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Participation of PMSG-based wind farms to the grid ancillary services

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ABSTRACT

With the increased penetration of wind energy in many utility grids throughout the world, transmission system operators (TSO) are facing further difficulties regarding power system control and stability. Therefore, modern wind farms should participate to the primary voltage and frequency control of power systems. This paper presents the design of a supervisory control strategy for grid-connected wind farms. Wind turbines within the investigated wind farm are pitch controlled and use the Direct Drive technology. It has a total installed capacity of 50 MW and it includes 25 PMSG-based wind turbines with a rated power of 2 M each. The proposed supervisor is developed with all features that make the wind farm able to provide active and reactive power control. It includes automatic voltage and frequency control with droop and dead band. Performances of this supervisor are evaluated in terms of compliance with the Danish TSO requirements.

1. Introduction

Currently, wind systems are considered as a reliable and a well-proven technology for electricity generation from a renewable source [1]. Today, due to the increased penetration of wind energy in certain power systems, wind farms are required to provide auxiliary services which help stabilize the grid [2]. Indeed, many country such as Danemark, Portugal, Spain and Germany have achieved penatration rates of 27%, 17%, 16% and 11%, respectively [3]. With such penatration levels, conventional generating units should react promptly to the variations of wind power production to avoid any mismatch between the produced power and energy consumption. In such situations, it becomes more difficult for TSOs to maintain the stability of the system and to manage power production with the lowest possible cost [4]. Therefore, large scale wind farms are required to participate in power system stabilization by providing primary frequency and voltage control [4]. Many concise specifications and grid codes were introduced by TSOs that define wind farm response during frequency excursions or voltage drops. Obviously, the most stringent requirements are found in countries with the highest penetration levels. According to the Dansish TSO requirements, active power control capabilities should include balance, delta and frequency droop control as well as power gradient limitation. Reactive power control and voltage droop control at the point of common coupling are also required [4]. To comply with these requirements, many automatic and advanced wind farm controllers were developed. Ref. [5] gives a review of grid code requirements and control methods developed so far about this issue. The first controller of such type was proposed in 2002 for the Yega (Spain) wind farm consisting of 37 Gamesa wind turbines (660 kW) using the DFIG technology [6]. The controller consists of a supervisory control level which allows to control seperatly active and reactive powers for each turbine according to a set points provided by the TSO. Another controller was also developed for the Horns Rev large scale wind farm which is made up of 80 wind turbines (2 MW) with the DFIG technology [7]. This controller allows primary frequency control along with reactive power control through a reference setpoints given by the utility manager. Results of these investigations have shown that the considered wind farm can participate in the power system control and a better wind farm integration could be achieved by implementing a supervisory control level. Another algorithm was also proposed in [8] for controlling DFIG based wind farms. A dispatching system was developed which sends out appropriate power references to each individual wind generator. In Ref. [9], authors have propsed an approach for controlling the production of wind generators during the frequency droop events taking into account actual wind speeds, wake effects and the different arrangements of wind turbines inside the wind farm. An optimization algorithm was proposed in

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Nomenclature

Abbreviations

DFIG	doubly fed induction generator
MPPT	maximum power point tracking
PMSG	permanent magnets synchronous generator
SG	synchronous generator
TSO	transmission system operators

Symbols

β	pitch angle
c_i	constant values of the rotor model
C_p	power coefficient
D_{mp}	damping coefficient
δ	regulation droop value
f_0	rated grid frequency
H_G	total inertia of the generator and the steam turbine
i_{gd},i_{gq}	stator currents
J_{tot}	total inertia of the rotating parts
L_d, L_q	longitudinal and transversal synchronous inductances
λ	tip speed ratio
p	number of pole pairs
P_0	wind farm power production before frequency faults.
P_L	total power demand on the grid.
P_{gr},Q_{gr}	active and reactive powers injected to the grid by a single turbine
P_{rec},P_{inv}	active powers at the rctifier output and inverter input
P^*_{TSO}, Q^*_{TSO}	active and reactive power setpoints for the whole wind farm
$P^*_{WT\_i}$, $Q^*_{WT\_i}$	setpoints for active and reactive power production for individual turbines
$P^m_{WT\_i}$	maximal available power for individual turbines
P^m_{WF}	maximal available power for the whole wind farm
P_{WF}	active power produced by the whole wind farm
ρ	density of the air
R	rotor radius
R_g	resistance of stator phases
S_G	rated power of the synchronous generator
sl^*_p, sl^*_q	mode selection signals
T_{em}	electromagnetic torque
T_{mec}	torque developed on the mechanical shaft
U	equivalent wind speed
u_{dc}	DC link voltage
v_{gd},v_{gq}	stator voltages
X^*	set point value for any variable X
X'_G	transient reactance of the synchronous generator
X_L	impedance of the transmission line
ψ_{gd}, ψ_{gq}, $\hat{\psi}_v$	stator and rotor flux
ω_0, ω_r	rated and actual rotational speed of the synchronous generator

[10] to reduce power losses and improve voltage profile on the network by controlling reactive power output of the whole wind farm. However, this issue has not been adressed intensly in literature when it comes to wind farms using the Direct Drive technology. This concept is designed based on a multi-poles permanent magnets synchronous generator (PMSG) which allows gearbox removal. In Refs [11,12], authors have proposed to use pitch regulation in order to make PMSG-based wind farms participate to frequency control. However, in both cases, the wind farm was modeled as a single generating unit and consequently, the problem of power dispatching between individual turbines was not adressed. Therfore, the aim of this paper is to propose a new centralized controller for a 50 MW wind farm made by PMSG wind turbines. This advanced controller is developed to fully comply with all control modes specified in the Danish grid codes. It receives the desired control type from the TSO and, accordingly, it elaborates active and reactive power set points for each turbine. Section 2 describes wind farm behaviour for voltage and frequency regulation based on requirements of Danish TSOs. The third section presents the model of the 2 MW, PMSG wind turbine used for wind farm simulation. Control scheme of such wind turbines is briefly discussed including the MPPT algorithm and pitch angle regulation. To evaluate the supervision performances, a model of a test case wind farm is developed in Section 4 while Section 5 presents a simplified grid model. The design of the overall supervision strategy is then presented in Section 6. It aims to manage wind farm production during the different operating modes. The performances are evaluated by simulation and the results are compared to the GCR.

2. Ancillary service requirements for wind plants

The rapid variations of the power produced by wind farms may induce grid frequency fluctuations; activate primary frequency control of generating units and make use of their primary power reserve. For power systems with a high penetration rate of wind energy, the absence of ancillary services provision complicate the task of power reserve allocation and decrease the total inertia of the grid. Consequently, the power system is more exposed to the imbalance between generation and demand. Divergence of this equilibrium results in frequency deviations which may cause the disconnection of generation and eventually leading to a black-out. Therefore, utility scale wind farms should contribute to voltage and frequency control in the power system. Regulation is mainly performed by providing active and reactive power to the grid. Danemark is one of the countries with the highest penetration level and, therefore, it has issued the first requirements for grid connected wind farms starting from 2000. In 2004, new regulations were issued which were more specific regarding frequency control [13]. These specifications include different types of power/frequency control. Indeed, it should be possible to reduce the wind farm power production to a constant level. The production level is set by an external signal from the TSO. This method is shown in Fig. 1a and it is known as *balance control*. The *delta control* method is depicted on Fig. 1b and it is used when the difference between the available and the produced powers should be kept. This constant reserve can be used for primary frequency control. *Automatic frequency control* is considered as the most important control method. It must include droop control between a certain range (47–52 Hz) with a dead band (49.85–50.15 Hz) as depicted in Fig. 1c. In normal operation, the power production P_0 will be the maximum available wind power. Unless power limitation is activated (delta or balance control), the power/frequency characteristics would only have droop for frequencies which are above the dead band. For underfrequencies, if there is not any reserve power, power production is kept equal to P_0. The Danish specifications also require that at least a variation rate of 100% of the available power per minute should be possible.

Wind farms should also have the ability of reactive power/voltage control. Ractive power requirements are generally expressed in term of *PQ* diagram. Fig. 2a shows the *PQ* diagram specified by the Danish grid codes for wind plants with an installed capacity higher than 25 MW [14]. This means that individual wind turbines should have an additional capacity for