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Coordinated operation of wind turbines and flywheel storage for primary frequency control support

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ABSTRACT

This work assesses the participation of wind power plants in primary frequency control support. To participate in frequency control-related tasks, the wind power plants have to maintain a certain level of power reserves. In this article, the wind power plant is equipped with a flywheel-based storage system to fulfil the power reserve requirements set by the network operator. The article focuses on two main aspects: the definition of the control strategy to derate the wind turbines to provide a part of the required power reserves; and the coordinated regulation of the power reserves of the wind turbines and the flywheels while participating in primary frequency control. This coordinated regulation enables the wind power plant to maintain the net level of power reserves set by the network operator while alleviating the need of deloading the wind turbines. The performance of the proposed control schemes are shown by simulation.

Introduction

The increasing importance of wind power plants (WPPs) in the electrical network affects system operation due to the stochastic nature of wind power [1]. For that reason, more stringent requirements are gradually developed by system operators for the grid integration of WPPs [2–4]. These regulations require WPPs to behave in several aspects similar to conventional synchronized generating units. Among other requirements, the participation of WPPs in system frequency control-related tasks is set (as indicated, for instance, by the Irish operator [3]).

Wind turbines (WTs) are capable of providing system frequency control support [5–9]. In [5] an analysis on the effects of the displacement of the conventional generating units in a power system with high penetration of WPPs is proposed. Results highlight the necessity of WPPs to participate in frequency control as the synchronized inertia of the system is lowered by the decoupling of the rotor inertia of the wind turbines by fast controlled power electronics. Frequency stability may be compromised with reduced levels of synchronized inertia since high rates of change of frequency can be registered.

For ensuring the constancy and stability of the frequency of the electrical network, a certain level of active power reserves is required. These reserves are continuously regulated to match the power consumption and generation in the network, but also in presence of power disturbances such as sudden trips of generating units in order to participate in frequency control. Wind turbines have to be operated not extracting the maximum available power from the wind but maintaining a certain power margin in order to participate in primary frequency control.

But maintaining a power margin is a major drawback from the point of view of the operators of WPPs, as they are losing revenues from not selling up to 10% of the available power that can be captured from wind in normal and continuous operation. In addition, the primary frequency support WPPs can provide, depends on the wind speed and the control techniques applied for regulating the power margin.

From the above mentioned considerations, it could be interesting to the owner of a WPP to connect an energy storage system in the point of common coupling of the generating facility with the external grid. In this case the wind turbines could be operated extracting the maximum available power from the wind. The

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Nomenclature

Parameters

A	area covered by WT blades, (m^2)
$C_{p_{opt}}$	optimal betz coefficient for WT, (–)
H	inertia constant for conventional generation, (s)
J_{fw}	inertia of a flywheel unit, ($kg\,m^2$)
$K_{Cp}(\cdot)$	optimal torque coefficient for WT, (Ws^2/rad^2)
n_{fw}	number of flywheel units, (–)
R	primary control droop for synchronous gen., (–)
R_{wpp}	primary frequency control droop for WPP, (–)
T_{loss}	flywheel torque losses, (Nm)
v_w	wind speed, (m/s)
$v_{w_{rated}}$	rated wind speed for WTs, (m/s)
x^*_{sd}	steady state power margin Ref. for the WPP, (–)
δ	time constant, (s)
ω_{min}	minimum operating speed for flywheels, (rad/s)
ω_{max}	maximum operating speed for flywheels, (rad/s)
$\omega_{t_{rated}}$	Rated speed for WTs, (rad/s)

Variables

$C_{p_{del}}$	betz coefficient for a WT while being deloaded, (-)
f_e	electrical frequency of the network, (Hz)
P_{cap+}	power that flywheels can inject for 30 min, (MW)
P_{cap-}	power that flywheels can absorb for 30 min, (MW)
P_{load}	network load demand, (MW)
$P_{loss_{wt}}$	power losses in the WPP collection grid, (MW)
P_{opt}	max. power WTs can extract from wind, (MW)
$P_{opt_{del}}$	output of a WT while being deloaded, (MW)
$P^*_{storage}$	power reserve that flywheels can handle, (MW)
P_{wt}	power generated by WTs measured at PCC, (MW)
$P_{wt_{max}}$	max. power WPP can extract from wind, (MW)
T^*_e	WT electrical torque reference, (Nm)
$T_{opt_{del}}$	WT torque while being deloaded, (Nm)
$v_{w_{min}}$	wind speed for which the WT achieves its rated speed while maintaining a power margin x, (m/s)
x	power margin, (–)
x_{cap+}	magnitude P_{cap+} in per unit of the maximum available power that WTs can capture from wind, (–)
x_{cap-}	magnitude P_{cap-} in per unit of the maximum available power that WTs can capture from wind, (–)
x^*_{wt}	total power margin reference for WTs, (–)
$x^*_{wt_{sd}}$	power margin reference in steady state, (–)
β	pitch angle, (degrees)
β_{max}	pitch angle for power margin x at rated wind speed, (degrees)
Δf	frequency deviation, (–)
$\Delta t(f_e)$	time length that flywheels would be required to inject or absorb power continuously, (s)
Δx	power margin interval, (–)
Δx_{wt}	power margin variation required to WTs, (–)
ω_{fw}	flywheel speed, (rad/s)
ω_t	turbine speed, (rad/s)

energy storage system would provide the required power reserves for the participation of the WPP in primary frequency control therefore. The economic viability of the project would be determined by a cost-benefit analysis considering the cost of the storage system against the alternative of operating the wind turbines in a deloaded mode in a continuous basis.

Of course, from the point of view of the network operation, the inclusion of an energy storage system in the point of connection of a generation facility could not be the better allocation. The installation of the storage facility near the network loads in order to reduce transmission losses could be preferable. However, it is also interesting to study the allocation of the storage system in the point of connection of a WPP for several reasons: (i) the exploitation of the high-ramp power rates and short time responses of an adequate storage technology could lead to a great system primary frequency support from the point of common coupling of the wind facility to the grid; (ii) to install a storage facility could help the WPP to fulfil the gradually increasing requirements of the grid codes regarding the grid integration of renewable-based power plants [1].

Several energy storage devices suitable for frequency control – related tasks can be found. Among them, the literature considers the application of large scale storage systems like pumped-hydro, compressed-air and hydrogen-based systems. Also, it is worth noting that batteries, flow batteries and those storage devices with very high ramp power rates and short time responses like Superconducting Magnetic Energy Storage (SMES) and flywheels are specially well-suited for this application [1]. Remarkable characteristics of flywheels are their very high ramp power rates, high cyclability and energy efficiency (around 90% [10,11]). On the other hand, standing losses are non-negligible. In fact, self-discharge rates are about 20% of the stored capacity per hour [12].

This work considers the inclusion of a flywheel-based storage plant in the point of common coupling (PCC) of a WPP with the external grid. The flywheels are considered to be part of the WPP and provide part of the power reserves indicated by the system operator to the WPP. This way, the WPP participates in primary frequency control. Wind turbines are required to operate to some extent in a deloaded mode depending on the level of power reserves of the flywheels, i.e. depending on their State of Charge (SoC). Thus, the required power reserves by the system operator to the wind facility can be computed by the sum of the power reserves of the flywheels and the power reserves provided by the wind turbines. The latter can be deduced from the capability of the wind turbines to increase their generation level up to the maximum available power that can be extracted from the wind. Conceptually, the scope of the work responds to Fig. 1.

Two contributions from the present work can be pointed out:

- The design of the central control system of the WPP and the local controllers of the wind turbines and the flywheels. These control systems are in charge of regulating the power reserves maintained by the wind turbines and the flywheels under network disturbances and also in normal operating conditions. In case of a network disturbance, i.e. of a system frequency deviation from its set-point, the power reserves of the wind turbines and the flywheels are immediately activated by their local controllers. This activation though, is supervised by the central control system of the WPP, and this is the main contribution of the article.
- The determination of the control method to allow the wind turbines to maintain a certain power margin from the maximum available power that can be extracted from the wind. This control method is included in the local controller of the wind turbines. It is adopted and adapted from that presented in [13]. This is intended as a minor contribution of the paper.

Proposed control schemes for the wind power plant

In regard of the main contributions of the article, this section deals with the presentation of control techniques for enabling a wind turbine to operate maintaining a power margin from the maximum available power that can be extracted from the wind.