same wind speed (u). Figure 3b is useful for similar wind speeds, where the average wind speed (u_{av}) is the input to the re-scaled wind turbine. And finally, Fig. 3c represents a more suitable wind model, where an equivalent wind speed (u_e), obtained from the power curve of the individual wind turbines, allows the aggregation of all the wind turbines of the wind park, in case of different incoming winds, into a single equivalent wind turbine (without clustering). This model supposes the best way of reducing the model order and the simulation time, achieving an adequate approximation of the collective response of the wind park when carrying out dynamics simulations, e.g. in transient stability studies, when the mechanical behaviour has generally no big impact on voltages and power flows at PCC [43].

However, when simulating longer term dynamics, the aggregation of wind turbines into an equivalent one, that experience an equivalent wind speed, cannot predict the wind park's behaviour with sufficient accuracy, due to the highly

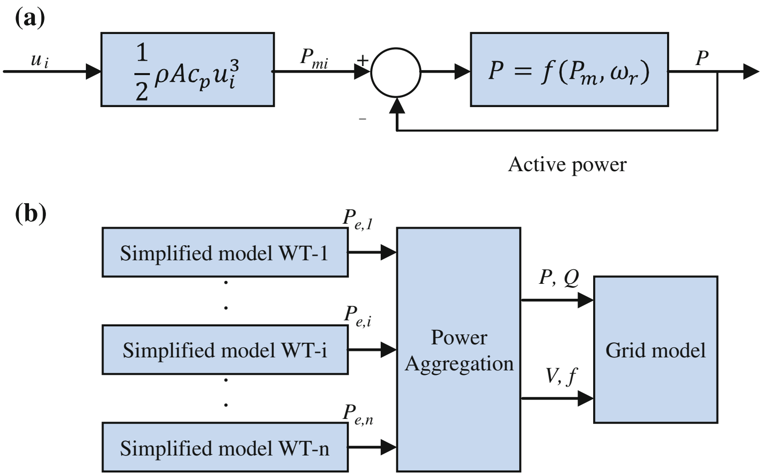

Fig. 4 **a** Simplified model of variable wind turbine. **b** Structure of the aggregated model of variable speed wind park

nonlinearity of the mechanical system. A good compromise between model accuracy and simulation time consists of aggregating just the generation systems (generators, power converters and controls) and representing the mechanical systems of all the individual wind turbines to be aggregated [43]. This 'compound' model is applied by [48] in case of variable speed wind turbines aggregation, since there is no unique relation between a wind speed value and the generated power. Therefore, the rotor speed of the individual wind turbines, combined in an aggregated model, needs to be recorded in order to get a suitable approximation of the generated power, with the following simplifications:

- The rotor model can be simplified by assuming that the wind turbine operates at the optimal value of the power coefficient over the whole operating range.
- The rotor speed controlled is simplified by approximating the rotor speed versus power control characteristic with a first order approximation.
- When the rotor speed is limited at its maximum value, the pitch angle controller can be omitted.

Figure 4 shows the simplified variable speed wind turbine model and the structure of the aggregated model of the wind park proposed in [48].

With the same philosophy, a 'compound' aggregated model is considered in [16] for fixed speed wind parks, and in [15] for a DFIG variable speed wind parks, located on topographically complex terrains (e.g. mountain ladder) or with widely separated wind turbines. The aggregated models are represented by an equivalent wind turbine with an aggregated generation system model and a simplified model of each individual wind turbine, which approximates the operational point of each one according to the incoming wind speed. These simplified models are composed of the rotor (rotor disk model) and the drive train models (two masses-model), the

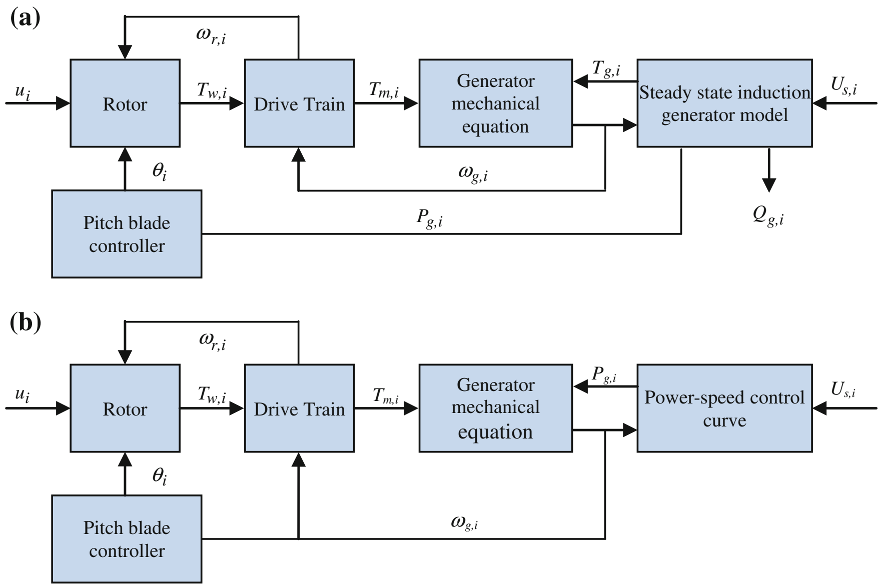

Fig. 5 Simplified models of: **a** fixed speed wind turbine, **b** variable speed wind turbine

blade pitch angle controller and the induction generator (first order model, represented by its mechanical equation). In case of fixed speed wind turbines (Fig. 5a), the simplified model is completed by the steady-state generator model to obtain the electrical torque and the calculation of the reactive power of each individual wind turbine. In case of variable speed wind turbines (Fig. 5b), the model includes the rotor speed controller represented by the power speed control curve.

The simplified models of each wind turbine approximate their operation point according to the corresponding incoming wind speed. The equivalent wind turbine presents n-times the size of the individuals, with an equivalent generation system composed of the equivalent induction generator (and power converter, in case variable speed wind parks), represented by the same model of the individual generation system, and with the same parameters at per unit. The equivalent wind turbine presents an aggregated mechanical torque, obtained from the simplified models, and used as incoming to the equivalent generation system in order to calculate the equivalent generator mechanical torque.

The structure of the equivalent wind turbine without aggregation of mechanical system is shown in Fig. 6, for both fixed speed wind parks (Fig. 6a) and variable speed wind parks (Fig. 6b). Both models have the same structure, but, the equivalent model for fixed speed wind turbines include compensating capacitors with variable reactance for a suitable approximation of reactive power, due to the great dependence of the reactive power on the active power and generation voltage. On the other hand, the equivalent model for variable speed wind turbines

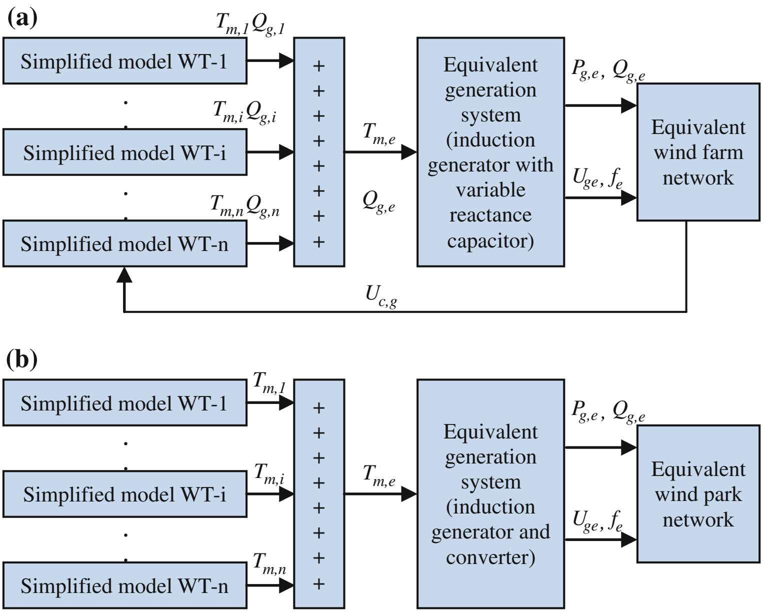

Fig. 6 Structure of the equivalent wind turbine of the: **a** fixed speed wind park, **b** variable speed wind park

needs a suitable control of active and reactive power when the wind turbines are operating with down power regulation. The active and reactive power references of the equivalent wind turbine must be equal to the sum of the active and active power references of the aggregated wind turbines.

The equivalent generation system is commonly represented by the same model of the individual wind turbines and with the same mechanical and electrical parameters at per unit [43]. Only a few authors have considered other methods of aggregating generation system and always based on aggregation methods applied to induction motors for transient stability. These aggregation methods can be seen in [46], where it was applied the method proposed by Franklin and Morelato [18], based on the steady-state theory of the induction motor and the equivalence criterion of the active power absorbed. In the same way, Trudnowski et al. [57] obtained the parameters of the equivalent generator using the method proposed by Nozari and Kankam [40]. In this method, the equivalent parameters are calculated from the rated power weighted average admittances of each branch of the induction machine equivalent circuit.

Jin and Ju [29] obtained the parameters of an equivalent induction generator by using a weighted average method based on the apparent power of the generator, although their main contribution is a suitable method of clustering aggregation in case of different kinds of wind turbines according to a slip coherency criterion. They assumed that the synchronous generators present a coherent response if they have similar rotor angles responses or the same rotor speed following a disturbance. However, they considered, with respect to the induction generator, that the slight variety of the slip causes marked changes in both active and reactive power, and the coherency analysis must be applied according to the slip response. As result of the analysis, the wind turbines of a wind park can be clustered by the value of the product of the rotor resistance by the combined inertia constants of the generator and turbine. This criterion is in agreement with the index proposed by Taleb et al. [52] as indicator for grouping induction machines.

The power converter and the control system of the equivalent wind turbine keeps the same structure as the individual, excepting the blade pitch angle controller in case of compound model, because the simplified model of each wind turbine includes this control [15].

Finally, the equivalent wind turbine operates in an aggregated wind park network, obtained from the equivalent of the lines and/or transformers of the common network of aggregated wind turbines. As usual in dynamic power systems, the internal network was commonly modelled by its static model, assuming that the short-circuit impedance of the equivalent wind park must be equal to the short-circuit impedance of the complete wind park [15]. Thus, Fig. 2 shows the equivalent internal electrical network of the wind park showed in Fig. 1, where the impedances $Z_{lm,e1}$ and $Z_{lm,e2}$ are the equivalents of the internal network of both wind parks connected to the same feeder.

When the studies focuses on developing an equivalent wind park model for power system planning studies, the equivalent internal network is modelled considering the criterion of apparent power losses, as can be seen in [39].

2.3 Wind Park Models Simulations

Some of the equivalent wind turbine models are implemented and verified their dynamic responses by comparison with the complete model. Three cases are studied in order to present results of the complete and reduced models of wind parks for dynamic power system analysis during wind fluctuations and electrical faults.

2.3.1 Case 1: Normal Operation in a Variable Speed Wind Park with Identical Wind Turbines

The wind park under consideration, Fig. 7, is composed of 6 DFIG wind turbines of 2 MW organized into a network with two sections [15].

Figure 7a shows the radial structure of the wind park, while Fig. 7b shows the impedances of the internal network. In this figure, Z_{lmij} is the short-circuit impedance of the low/medium voltage transformer of the wind turbine j of the branch i; Z_{mij} is the medium voltage line impedance of wind turbine j of the branch i; Z_{mi} is the medium voltage line impedance of the i branch; Z_{mh} is the short-circuit impedance of the medium/high transformer and Z_f is the feeder impedance of the wind park.

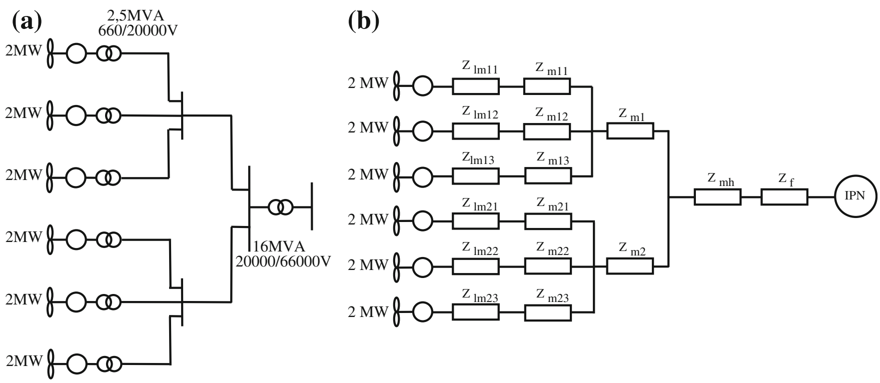

Fig. 7 Variable speed wind park: **a** structure, **b** equivalent circuit of the internal network

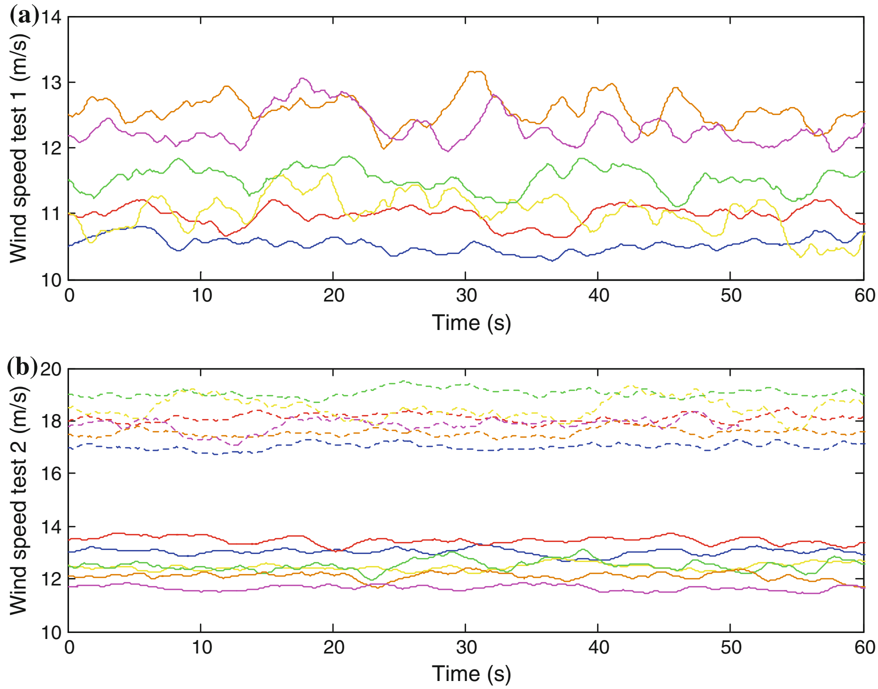

Fig. 8 Wind speeds incident on the wind turbines: **a** test 1, **b** test 2

This variable speed wind park is evaluated under wind speed fluctuations with different incoming wind between the wind turbines, as shown in test 1 of the Fig. 8, where the most of the incoming wind speeds are near to the rated wind speed.

In this case, three models of the wind park presented in Fig. 7 are implemented:

- *Complete model* Composed of all the wind turbine models of the park and the model of the internal grid of the wind park.
- A *single equivalent model*, as presented in [14] A re-scaled wind turbine that experiences an equivalent wind speed obtained from the power curve of the individuals.
- *A compound equivalent model*, as presented in [15] An equivalent wind turbine with an aggregated generation system model and a simplified model of each individual wind turbine approximating the operational points of each one according to its incoming wind speed.

The evaluation of these models is performed by comparing their active and reactive power responses for the incoming wind speeds of test 1 and considering that all the wind turbines are operating with unity power factor and rated active power reference.

Simulation results, presented in Fig. 9, show a high correspondence between the response of the complete and equivalent wind turbines, with few discrepancies in the compound equivalent model due to the approximation of the operational point of every wind turbine achieved by its simplified model and the adjust of the controller in the equivalent generation system.

2.3.2 Case 2: Normal Operation in a Fixed Speed Wind Park with Two Different Wind Turbines

In this case, the wind park under consideration is shown in Fig. 1. It presents a radial structure with six 350 kW wind turbines organized in three branch with two wind turbines for each one, and others six wind turbines of 500 kW of rated power with the same organization.

Twelve wind speed time series are used to evaluate the behaviour of the fixed-speed wind park under wind fluctuation, as shown in test 2 of Fig. 8. The 350 KW wind turbines experience different wind speeds between 11.7 and 13.5 m/s (under rated wind speed) and the 500 kW wind turbines experience wind speeds between 17 and 19 m/s (above rated wind speed).

As in the case 1, three models of this fixed speed wind park are implemented:

- *Complete model* Representing all the individual wind turbines.
- *A compound equivalent model* A simplified model of each wind turbine, as presented in [14], is used to aggregate the mechanical torque as incoming to an equivalent generation system, which is obtained from the aggregation of all the individual induction generators, applying the method proposed in [18].
- *A cluster equivalent wind model* It presents the same model than that proposed in [16], but with two clusters composed each one by a single equivalent model of six wind turbines.

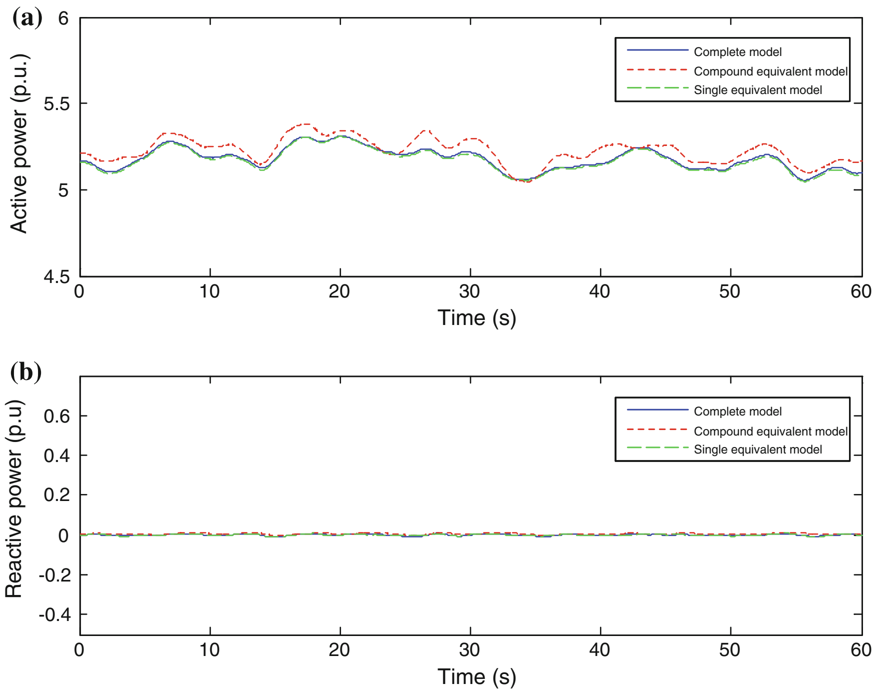

Fig. 9 Dynamic simulation results of complete and equivalent wind parks during normal operation in a variable speed wind park with identical wind turbines: **a** active power, **b** reactive power

The comparison of these models is shown in Fig. 10. It is performed assuming that the compensating capacitor banks of every wind turbine are designed to achieve unity power factor (zero reactive power) with rated incoming wind speed.

Analysing the simulation results presented in Fig. 10, it can be concluded that the equivalent models allow an accurate approximation of the dynamic response of the wind park with two different wind turbines. The best results are obtained by the equivalent wind park model without aggregation of the mechanical system (compound equivalent model). The equivalent wind model, organized in two clusters as shown in Fig. 2, presents worst results, because a worst approximation of mechanical torque obtained from the equivalent wind that experiences the single equivalent re-scaled model of the cluster 1, where all the wind turbines receive incoming wind speeds above the rated value.

As summary, regarding the simulation time, an approximate reduction of 93 % is obtained for the cluster equivalent wind model and 72 % for the compound equivalent model of the wind park shown in Fig. 1.

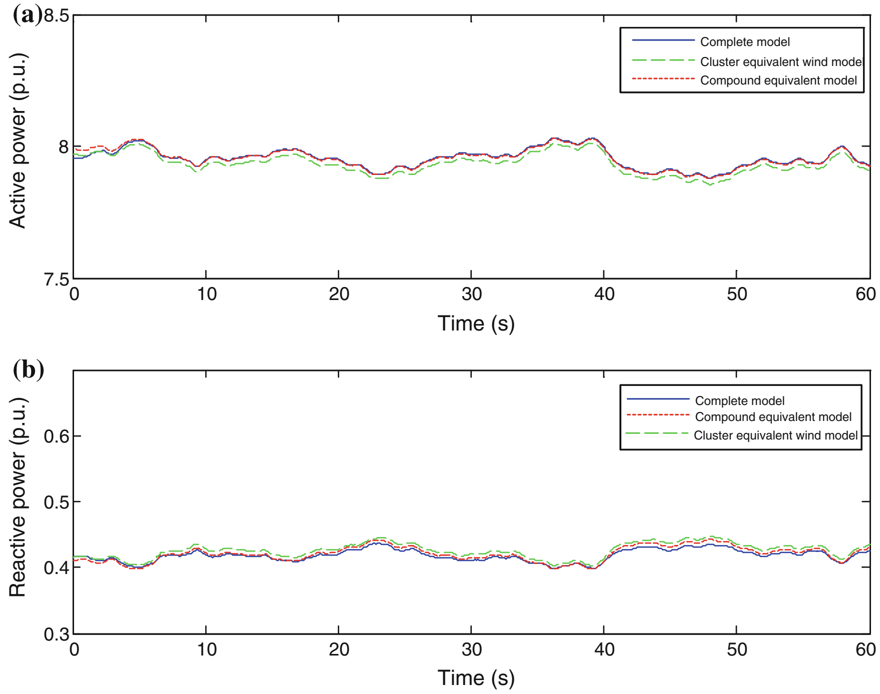

Fig. 10 Dynamic simulation results of complete and equivalent wind park during normal operation in a fixed speed wind park with identical wind turbines: **a** active power, **b** reactive power

2.3.3 Case 3: Abnormal Operation (Response to Voltage Dip) in a Variable Speed Wind Park with Two Different Wind Turbines

The equivalent models are evaluated during grid disturbances for two variable speed wind parks connected to the same feeder, the first of them with 6 wind turbines of 660 kW and the other with 6 wind turbines of 2 MW of rated power, as depicted in Fig. 11.

Figure 11a shows the radial structure of the wind parks, while Fig. 11b shows the impedances of the internal network. In this figure, Z_{lmij} is short-circuit impedance of the low/medium voltage transformer of the wind turbine j of the branch i; Z_{mij} is the medium voltage line impedance of wind turbine j of the branch i; Z_{mi} is the medium voltage line impedance of the i branch; Z_{mhk} is the short-circuit impedance of the medium/high transformer of the wind park k; and Z_f is the feeder impedance of the wind parks.

To verify adequately the robustness of the equivalent models, a voltage dip at the PCC is considered, with 0.8 p.u. of depth and a width of 1 s. As usual in short term stability simulations, constant incoming winds are assumed, with different

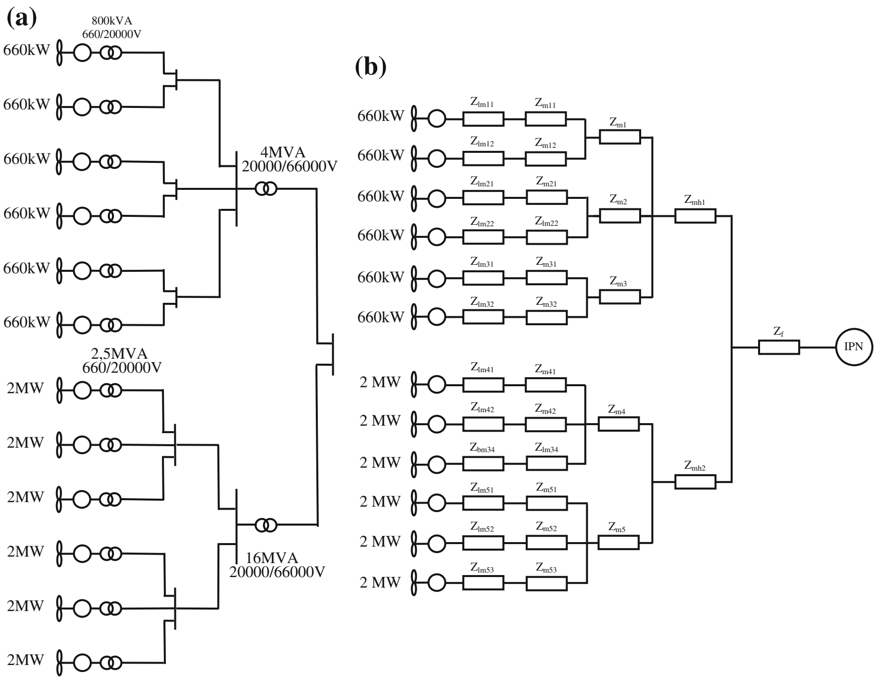

Fig. 11 Variable speed wind parks: **a** structure, **b** equivalent circuit of the internal network

values above the rated wind speed for both types of wind turbines. Figure 12 shows the power response during the slow voltage dip. The simulation results of the complete and equivalent models show a high correspondence, although a little faster and less damped in the equivalent models.

Figure 13 shows the voltage at the PCC to grid and the wind turbine voltage at every wind turbine of the complete wind park and at the aggregated wind turbine of each equivalent model. In this case, the voltage recovery in the compound model is slower than that obtained with the equivalent model, where only one re-scaled wind turbine represents the whole wind park.

3 Wind Park Control System

Until relatively recently, wind parks have commonly operated delivering the available energy to the grid. Hence, the wind turbines maximized the energy captured from the wind, without exceeding generator limits and operating with unity power factor (zero reactive power). However, the wind parks production has been voluntarily reduced by disconnecting wind turbines from the grid at special conditions (especially during low consumption periods or strong winds). During

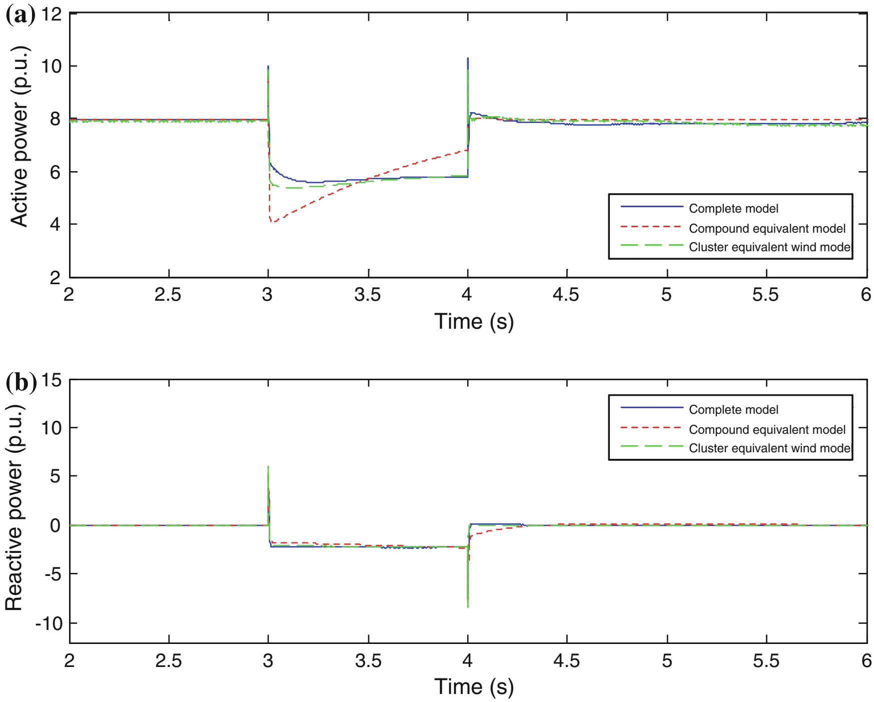

Fig. 12 Active and reactive powers of the complete and equivalent models of the wind park for a slow voltage dip

these conditions, system operators recommended the reduction of wind parks production in order to maintain the stability and reliability of the power systems with high wind power penetration.

The increase of wind power penetration on power systems has led to partial substitution of conventional power plants by current wind parks. Therefore, large wind parks are today required to participate actively in the power system operation as conventional power plants. Thus, the system operators have revised the grid connection requirements for wind parks, demanding an operational behaviour with several control tasks similar to those of conventional power plants [28]. The requirements encountered in the majority of grid codes, concerning to the wind park interconnection, including [51, 58]:

- *Fault ride-through* Wind parks connected to transmission networks must withstand voltage dips to a certain percentage of the nominal voltage and for a specified duration. Some of the grid codes prescribe that wind parks should support the grid by generating reactive power during a network fault, to support and faster restore the grid voltage.

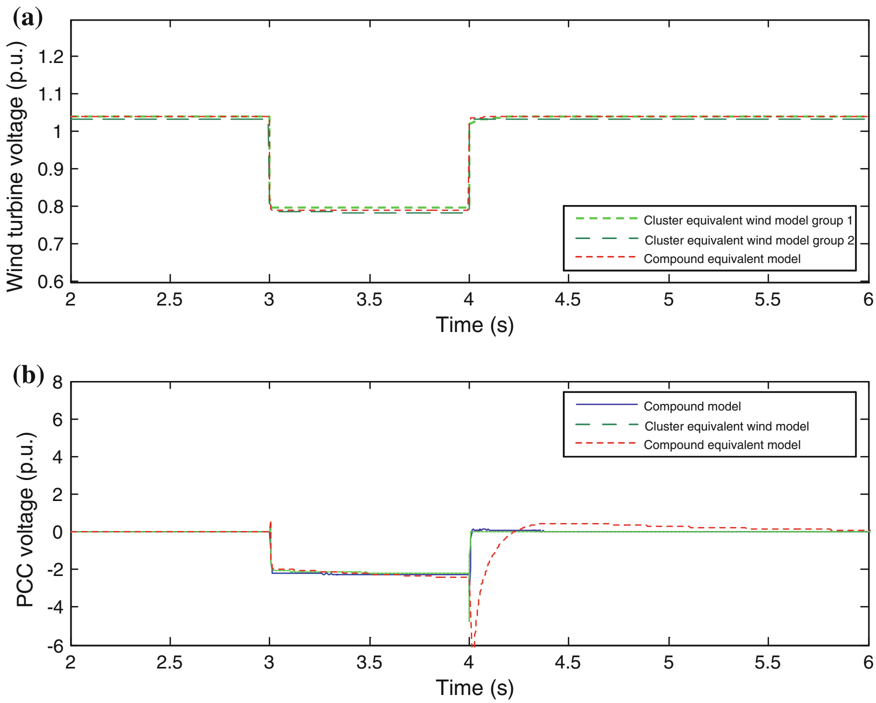

Fig. 13 Voltage at the PCC to grid and wind turbine voltage of the complete and equivalent models for a slow voltage dip

- *System voltage and frequency limits* Wind parks must be capable of operating continuously within the voltage and frequency variation limits encountered in normal operation of the system.
- *Active power regulation and frequency control* Wind parks should control their active power output to a defined level, either by disconnecting turbines or by pitch control action. In addition wind parks are required to provide frequency response, regulating their active output power according to the frequency deviations.
- *Reactive power/power factor/voltage regulation* Some grid codes demand from wind parks to provide reactive output regulation, often in response to power system voltage variations, like conventional power plants.

A main consideration to operational behaviour of large wind park is the technology of the generation system of the wind turbines, affecting the influence on the grid [20]:

- *Fixed speed wind turbines* These wind turbines are based on an induction generator directly connected to grid (Danish concept). In passive stall application, the blades are kept at a fixed angle, while in active or semi-active stall the control is used to compensate for wind variations. The induction generator draws reactive power, which might be supplied from the grid or from installed compensation equipments (capacitor banks or FACTS, Flexible AC Transmission Systems). The dynamic response and controllability are therefore poor compared with variable speed wind parks.

- *Variable speed wind turbines* The generation system is composed of a variable speed generator, that have the ability to control both the active and reactive power delivered to the grid, optimizing the grid integration with respect to steady state conditions, power quality, voltage and angular stability [34]. Two main types of generation system can be found:

– *The variable speed wind turbine with Doubly Fed Induction Generator* (*DFIG*) The generation system can be controlled with a back-to-back converter in the rotor. It presents some difficulties to ride-through voltage dips, and the rotor converter rating (typically 30 % of generator rated power) determines the frequency response.
– *The variable speed wind turbine with Permanent Magnetic Synchronous Generator* (*PMSG*) It is connected through a full back to back converter that totally decouples the generator from de grid. This provides maximum flexibility, enabling full real and reactive power control and fault ride-through capability during voltage dips.

A second consideration to their operational behaviour is how the internal network of the wind parks is connected to the grid, especially for long distance power transmission (e.g. offshore wind park), where High Voltage Direct Current (HVDC) may be an interesting option. In this case, a common or a separated AC/DC power converter system converts the AC voltage into a DC voltage and transferred to a DC/AC power converter system that are connected to the grid [10]. This power converter decouples the wind turbines from the grid and can be used for controlling the active and reactive power delivered to the grid and improving their dynamic response.

3.1 Active Power Regulation and Frequency Control

The generated power in the power system must be in balance with the demand from the loads and losses in the system [50]. The active power output of the generators is determined by the mechanical power input from their prime movers. The consequence of a mismatch between the generation and the demand for active power is a change in the rotational energy stored in the rotating mass of the generator, and hence, a drift in the system frequency [34]. Therefore, the power balance in the system can be obtained by controlling the rotational speed of the generator (primary control), and in case of conventional power plants, there is a proportionality between the speed of the generators (prime movers) and the power

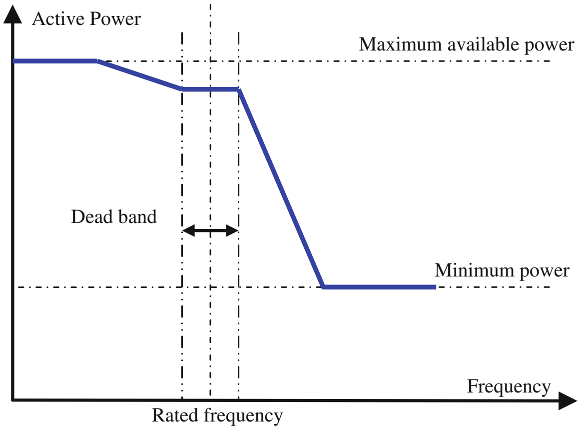

Fig. 14 Typical frequency controlled regulation of active power

system frequency. This power balance requires an operating reserve 'spinning reserve' to control those faster fluctuations and a 'supplementary reserve' to cover slower power fluctuations.

With these considerations, frequency regulation ancillary service may consider three functions:

- *Primary frequency control*, limits variations caused by sudden power unbalance in the grid. It is performed locally by the speed governor of each generation system.
- *Secondary frequency control*, restoring frequency and interchanges power to their scheduled values. It is performed by an automatic central controller.
- *Tertiary control*, supporting the secondary control and re-establish the power reserve consumed by it.

Wind power plants, as conventional power plants, must operate within strictly frequency margins. They should change their production in agree with system operators requirements to maintain frequency limits. A typical characteristic of primary frequency control is shown in Fig. 14 [34].

This typical frequency control curve shows that the frequency can be limited as function of the available power. Thus, high-frequency response can be provided from full output to a reduced output when the frequency exceeds the dead band of the rated power and the grid codes require that, when the frequency increases above the rated value, power plants should decrease their output at a given rated. On the other hand, at nominal frequency, the wind parks would be required to limit their power output below the maximum achievable power level, and so, if the frequency starts to drop, the wind park would increase the power output to the maximum achievable power, trying to sustain the frequency. As summary, a wind park should be capable of providing frequency response, and it would be used by the system operator. The active power levels of the wind park are determined by the system operator, according to the system demand.

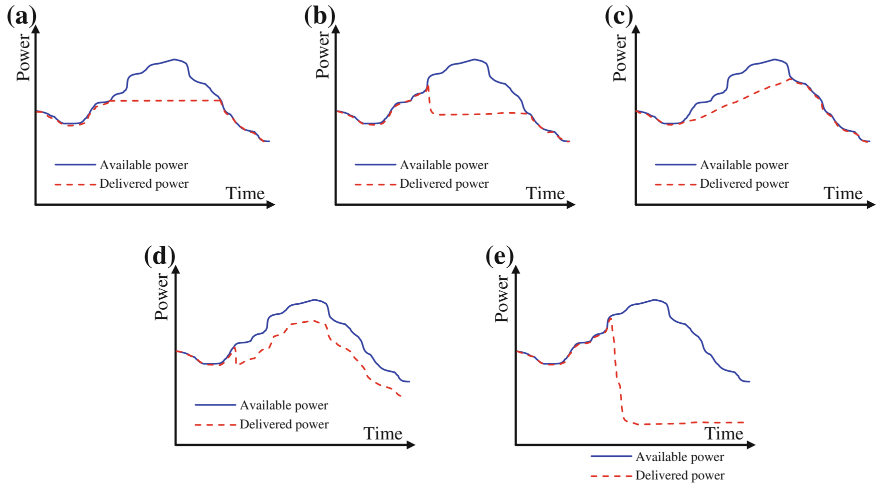

Fig. 15 Different power control possibilities: **a** absolute power limitation, **b** balance control **c** power rate limitation, **d** delta control, **e** system protection

The active power output of a wind park can be determined by the mechanical input power of the wind turbines and, thus, by the wind energy, a fluctuating source. In case of large wind parks, significant power fluctuations, caused by the uncontrollability of the wind source, may affect the grid if it is not appropriately controlled by the system operators. Hence, large wind parks may participate in grid management as a conventional power plant, including provision of regulating power, generation management and power reserve. Thus, some types of power control possibilities are necessary to use the wind park as a wind power plant supporting the power balance [32]:

- *Absolute power limitation* As seen in Fig. 15a, the delivered power output of the wind park will never exceed a pre-set maximum.
- *Balance control* In this case, the wind park must be able to change quickly its power as shown in Fig. 15b. It is helpful in order to balance the production and consumption of active power in the grid.
- *Power rate limitation* This possibility avoids fast gradients of output power in the wind park with regard to slower gradient of conventional power plants to keep the power balance. Figure 15c shows increase rate limitation.
- *Delta control* The wind park runs as a spinning reserve, with a power output below available in an adjustable margin. Figure 15d shows this type of control that allows the wind park to take part in the frequency control.
- *System protection*, such as the drastic reduction of the output power in the wind park when there are overloads in the grid, shown in Fig. 15e.

3.2 Reactive Power Control and Voltage Regulation

In power systems, the voltage is controlled by the power flow from the power plants, where the reactive power exchange controls the magnitude of the voltage, whereas the phase difference is related to the active power exchanging. Then, the active and reactive powers flow between the generation and the load in the power system must be balanced in order to avoid large voltage (and frequency) excursions.

Grids codes require that a minimum of the reactive power from a large wind park can be controlled to a specific interval, which is close to unity power factor. This requirement is usually specified with a limiting curve, as depicted in Fig. 16 [34]. If the wind power plant provides low active power, the power factor may deviate from unity because it can support additional leading or lagging currents due to the reactive power demanded. When the wind park is working under nominal conditions, the power factor must be kept close to unity or else it will be excessive currents. In addition, local reactive power generation reduces losses in the system.

The dependence between reactive power and voltage can be expressed by a voltage control, in a similar way as the frequency control shown in Fig. 14, integrating a combined droop and dead band control. But, in this case, reactive power is exchanged to the grid in order to compensate for the deviations in grid voltage.

3.3 Control Structure of Wind Parks

The basic structure of a wind park main controller is illustrated in Fig. 17. The aim of the wind park controller is to regulate, in a centralized way, the active and reactive powers injected by the whole wind park into the grid (when the it operates as a PQ node) or the active power and the voltage at the PCC (when it operates as a PV node). In addition, in some circumstances, the wind park controller has to adjust frequency margins.

As shown in Fig. 17, the Wind Park Main Controller (WPMC) receives set point commands in agree with the required operation and the wind park current status (system operators receive monitoring signals of the status of wind parks). The WPMC computes the incoming reference settings, the wind turbines status and delivers the wind park operation references that assure a correct production. Finally, a dispatch centre must distribute the operation references between the wind turbines.

The main objective of the WPMC is to assure the wind park production in a similar way as a conventional power plant. Although the WPMC performance depends on the wind turbine technology, the basic objective is the same: it controls the power production of the wind park (active and reactive power) considering

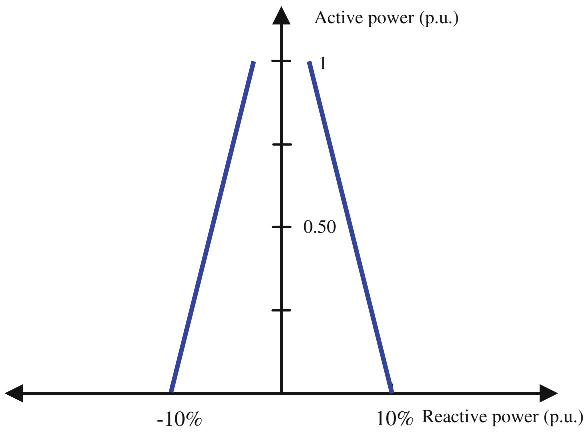

Fig. 16 Typical reactive power limiting curve

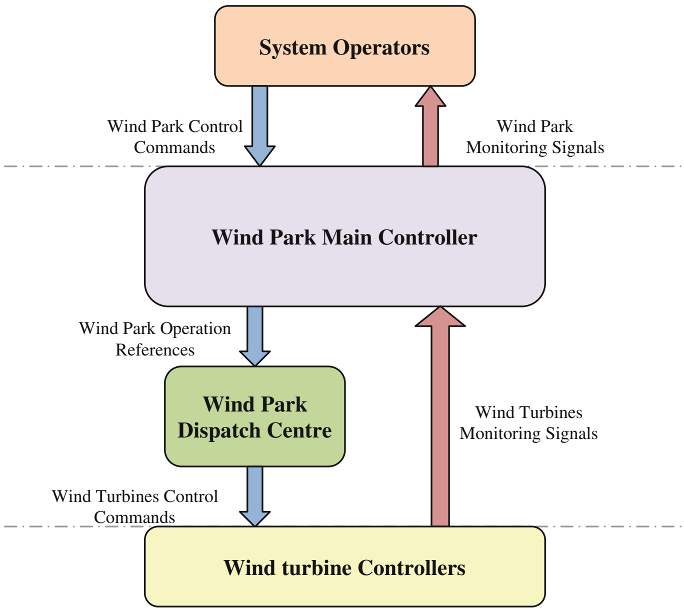

Fig. 17 Basic structure of the wind park main controller

some of the control functions described in Sect. 4.1 for the active power and for reactive power in Sect. 4.2. In addition, large wind parks must be able to provide advanced grid support (frequency and voltage control).

The most typical WPMC structure is composed of two separated PI control loops, one for the active power control (frequency control) and another for the reactive control (voltage control). This structure is used in [24] for a variable speed wind park composed of three 2 MW DFIG wind turbines, including automatic frequency control and voltage control function and focused on the wind park's capability to regulate active and reactive power production. In the actual WPMC, the active power control with balance control, delta control, ramp limitation and the reactive power control are implemented.

In a similar way, Rodríguez-Amenedo et al. [44] present two PI controllers (active power control loop and reactive power control loop) for a variable speed wind park with 37 DFIG wind turbines of 850 kW rated power. In addition, it presents the WPMC for a fixed speed wind park composed of 21 stall regulated wind turbines of 900 kW rated power. The results show that the controller performance depends on the wind turbine technology. Each fixed speed wind turbine is provided with a low voltage variable capacitor bank of a total rated of 450 kVAr at its terminals. These capacitor banks are coordinated with an under-load tap changing (ULTC) booster transformer located at the wind park substation, and an additional medium voltage capacitor bank of 6.2 MVAr.

The active power control is based in a wind turbine disconnection strategy, with a PI control loop and a hysteresis band controller to obtain the connection or disconnection order to each wind turbine. Furthermore, a PI regulator is responsible for maintaining the medium voltage level and two PI regulators control the reactive power generated by the capacitor banks at the terminals of each induction generator in order to compensate the power factor (capacitor banks of each wind turbine) and reach the wind park reactive power reference (wind park capacitor bank).

The WPMC structure presented above, with PI controllers in two separated control loops, is showed in Fig. 18 [13]. In this figure, the active power control loop is based on a PI controller that assures the wind park production according to the set point ordered by the system operator ($P_{wp\_so}{}^{*}$). This controller computes the active power error and set up the power reference ($P_{wp}{}^{*}$) for the whole wind park. The other control loops presents a switch to select the reactive power control or the node voltage control. Thus, the wind park can operates as a PV node, trying to adjust the voltage (V_{wp}), at the wind park node, to the voltage reference ordered by the system operator ($V_{wp\_so}{}^{*}$). This control is performed by a PI controller that sets up the reactive power reference ($Q_{wp\_vc}{}^{*}$). On the other hand, the reactive power reference ($Q_{wp\_so}{}^{*}$) is obtained from the system operator. In both cases, a PI controller sets up the reactive power reference ($Q_{wp}{}^{*}$) for the whole wind park.

This WPMC is implemented for the wind park shown in Fig. 19, consisting of three 2 MW rated power DFIG wind turbines. Each wind turbine is connected to the internal network through a transformer of 2.5 MVA, and the wind park connection to the grid is performed through a substation with a transformer of 8 MVA and a long feeder.

As can be seen in Fig. 17, a wind park dispatch centre is needed to compute the active and reactive power references. Different strategies for the dispatch function can be used:

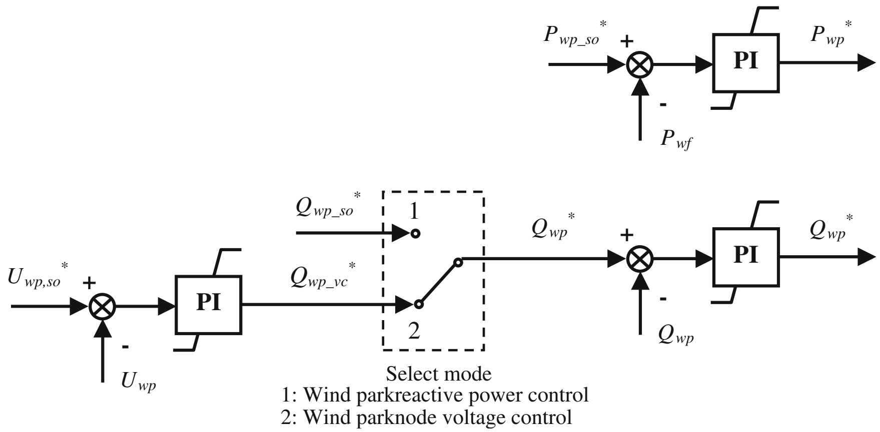

Fig. 18 Wind park main control structure

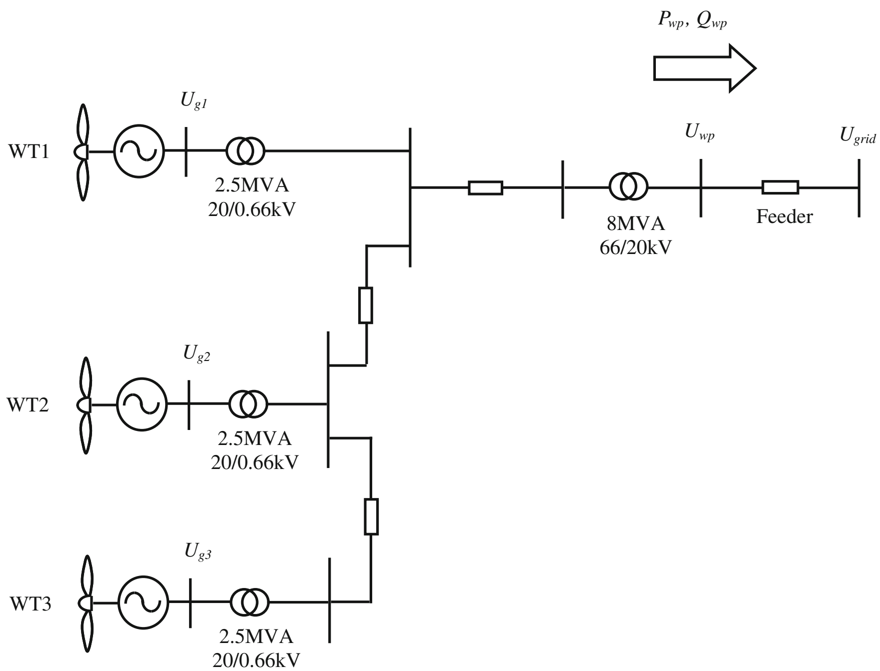

Fig. 19 Variable speed wind park layout [13]

- The simplest strategy is based on computing the same power references for each wind turbine [44]:

$$P_{gi}^{*} = \frac{P_{wp}^{*}}{n} \quad Q_{gi}^{*} = \frac{Q_{wp}^{*}}{n} \tag{2}$$

- A more efficient strategy is proposed in [24], where the power references are defined from a proportional distribution of the available active and reactive powers:

$$P_{gi}^{*} = \frac{P_{ava\_gi}^{*}}{\sum_{i=1}^{n} P_{ava\_gi}^{*}} P_{wp}^{*} \quad Q_{gi}^{*} = \frac{Q_{ava\_gi}^{*}}{\sum_{i=1}^{n} Q_{ava\_gi}^{*}} Q_{wp}^{*} \tag{3}$$

where $P_{ava\_gi}^{*}$ is the available active power for the *i*th wind turbine in one specific moment, calculated from the power-speed control curve of the wind turbine; and $Q_{ava\_gi}^{*}$ is the available reactive power for the *i*th wind turbine computed from the operating Q–P curve of the wind turbine.

- An optimized dispatch control strategy for optimizing the active and reactive power references of each wind turbine is presented in [36]. In this work, an optimal power flow algorithm is adopted at the wind park control level to define the active and reactive set points, considering the generator terminal voltage and other operational constrains, such that, a minimization of the mismatch between the total wind park generation output (active and reactive) and wind park dispatch centre request is achieved.

The dispatch control strategy applied to the WPMC of the wind park showed in Fig. 19 is based on the second option, a proportional distribution of the available active and reactive powers. In addition, the wind turbines can autonomously operate with power optimization or power limitation (the active power reference of the wind turbine is set up at its rated value), and only when down power regulation is required, the power reference is changed to the value defined by the dispatch centre control.

An adequate wind speeds time series, showed in Fig. 20, allow the evaluation of the WPMC in any operating conditions (power optimization, power limitation or down power regulation).

The performance of the described control system is assessed through two different simulations:

- *Wind park operating as a PQ node* (Fig. 21) The capabilities of the WPMC to regulate the wind park production according to the power references ordered by the system operator are tested. In this simulation, the wind park produces the maximum possible output power during the first 60 s (power optimization). At this time, the wind park receives a 60 % reduction of the active power reference by a slope of 0.1 (power down regulation and rated limitation). Finally, a change in the reactive power reference is ordered at 80 s. The wind turbine changes from unity power factor operation to maximum reactive power generation, with a slope of 0.1 (reactive power maximizing).

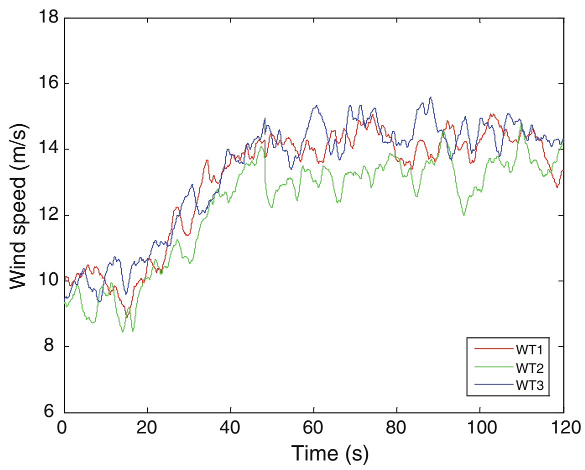

Fig. 20 Incoming wind speed time series on the wind turbines [13]

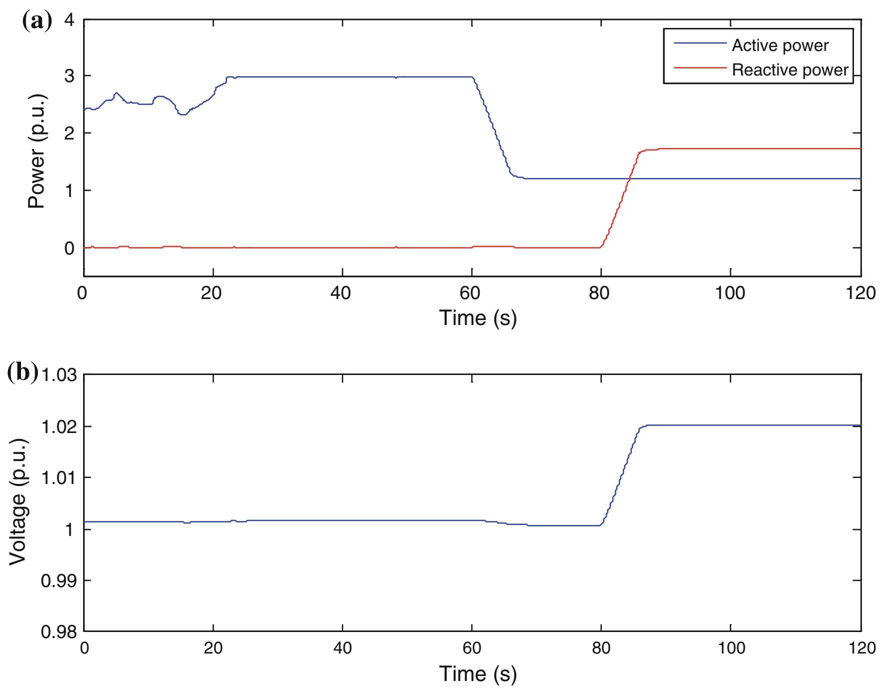

Fig. 21 Response of the wind park operating as a PQ node

- *Wind park operating as a PV node* (Fig. 22) To evaluate the WPMC when the wind park production is regulated, a second case is simulated, in which the active power and voltage at the wind park node are controlled according to

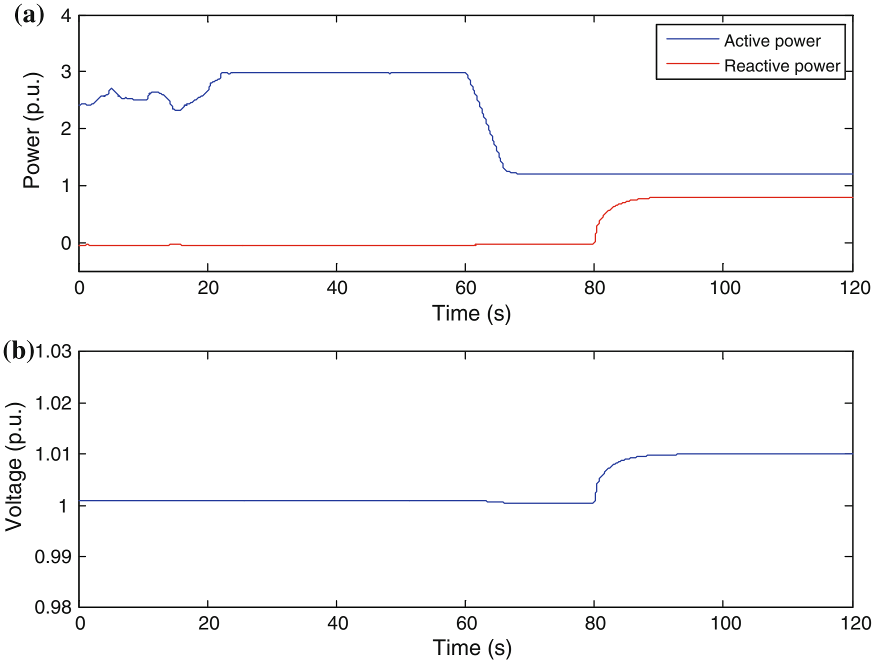

Fig. 22 Response of the wind park operating as a PV node

the references ordered by the power system operator. In this simulation, the wind park operates with the same active power references as in the first case. However, the voltage reference at the wind park node is set to 1 p.u. during the first 80 s and 1.01 p.u. for the rest of the simulation.

More complex WPMC structures can be used when the scope of the researches is more than the behaviour of a wind park as a conventional power plant, considering powers and voltage controls. In these cases, the wind parks may contribute to the electrical network stability, maintaining the network frequency or contributing to network stability, operating the wind parks as compensator devices. Fernandez et al. [17] consider this philosophy and they propose control laws based on energy function. These control laws are independent of operating points, and linearization techniques are used to assure the contribution of DFIG variable speed wind parks over a wide range of different working conditions. They proposed steady state controls (normal operating conditions) plus corrections looking for contributing to the network stability:

$$P_{wp} = P^*_{wp} + \Delta P_{st} \quad Q_{wp} = K_{QV} \cdot \Delta V + \Delta Q_{st} \tag{4}$$

The total active power of the wind park P_{wp} is obtained from the power reference, given by a supervisory control (P^*_{wp}), and the correction which contributes to the network stability (ΔP_{st}). Meanwhile, the reactive power is controlled by considering the voltage profile with the voltage gain K_{QV} for contributing to the energy quality and the correction ΔQ_{st} for collaborating with the electromechanical oscillations. These non-linear active and reactive power corrections are obtained by forcing the incremental energy function of the network to decrease.

Some authors have focused their studies on improving the voltage control at a specified location, without using additional compensating devices. Ko et al. [31] present a voltage control scheme for a DFIG variable speed wind park, using a control-design technique, known as the 'linear quadratic regulator', and a reduced-order linear approach of the wind turbines. These linear models force a reformulation of the problem in order to find a common Lyapunov function for the set of considered linear systems. These are accomplished by representing the underlying control optimization problem in terms of a system of linear-matrix-inequality constraints and matrix equation to be simultaneously solved to ensure a robust and reliable operation of the linear quadratic regulator, in case of a three-phase symmetrical fault in the transmission line of a variable speed wind park composed of 3 DFIG wind turbines of 3.6 MW rated power.

Others authors focus their researches on reactive power control generated by variable speed wind parks. Zhao et al. [64] present a reactive power control and distribution network reconfiguration to reduce power losses and improve voltage profile. They use a joint optimization algorithm to obtain the optimal reactive power output of a wind park and network reconfiguration simultaneously. To find the optimal reactive power output of a wind park, they apply an improved hybrid particle swarm optimization with wavelet mutation algorithm. Furthermore, they develop a binary particle swarm optimization algorithm to find the optimal network structure of the wind park. On the other hand, Tapia et al. [56] study the behaviour of a wind park as a continuous reactive power source. They devised a PI-based control strategy to manage the net reactive power exchanged between the grid and DFIG variable speed wind parks. They present experimental results of the proposed strategy when applied to a wind park comprising 33 wind turbines of 660 kW rated power.

Control systems for large offshore wind parks, with high voltage DC (HVDC) connection to the main onshore network, needs a special consideration. A typical offshore wind park layout is shown in Fig. 23, where each wind turbine is connected through a small transformer to a common AC grid, which finishes in a power electronic rectifier to transform the AC voltage to a DC link. At the end of this link, an output power electronic inverter controls the power flow over the AC transmission network. Another layout is also possible when the power generated by every wind turbine is rectified and connected to the DC bus using a DC/DC converter.

As considered in [61], a wind park with HVDC connection to the AC network results in a flexible installation, with the capability to control the active and reactive power in a wide range. The four-quadrant controllability of HVDC is similar to an electrical machine without inertia, but improving system dynamics. However, there are some limitations over the amount of the active and reactive power to be injected. From the AC transmission network point of view, the main limitation is the impedance, seen from the point of the common coupling where the

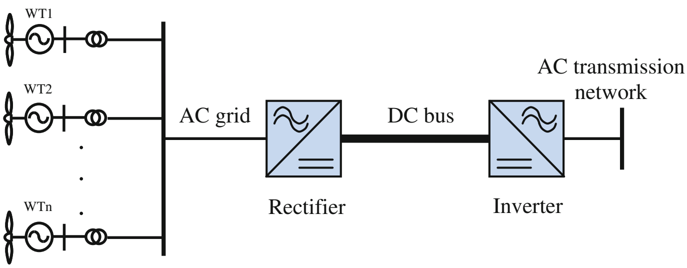

Fig. 23 HVDC wind park layout

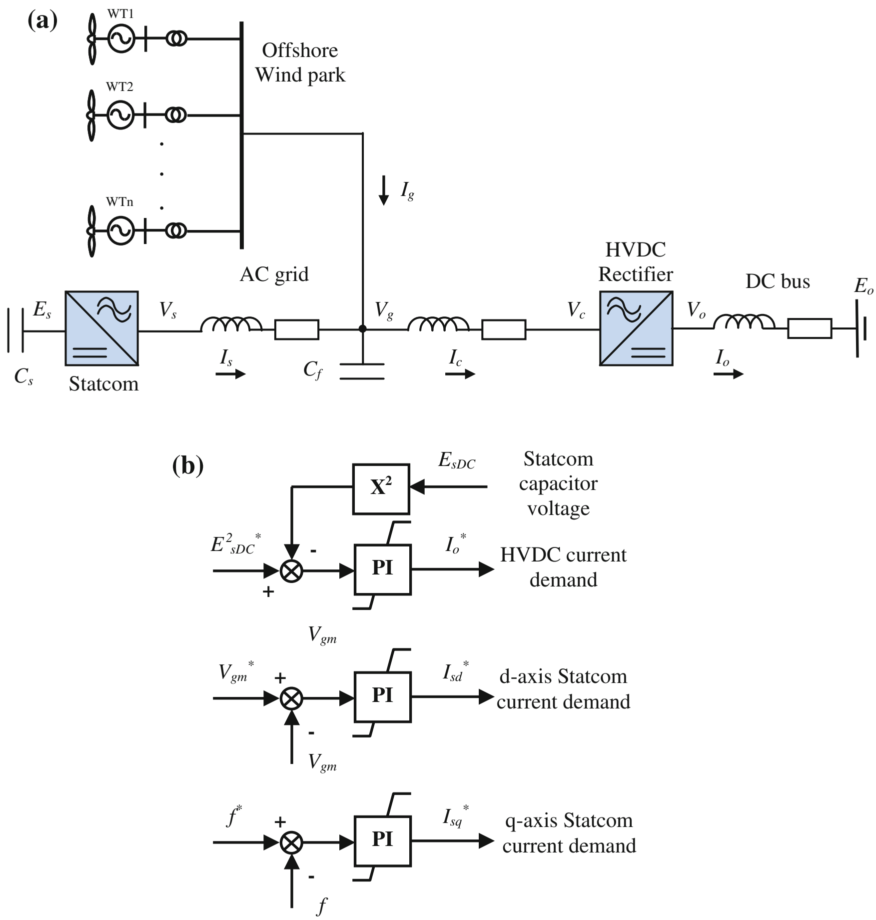

Fig. 24 **a** Simplified scheme, and **b** control structure of the system studied in [8]

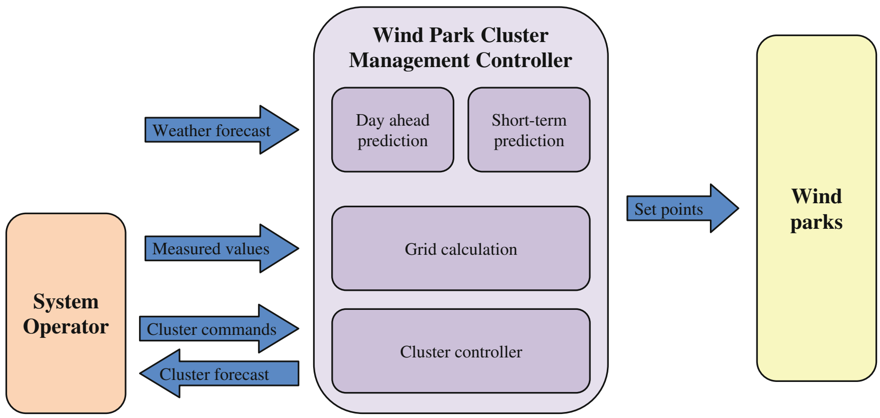

Fig. 25 Modular structures of a Wind Park Cluster Management System

wind park is installed, because, with high grid impedance, less full-regulation area of the voltage is feasible.

Bozhko et al [8] study the grid integration of large offshore DFIG wind parks with a common collection bus controlled by a STATCOM. Figure 24a shows a simplified scheme of the system to be controlled in order to regulate the voltage and frequency of the offshore AC bus, while the power flow is regulated controlling the DC bus. In this scheme, the capacitive filters compensate for the HVDC converter reactive absorption in lumped amounts, while the STATCOM provides fine reactive power control and commutation voltage during disturbances, in collaboration with the DFIG wind turbines. It can be seen in Fig. 24b the basic control structure of the system, where the DC bus current demand (I_o^*) is derived from the dc-link STATCOM voltage controller, while the *dq*-axis current demands (I_{sd}^*, I_{sq}^*) are derived from the grid voltage vector controllers (V_{gm}^*, f^*). The controlled plant is shown to be a third-order system linearized about the operating rectified firing angle, and decoupled through the use of appropriate feed forward terms.

An evolution of the WPMC can be found in [63], an initiative supported by the European Union and focused on preparation of the European electricity network for the large-scale integration of wind parks through the design, development and validation of new tools and devices for its planning, control and operation in a competitive market. This consortium has created a new concept: the Wind Park Cluster Management System (WCMS). The WCMS consists of the implementation of advanced techniques and control strategies, combined with high-tech wind energy technologies, to provide the system operators the needed tools to control and manipulate wind energy as a conventional power source by a logical aggregating (cluster) of existing wind parks, which are connected to a certain grid node.

One of the main characteristics of the WCMS architecture is to consider the existence of different companies, with different aims and business issues, relations between them and needs concerning a reliable wind energy management. In fact, some grid codes have included in their requirements that, when several wind parks are connected in a PCC of the transmission network, there must be an intermediate between the Transmission System Operator (TSO) and the wind parks owners. Thus, WCMS considers two operation layers:

- The TSO layer, who is mainly responsible for grid security issues, and
- The dispatch centres of the companies, which are in charge of the relation between the wind parks and the TSO.

In normal conditions, the TSO sends set points to all the dispatch centres, which are controlling all wind parks of a cluster. It is also required that the information data flows in the opposite way, so that the TSO receives all available power production data of the controlled wind parks into the cluster, in order to know in real-time the operational status of the cluster. Figure 25 describes the WCMS modular structure.

The WCMS includes a grid calculation module which calculates the required power flow of the cluster grid model in order to determine the capability of active and reactive powers at the PCC of the cluster. In addition, the dispatch set points for the wind parks are calculated in this module. Furthermore, the WCMS grid calculation module allows the development of a reactive power management tool to control not only the reactive power, but the power factor and voltage changes caused by wind power generation.

To achieve the controllability of wind power at a transmission cluster level, it is necessary to determine the capability of active and reactive power (P/Q availability) at this point. The active power capability is determined based upon the technical capabilities of the wind turbines within the cluster. The reactive power capability is described through the P/Q characteristic of every wind turbine. Once the P/Q profile of the wind park level is determined, it is necessary to perform grid calculations in order to determine the active losses and reactive power consumption of the wind park grid, and obtain the P/Q capability at the cluster level. Based upon this information, grid operators are able to perform internal grid calculation to set the active and reactive power requirements of the cluster for the next time interval.

Once the set points from the TSO are issued and they lies within the forecasted P/Q capabilities, the WCMS must perform a dispatch calculation procedure to obtain the clusters active and reactive power set points in agree with technical requirements and capabilities.

4 Wind Parks with Special Devices for Enhancing Their Impact into the Grid

Normally, wind power plants have less rated power than the conventional ones [7], and thus, they supply only a fraction of the total power demand, taking part of the called Distributed Generation (DG) of the power system. In some countries, penetration levels of DG have increased in the last years not only to reduce CO_2

emissions but also an interesting economic alternative in areas with appropriate wind resources [3]. Thus, the impact on the grids become more significant, that has conducted to more severe network requirements.

The problems and constrains encountered when a wind power plant is connected to the grid are similar to the one of the conventional power plants, plus those related to the stochastic nature of wind:

- *Grid Capacity Constraints* Such as steady state thermal constraints and network congestion, short-circuit powers and currents or steady state voltage profile [7].
- *Power Quality Issues* [27] Voltage fluctuations and flicker respect to impact on voltage quality, harmonics emitted by power electronic converters and disturbances of remote control signals [38].
- *Protection Issues:* Sensitivity and selectivity of the protection scheme.
- *Dynamic behaviour and stability* [11]: Capability to be able to ride through voltage dips or faults.
- *Ancillary Services Issues* [53] Voltage control-reactive power compensation and power fluctuations-frequency control.

Some of these problems are typical of weak grids, and the solutions are simple but often expensive grid reinforcement. Nevertheless some constrains require system flexibility and application of monitoring and control systems, and depends on the wind park capabilities, with the agreement of the network operators.

Wind park capabilities depend directly on wind turbines [33], so that challenges in grid requirements have forced the development trends of wind generator systems. The simply and robust fixed speed wind turbine known as the "Danish concept" is clearly in decreasing [23]. Today, variable speed concepts, where the power electronics play an important role, are widely used. DFIG wind turbines with partial-scale power converter and direct-drive PMSG wind turbines with a full-scale power converter are the most used technologies, since they enhance performance and controllability but with interaction in power quality [53]. Thus, the main characteristics of fixed speed wind turbines are [7]:

- Very simple and robust.
- Lack of power control possibilities.
- Large mechanical loads.
- Large fluctuations in output power.

On the other hand, variable speed wind turbines present power electronic converters, typically a full back-to-back converter, which increases wind turbine features:

- Higher rotor energy efficiencies due to that optimal rotor speed can be achieved for each wind speed.
- Reduction of mechanical loads.
- Controllability of active and reactive power.
- Fewer fluctuations in output power.

In spite of these advantages, the availability of the wind speed and its fluctuations are the main disadvantages of wind power generation [30].

When wind power penetration is high, wind parks must participate to maintain the short term balance, sharing frequency control participation between different generation units. Decrease output power is relatively easy switching on and off the wind turbines in the wind park and, in case of variable speed wind turbines, controlling power electronic converters. On the other hand, increase output power needs a reserve that can be used when necessary, decreasing maximum power generation to achieve controllability.

Long term balancing is very limited in wind parks due to wind speed dependence. Therefore, there must always be other means available for assuring the long term balance, such as conventional generator, electricity storage or controllable loads [3].

Voltage control capabilities of wind parks depend on the wind turbine technology. Thus, fixed speed wind parks cannot be used to control voltages nodes unless they are equipped with special devices. Variable speed wind parks can control reactive power generation by means of the power electronic converters connected to the wind turbines and taking part in voltage control at the connection points across a suitable control strategy between the different wind turbines of the park. For this reason, converter sizing is one of the priority factors when voltage control capability is desired.

4.1 Special Devices for Enhancing Reactive Control Capabilities of Wind Parks

The special devices required at the grid connection points by fixed speed wind parks or, in some circumstances, by variable speed wind parks, to satisfy voltage control capabilities are based on different compensator capacitor technologies.

4.1.1 Thyristor-Switched Capacitor

As shown in Fig. 26, Thyristor-Switched Capacitor (TSC) circuit consisting of capacitors and reactors switched on the network by solid state power electronics that are fired at the natural zero crossing of the capacitive current. As a result, capacitors are connected to the network without transients. The control is such that, only complete alternations of the current are allowed, ensuring that no harmonics are generated [1].

4.1.2 Static VAr Compensator

As can be seen in Fig. 27, basic SVC approach is based on conventional capacitor banks together with parallel thyristor controlled reactor branches, which consume the excess of reactive power generated by the capacitor bank. In the grid

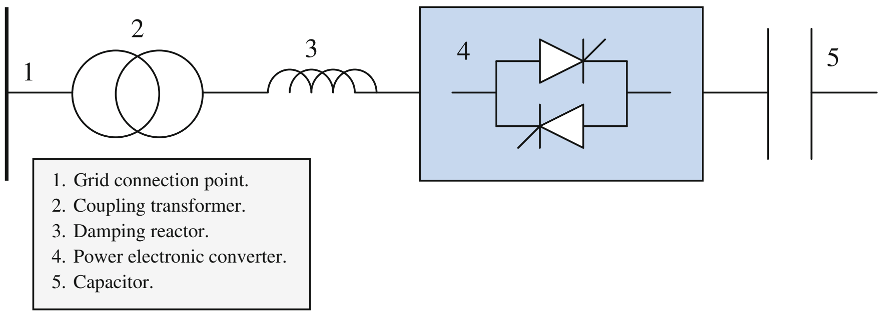

Fig. 26 TSC building blocks

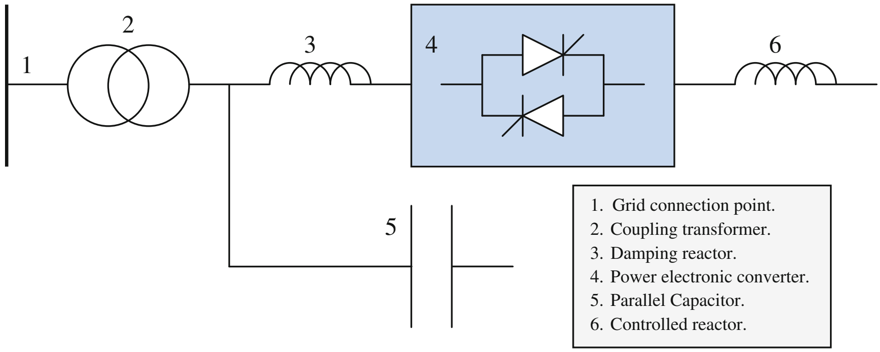

Fig. 27 SVC building blocks

connection point, a centralized SVC provides the necessary balance of reactive power and controls the voltage, making it possible to transmit the desired power levels. It is preferred to use some kind of regulating scheme continuously controlling the reactive power injection in the power grid as a function of the active power generated [12].

As much in TCS as in SVC, the power electronic converter consists of a Thyristor Switched Capacitors (TSC) or Thyristor Switched Reactances (TCR). The coordinated control of these branches varies the reactive power following the curve shown in Fig. 28.

For a sinusoidal voltage, the expression of the fundamental frequency current can be found by using Fourier analysis:

$$I_{SVC} = j\frac{V}{X_c \cdot X_L}\left\{X_L - \frac{X_c}{\pi}[2(\pi - \alpha) + \sin 2\alpha]\right\} \quad (5)$$

where X_c and X_L are de SVC reactances, and α is the firing angle of the semiconductors components.

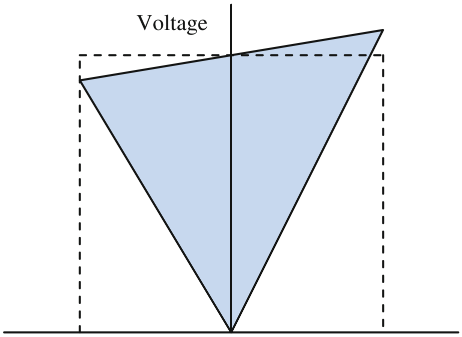

Fig. 28 Reactive current versus voltage of an SVC

4.1.3 STATic Synchronous COMpensator

A STATCOM is a voltage source converter (VSC) based device, with the voltage source behind a reactor (Fig. 29). The voltage source is created from a DC capacitor. STATCOM provides outstanding performance not only in steady state operation as in dynamic voltage control and behaviour during grid faults, adding functionality to wind parks behaviour in order to integrate them into grids with demanded connection requirements.

Figure 30 shows the reactive current versus connected voltage of a STATCOM. The performance is similar to a SVCm, but it performs smooth variation of reactive current across its operating range.

4.1.4 Simulations of a Fixed Speed Wind Park with Special Devices for Enhancing Reactive Power

A small fixed speed wind park of 9 MW is considered in this case. As can be seen in Fig. 31a, the wind park is composed of three 3 MW with an internal cluster structure connected of 25/120 kV transformer that exports the generating power to the grid through a 25 km feeder. Figure 31b presents the impedances of the equivalent circuit of the park. In this figure, Z_{lmi} is the short-circuit impedance of one of the 4 MVA low/medium voltage transformers; Z_{mi} represents the internal medium voltage line to the internal common coupling point; Z_m and Z_{mh} are the feeder and the transformer impedances. For this wind park, two FACTS devices, a 3 MVAr SVC and a 3 MVAr STATCOM with the same operating limits, are simulated.

Figure 32 depicts the behaviour of the wind park when the FACTS devices are demanded to operate at 3 MVAr (rated power) or generate only 1 MVAr. The wind speed applied to each wind turbine is set at 8 m/s, above the nominal wind speed (9 m/s) and a gust of wind is applied to the first turbine after 5 s to reach 11 m/s after 1.5 s. The same gust of wind is considered in the others wind turbines with 5 and 10 s delays.

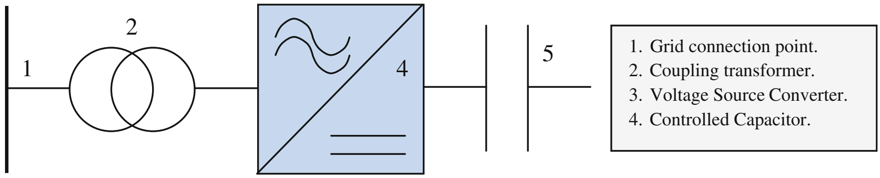

Fig. 29 Statcom building blocks

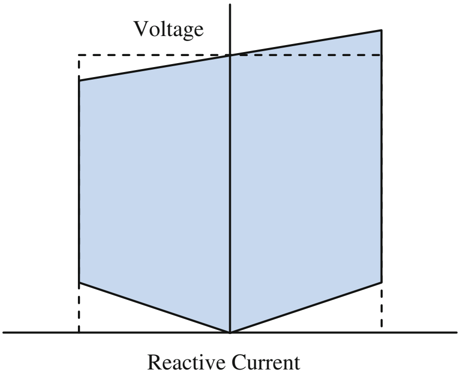

Fig. 30 Reactive current versus voltage of a STATCOM

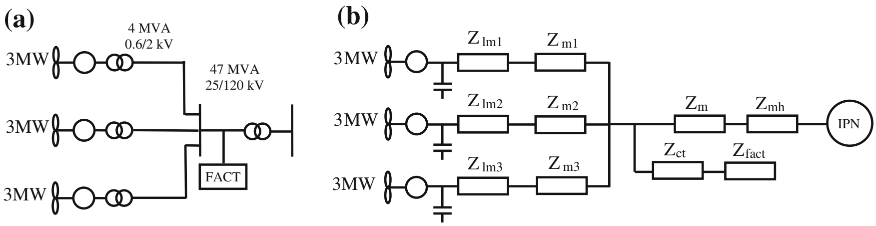

Fig. 31 A 9 MW fixed speed wind park with FACTS: **a** structure, **b** equivalent circuit of the internal network

The responses of both devices are similar because only requirement is to provide the specified reactive power. As the capacitor bank, in each wind turbine, compensate a fraction of the generator requirements (400 kVAr), the wind park consumes reactive power without FACTS device (consumer criterion). When they are working at rated power, the reactive power is less than zero (reactive power generation). The bus voltage at the wind park PCC reflects the dependence showed in Sect. 3.2, and thus, a reactive power consumption increase causes greater voltage drops. As seen in Fig. 32b, the FACTS devices do not affect active power generation.

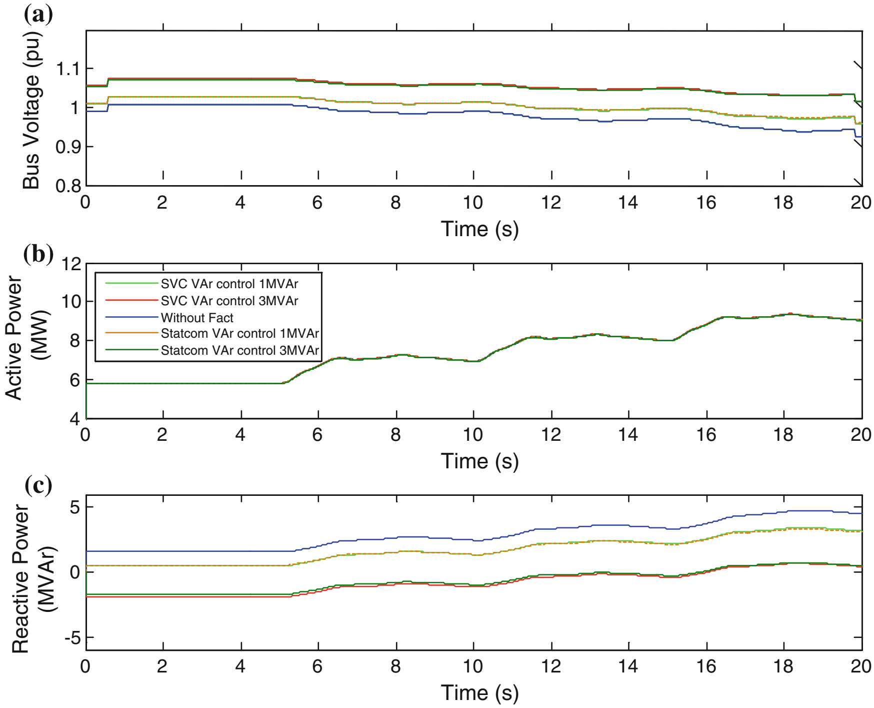

Fig. 32 Response of the fixed speed wind park with SVC and STATCOM in case of reactive power control

Figure 33 depicts the behaviour of the wind park under the same incoming wind but with a different control law in the FACTS devices. In this case, the STATCOM device is trying to maintain voltage bus level at 1 p.u., with a slope in the V–I characteristics of 0.03 p.u.

After the third wind gust at 15 s, all the wind turbines are above nominal wind speed and the wind parks needs over 4 MVAr, while the bus voltage level falls to 0.92 p.u. When the STATCOM is connected, it supplies the reactive power that the wind park demands and the bus level remains over 0.98 p.u.

4.2 Special Devices for Enhancing Power Quality of Wind Parks

Besides maintaining acceptable steady state levels and voltage profiles in all operating conditions exchanging reactive power with the grid, a fast control of this reactive compensation is required to relax possible voltage stability constrains related to the wind park [53].

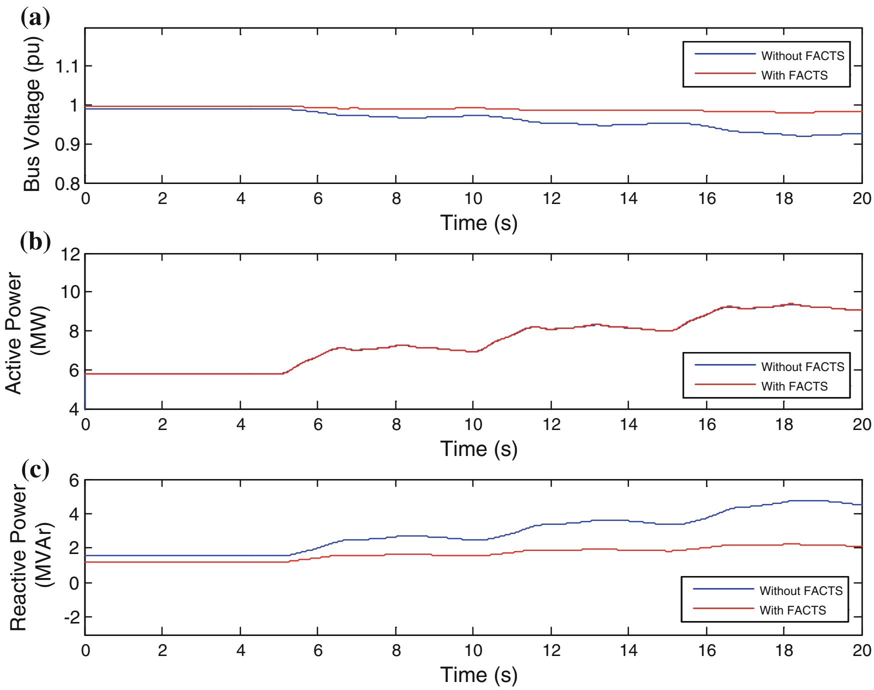

Fig. 33 Response of the fixed speed wind park with STATCOM in case of voltage control

In transient stability, grid codes have specified that wind parks have to be able to cope with grid disturbances without disconnection and they should supply active and reactive power after the fault has been cleared [6]. This implies that wind turbines must be able to 'ride through' temporary faults and contribute to the provision of short-circuit capacity. In this case, if the generation system of the wind turbine is composed of an induction generator, the risk of voltage collapse is important because this type of generator consumes large amounts of reactive power when its speed slightly deviates from the synchronous speed and fast support of reactive power is required [21]. Special devices used to address issues related to voltage control capabilities (control and stability), such as TSC, SVC and STATCOM, are not fast enough to solve satisfactory transient stability and power quality functions. In these cases, Distribution-STATic synchronous COMpensator (D-STATCOM) and Dynamic Voltage Restorer (DVR), that are composed of power electronic converters based on Voltage source converter (VSI), provide as much as power control as power quality functions [6].

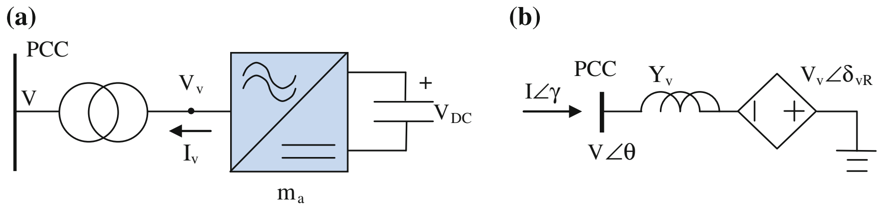

Fig. 34 D-STATCOM system: **a** VSC connected to the AC network via a shunt-connected transformer, **b** shunt solid-state voltage source

4.2.1 Distribution-STATic Synchronous COMpensator

The D-STATCOM configuration consists on a Current Source Inverter (CSI), a DC-energy storage device, a coupling transformer connected in shunt with the PCC at the wind park terminals and associated control systems [6].

A schematic representation of a D-STATCOM and its equivalent circuit are shown in Fig. 34. The equivalent circuit corresponds to the Thevenin equivalent as seen from bus, where the voltage source V_v is the fundamental frequency component of the VSC output voltage, resulting from the product of capacitor voltage (V_{DC}) and amplitude modulation ratio (m_a). Thus, the D-STATCOM is represented as a variable voltage source V_v, whose magnitude and phase angle may be adjusted, by using a suitable iterative algorithm, to satisfy a specified voltage magnitude at the point of connection with the AC network [2].

4.2.2 Dynamic Voltage Restorer

The DVR contains a three phase voltage-source inverters (VSI) with three single phase series transformer, a passive filter and an energy storage device. It can mitigate voltage dip and restore distorted voltage signal at the PCC of the wind park [59].

The DVR injects voltage in quadrature with one of the line end voltages, in order to regulate active power without drawing reactive power from the grid. It has its own reactive power provision from the capacitor, enabling the regulation of reactive power and nodal voltage magnitude. A schematic representation of the DVR and its equivalent circuit are shown in Fig. 35, where the series voltage source is a function of the capacitor rating and the phase quantities. The magnitude and phase angle of the DVR model are adjusted by using suitable iterative algorithm to satisfy a specified active and reactive power flow across the DVR.

4.2.3 Unified Power Flow Conditioner

A D-STATCOM and a DVR may be combined sharing a common capacitor on their DC side and a unified control system. A simplified representation of the Unified Power Flow Conditioner (UPFC) is shown in Fig. 36a, and its equivalent circuit in Fig. 36b, as can be seen in [2].

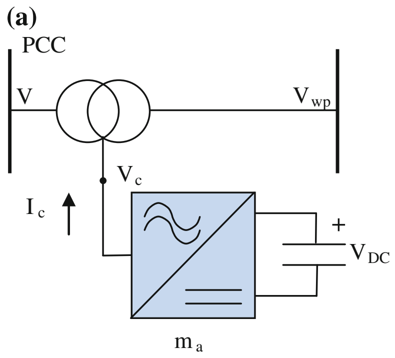

Fig. 35 DVR system: **a** VSC connected to the AC network using a series transformer, **b** series solid-state voltage source

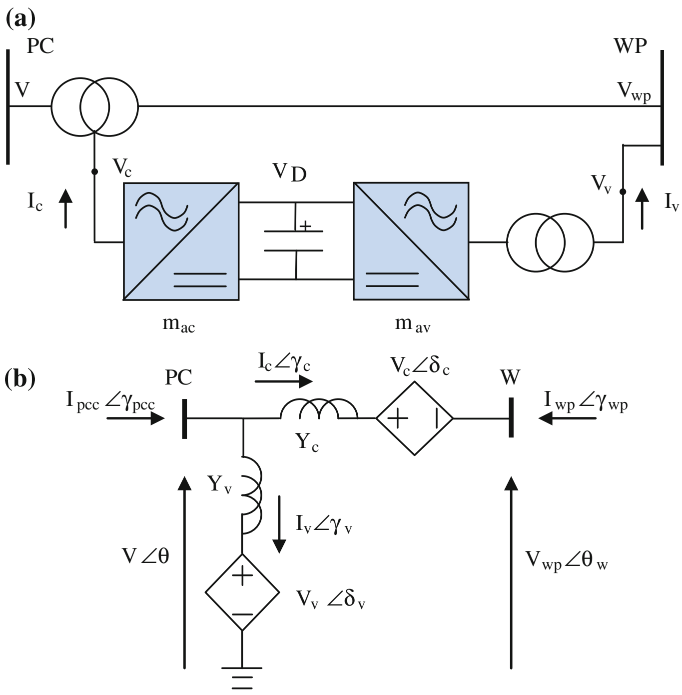

Fig. 36 UPFC system: **a** Simplified representation; **b** Equivalent circuit

The equivalent circuit shown in Fig. 36b consists of a shunt and a series VSI connected to the system through inductive reactances representing the VSC transformers. The constraint equation which links the VSI can be expressed as:

$$Re\{V_v.I_v^* + V_c.I_c^*\} = 0. \tag{6}$$

Thus, the transfer admittance equation can be written as:

$$\begin{bmatrix} I_{pcc} \\ I_{wp} \end{bmatrix} = \begin{bmatrix} (Y_c + Y_v) & -Y_c & -Y_c & -Y_v \\ -Y_c & Y_c & Y_c & 0 \end{bmatrix} \begin{bmatrix} V \\ V_{wp} \\ V_c \\ V_v \end{bmatrix}. \tag{7}$$

The UPFC allows simultaneous control of active, reactive power flow, and voltage magnitude at the UPFC terminals. Alternatively, the controller may be set to control one or more of these parameters in any combination or to control none of them.

4.2.4 High-Voltage Direct-Current Based on Voltage Source Converters

High-Voltage Direct-Current based on Voltage Source Converters (HVDC-SVC) is composed of two VSCs connected back-to back or link together by a DC cable, one operating as a rectifier and the other as an inverter. Its main function is to transmit constant DC power from one to another VSC with high controllability. A simplified representation of the HVDC-SVC is shown in Fig. 37a, and its equivalent circuit in Fig. 37b, as can be seen in [2].

The equivalent circuit showed in Fig. 37 consists of shunt-connected VSI linked together by the following active power constraint equation and transfer admittance equation:

$$Re\{V_{v1}.I_{v1}^* + V_{v2}.I_{v2}^*\} = 0 \tag{8}$$

$$\begin{bmatrix} I_{pcc} \\ I_{wp} \end{bmatrix} = \begin{bmatrix} Y_{v1} & -Y_{v1} & 0 & 0 \\ 0 & 0 & Y_{v2} & -Y_{v2} \end{bmatrix} \begin{bmatrix} V \\ V_{v1} \\ V_{wp} \\ V_{v2} \end{bmatrix}. \tag{9}$$

Besides active and reactive power flow control, voltage control capabilities and transient stabilities, these devices allow power quality enhancement in case of other different disturbances such as harmonics, interharmonics, long and short interruptions, overvoltages, etc. [25]. This group of devices, used for enhancing power quality is called Custom Power Systems (CUPS) if there are used in the distribution level (up to 60 kV) and Flexible AC Transmission Systems (FACTS) if the devices are use on transmission level [60].

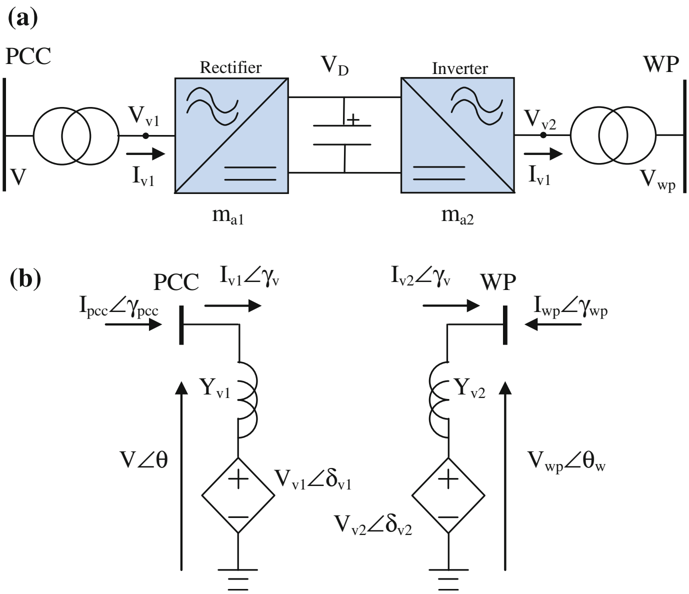

Fig. 37 HVDC-VSC system: **a** Simplified representation, **b** Equivalent circuit

4.2.5 Simulations of a Fixed Speed Wind Park with Special Device for Enhance Power Quality

In this case, a 3 MVA DVR is connected in series at the PCC of the fixed speed wind park showed in Fig. 31. The injected voltage at the wind park bus is limited to 0.3 pu and a maximum change rate of the voltage reference of 3 pu/s.

Figure 38 depicts the comparison between the responses of wind parks with and without DVR. In both cases, all the wind turbines are operating at nominal wind speed (9 m/s), so that the wind park generates about 8.5 MW and consumes over 3.8 MVAr, if the DVR is disconnected. When the VDR is connected, three different references have been applied:

- From 0 to 5 s, the quadrature voltage reference of the DVR control is set to 0, and the DVR upstream and downstream voltages are very close, since the difference is the internal drop voltage.
- From 5 to 10 s, the DVR quadrature voltage reference is increased to 0.2, and thus, the DVR upstream voltage is 1 p.u., while the downstream voltage reaches 1.05 p.u..
- From 10 to 15 s, the reference voltage is set to 0.28. In this case, the wind park achieves a voltage of 1.07 and 1.016 p.u. at the beginning of the feeder.
- At last, the reference voltage is set to 0.1, and then, both voltages decrease to 1.01 and 0.98, respectively.

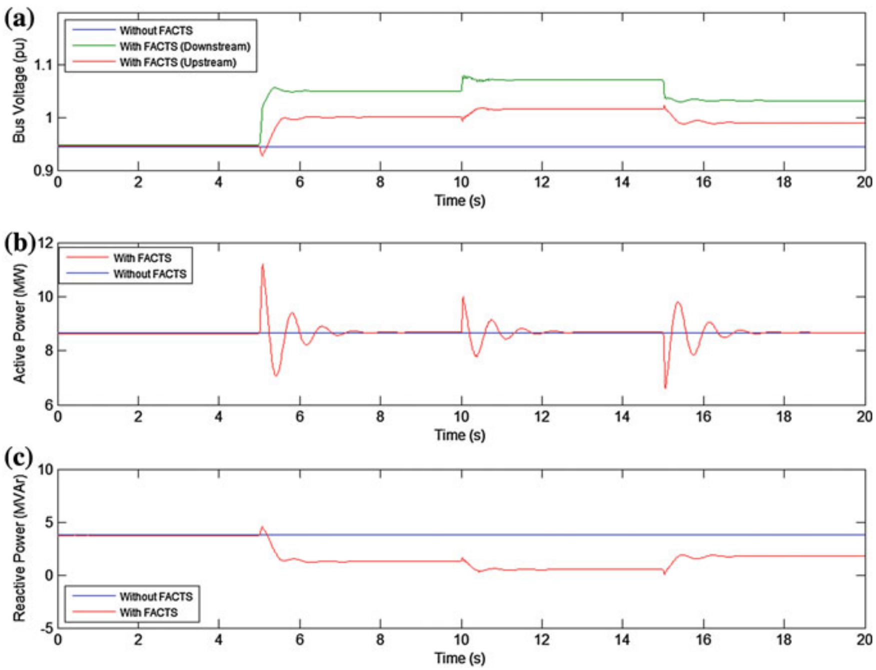

Fig. 38 Response of the fixed speed wind park with VDR in case of voltage reference changes

The DVR device is also tested during a grid disturbance. In this case, it is considered a voltage drop of 0.3 p.u. at 10 s with duration of 400 ms, and after the fault, the voltage starts to recover. As the grid disturbances are much faster than a wind speed fluctuation, the wind speed is assumed constant. Figure 39 shows the wind park response in two cases: when the DVR is bypassed and when it is controlling the injected voltage, setting its reference at 0.28 p.u. while the fault occurs.

The voltage injected by the DVR in quadrature with the line voltage (at the beginning of the feeder) allows increasing the voltage at the PCC of the wind park, while the drop voltage occurs and thus, a faster voltage recovering. During the fault, the DVR tries to regulate the active power, increasing during the first part of the drop and decreasing in the second part. Meanwhile the device provides reactive power (consumer criterion), as can be seen in Fig. 39.

Figure 40 depicts the behaviour of the DVR during the voltage drop. In Fig. 40a, it is shown the device upstream and downstream voltages. The difference between the two voltages is due to the injected voltage by the DVR, as seen in Fig. 40b. The reactive power injected by the device to the wind park is shown in Fig. 40c. In this case, only when the voltage drops occurs the device injects reactive power.

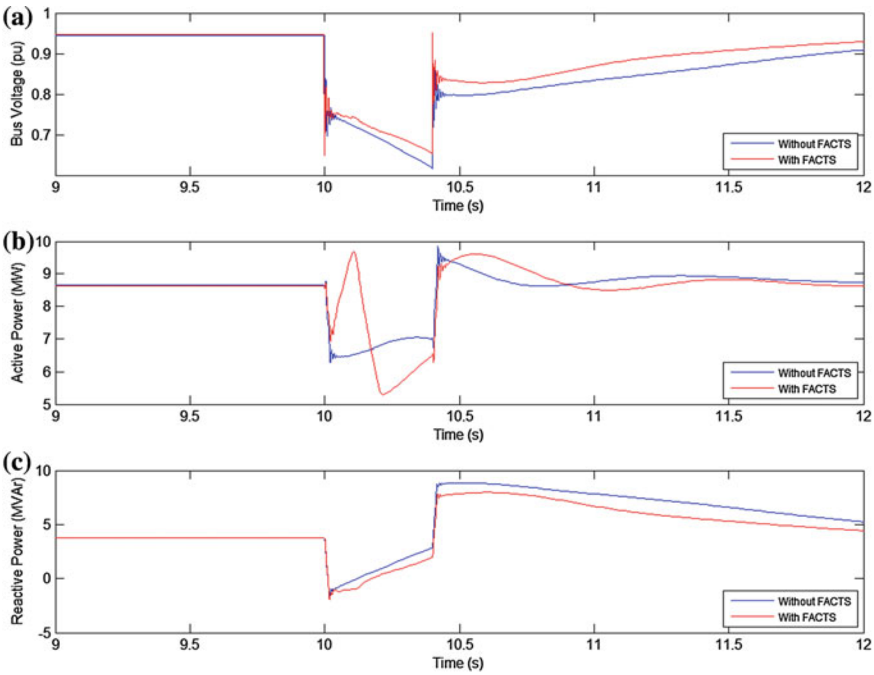

Fig. 39 Response of the fixed speed wind park with VDR in case of grid fault

4.3 Energy Storage Systems for Enhancing Power Quality of Wind Parks

Another way to improve low power quality of wind power is to use energy storage systems. They avoid short-term fluctuations and allow the perfect adjust of the demanding and generating curves, because they store energy surpluses when produced, and then release when the demanding level exceeds production. Voltage stability is also affected, because they help to minimize the peaks and sags that can appear in the grid. Furthermore, the existence of a proper storage system reduces the necessity of power plants in reserve, covering the demand peaks with the stored energy.

The technology in the field of energy storage systems is wide and varied. A huge range of devices has been developed in order to improve the capacity and efficiency of the already existing. Of all the numerous types of energy storage systems, the most important devices in the wind power generation field are [22]:

- *Batteries* The most important feature is the independence between the power and energy values. There are different types of batteries, from the classic lead acid to flow batteries, whose commercial application has not been achieved yet.

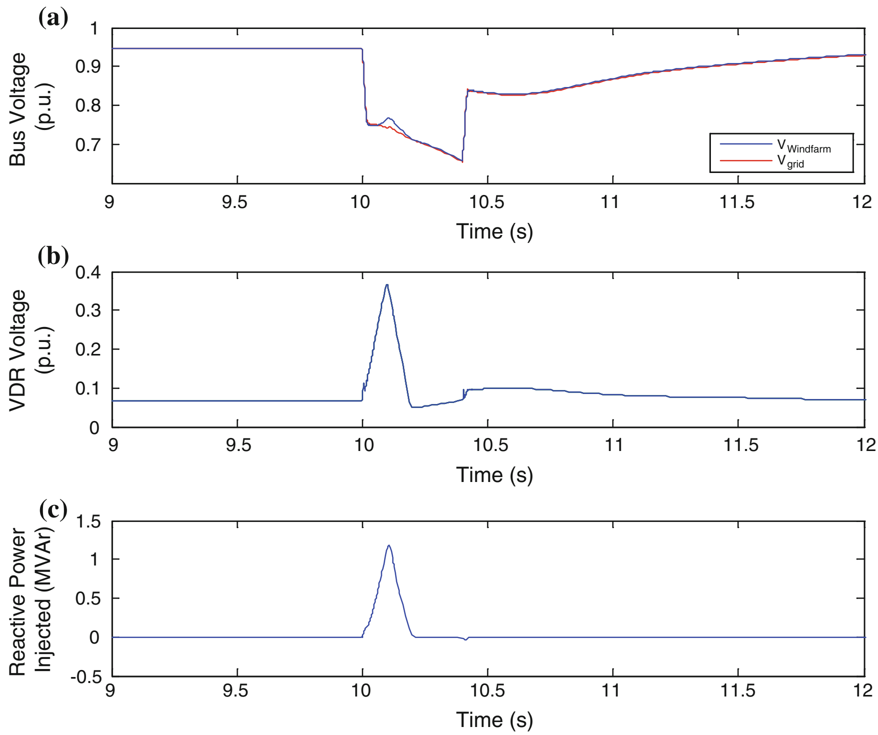

Fig. 40 Response of the VDR in case of grid fault

- *Supercapacitors* They store energy through the conservation of an electric field between two electrically conducting plates. They have several great advantages, however they are relatively new and expensive, but they are very promising devices for application in a near future.
- *Flywheels* They store electric energy as kinetic energy in a rotating mass. They have found interest as load levelling devices acting together with wind energy systems.
- *Superconducting magnetic energy storage systems (SMES)* These devices store electric energy in a magnetic field generated by a DC current flowing through a superconducting magnetic coil. They present high efficiency and no moving part. However, the main drawback is related to their high costs.
- *Fuel cells (FC)* They can act as an energy barrier and adjust power output effectively [62].
- *Hydrogen production* It is considered one of the most attractive energetic alternatives in the near future. As a result, a number of researchers are working on the development of new producing and storing possibilities. At the same time, the currently existing hydrogen storage technologies are progressing in their efficiency and capabilities.

4.3.1 Simulations of a DFIG Wind Turbine with Energy Storage System

A variable speed wind turbine integrating a battery is considered to evaluate the behaviour of a wind park with energy storage system. Figure 41a depicts the proposed structure: a 1.5 MW DFIG wind turbine connected to a battery with DC/AC inverter as energy storage system. The whole system is connected to a 30 km feeder and a 25/120 kV transformer that evacuate the generated power. Figure 41 b shows the impedances of the equivalent circuit, where Z_{lm} is the short-circuit impedance of the 1.75 MVA low/medium voltage transformer; Z_m represents the internal medium voltage line to the internal common coupling point; while Z_f and Z_{mh} are the feeder and the medium/high voltage transformer impedances.

The hybrid generation system (DFIG wind turbine with battery) and its control system are modeled and simulated as performed in [45]. The only difference is that the battery is located outside the wind turbine and connected to the 25 kV line by means of a DC/AC inverter. A supervisory control system based on a state machine control strategy is responsible for setting the battery power reference depending on the battery State of Charge (SOC) and the operating conditions.

In the performed simulation, a constant wind speed of 14 m/s is considered. The active power demanded by the grid is set to 0.8 p.u. during the first 60 s, and it is changed to 1.2 p.u. for the rest of the simulation. At the same time, the reactive power is controlled to unity power factor until 90 s, and then, it is increased up to 0.1 p.u. (consumer criterion) with a rising slope of 0.1 p.u./s. In this case, the control system maintains the reactive power consumed by the wind turbine at 0 p.u., while the battery inverter is controlled to achieve the desired grid demand.

Figure 42 shows the evolution of active and reactive powers and battery SOC during the simulation. As seen in Fig. 42a, during the first 90 s, the battery stores the surplus energy between the active power reference and the available wind power, increasing the battery SOC from 60 to 61 %. In the rest of the simulation, the active power reference exceeds the available power in the wind turbine, so that the battery supplements that generation to provide the demanded power, which causes the battery discharge (Fig. 42b). The suitable reactive power control is shown in Fig. 42b.

The energy stored in the battery allows maximum wind energy capture even when the power demand is low. It enables the possibility to decouple generation from demand, and optimize the energy. Other variables, such as reactive power and voltage, can be regulated by applying an adequate control strategy. Hence, the inclusion of an energy storage system enhances the wind turbine capabilities, allowing a higher and less fluctuating power output to the grid.

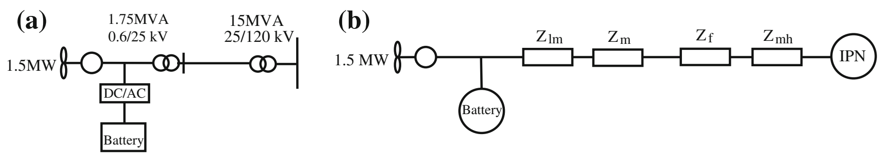

Fig. 41 A 1.5 MW DFIG wind park with battery as energy storage system: **a** structure, **b** equivalent circuit of the internal network

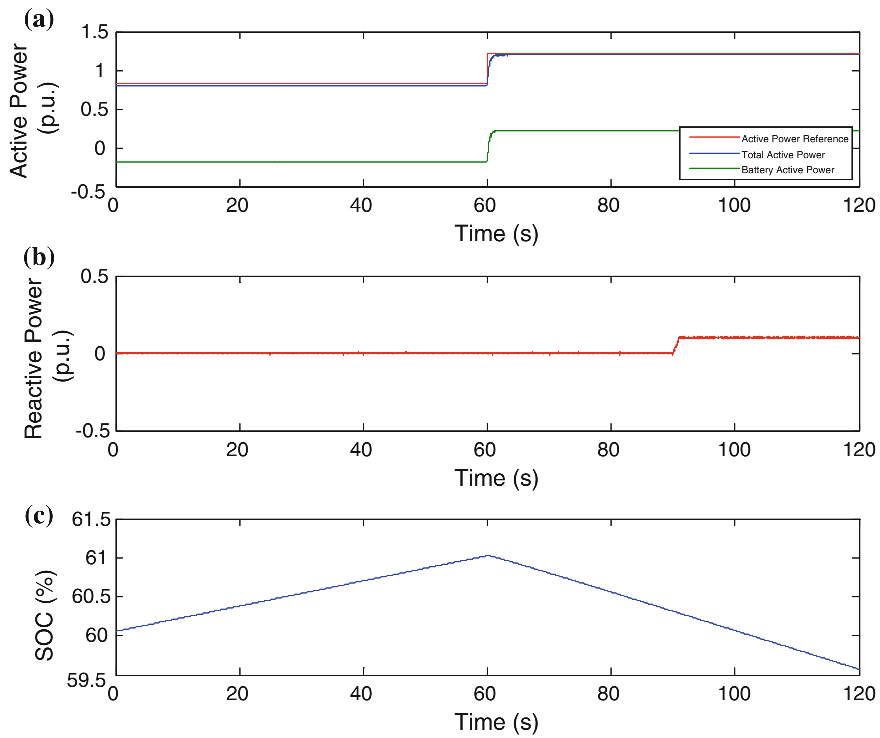

Fig. 42 Response of a 1.5 MW DFIG wind park with battery energy storage

5 Conclusion

This chapter has dealt with some of the main issues related to wind energy penetration and its grid integration, mainly focused on transient stabilities studies. First of all, it is considered the necessity of suitable models to evaluate wind parks dynamic behavior. Thus, when the scope of study is the wind park as a whole power plant, the complexity of the models is reduced by aggregating wind turbines into equivalent models, as usual in transient stability studies in case of wind fluctuations and grid disturbances. These equivalent models are qualified in several groups depending on the wind speed that receives every wind turbine and the types and rated values of the machines that compose the wind park. Secondly, the wind park control is considered, since wind parks are today required to participate in the power system operation like conventional power plants do, assuring stability and quality of the system. The main requirements to assure adequate grid integration are active power and voltage regulations and reactive power and frequency controls. Furthermore, the main controller and the dispatch center are analyzed as the leading components of the control structure. Finally, additional devices are described, such as FACTS or energy storage systems, which can be used in wind parks for improving the power quality, the control capabilities, and thus, the grid integration.

As a result, wind park capabilities are near to the ones of conventional power plants, assuring a great adaptation to grid code requirements and making feasible to integrate wind power to a significant extent without major system changes.

Appendix: Wind Park Models Parameters

(a) **350 kW fixed speed wind turbine**

Rated power: 350 kW, rated voltage: 660 V, $R = 15.2$ m, $H_r = 5$ p.u., gear box ratio: 1:44.5, $K_{mec} = 100$ p.u., $D_{mec} = 10$ p.u., $H_g = 0.5$ p.u., $R_s = 0.006$ p.u., $R'_r = 0.006$ p.u., $X_{\sigma s} = 0.007$ p.u., $X'_{\sigma r} = 0.19$ p.u., $X_m = 2.78$ p.u., $X_c = 2.5$ p.u (Fig. 43).

(b) **500 kW fixed speed wind turbine**

Rated power: 500 kW, rated voltage: 660 V, $R = 28$ m, $H_r = 5$ p.u., gear box ratio: 1:89, $K_{mec} = 200$ p.u., $D_{mec} = 15$ p.u., $H_g = 1$ p.u., $R_s = 0.01$ p.u., $R'_r = 0.01$ p.u., $X_{\sigma s} = 0.01$ p.u., $X'_{\sigma r} = 0.08$ p.u., $X_m = 3$ p.u., $X_c = 2.3$ p.u (Fig. 44).

(c) **660 kW DFIG wind turbine**

Rated power: 660 kW, rated voltage: 660 V, $R = 23.5$ m, $H_r = 0.5$ p.u., gear box ratio: 1:52.5, $K_{mec} = 90$ p.u., $D_{mec} = 15$ p.u., $H_g = 3$ p.u., $R_s = 0.01$ p.u., $R'_r = 0.01$ p.u., $X_{\sigma s} = 0.04$ p.u., $X_{\sigma r}\prime = 0.05$ p.u., $X_m = 2.9$ p.u (Fig. 45).

(d) **1.5 MW DFIG wind turbine**

Rated power: 1.5 MW, rated voltage: 600 V, $R = 41$ m, $H = 4.64$ p.u., $R_s = 0.005$ p.u., $R'_r = 0.004$ p.u., $X_{\sigma s} = 0.125$ p.u., $X'_{\sigma r} = 0.179$ p.u., $X_m = 6.77$ p.u (Fig. 46).

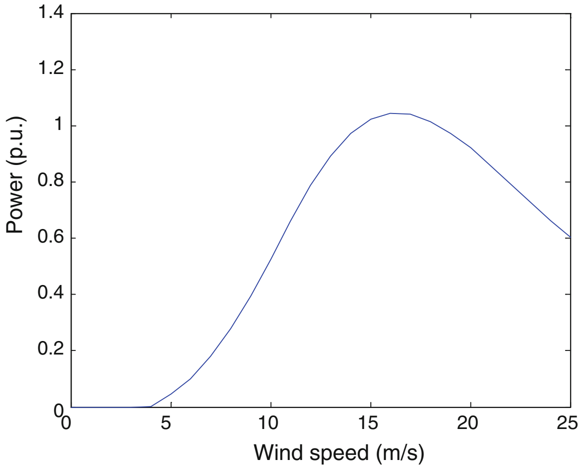

Fig. 43 Power curve of a 350 kW fixed speed wind turbine

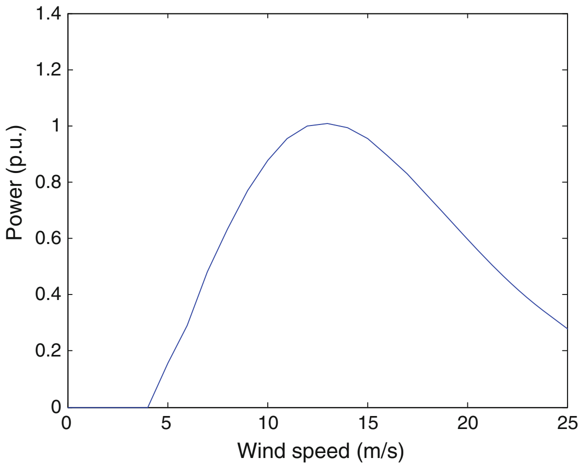

Fig. 44 Power curve of a 500 kW fixed speed wind turbine

(e) **2 MW DFIG wind turbine**

Rated power: 2 MW, rated voltage: 690 V, R = 38 m, $H_r = 0.5$ p.u., gear box ratio: 1:89, $K_{mec} = 95$ p.u., $D_{mec} = 40$ p.u., $H_g = 2.5$ p.u., $R_s = 0.01$ p.u., $R'_r = 0.01$ p.u., $X_{\sigma s} = 0.1$ p.u., $X'_{\sigma r} = 0.08$ p.u., $X_m = 3$ p.u (Fig. 47).

(f) **3 MW fixed speed wind turbine**

Rated power: 3 MW, rated voltage: 600 V, R = 45 m, $H_r = 4.29$ p.u., gear box ratio: 1:89, $K_{mec} = 296$ p.u., $D_{mec} = 15$ p.u., $H_g = 0.90$ p.u., $R_s = 0.003$ p.u., $R'_r = 0.002$ p.u., $X_{\sigma s} = 0.063$ p.u., $X'_{\sigma r} = 0.089$ p.u., $X_m = 3.38$ p.u (Fig. 48).

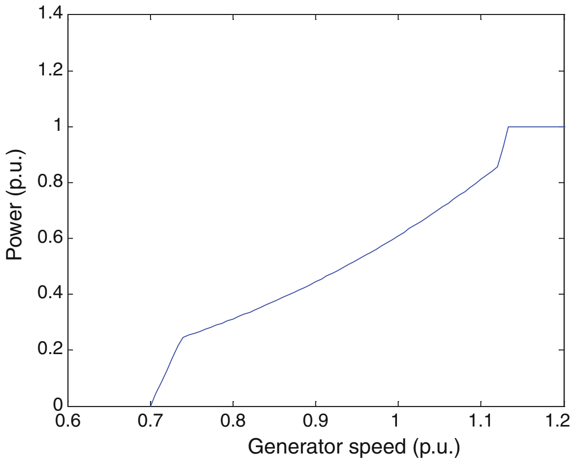

Fig. 45 Power curve of a 660 kW DFIG wind turbine

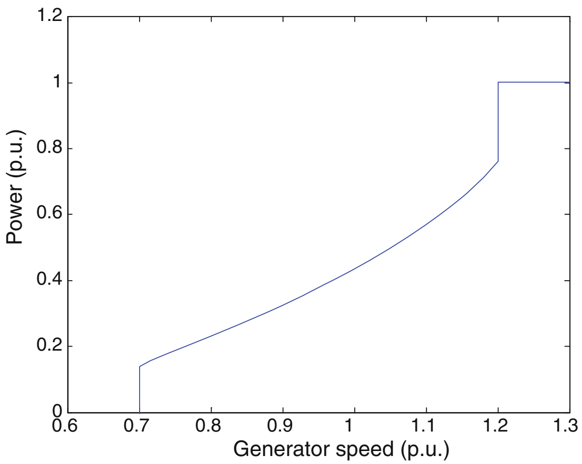

Fig. 46 Power curve of a 1.5 MW DFIG wind turbine

(g) **Electrical network of the fixed speed wind park with 6 wind turbines of 350 kW and 6 wind turbines of 500 kW**

LV lines Cluster 1 (r = 0.4 Ω/km, x = 0.1 Ω/km, length = 200 m); Cluster 2 (r = 0.4 Ω/km, x = 0.1 Ω/km, length = 300 m).
LV/MV transformers Cluster 1 (800 kVA, 20/0.66 kV, ε_{cc} = 6 %); Cluster 2 (1,250 kV, 20/0.66 kV, ε_{cc} = 5 %).
MV lines Cluster 1 (r = 0.15 Ω/km, x = 0.1 Ω/km, length = 500 m); Cluster 2 (r = 0.15 Ω/km, x = 0.1 Ω/km, length = 600 m).
MV/HV transformers (10 MVA, 20/66 kV, ε_{cc} = 8 %).
Feeder (r = 0.2 Ω/km, x = 0.4 Ω/km, length = 10 km).
Grid Short circuit power at PCC = 500 MVA, X/R ratio = 20.

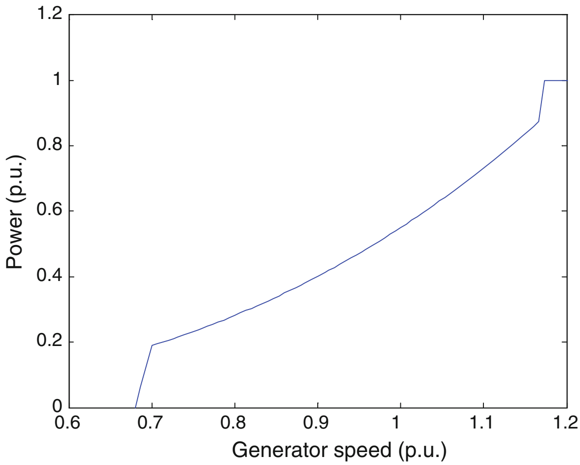

Fig. 47 Power curve of a 2 MW DFIG wind turbine

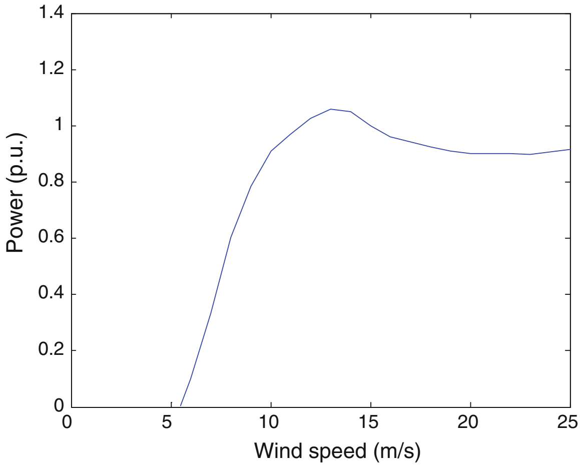

Fig. 48 Power curve of a 3 MW fixed speed wind turbine

(h) Electrical network of the DFIG wind park with 6 wind turbines of 2 MW

LV/MV transformers (2.5 MVA, 20/0.66 kV, $\varepsilon_{cc} = 6\ \%$).
MV lines (r = 0.3 Ω/km, x = 0.1 Ω/km, length = 200 m).
MV cluster lines Cluster 1 (r = 0.15 Ω/km, x = 0.05 Ω/km, length = 1 km); Cluster 2 (r = 0.15 Ω/km, x = 0.1 Ω/km, length = 2 km).
MV/HV transformers (15 MVA, 20/66 kV, $\varepsilon_{cc} = 8.5\ \%$).
Feeder (r = 0.16 Ω/km, x = 0.35 Ω/km, length = 20 km).
Grid Short circuit power at PCC = 500 MVA, X/R ratio = 20.

(i) **Electrical network of the DFIG wind park with 6 wind turbines of 660 kW and 6 wind turbines of 2 MW**

LV/MV transformers Cluster 1 (800 kVA, 20/0.66 kV, $\varepsilon_{cc} = 6$ %); Cluster 2 (2.5 MV, 20/0.66 kV, $\varepsilon_{cc} = 6$ %).
MV lines Cluster 1 (r = 0.3 Ω/km, x = 0.1 Ω/km, length = 200 m); Cluster 2 (r = 0.4 Ω/km, x = 0.1 Ω/km, length = 200 m).
MV cluster lines: Cluster 1 (r = 0.15 Ω/km, x = 0.05 Ω/km, length = 500 km); Cluster 2 (r = 0.15 Ω/km, x = 0.1 Ω/km, length = 2 km).
MV/HV transformers Cluster 1 (4 MVA, 20/66 kV, $\varepsilon_{cc} = 8$ %); Cluster 2 (15 MVA, 20/66 kV, εcc = 8.5 %).
Feeder (r = 0.2 Ω/km, x = 0.4 Ω/km, length = 10 km).
Grid Short circuit power at PCC = 500 MVA, X/R ratio = 20.

(j) **Electrical network of the fixed speed wind park with 3 wind turbines of 3 MW**

LV/MV transformers (4 MVA, 25/0.60 kV, $\varepsilon_{cc} = 7.7$ %).
MV lines (r = 0.115 Ω/km, x = 0.33 Ω/km, length = 1 km).
MV cluster line (r = 0.115 Ω/km, x = 0.33 Ω/km, length = 25 km).
MV/HV transformers (47 MVA, 25/120 kV, $\varepsilon_{cc} = 3.3$ %).
Grid Short circuit power at PCC = 2,500 MVA, X/R ratio = 10.
SVC (3 MVA, 25 kV, $t_{delay} = 4$ ms).
STATCOM (3 MVA, 25 kV, R = 0.007 pu, X = 0.22 pu, $C_{eq} = 1{,}125$ μF).

(k) **Electrical network of the DFIG wind park with 1 wind turbine of 1.5 MW**

LV/MV transformers (1.75 MVA, 25/0.60 kV, $\varepsilon_{cc} = 7.7$ %).
MV line (r = 0.115 Ω/km, x = 0.33 Ω/km, length = 1 km).
MV cluster line (r = 0.115 Ω/km, x = 0.33 Ω/km, length = 30 km).
MV/HV transformers (15 MVA, 25/120 kV, $\varepsilon_{cc} = 6.3$ %).
Grid Short circuit power at PCC = 2,500 MVA, X/R ratio = 10.
Battery (585 Ah, 624 V).

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