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Provision of ancillary services by renewable hybrid generation in low frequency AC systems to the grid

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ABSTRACT

Wind energy high penetration levels in power systems lead to continuous power imbalance due to the intermittent nature of wind power. This paper proposes and investigates different methods to enable a hybrid generation system to provide frequency support to the grid. The hybrid generation is 100% renewable and composed of a wind farm and hydropower plant (HPP) of comparable generation capacities, and they are interconnected through a Low Frequency AC system (LFAC). The grid–tie is composed of a Voltage-Source Converter based High-Voltage, Direct Current (VSC-HVDC) junction that acts as frequency changer to maintain the grid nominal frequency. The HPP provides two types of ancillary services: wind power smoothing and frequency drops mitigation to avoid the use of thermal generation and battery energy storage. The paper offers different control methods to provide the two AS with improved coordination between the different controls in the hybrid generation system and complying with the common requirements of Grid Codes. The results obtained show that the frequency at the LFAC can tolerate mild drops to provide frequency support to the grid. The controllers' parameters have a clear impact on the frequency response at both systems. Simulation environment is MATLAB and Simulink.

1. Introduction

The key challenge of maintaining the power balance between generation and demand is facing the increased penetration of wind and solar energy. Mainly because the output power of wind farms (WFs) is intermittent and difficult to forecast accurately. At low levels of wind power penetration, wind power plants can be regarded as discretely located and fluctuating negative loads, which can be resolved by the frequency regulation provided by baseline thermal generation. However, the high penetration of wind energy requires more support to compensate power more frequency and larger power imbalance. The consequent influences of generation intermittency are mainly frequency drops, transmission congestions and voltage fluctuations. Frequency drops are the main risk as they can lead to the disconnection of vulnerable generators due to the action of the Rate of Change of Frequency (RoCoF) and under frequency relays and even load shedding [1–4]. In addition, WFs with conventional controls (i.e. maximum power tracking: MPT), are incapable of providing frequency support compared to synchronous power plants that dominate the current power systems. To overcome the stochastic nature of wind power generation, many researchers focused on proposing new control methods for baseline generation that relied on fossil fuel and ancillary equipment [5]. On the other hand, demand side management could be a cost-effective solution to tackle this problem, but it could affect negatively the preferences of customers, which makes it subject to consumers' resistance [6,7]. Wind power can also provide frequency support through the widely applied techniques: droop de-loading, kinetic energy extraction and over-speeding, but they waste wind energy compared to MPT, and mitigate the efficiency of wind power collection [8].

LFAC, also known as the fractional frequency transmission system is a technology that was initially designed to deliver larger power capacities across relatively longer distances. The core idea was proposed by Wang in 1990 s [9,10]. Compared to high voltage direct and alternating current technologies (HVDC and HVAC respectively), LFAC could have economic advantages, when the distance to shore is between 50 and 200 km according to some studies [11–15]. It can also extend the steady state stability compared to standard AC, due to the lower shunt susceptance. Another advantage is that the most existing operation experience and control strategies for power generation and transmission are still functional and adoptable in LFAC as the LFAC is derived from standard AC. However, further strategies on controlling frequency changers including three phase transformer containing saturating

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Nomenclature

AS	ancillary service
WF	wind farm
WS	wind speed, m/s
WTG	wind turbine generator
MPT	maximum power tracking
LFAC	low frequency alternating current system
VSC-HVDC	voltage-source converter high voltage direct current
HPP	hydro power plant
PLL	phase-locked loop
PMSG	permanent magnet synchronous generator
PMU	Phasor Measurement Unit
P_W^f	forecasted output power of wind farm, MW
P_W	actual output power of wind farm, MW
P_d	subtraction between P_W^f and P_W, M
P_H	actual output power of hydro turbine, MWZ
P_H^{ref}	output power reference of hydro generator, per unit
$P_H^{ref\_init}$	initial active power set-point of hydro generator, per unit
P_H^{rated}	rated power of hydro generator, MW
ΔP_H^{ref}	adjustment quantity of power reference of hydro generator, per unit
P_{vsc}	actual delivered active power of VSC station, MW
P_{vsc}^{ref}	reference of delivered active power of VSC station, per unit
$P_{vsc}^{ref\_init}$	initial active power set-point of VSC station, per unit
P_{vsc}^{rated}	rated power of VSC station, MW
ΔP_{vsc}^{ref}	active power set-point of VSC station at LFAC, per unit
$\Delta P_{vsc}^{ref\_max}$	maximum value of ΔP_{vsc}^{ref}, per unit
Ratio A	coefficient of VSC
Ratio B	coefficient of hydro-power plant
Ratio A:B	combined coefficient of VSC and hydro-power plant
RoCoF	Rate of Change of Frequency
Δf_{Grid}	frequency deviation at Grid, Hz
T_{GCCS}^{init}	initial time point of basic control, sec
T_{GCCS}^{peak}	time point where ΔP_{vsc}^{ref} of basic control reaches the peak, sec
$T_{Grid}^{rec\_GCCS}$	time point where the frequency of Grid recovers, Δf_{Grid} is less than 0.3 Hz in
Kp Ki and Kd	proportional gain, integral gain and derivative gain of PID regulator of hydro governor
H	inertia
Tw	water starting time of hydro turbine, sec
Kf	damping filter gain

ferromagnetic coils, phase-controlled AC-AC cycloconverter and matrix AC-AC cycloconverter were presented in [16–19], where stable and quick response at power flow and voltage balancing control were exploited.

Many research focused on the control and operation of LFAC, but less effort considered the integration of hybrid generation to LFAC, which is interconnected to the Grid, and its ability to provide Ancillary Services (AS) to the Grid. This paper offers a hybrid 100% renewable generation (i.e. hydro and wind) LFAC which is enabled to provide power smoothing and frequency drops mitigation to promote the potential of using hydropower to provide frequency regulation at high penetration of renewable energy. A novel topology is adopted to connect the LFAC to the Grid, where the VSC-HVDC acts as frequency changer instead of thyristor-based cycloconverters. Such isolated generation system can be attractive for nations with several hydro and wind energy resources that are remotely located from load centres in the Grid. The HPP provides AS taking place of the conventional thermal generation and the expensive battery storage fully or partially. In particular, HPPs can provide responsive highly controllable, and sustainable frequency regulation. This capability could be curtailed by the parameters of governor controls (e.g. proportional and integral gains) and the width of the applied frequency deadband, which are commonly applied to avoid frequency overshoots at the very early stage of the event. Such isolated generation system can be attractive for nations with several hydro and wind energy resources that are remotely located from load centres in the Grid (e.g. Norway and south western areas of China). The number of pole-pairs of the HPP is selected to comply with the low synchronous speed of the LFAC. The integrated models are adapted to comply with the targeted research objectives and the investigated case studies. This includes the controller parameters, and Phase-Locked Loop (PLL) constants for the applied low frequency (50/3 Hz). A novel and simplified supplementary controller is proposed to dispatch the VSC-HVDC and the HPP to accommodate/cover surplus/deficit power between the forecasted and actual wind power. In addition, two controllers are proposed to make the HPP provide frequency support to the Grid in coordination with the VSC-HVDC station. The results obtained reveal the impact of such methods on both the frequency responses of the LFAC and the Grid. The authors have developed a comprehensive test system that includes the detailed models of the power electronics of converter stations as well as the HVDC connectors in MATALB/Simulink.

This paper exploits the novel integration of a hybrid LFAC generation system that is composed of renewable power plants, i.e. hydropower and a WF. Moreover, three novel control methods are proposed and tested to provide wind power smoothing and frequency support services by this isolated generation system without applying special controls to the WF to avoid any undesirable reduction in the WF production. In particular, the hydropower plant is responsible for providing these services in coordination with the WF production and the Grid frequency response. The key parameters of the three control methods are carefully tuned through well-defined case studies that provide comprehensive sensitivity study of each parameter, and in relation to other factors. The credibility of the obtained results is improved through the detailed test system that includes the power electronics models, wind speed variations and full models of the WF, HPP, and the Grid.

This system can act as an attractive choice to connect offshore and onshore WFs to the Grid, as it combines the benefits of HVDC transmission systems and the LFAC system that has natural inertia and is considered as a compromise between HVDC and HVAC.

The paper is composed of six sections including this introduction. Next section explains the applied methodologies of power smoothing and frequency drops mitigation. Section 3 describes the applied case studies of power smoothing and three kinds of frequency drops mitigation. Results are discussed in Section 4, and Section 5 concludes.

2. Methodology

The strong move towards offshore wind energy includes the integration of different transmission technologies like LFAC and HVDC. This paper exploits the dynamic stability of a novel energy system that integrates a WF and a HPP that are interconnected through a LFAC. The HPP could be a hydro energy storage system or a conventional HPP [20]. The LFAC system is connected to the Grid through a HVDC junction using VSC power electronics interface as shown in Fig. 1. In this paper, the dynamic study is focused on the role of such hybrid generation to provide frequency AS to the Grid: wind power smoothing and frequency drops mitigation.

2.1. Wind power smoothing

The proposed method utilizes the HPP as a 'power buffer', which