Chapter

Provision of Ancillary Services by Wind Power Generators

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Abstract

The current and future power systems foresee very deep penetration of renewable power plants into the generation mix, which will make the provision of ancillary services by renewables an ultimate necessity. This would be further emphasised when green power stations replace conventional power plants that rely on fossil fuels. In this context, many control methodologies could be applied to the controllers of the green generators to enable the provision of these services, mainly frequency support and voltage regulation. Most of the available models (i.e. in power system simulators) do not include such supplementary controls to provide ancillary services. Hence, this chapter exploits key examples of these controllers that proved to be efficient and widely accepted. In addition, this chapter considers their integration into the conventional controls of green generators, where the focus is on wind energy.

Keywords: frequency stability, inertia, reactive compensation, small signal stability

1. Introduction

The European Union has announced the binding objectives of 27–32% of energy to come from renewable energy sources (RES) by 2030, with an associated CO2 emissions reduction target of 40% (relative to 1990) and at least 32.5% increase in energy efficiency following the COP24 (held in Katowice) to keep global warning well below 2°. To do so, some future European energy scenarios even foresee a very high RES penetration close to 100% by 2050. Presently, the most competitive RES technologies are wind and solar photovoltaic (PV) with hydropower pumped storage and small hydropower stations to support this drift.

Common characteristics of RES technologies (except conventional hydropower) are the variability of the primary energy source and the fact that they are typically connected to the power system through power electronic (PE) converters. Therefore, RES power plants are not synchronous and hence do not contribute naturally to system inertia. Moreover, they are not mandated to provide any type of ancillary services (AS)[1], which is still valid given the high share of conventional synchronous power plants in the present power systems. Hence, it is still not clear how the system stability could be maintained with high penetration of non-synchronous RES generation and associated reduced inertia. This is already a challenge in small networks such as that of Ireland, and it is a growing obstacle in larger

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[1] Ancillary services are grid support services required by the power system (transmission or distribution system) operators to maintain integrity, stability and power quality of the power system.

synchronous areas of Europe (e.g. Great Britain, Central and Southern Europe and Nordic countries). Thus, serious economic consequences may result if efficient and cost-effective solutions are not identified and implemented. However, the ambitious plans of achieving very high RES penetration into the installed generation capacities (i.e. retirement of synchronous plant) will require the strong participation of RES plants to support all aspects of power system stability and security of the electricity supply.

To incorporate AS provision from RES plants in an effective manner, a series of design and operation tools must be created to identify the optimal approach to be taken. These tools, and the incorporated benchmark models, must address crucial aspects such as, PE converter interfaces, intelligent controllers, market structures, communications, and overall power system optimised operation, including system health and assets degradation.

The coordination between a wide range of RES plants and the correlated technologies (e.g. high-voltage direct current (HVDC) corridors and energy storage systems (ESS)) must be considered through comprehensive controllers, which dispatch and regulate the contributions of these assets to maintain system stability during normal conditions and severe events. Thereupon, to model, evaluate and validate such scenarios, there is the need for developing comprehensive models of RES generation units that include supplementary controllers to enable these units to provide a wide range of AS. In this context, this chapter presents the main control concepts to provide frequency and voltage support as well as oscillation damping by wind turbines and farms according to the state of the art.

2. Modelling of frequency support

One of the key roles of transmission system operator (TSO) is to maintain the balance between power generation and load demand. However, the ideal balance (i.e. zero deviation) is unrealistic due to the dynamic nature of load, which cannot be fully controlled by the TSO. Hence, there is always an allowed margin of deviation, which reflects to the power system frequency and the associated band of acceptable frequency oscillations (typically 20–30 mHz for a 50 Hz power system) [1].

For the ages of conventional power systems, where synchronous, centralised and fully dispatched generation units dominated, frequency stability has not been a problem. In other words, each generation unit has a defined role, achieved through simple controls (e.g. governors) to maintain frequency stability. This includes fine changes in frequency due to normal load dynamics, major events which could occur due to sudden loss of generation units, or network issues as transmission lines tripping. Such events initiate large deviation between generation and demand leading to severe drops/overshoots in the system frequency. The interconnected generation units have to respond as quickly as possible to these events to curtail the magnitude of the frequency deviation (frequency nadir) and rate of change of frequency (ROCOF) and restore the frequency to the safe 'deadband'. Why? Because if this does not happen, the protection relays operating on these signals will trip, disconnecting the generating units, which would excavate the event and could lead to a total blackout.

Conventional generation responds 'naturally' to any frequency deviation due to the inertia of their rotating parts. In particular, the generation units release some of the stored kinetic energy (KE) in its rotating parts, converting it to electrical energy to tackle the power imbalance (i.e. *inertia response*). The same process occurs in the case of frequency positive deviation, but the unit stores more KE (i.e. the machine accelerates). Typically, thermal power stations have a second defence mechanism, 'speed governor', which regulates the input mechanical power (e.g. from a steam turbine) to maintain the deviation between mechanical shaft speed and the synchronous electrical speed within the deadband. This is called the *primary response*. There is a second control loop, which is effective for small deviations, and it is applied to restore the frequency to the safe deadband that is the *secondary response*. After a sudden change in load, the unit is *re-dispatched* to increase or decrease its generation set point according to the new conditions (i.e. *tertiary response*). In conclusion, the conventional generation unit applies four successive mechanisms to preserve frequency stability by diminishing any incident power imbalance: (1) natural inertia response (within 5 s from the event), (2) primary response (within 30 s from the event), (3) secondary response (within 10 min of the event) and (4) tertiary response (within 1–2 h of the event).

2.1 The widely proposed concepts

The main objective of frequency support (FS) supplementary controllers is to provide and regulate a certain of responsive additional active power during frequency excursions. FS controls usually have two operation modes: normal operation (active when frequency is within safe deadband) and support operation (active during frequency events). At normal operation, the controller has to maintain a predefined amount of power reserve that could be utilised at frequency events, i.e. support operation. However, the KE extraction concept does not apply any special control strategy on the wind turbine in normal operation as explained later. The three main concepts are illustrated in **Figure 1**.

2.1.1 KE extraction

This is the most economic concept from wind farms operators' viewpoint, as it does not violate MPT at normal operation. This method relies on extracting and converting a certain amount of the stored KE in the rotating parts of the wind turbine (WT) and converts it into electrical energy, i.e. active power to tackle frequency drops [2]. This process mimics the natural inertia response of synchronous generators, which are directly connected to the AC grid and not decoupled by the power electronic interface as the case in WTs.

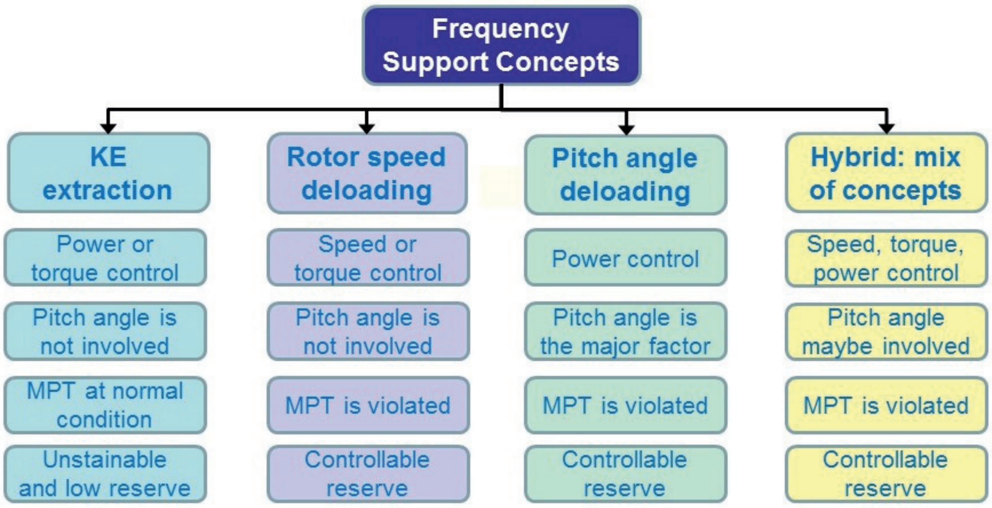


Figure 1.
The main concepts of FS in wind power generation (maximum power tracking (MPT)).

The method could be a high risk to power system stability, as the amount of extractable KE is strongly dependent on the incident wind speed, and usually this amount is rapidly depleted (2–5 s) according to the magnitude of support power and the moment of inertia of the rotating parts, mainly the rotor blades and the generator set.

The widely used control models to equip a WT with this method are focused on an inner control loop of P or PI type where a predefined constant or frequency-dependent power step is applied. Hence, the wind turbine is forced to slow down, as the input harnessed wind energy is less the electrical demand. The controller always suffers several discontinuities due to the applied limiters, e.g. on the allowed WT speed not to drop beyond a certain threshold to avoid WT complete stop. Likewise, when the WT recovers its nominal rotor speed, its output has to be regularly and slightly reduced below the available input aerodynamic energy to ensure a smooth and safe recovery to the nominal speed without major power perturbations.

2.1.2 Pitch angle deloading

This is the most applicable method used by the industry due to its simplicity, as it does not interfere with the main controls of the WT. The pitch angle (β) is the inclination of the WT blade from the axis of the incident wind speed. To harness the maximum possible wind energy, pitch angle should be zero. However, a small non-zero pitch angle would 'deload' the input wind energy to the WT. Hence, in this FS method, an amended set point is fed to the pitch angle controller to reduce the input power to the WT according to the applied deloading approach. There are two types of deloading; the first is when the input power is deloaded by a certain ratio of the available optimum input, i.e. deloading factor is a percentage, and this is called the delta deloading. The second type is to maintain a constant power reserve by reducing the input by a certain magnitude in MW, and this is called balanced deloading [3].

2.1.3 Rotor speed deloading

This method is relatively new compared to the other two concepts. It was mainly proposed to enable consistent deloading of WT output without using pitch angle control. The concept uses a P or PI controller to run the WT at a slightly higher or slower rotor speed than the reference speed produced by MPT technique. This approach has two outcomes: (1) the WT output is slightly deloaded; however, it is challenging to maintain a constant deloading ratio compared to pitch deloading. (2) The amount of extractable KE is influenced. Accordingly, it is preferable from the KE perspective to run the WT at a slightly higher speed; however this is not the favourite option from WT load and fatigue viewpoint [4].

When the WT implements overspeed deloading, at the very early interval of the frequency drop, this method provides frequency support with two components: (1) the extracted KE as the WT slows down towards the optimum rotor speed (i.e. MPT speed) and (2) the margin between the available input power and the deloaded output. However, for some control designs, this process ends up rapidly and leaves the WT without controllable reserve until the event ends, and the WT recovers the normal overspeed operation.

2.1.4 Hybridization of concepts

As expected from the title, many researchers tried to mix two or even three concepts to provide FS by wind power [5–7]. The overall objective of these trials is to avoid the drawbacks of every concept that can be summarised as follows:

- Energy wasting due to continuous deloading [8]
- Excessive mechanical loads due to continuous pitching
- Uncontrollable during the event and very short-lasting support
- Unconfirmed predefined reserve amount

The following example illustrates how the three concepts could be applied.

Example: A double-fed induction generator WT (type 3) has a rated power of 2 MW and speed control range between 0.7 and 1.2 per unit with reference to WT base rotor speed. The WT is equipped with active pitching system (β ranges from 0 to 50°). The WT applies a conventional torque-speed control to track the rotor speed that achieves the maximum power point [9].

The grid operator requires the WT to respond to frequency drops, providing an incremental positive change in its output within 0.5 s from the instant the frequency departs the safe deadband. What are the possible solutions to comply with this requirement?

Possible solutions: As a WT operator, they would need to decide the amount of support and the adopted FS concept (hint: the economic aspect is not considered in this discussion). As the grid operator requirements are so flexible, the *KE extraction* could be a reasonable option such that the WT provides 'something' when the frequency drops. In that case, the amount of reserve is not predefined but relies on the operation conditions of the WT when the frequency events occur. The simplest way to achieve this is to apply an incremental positive change in the reference torque (or power) using Eq. (1):

$$\tau_{ref} = (1 + O_F) \cdot \tau_o \tag{1}$$

where τ_{ref} is the reference torque input to the outer control loop, τ_o is the optimum torque and O_F is the overloading factor, typically 10–15%. This exceptional set point continues as long as the frequency event persists or when the WT reaches its minimum rotor speed (0.7 per unit in the given example).

Alternatively, it could be assumed that WT would provide a constant reserve of 10% of the optimum output; hence the simplest way to achieve this is to apply *pitch angle deloading*, using Eq. (2):

$$P_{ref} = (1 - D_F) \cdot P_o \tag{2}$$

where P_{ref} is the reference power input to the pitch angle controller and D_F is the deloading factor adjusted to 10% and P_o is the optimum output (all values are in per unit). The available reserve is $D_F \cdot P_o$.

Another more sophisticated solution is to maintain a constant reserve of 5% of the WT rated power, i.e. 0.1 MW. This could be achieved using *pitch angle deloading* using Eq. (3):

$$P_{ref} = P_o - \frac{D_M}{P_r} \tag{3}$$

where P_r is the rated power of the WT, namely, 2 MW and the deloading margin (D_M) is 0.1 MW. The available reserve for this approach is D_M.

Both Eqs. (1) and (2) are applied during normal operation, and when frequency violates the safe margin, P_{ref} switches to be equal to P_o; hence the pitch angle is reduced or restored to zero if the incident wind speed is below the rated wind speed of the WT.

The next subsection explains and exploits the modelling and integration of different supplementary controllers.

2.2 Modelling and integration of supplementary controls

The supplementary controllers always act on reference torque or power that are input signals to the power electronics interfacing the WT to the network (see **Figure 2** for a type 3 double-fed induction generator WT). The design of the controller relies on the adopted support method, for example, a pitch deloading controller receives the WT output power as an input and provides the incremental change in the reference power that is fed to the pitch angle controller [10] as shown in **Figure 3**. This would apply an increment change in the actual pitch angle, normally by 2–5°, to deload WT output by a certain margin.

This controller could be integrated into the DFIG library model in the Simscape Power Systems or DIgSILENT library, which is explained in the next subsection.

2.2.1 Integration of supplementary controllers to library models

The key challenge to the integration process successfully is to adapt the input and output signals of the supplementary controller to the main model. This includes the units of signals (per unit or actual), the acceptable range of each signal and the

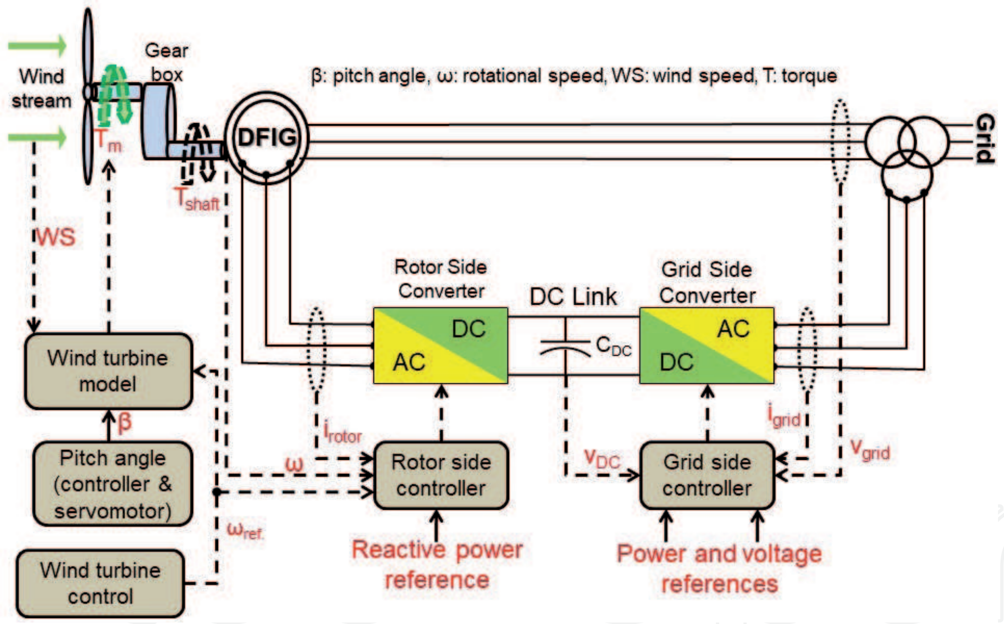


Figure 2.
Detailed block diagram of the electromechanical system of a DFIG wind turbine and the associated controls.

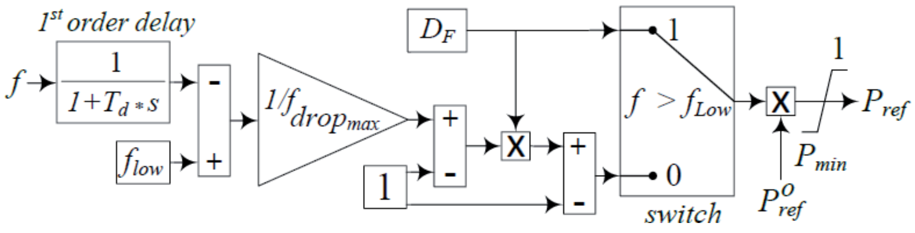


Figure 3.
Pitch deloading controller with nominal reference power as an input (D_F, deloading factor; f_{dropm}, worst frequency drop to waive the deloading; f_{low}, frequency at end of safety deadband; T_d, delay time constant).

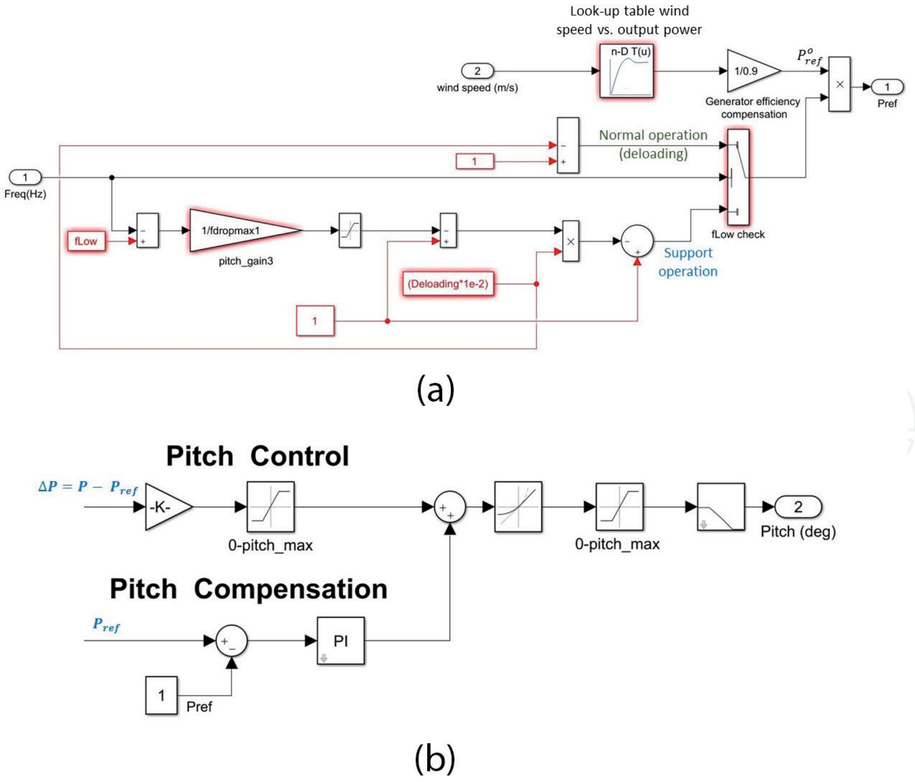


Figure 4.
(a) The Simulink model of the pitch deloading support and (b) a possible way of integration to the DFIG library model controller (the pitch angle controller).

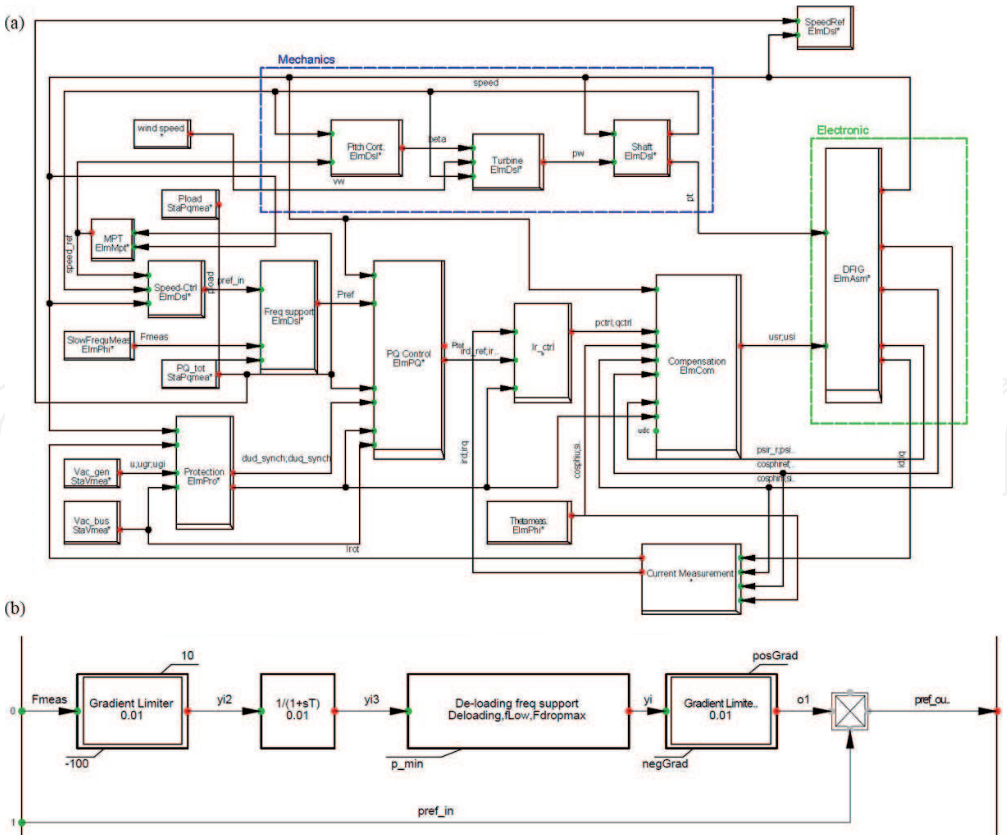


Figure 5.
(a) The Simulink model of the pitch deloading support and (b) a possible way of integration to the DFIG library model controller (the coloured frames in figure a mark the additional blocks to the generic model in DIgSILENT).

sampling time that suits the functions of the controller. For example, the controller in **Figure 3** could be integrated into the average WT model in MATLAB as illustrated in **Figure 4**.

The same control concept could be integrated into the DFIG model in DIgSILENT library as illustrated in **Figure 5**. The integration idea is simple, where the default reference power signal (P^o_{ref}) embedded within the generic frame of the WT is amended through an addition block (blue framed) using the controller illustrated in **Figure 3**. The block has two input signals, system frequency measurement at the point of common coupling of the wind farm and P^o_{ref}.

The frequency signal is obtained from an additional block (green framed), which is a standard phase-locked loop (PLL) block that can be found in the DIgSILENT library. The implementation of this support method in DIgSILENT is tested through several case studies in [11], where the response of both the WT and the connected power system is captured and analysed.

One of the challenging tasks is to tune the parameters of the PLL [12] to achieve an accurate and clean frequency measurement, so that it does not affect the performance of the controller negatively. Hence, there is a strong research trend towards support methods that do not require frequency measurement [13].

3. Modelling of voltage support

The provision of reactive power/current support is not as challenging as active power support (frequency issues and generation-demand balance), as it does not require securing power reserves. However, it is a very critical task due to its execution within very short time (milliseconds) compared to frequency support, mainly during faults. In addition, grid code requirements are always very strict in this regard; hence it could be challenging for WTs to comply. An interesting question may arise: Why are voltage requirements more critical and restrictive while one of the most key issues of power system stability is the active power balancing? The answer is already implicit in the question, which is because of the power balancing, as these requirements ensure that generation units stay connected to the grid. Hence, these units would continue generating power to the grid as soon as the fault is cleared, avoiding any consequential power imbalance.

3.1 Grid code requirements of voltage regulation

Regarding voltage support, the main objective of a grid code is to define when the generation unit is allowed to disconnect, commonly known as fault ride through requirement. As an illustration, and as shown in **Figure 6**, the generator must be kept connected as long as the minimum voltage (V_{fault}) is sustained for a duration shorter than t_{clear}, which is the clearance time of the fault. Likewise, the relays sensing the rate of change of voltage must be tuned to accommodate the post-fault rate of voltage recovery (from t_{clear} to t_{rec1}). The recovery could halt where a low-level voltage sustains until t_{rec2}; however, the generator must be kept connected within the defined time span and so on. This pattern differs from one system operator to another; in some cases, the intermediate recovery phase is not included to allow higher tolerance [14, 15]. The typical values of the pivot voltage and time points of this pattern are summarised in **Table 1**. This should be the first part of compliance, where the second part is related to the provided support to voltage recovery to the acceptable margin (i.e. typically 1 ± 0.1 per unit). According to the majority of grid codes [16, 17], the generation unit should maintain a 1 per unit reactive power/current injection during voltage dips, and it reduces gradually in relation to the voltage

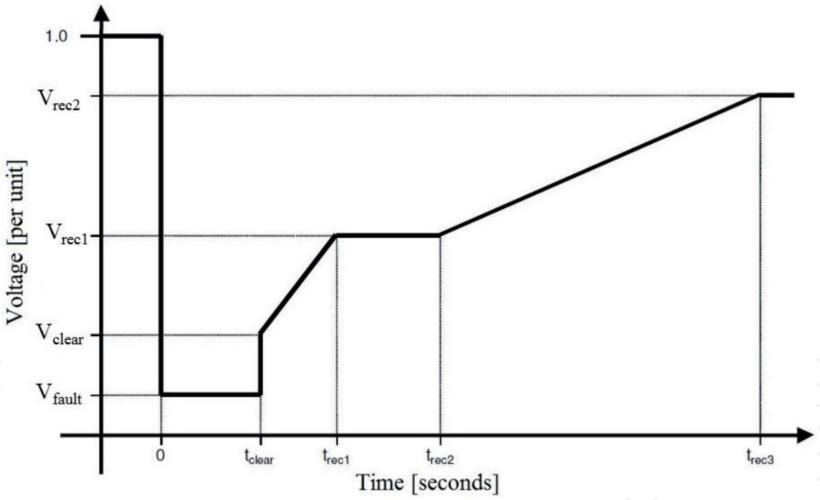


Figure 6.
Generic low voltage ride through (LVRT) grid code requirements.

Voltage limits	Value	Time limits	Value
V_{fault}	5–30%	t_{clear}	0.14–0.25 s
V_{clear}	70–90%	t_{rec1}	$t_{rec1} \geq t_{clear}$
V_{rec1}	$V_{clear} < V_{rec1} < V_{rec2}$	t_{rec2}	$t_{rec1} < t_{rec2} < 0.7$ s
V_{rec2}	85–95%	t_{rec3}	$t_{rec2} < t_{rec3} < 1.5$ s

Table 1.
Reference parameters during frequency events.

recovery. Some grid codes define the required pattern of the injected reactive current at different voltage levels, similar to the main ride through curve; however, it is more accurate to define the reactive current rather than the reactive power as the voltage dip mitigates the capability of reactive power transmission; hence the current value is more reflective and critical.

3.2 Modelling and integration of supplementary controls

There are three main solutions that enable the WT to ride safely through voltage dips; these solutions require the connection of additional equipment to the WT, and it differs based on the WT type; however type 3 is brought to focus in this chapter. The first solution is the dominant one, namely, a *crowbar circuit*, connected between the rotor-side converter (RSC) and the rotor windings of the induction machine of a DFIG. According to the applied technology of the converter, either IGBTs or an advanced voltage source converter (VSC), in addition to the ratio between stator and rotor voltages, the presence of a step up transformer between the RSC and rotor windings is decided. However, the modern designs avoid the presence of this transformer to mitigate the size and cost of the WT. The crowbar has different topologies and a three-phase resistive load to dissipate the additional energy during the fault and provides an alternative path for fault currents bypassing the RSC. The same concept can be applied using dc resistive load connected via a three-phase bridge [18]; however the crowbar circuit is one of the drawbacks of the DFIG compared to the PMSG full-rated converter type 4 WT [19]. As an illustration, the WT losses controllability during this stage because the RSC is decoupled and replaced by the crowbar circuit to protect the WT back-to-back converter from high currents and voltages, including the dc link voltage

[20]. Hence, it is aimed to reduce the connection time of the crowbar circuit without compromising the safety of the WT. In addition, this allows to provide reactive current support earlier when the controllability of the RSC is retained. The second LVRT method is applicable for both types 3 and 4, where a dc chopper is connected across the dc link between the RSC and grid-side converter (GSC), as shown in **Figure 7**, to dissipate the additional energy and stop the evolution of the magnetic flux of the machine. However, this method is more expensive than conventional crowbar circuit [21, 22]. The third method is relatively novel, where a superconducting fault current limiter (SFCL) is connected between the RSC and GSC as shown in **Figure 8**. The SFCL operation is based on the physical nature of the integrated superconductor where it changes its conducting state from normal to superconductivity according to the material characteristics, as well as the ambient temperature and the expected current continuity to which the device is designed. There are novel topologies of SFCL which are exploited to anticipate dc faults for large-rated dc connections within very short time and with reduced current surges [23]. This chapter will consider the resistive SFCL type, which is already applied to a wide range of electrical equipment; however, it is still an immature technology in LVRT hardware of wind turbines [24].

3.2.1 Key control features

The key features of voltage support for wind, applicable to any power electronics interfaced to the grid by power electronics, are as follows:

- The triggering time: duration of sustainable fault conditions to trigger the support operation mode (typically two to three cycles).
- Connection/activation time: the time for which the LVRT equipment and/or operation mechanism remains active from the instant of triggering. It does not have a typical value, but it has two main approaches: first, setting a constant duration regardless of the fault conditions and second, observing the fault and stopping the LVRT operation after a certain period of fault clearance assurance.
- The way to sense the fault occurrence: this could be achieved by observing the voltage level at the connection point (of the wind farm), machine rotor current (in the case of a DFIG wind turbine) and the dc link voltage (the link between the GSC and RSC).

These three main features are illustrated in **Figure 9**. These features were tested through comprehensive scenarios, and their dynamic performances were critically analysed in [25]; however, this chapter is focused on the modelling aspect rather than the impact of these controls on the power system and WT.

The SFCL has not been practically deployed as a LVRT hardware in the wind power industry. However, it has a promising potential, mainly that it showed merit when it is applied in the protection of distribution networks [23].

The crowbar circuit can be modelled in different ways, where the simplest approach is to use ideal switches whose on/off signals are generated by the applied LVRT control as illustrated in **Figure 9** (The output signal is used to trigger the LVRT hardware). The crowbar circuit can have different topologies: delta-connected equal resistors or Wye-connected equal resistors or dc resistors [18]. The most challenging aspect would be the selection of the correct value of the resistor that achieves a compromise between suppressing the fault current below safety

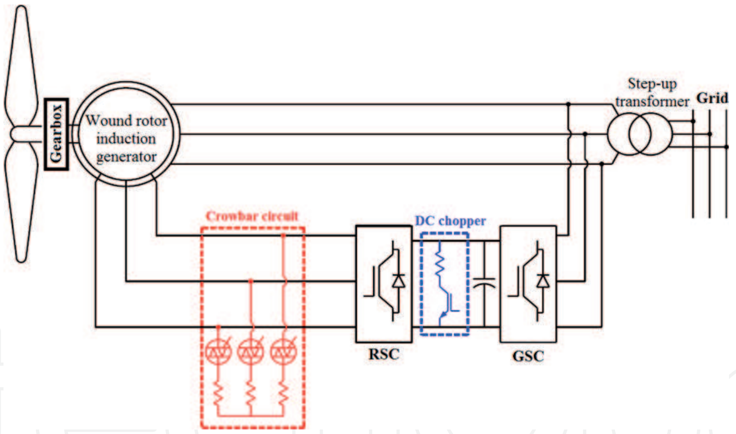


Figure 7.
Three different LVRT solutions of the DFIG type 3 (GSC, grid-side converter; RSC, rotor-side converter).

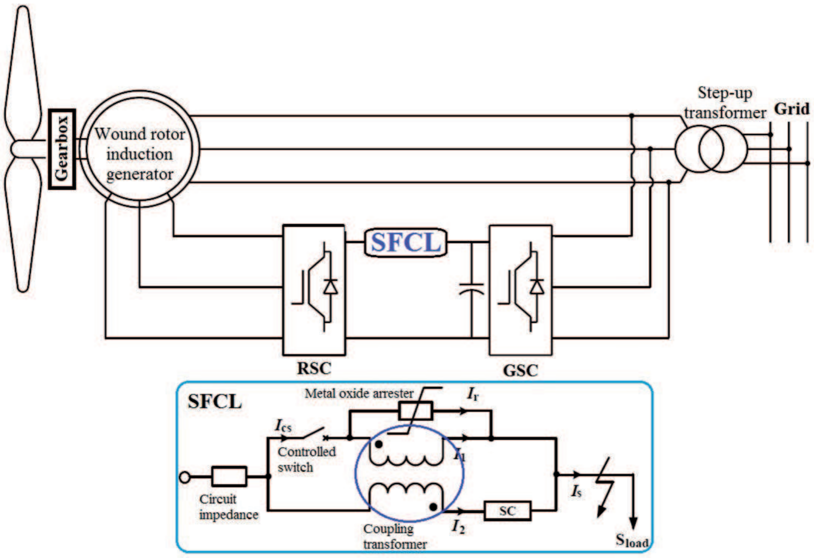
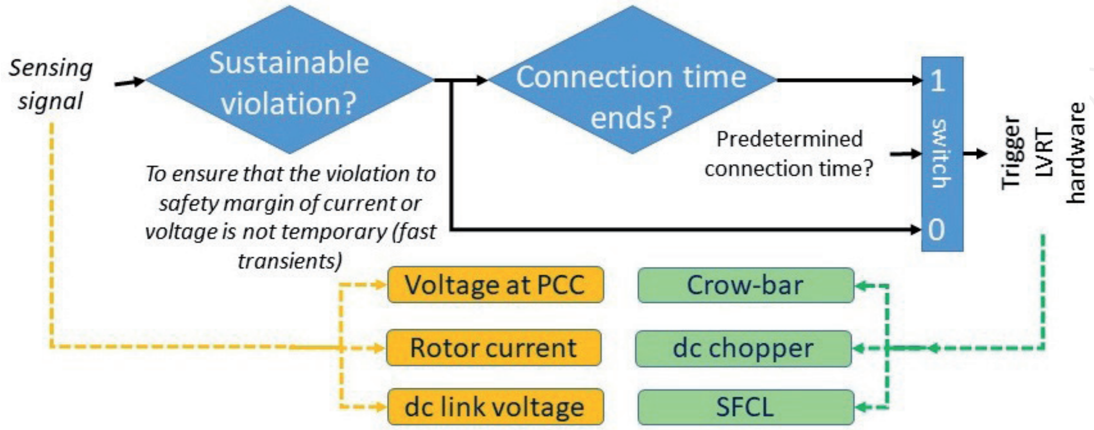


Figure 8.
Schematic representation of the reaction SFCL connection to DFIG.



To ensure that the violation to safety margin of current or voltage is not temporary (fast transients)

Figure 9.
The main features and their common solutions in LVRT for renewable energy units/farms (SFCL, superconductive fault current limiter).

limit, without causing excessive heat. The crowbar can be connected in series with the RSC as illustrated in **Figure 10**.

The second LVRT hardware is the dc chopper that can be simply modelled as a resistor in series with an ideal switch and connected across the capacitor of the dc

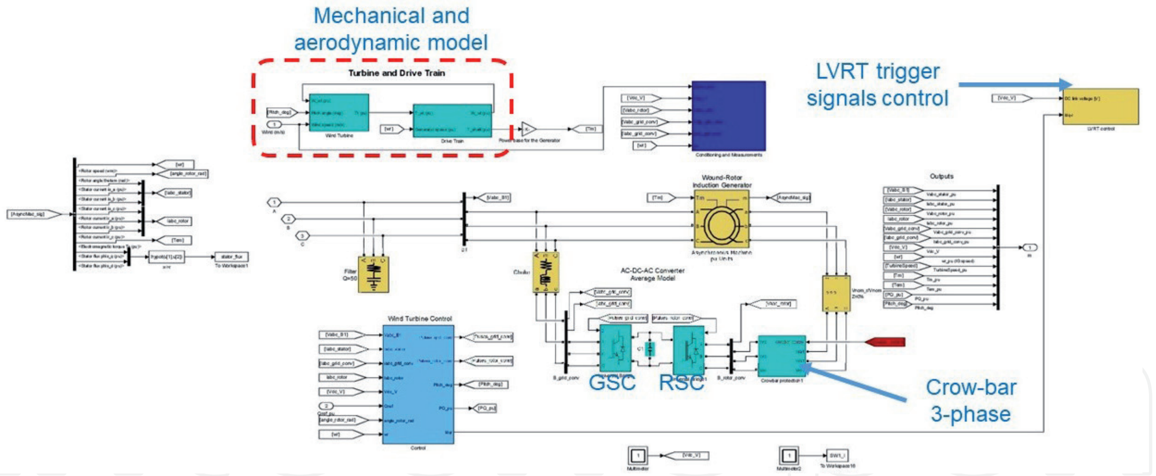


Figure 10.
An overall view of the DFIG-detailed benchmark in Simulink.

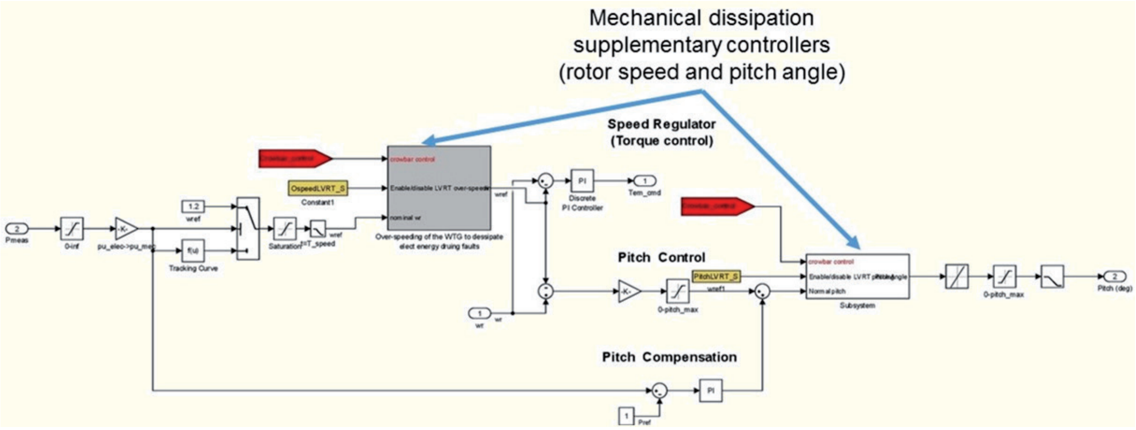


Figure 11.
The implemented supplementary controllers in DFIG-detailed benchmark in Simulink to enable mechanical aid to LVRT in chapter 1.

link between the GSC and MSC. The triggering signal to the ideal switch is provided by the applied controller, similar to the crowbar circuit. All these components are easy to find and assemble in MATLAB Simscape, where the main challenge is to set the values of the controller parameters as well as the dc chopper resistor.

A mechanical ride through method could be used, which relies only on a supplementary controller and does not require special LVRT hardware. As an illustration, the key role of protection devices is to dissipate the high fault currents through the device impedance; thus it would be helpful to mitigate the input mechanical power to the WT, in turn, reducing the generated electrical power feeding fault currents. Nevertheless, the speed of response of such mechanical methods might not be fast enough to tackle the fault currents, which will be examined through this research work. The main idea is to dissipate the input KE (i.e. wind energy) to the WT, by increasing the pitch angle to its maximum and using the excess energy to accelerate the rotor instead of causing magnetic flux evolution. However, the speed should not violate the maximum allowed limit. The pitch control retains normal conditions, and the generator speed is decelerated, such that the WT is able to resume normal power production promptly after the event [26]. An example for integrating this concept to the benchmark DFIG model in Simscape power library is depicted in **Figure 11**, where it is has two main components: the first part is responsible for slightly overspeeding the WT during the fault by implementing an increment change to the default reference rotor speed signal. The second part slightly increases the pitch angle if necessary to reduce the harnessed wind energy during a fault, hence reducing the generated electric current by the induction machine.

This method could be supplementary not the sole LVRT method, as it is not sufficient to replace the electrical solution (i.e. crowbar, dc chopper, etc.), due to its slower response; hence it could not ensure a very rapid suppression of over-currents and voltages across the WT converters, which makes the WT subject to possible risks of damage and tripping protection.

4. Modelling of oscillation damping controllers

Similar to the case of voltage support provision, oscillation damping does not require securing power reserves but proper power management and flexibility.

In the previous ancillary services presented, control variables were clearly identified to each end (i.e. frequency-active power, voltage-reactive power), while it is not the case of power oscillations. These oscillations are a natural response of the power system and/or other connected systems to any perturbation which could excite it. The oscillations can be observed in any electrical variable, including power, voltage and phase angle, among others.

Historically, the stability problem (commonly known as small signal stability) has been mainly the synchronous generators, as they are the large dominating machines governing the dynamics of power system under low renewable penetration. However, lately new causes of oscillations are evolving due to control interactions or sub-synchronous oscillations. Generally, oscillation modes can be classified depending on the systems that provoke it and their frequency, as follows:

- Inter-area: the oscillations due to an interaction of a group of generators nearby (area) with another group of generators in another area which are interconnected (typical frequency range of 0.1–0.7 Hz).

- Intra-area: the oscillations of a single generator to the rest of the system or area (typical frequency range of 0.7–2 Hz).

- Torsional: this is interactions among the mechanical electrical parts of a generator (typical frequency range: above 2 Hz).

- Control: this is related to the interplay between the controllers themselves and power system dynamics (typical frequency range: above 2 Hz).

The last two types are commonly known as sub-synchronous resonances.

Due to the importance of this stability problem, some grid codes are already requesting this service to provide oscillation damping as well as ensure that integrated controllers provide other services do not cause unexpected oscillations [27].

A common simple model for designing power oscillation enhancement controllers in conventional generation (known as power system stabilizers) is the well-known Heffron-Phillips, which represents a conventional generator connected to an infinite bus [28]; this model is built in MATLAB/Simulink as shown in **Figure 12**.

The beauty of such model is that it presents a very simple case presenting the minimum dynamics of a conventional generator allowing the design of the PSS to damp out the local (inner) oscillations. As it can be seen normally, the PSS uses the frequency or generator speed as an input and modifies the exciter voltage. The conventional control structure includes a washout filter, to ensure acting only on the desired frequency range, and after that a phase compensator (or lead/

lag block) which ensures the proper modification of the dynamic response of the generator.

4.1 Wind power to mitigate oscillation resonances

As previously stated, such oscillations could be damped or mitigated by the proper regulation of WT controllable variables. To apply this without major modifications of WT control, a supplementary controller could be integrated. From a wind power perspective, the input signal for the supplementary controller could be any signal that ensures observability of the oscillations (e.g. active power, frequency, phase angle of synchronous generators, voltage magnitude and/or phase) and produces a signal which could impact power flow within the power system (e.g. active and/or reactive power reference of WT and voltage at the connection point, among others).

It is worth to indicate that the typical structure for oscillations damping in synchronous generators is known as power system stabilizers, which are designed to damp out the generator oscillations of certain frequencies by using a bandpass filter and a lead/lag control which ensures stability of the generator by taking the advantage of the phase margins (as shown in **Figure 13**). Although this methodology could be used in WTs, the control can be simplified due to the fact that wind farm does not have a direct impact on the phase margin of the generator but only on the general power flow [29].

Generally, the WT support on oscillation damping could be classified according to the type of power being regulated, i.e. active or reactive. In **Figure 14**, potential methods to regulate relevant variables are presented, using appropriate controllers to achieve small angle stability.

The damping capability of each variable is completely different. As expected, the regulation using active power has a larger impact on enhancing stability than using reactive power as a main signal [30].

4.2 Modelling and integration of supplementary controls

It is important to remark that small signal stability is usually evaluated by two main methods: linear algebra techniques (mainly, eigenvalues and eigenvectors) and time-domain simulations.

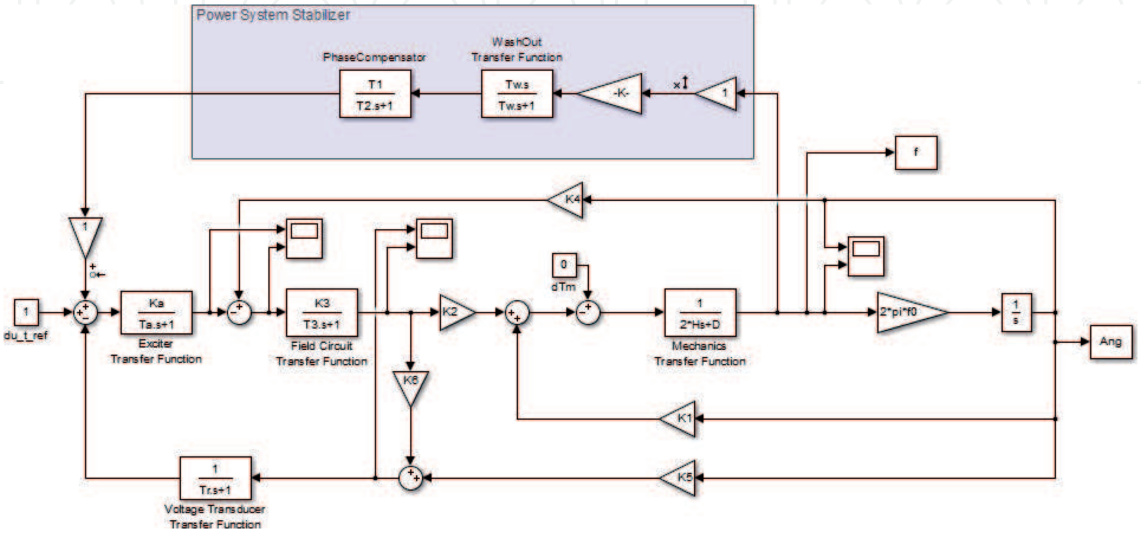


Figure 12.
Heffron-Phillips model for a synchronous generator-infinite bus model.

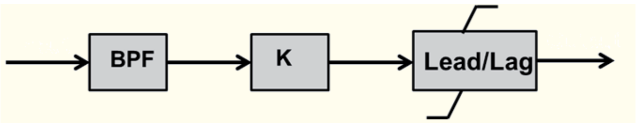


Figure 13.
Conventional PSS scheme (BPF, bandpass filter).

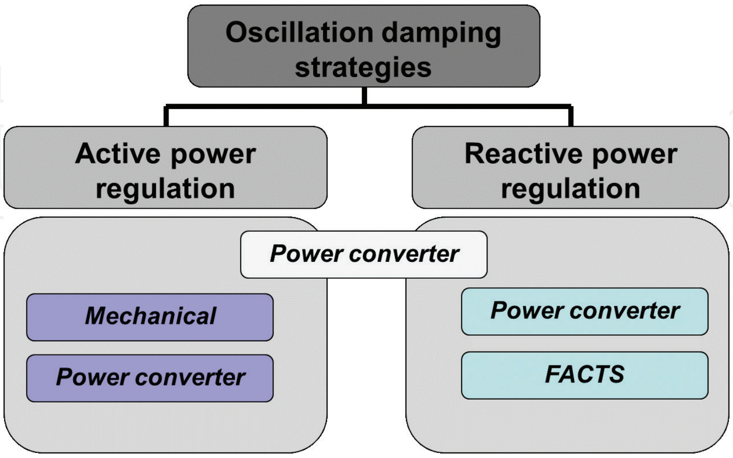


Figure 14.
Simple classification for oscillation damping provision.

The first method, based on a linearized system mathematical model, provides a simple method to identify the oscillatory dynamics within the system through the eigenvalues (i.e. $\lambda = \sigma \pm j{\cdot}\omega$). In this case, ω refers to the frequency of the oscillation ($\omega = 2{\cdot}\pi{\cdot}\ f$); and σ refers to the non-oscillatory part, which indicates the stability (negative = stable and positive = unstable), as well as the damping ratio (damping = $-\sigma/(\sigma\string^2 + {\cdot}\omega\string^2)$).

One common model benchmark for the power oscillation analysis is known as the Kundur (two-area model) [31].

In order to analyse the impact and contribution of wind power, the supplementary controllers could be integrated into comprehensive model which includes a detailed wind farm (each wind turbine represented by a separated mode) or aggregated (wind farm represented by one wind turbine of equivalent rating); an example is shown in **Figure 15**. This model is developed in MATLAB/Simulink environment which already included different built-in models. It is worth noting that the wind farm is based on the GE 3.6 MW model [32], which include active and reactive power control and voltage regulator, among other control systems, as shown in **Figure 16**.

The supplementary controls have been applied to the main control loops to adjust the reference values accordingly. The impact of the supplementary controller is clear at the GSC of the WT, as it is responsible for the interaction with the power system. It is of note that in the case of DFIG WT, the maximum reactive power limited by the generator rating not the grid-side converter rating.

Finally, from the modelling and control design perspective, one advantage of using MATLAB/Simulink for these studies is the integrated toolboxes for linearization of the whole system, which include system state identification and simplify the control design and oscillation detection. With the system identification methods (from the linear perspective), the user could select the desired input and output of the plant and identify the transfer function that links these signals. Linear transfer functions help to produce the state-space model; hence the eigenvalues and eigenvectors can be easily computed to obtain the corresponding oscillation modes and

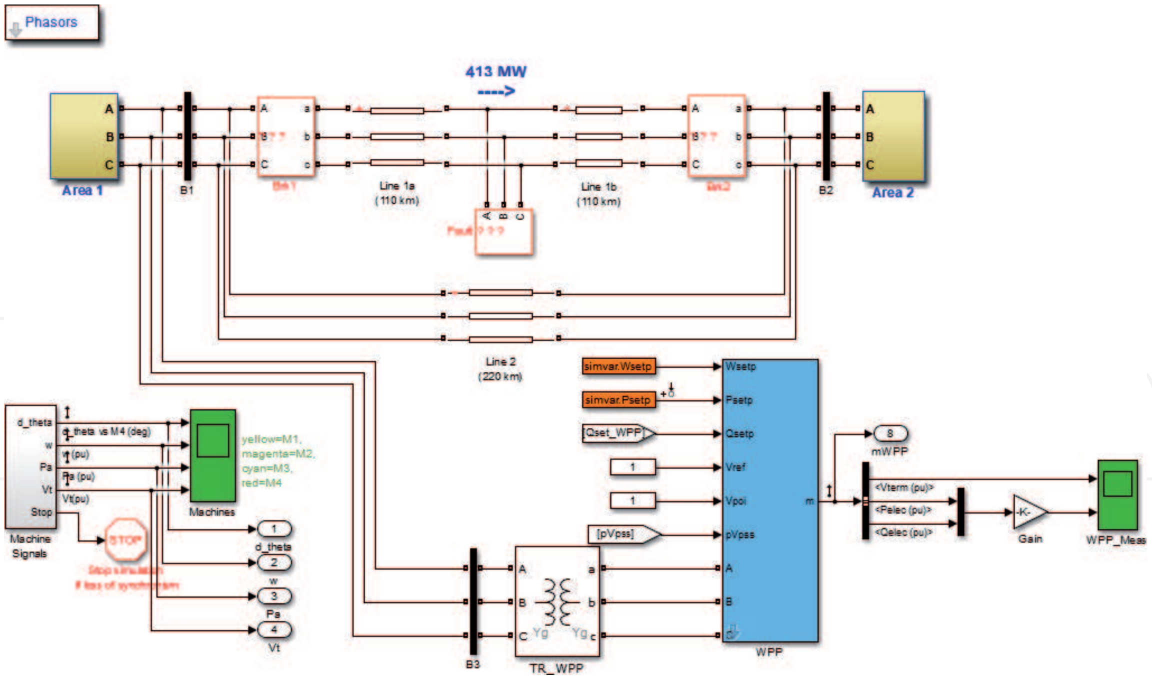


Figure 15.
Adaptation of Kundur's model by including wind power plants in MATLAB.

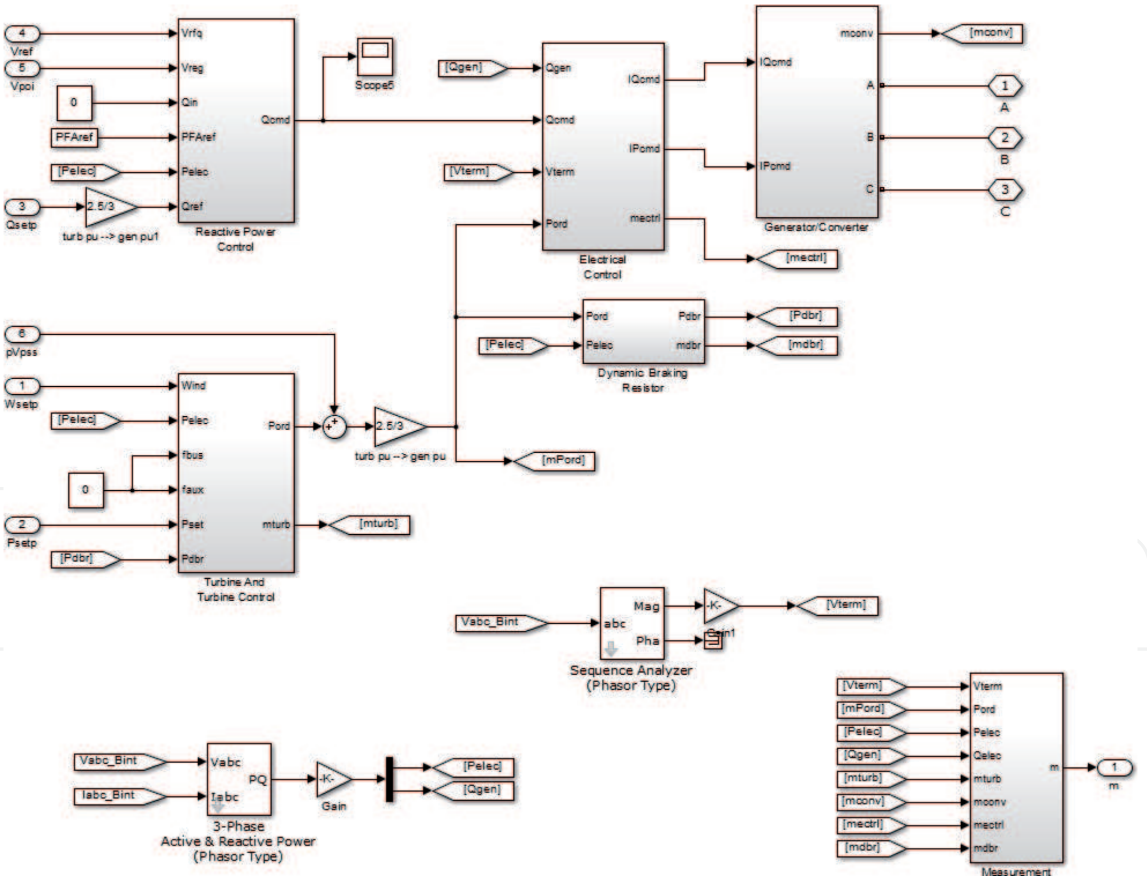


Figure 16.
Wind power plant based on GE-3.6 simulation model.

their main causes. Finally, with the state-space model or the transfer function, any type of control which allows modifying the desired dynamics could be applied, for example, pole placement, root locus and other advanced techniques as H-infinite. In case of implementing this type of studies to different simulation software as DIgSILENT PowerFactory (previously presented), it has a toolbox for eigenvalues and oscillation mode identification (computed internally by the software), but in the case of model identification and control design, it could be linked with MATLAB and python through some existing scripts.

5. Discussion

This section describes the key simplifications and potential limitations to apply these methods in the real world. It also provides a brief discussion for the main applicability barriers and practical limitations for the represented control methods.

5.1 Reasonable simplifications and potential limitations

It is worth noting that all simplifications introduced before are commonly accepted and applied in order to simplify control design and development in an acceptable model which does not include additional complexity which could slow down simulations without providing significant additional information.

5.1.1 Wind turbine/farm wise

The proposed modelling solutions are subject to some simplifications where the model parameters of the wind turbine are considered constant; however this is not ideally accurate as changes in some parameters, due to operation conditions, could lead to considerable drift in the performance of the WT when it provides a certain service. For example, the WT inertia is always seen as a constant value (1.5–3 s) according to its size and gearbox technology, but actually this inertia suffers marginal changes subject to the incident WS and the mechanical characteristics of its blades. A change in the inertia would impact the amount and duration of the provided support power during frequency drops.

In addition, one of the widely-used simplifications is to ignore the modelling of the power electronic interface (i.e. rotor-side and grid-side converters for both types 3 and 4 WTs). In fact, many power system researchers consider the power electronic interface as an ideal box with zero-time delay, where the required set-points (amended reference power, torque or speed), which are produced by the ancillary services controllers, are well received and applied by this interface. In real world, this could have minor implications; however, these interfaces are very efficient (98–99.5%), and the induced delays do not exceed a few milliseconds. This assumption is perfectly acceptable for frequency stability studies, as frequency dynamics occur within a much larger time scale (the most relaxed ROCOF restriction is 0.5 Hz/s).

Pitch angle actuator could be also a challenging aspect for modelling the WT response for pitch deloading techniques. Most of the literature considers only the delay of the servomotors, ignoring the elapsed time to move the blades (i.e. inertia of the blades as rotating masses). However, this is very minor as the blades are not moved from stationary status. Additionally, it is not easy to obtain the accurate/authentic parameters of the empirical equation which describes the variations of harnessed power against tip-speed ratio and pitch angle [33]. All WTs manufacturers do not provide open access to such critical information as it could reveal their unique aerodynamics designs of their blades.

Conversely, the previous three simplifications should not have any influence on voltage support except the accurate modelling of the power electronic interface. Actually, this interface is completely responsible for the reactive power compensation, and hence it should be modelled as accurate as possible. However, some researchers simplify the PQ limitations of the converter and set it as a square of 1 per unit for each side, which leads to 'optimistic simulations' compared to the real world.

All the previous simplifications are influential regarding the provision of oscillation damping, as this service is a complex mix between active and reactive power balancing and compensation. The oscillation modes are also sensitive to rotor inertia and dynamics as well as the capabilities of the integrated power electronic interface.

The limitations are mainly related to the expected WT response and the provided support using these models. The amount of power support (i.e. ΔP) relies to some extent on the incident WS, which is always fluctuating in contradiction to most of the models that assume that WS is constant during the event. This assumption could have a clearer influence when the amount of reserve (i.e. sustainable ΔP) is evaluated. As an illustration, in balanced deloading for example, it would be very challenging to maintain a fully constant ΔP for long durations due to the interactions of WT inertia, incident WS and different WT controls. However, in simulations this is achievable. Likewise, WS measurement is essential for many of the proposed controllers; however, in reality, this could be subject to errors and failures, where the state-of the-art technology relies on laser and could experience 0.25–0.5 m/s error [34], which should not be significant to support operation; meanwhile most of the models assume ideal WS measurement.

The assessment of the economic value of providing these services, mainly frequency support, is also limited by the accuracy of the implemented MPPT power curve which is usually provided in the vendor manual [35].

5.1.2 Power system wise

The power system main simplification and limitation at the same time are the accurate measurement and communication of system frequency to the relevant supplementary controller in the WT and/or the WF. The frequency measurement is always obtained using PLLs, and it is prone to noise and errors [36]. However, most of the implemented models in the literature applies a clean frequency signal to focus only on the merits of the proposed support methods.

The second limitation is that most of the models ignore the modelling of either the protection relays or at least their impacts. For example, the influence of ROCOF relays could be significant (stop the simulation and in reality trigger the WT protection so it comes to a complete stop) if the ROCOF threshold is violated. Many studies overcome this simplification by showing the ROCOF behaviour during the event to ensure that its presence is within the safe limits.

The same applies to voltage support, where the WT of WF converter station overcurrent relays could stop the simulation, if the overall current exceeds the limits (typically 1.4 per unit sustained for 1–3 s). This is likely to occur during symmetric faults or when the WT is operating in LVRT and suddenly switch to reactive compensation mode. In particular, as soon as the fault is cleared, the WT is required to recover the full pre-fault active power as well as maintain high reactive current to recover the nominal voltage level [13]. However, commercial simulators, e.g. DIgSILENT and PSS®E, include these protection gears or at least mimic their influence, in most of their library models.

A third key simplification is the 'ideal consistency' where all the integrated WFs models, usually a single WT of an aggregated capacity to represent each WF, are consistent in all aspects except only one or two according to the applied case study.

5.1.3 Synchronous machine infinite bus simplifications

The model presented (Heffron-Phillips) is a very simple model which mainly represents the mechanical behaviour of power system that represents the basis of frequency dynamics of the electrical network. Such simplified model neglects all electrical parts of the power systems and existing interactions among different variables as voltage, current, cable limits, etc.. In addition, as it occurs with the wind turbine/farm modelling, the delays impacting on communications and measurements must be considered when implementing such concepts for real experimentation and replicability. However, these models are widely accepted for control development.

5.2 Implementation challenges

The implementation of the proposed methods on a wide scale and in large wind power plants will face two main obstacles: data access and communication as well as standardisation. The required volume of data is massive, including models, control parameters, live measurements and signals across the coordinated assets. In addition, communicating these data with minimum delays and no corruption and securely is a significant ICT challenge; that is why cyber security is a leading topic for future power systems [37].

The second challenge is the wise planning and implementation of what we can call the grid codes evolution to *standardise* the provision of ancillary services by renewable energy. This should consider tailoring the definition of reserve and inertia to versatile nature of the widely accepted frequency support methods. For example, should the TSOs adopt a pre-populated frequency-active power response or should they be granted a limited access to the holistic controls of renewable power plants to achieve power balance? How should the TSO ancillary service market coordination be achieved without curtailing both system stability and renewable power plants finance [38]? In addition, what is the standard definition of a renewable power plant, as it could be a hybrid energy source with energy storage system?

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