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Enhancing frequency stability by integrating non-conventional power sources through multi-terminal HVDC grid

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ABSTRACT

The 2050 targets established by the EU will foster both larger penetration of renewable energy, especially wind power, and more cross-border interconnections. Moreover, this new framework requires the non-conventional power sources and power converter-based systems to be responsible for the duties traditionally carried out by conventional synchronous generators as frequency support. This paper presents how different power-electronic based technologies can provide frequency support individually and in a coordinated manner (with different priority given by the deadbands) ensuring a stable operation.The implemented scenarios examine challenging conditions, where the primary reserve of the interconnected conventional, renewable, and storage generation is fully utilized to tackle frequency incidents. This demonstrates how the joint regulation of the power electronic-based technologies enhances the frequency stability of the AC synchronous areas. The different control schemes and their interaction are investigated in Cigré DC grid benchmark adapted for frequency stability studies and implemented in Matlab/Simulink simulation tool. This modified grid includes 5-terminal HVDC grid with two offshore wind farms and three AC networks including battery and onshore wind farms.

1. Introduction

The European Union (EU) has pushed towards the full decarbonization of the energy systems with the targets and plans set for 2050, which aim to reduce the greenhouse gas emission levels of 1990 by 80–95% [1]. It is expected that this objective will foster the electricity generation share of renewable energy sources up to 100% [2]. The European Wind Initiative (EWI) foresees that, under this green scenario, wind energy supply about 50% of Europe electricity needs [3].

To achieve such penetration level, wind power plant installations have to continue increasing. The current trend is to develop larger, in both size and ratings, wind turbines and to install them offshore due to less space restrictions and better wind conditions [4]. In addition, offshore wind farms are moving to farther locations with distances longer than 100 km from shore [5].

According to these changes, high voltage direct current (HVDC) transmission technology become an attractive option. For long distances and large amount of transmitted power, HVDC is a strong competitor compared to conventional high voltage alternate current (HVAC) [6]. In order to allow larger penetration of offshore wind power (and renewables in general) into the power system, more interconnection and power sharing capability between different countries are required (e.g. SuperGrid concept [7]). Thus, taking advantage of offshore wind power and the HVDC technology, multi-terminal HVDC networks can be integrated to make it real [8]. As an initial step, a HVDC link is planned to connect between Norway and Scotland (i.e. NorthConnect [9]).

The reduction of global inertia is one of the major barriers for power systems that is caused by the increased renewable energy penetration and the shutdown or replacement of conventional synchronous generators (e.g. nuclear) as well as the increment of generation connected through power electronic based systems (i.e. inverter-based, HVDC links, MultiTerminal-HVDC) and the installation of energy storage and FACTS which may help on ensuring stable and secure operation. This leads to a change in power system dynamics making the network more vulnerable to frequency excursions. In order to mitigate that critical impact and keep the power system stable and secure, transmission system operators (TSOs) are developing novel grid codes with more restrictive and/or novel requirements to the generation (including wind) and power transmission systems (i.e. HVDC) [10–13]. These novel grid codes state that HVDC systems and any type of generation of a

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certain size (above 50 MW in continental Europe, 10 MW in Great Britain or 5 MW in Ireland) should provide frequency support [11].

Since wind power and HVDC systems are power-electronic-based technologies, they have the capability of fast active power regulation, making them suitable for primary frequency support becoming the first protective barrier to frequency instability. In this regard, wind power may provide such support to the grid by different ways depending on the time-frame objective. On one hand, supporting fast primary response by delivering the kinetic energy naturally stored in the rotating masses within the wind turbine (i.e. inertia response) [14–16]. On the other hand, supporting slow primary response by either maintaining certain power reserves on wind turbines through de-loading or over-speeding control techniques [17–19], or coordinating wind farm response with energy storage systems [20,21]. In the HVDC based systems, the transmission network may contribute to frequency support through modifying the power sharing among the different stations [22–24] or by trying to take advantage of the existing energy stored within the capacitors of the DC side, which could act as DC grid inertia [25,26].

This paper integrates different theoretically-mature frequency support methods from wide range of conventional power sources and non-conventional power electronic based technologies including onshore and offshore wind power, battery energy storage and MT-HVDC. Thus, the interactions between the responses of these controllers are examined and compared. The key contribution is to show the need of potential coordination between different controllers that have the same major objective, because if they act simultaneously it could jeopardize their responses. The available control methods are modified to produce a simplified picture of the proposed coordination and its impact on frequency stability. For example, properly tuned deadbands could maintain reasonable coordination and prioritization relying on the profile of each technology (i.e. available power reserve, speed of response, control methods and parameters). The applied case studies have been developed to compare the integration and coordination levels between different generation assets and controllers that are able to provide frequency support. The proposed control methods acknowledge the operation limits of different elements (e.g. BESS state of charge, converter stations capacities, available primary reserve, etc.).

In addition, a supplementary controller is developed to enable the battery energy storage system (BESS) to respond to the abrupt changes in power delivery across the MT-HVDC grid. To improve the credibility of the obtained results different communication delays are applied, as well as severe scenarios (e.g. very steep wind speed drops and low available stored energy) are thoroughly investigated. This paper focuses on frequency stability, the control methods are dedicated to provide and enhance frequency support. The analysis of system response to other types of faults and stability issues is out of scope. However, the holistic control method of the MT-HVDC grid is capable of adapting the requirements of the integrated systems because it is based on consensus theory. As an illustration, if a MT-HVDC converter station suffers a fault or one of the dc lines is lost, the control will modify autonomously the power export/import set-points in all AC areas and wind farms trying to cope with the new operation conditions of the whole system. The proposed case studies are evaluated through dynamic simulations in a 5-terminal HVDC network based on the Cigré DC grid adapted for frequency stability studies. The model have been developed in Matlab/Simulink simulation tool. The implemented benchmark accommodates two offshore wind farms that are connected to two stations of the MT-HVDC and three synchronous areas. In one AC grid a battery energy storage system is installed; whilst in another AC network an onshore wind farm is integrated.

2. Frequency support methods

In this section, the frequency support methods applied to different non-conventional power sources including both onshore and offshore wind power plants, BESS and MT-HVDC are explained.

2.1. Wind power plants

As previously stated, to enable the wind power plants to provide frequency support an increment on active power generation is required. In particular, wind power plants can provide primary frequency support through two main ways, i.e. naturally stored kinetic inertia energy or maintaining certain reserve levels. In this paper, two different wind turbines are integrated offshore and onshore to investigate the interactions between WTGs from different manufacturers.

2.1.1. Onshore wind power plants

The partial de-loading method is implemented to the onshore wind farm (OWF) [18]. The partial de-loading method integrates two main concepts to enable wind power to provide frequency support, namely, pitch de-loading and kinetic energy extraction. This aims to minimize energy losses that occur due to continuous de-loading. This method applies four operation regions according to the incident WS as illustrated in Fig. 1. In this paper, an average WS is examined, hence, each WTG in the onshore WF in Area 2 is operating in region 2 under conventional pitch de-loading. This method does not rely on frequency measurement to manage the amount of provided support power but only as a trigger (i.e. activation-deactivation) signal. However, it requires rough estimate of the incident wind speed to determine operational region and the potential power reserves.

2.1.2. Offshore wind power clusters (OWPCs)

A continuous pitch de-loading approach is applied to OWPCs, where the pitch angle is adjusted to keep a certain percentage of the available power as reserve. A droop control is implemented to drive the supportive power surge such that it is proportional to the frequency deviation, as shown in Fig. 2(a). The frequency drop initiates a regulated removal of this de-loaded state until the frequency reaches a certain threshold where the wind turbine is already providing the total amount of available power to the grid, as can be seen in Fig. 2(b). The presumed de-loading ratio is widely discussed in literature [27,28] and it also has economic implications, where the curtailed production will lead to reduced income, however, the financial aspects are not of interest to this paper. Conversely to the partial de-loading, this method needs the frequency measurement but allows intermediate power management. This method is seen as a better option for offshore wind because of the higher and more constant wind speed profiles compared to onshore sites.

2.2. Battery Energy Storage System (BESS)

The BESS carries out different tasks such as the provision of frequency support, coping with the power mismatch caused by OWPCs during short-time. It also provides the balancing power to the local area for fulfilling the increment change in the imported/exported power of each AC area or OWPC according to the set-points provided by the MT-HVDC frequency support controller. The control method applied is a developed version of the control proposed in [20], implementing a rate-of-change-of-frequency (RoCoF) and droop based frequency control and an export power deviation balancing support, as shown in Fig. 3. In this paper, BESS controls have the capability of providing inertia