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Methodology for the economic optimisation of energy storage systems for frequency support in wind power plants ☆

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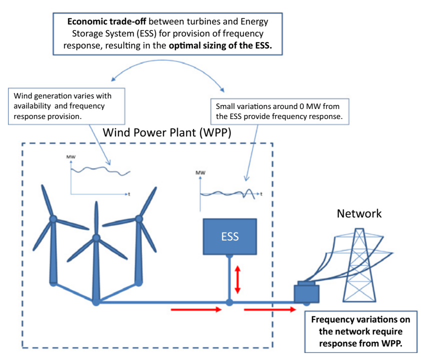
HIGHLIGHTS

- Optimisation of energy storage system with wind power plant for frequency response.
- Energy storage option considered could be economically viable.
- For a 50 MW wind farm, an energy storage system of 5.3 MW and 3 MW h was found.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper proposes a methodology for the economic optimisation of the sizing of Energy Storage Systems (ESSs) whilst enhancing the participation of Wind Power Plants (WPP) in network primary frequency control support. The methodology was designed flexibly, so it can be applied to different energy markets and to include different ESS technologies. The methodology includes the formulation and solving of a Linear Programming (LP) problem.

The methodology was applied to the particular case of a 50 MW WPP, equipped with a Vanadium Redox Flow battery (VRB) in the UK energy market. Analysis is performed considering real data on the UK regular energy market and the UK frequency response market. Data for wind power generation and energy storage costs are estimated from literature.

Results suggest that, under certain assumptions, ESSs can be profitable for the operator of a WPP that is providing frequency response. The ESS provides power reserves such that the WPP can generate close to the maximum energy available. The solution of the optimisation problem establishes that an ESS with a power rating of 5.3 MW and energy capacity of about 3 MW h would be enough to provide such service whilst maximising the incomes for the WPP operator considering the regular and frequency regulation UK markets.

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Nomenclature

Parameters

D	sample days
$E_{fr,t}$	requested frequency response, MW h
$E_{fr,t}^{max}$	maximum frequency response, MW h
$E_{max,t}$	energy available to turbines, MW h
N_s	number of samples
T_s	sample time, mins.
T_{sus}	sustain time for freq. response, mins.
u_t	frequency response sign, binary
Y	expected life of ESS, years
α_H	upper limit of state of charge
α_L	lower limit of state of charge
γ	ESS loss percentage
η^+	ESS charging efficiency
η^-	ESS discharge efficiency
λ_{cap}	price of storage by capacity, €/MW h
λ_{deg}	ESS degradation cost, €/MW h
$\lambda_{fr,t}$	frequency response price, €/MW h
$\lambda_{M,t}$	market price, €/MW h
λ_{pwr}	price of storage by power, €/MW

Variables

C_{deg}	ESS degradation costs, €
C_s	ESS capital costs, €
$I_{fr,t}$	income from frequency response, €
$I_{fr,t}^-$	income from low freq. response, €
$I_{fr,t}^+$	income from high freq. response, €
$I_{m,t}$	income from regular market, €
J	objective function, €
$P_{fr,t}$	turbine freq. response proportion
$P_{res,t}$	turbine reserve proportion
S_{cap}	ESS energy capacity, MW h
$S_{c,t}$	ESS charge, MW h
$S_{cu,t}$	ESS usable charge, MW h
$S_{fr,t}^-$	ESS low frequency response, MW h
$S_{fr,t}^+$	ESS high frequency response, MW h
S_{pwr}	ESS power, MW
$S_{loss,t}$	ESS energy loss, MW h
$W_{fr,t}^-$	turbine low freq. response, MW h
$W_{fr,t}^+$	turbine high freq. response, MW h
$W_{gen,t}$	turbine generation, MW h
$W_{res,t}$	turbine reserve, MW h
$\varepsilon_{fr,t}$	frequency response, MW h
$\varepsilon_{lc,t}$	ESS loss compensation, MW h
Θ_t	energy sold to grid, MW h

1. Introduction

Due to the stochastic nature of wind, the electrical power generated by Wind Power Plants (WPPs) is neither constant nor controllable. This affects network planning, as expected generation levels depend on unreliable wind forecasts. Power quality is also reduced, as the fast fluctuations of wind power can cause harmonics and flicker emissions [1–3]. For these reasons, network operators are gradually setting up more stringent requirements for the grid integration of wind power [5–7]. Amongst other restrictions, they require WPPs to withstand short-circuits and grid faults, to respect a threshold level with regards to the quality of the power generated, and to provide ancillary services to the grid such as frequency and voltage control. All these aspects require WPPs to behave in a similar manner to conventional network synchronised generators.

Network frequency control refers to the methods and capabilities to ensure a continuous balance between generation and power demand. In the case that generation exceeds the power demand, the rotating speed of synchronised generators throughout the network starts increasing, moving the electrical frequency above its set-point. The electrical frequency goes below its set-point in the case where power demand is greater than generation. Both the magnitude and the dynamics of electrical frequency have to be controlled for proper network operation and stability [4]. To match generation and demand, conventional synchronised generating units, such as gas-fired or hydro power plants, provide power reserves which are activated to maintain electrical frequency within admissible limits. These power reserves are distributed throughout different time scales, i.e. primary, secondary and tertiary reserves [8].

Primary frequency control refers to the automatic and local provision of primary power reserves by the generator's governor a short time after detecting a power imbalance in the network, i.e. after detecting an electrical frequency deviation from its set-point [8]. In the event of a frequency disturbance, the deployment of primary reserves recover the power balance in the network, thus stabilizing the frequency excursion at a new steady state level. In the case of a low frequency event, total power output must be raised, in the form of primary reserves, in order to balance the system frequency. Conversely, in the case of a high frequency event, the total output must be lowered. Primary reserves are delivered until replaced by other power reserves in the network, typically named secondary and tertiary reserves. The activation of these reserves bring the electrical frequency back to its initial set-point, whilst recovering active power interchanges between different control areas in the network to their set-points [8]. The deployment of power reserves in the event of a power imbalance in the network is graphically depicted in Fig. 1.

Even though the power generated by wind turbines depends on the unreliable and difficult-to-predict wind speed, there are methods for WPPs to actually provide primary power reserves and thus to participate in grid frequency control. Conventionally, wind turbines are operated at maximum aerodynamic efficiency and therefore do not provide power reserves. Given a wind speed v_w, the power generated by a wind turbine is computed by

$$P = \frac{1}{2}\rho A C_p(\lambda,\beta) v_w^3, \tag{1}$$

where A is the area swept by the blades of the rotor, ρ is the air density and C_p is the aerodynamic power coefficient, which depends on the pitch angle β of the blades and the tip speed ratio λ. The latter is computed by

$$\lambda = \frac{\omega_t R}{v_w}, \tag{2}$$

where ω_t the rotor speed and R the radius of the blades. Normally, the rotor speed ω_t is regulated by acting on the controller of the power electronics of variable speed wind turbines so as to optimize the tip speed ratio and in turn maximize the coefficient C_p.

In the case that wind turbines are required to provide power reserves, they have to be operated so that the aerodynamic coefficient is not maximised, i.e. so that they turn at non-optimal rotating speeds. In such circumstances, wind turbines become