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A review on frequency support provision by wind power plants: Current and future challenges

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ABSTRACT

The continuing increase of wind energy penetration into power systems, in combination with the retirement of conventional generation, raises new challenges for the maintenance of power system stability. This paper presents a comprehensive review of wind power plant capabilities to provide frequency support and the corresponding methods available in the published literature are thoroughly analysed and compared. The topic is covered from different perspectives giving a comprehensive overview on the work carried out in this field. In addition, the integration of energy storage technologies and dispatching of wind farms during frequency deviations are thoroughly discussed. Finally, technical challenges, future research lines and general recommendations are provided.

1. Introduction

The energy policies of various countries, and the strategies of leading companies, highlight that the future is reserved for renewable energy sources, e.g. wind energy, as alternatives to address the electricity supply challenges in order to mitigate carbon emissions and present a competitive alternative for expensive fossil fuels. Wind Europe (formerly EWEA) reveals optimistic plans to integrate a massive number of wind farms (WFs) in the North Sea [1–5]. Similarly, the Danish government has ambitious targets to achieve 50% wind power generation capacity by 2050 [6]. Germany is also progressing in a challenging plan to take out of operation all its nuclear power plants, and construct an additional 40 GW of wind power capacity within the next few years to achieve this target [7].

The expected high penetration levels of wind power into power systems, together with the increase of other power electronics-based technologies (i.e. energy storage, high voltage direct links (HVDC), PV farms, etc.) and the retirement of conventional synchronous plants will introduce power system stability issues. A major challenge will be the reduction of the total inertia, which will result in highly fluctuating and fragile dynamic responses. Accordingly, transmission system operators (TSOs) are developing new grid codes requiring contributions not only from conventional generators but also from renewable energies and power electronics-based technologies (e.g. HVDC). On this matter, ENTSO-e has published an initial draft of its first HVDC code [8,9].

Several issues related to the role of wind power in ancillary services have been discussed in the literature, including voltage and frequency support [10]. In this context, this paper focuses on the active power contribution of wind turbines (WTGs) and WFs to provide frequency support. The theory of frequency support is to provide active power surge during frequency events to mitigate the generation-demand imbalance. Securing stable energy resources and managing this power support are the key challenges that need to be addressed [11]. Frequency metrics and grid code requirements were reviewed in [12], meanwhile this review paper focuses on the technical aspects and the wide range of the control methods proposed in the literature. This paper also discusses the *dispatching* of WFs and WTGs during frequency events. An additional contribution is an investigation of *indirect* methods that enable wind power plants to provide frequency support, markedly energy storage systems. This review also highlights the potential role of HVDC links in frequency support because this connection topology is a promising alternative for offshore WFs.

1.1. Problem definition

Conventional generators have two critical responses to frequency variations, inertia response and primary response as illustrated in Fig. 1, further definitions for load-frequency control could be found in [13]. Inertia response is a natural reaction to sudden drops in system frequency that results in an instantaneous decrease in the mechanical speed of the turbine-generator set. This response extracts the stored kinetic energy (KE) in the rotating parts of the turbine and generator.

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Nomenclature

WS	Wind speed
WF	Wind farm
WTG	Wind turbine generator
A	WTG swept rotor Area
R	WTG rotor radius
DFIG	Double Fed Induction Generator
MPT	Maximum Power Tracking
T	Time interval
P	Active power
KE	Kinetic Energy
Δf	Frequency deviation
H	Inertia constant in seconds
PLL	Phase-Locked Loop
λ	Tip-Speed ratio
BESS	Battery Energy Storage Systems
ω	WTG rotational speed
HPES	Hydro-pumped energy storage
RoCoF	Rate-of-change of frequency
C_p	Performance coefficient
SOs	System Operators
M_v	Special gain of virtual inertia
H_v	Virtual inertia
$K_{i\ ll}$	Phase-Locked Loop integral gain
P_{cmd}	Power command for WTG
SOC	State-of-Discharge
DOD	Depth-of-Discharge
h	Water level in the HPES reservoir
fw	Flywheel
n_{fw}	Number of flywheels
P^*_{fw}	Injected/absorbed power by flywheels
$P_{WTG-MPT}$	WTG output at MPT
$P_{M.\ A}$	Moving average of $P_{WTG-MPT}$ in a time interval
N	Number of WTGs/WF
P_{cmd-WF}	Power command for WF
LIDAR	Light detection and ranging

KE is depleted to increase the mechanical output power of the generator to retain the balance between the electrical demand and mechanical output so that the WTG speed stabilizes at a new slower synchronous speed. However, the deceleration i.e. KE extraction, has a threshold that relies on the inertia constant of the generator (H, typically 4–7 s), and the nominal frequency of the grid [14,15]. The primary response is proportional to the incident frequency drop according to the selected droop value, which is typically 4–12% [14]. The secondary response, which follows inertia and primary responses is less critical to system stability, and it aims to achieve a complete balance between generation and demand to recover the frequency to the safe deadband.

The literature proposes three major concepts to obtain the main two responses *directly* from WTGs, namely 1) emulated (i.e. Synthetic) inertia, 2) droop and de-loading techniques, and 3) WTG overloading i.e. overload the WTG output when the incident wind speeds (WS) is above the WTG rated WS. This type of support could also be carried out by energy storage systems to avoid the integration of special supplementary control methods into WTGs [16].

Another aspect of frequency stability is the over-frequency and it can be solved by the reduction of wind power generation when the frequency deviations violate certain limits, however this aspect is out of scope of this paper. It was considered on a limited scale compared to under-frequency support. It is of note that, the majority of frequency support methods can also regulate the WTG output during over-frequency events [17,18].

2. Synthetic inertia

All renewable power generation technologies (except conventional hydro power plants) are decoupled from the grid through a power electronics (PE) interface that screens any variations in grid frequency due to the very fast response of the PE devices. Hence, the WTG cannot respond naturally to frequency drops although it has reasonable inertia which is comparable to that of conventional generators (i.e. WTGs do have stored KE as they include rotating masses, but they do not *sense* the sudden drop in grid frequency because the converters react very fast and alternate the control signals [19,20]). Here we consider how an artificial (it is also called synthetic and virtual) inertia response can be produced by variable-speed WTGs, specifically, type-3 Doubly-Fed Induction Generator (DFIG) and type-4 Fully-Rated Converter Generator.

In order to answer this question, it should be highlighted that the conventional operation of WTGs relies on Maximum Power Tracking (MPT), where the rotor speed is controlled to maintain the optimum performance coefficient (C_P), which is the portion of extractable energy by the WTG from the incident wind energy given by (1).

$$\text{Mechanical output power} = 00.5 \times \rho \times C_p(\lambda,\ \beta) \times A \times WS^3 \tag{1}$$

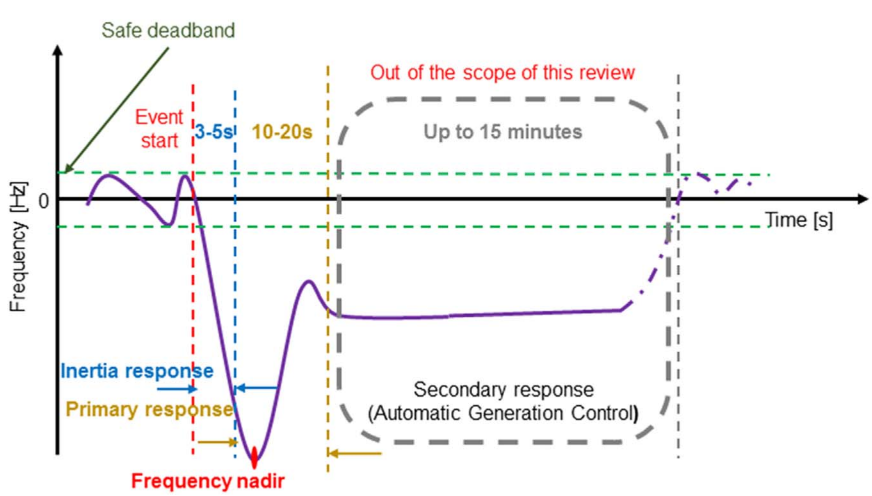

Fig. 1. The main responses provided by power plants to intercept and mitigate frequency drops.