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Novel concept of renewables association with synchronous generation for enhancing the provision of ancillary services

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HIGHLIGHTS

- Novel concept to associate renewables with conventional generation.
- It is adaptable to the controls of renewables' farms, converter stations and units.
- It is applied to enable the provision of voltage support by converter stations.
- It is also applied to provide frequency support by wind turbines.
- The proposed implementation method avoids frequency measurements.

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ABSTRACT

Renewable energy sources are foreseen as a provider of full range of ancillary services. An innovative concept of alignment between renewable power generation elements and synchronous generators is proposed: Renewables Association with Synchronous generators (RAS). It mitigates the dependence on direct frequency measurements, which are prone to noise and lack of accuracy, and enables perfect coordination between the responses of renewable and conventional power plants. RAS relies on a leader synchronous generator, connected at the point of common coupling of the renewable power plant or close to it. This synchronous generator is able to provide ancillary services (e.g. frequency support and reactive compensation). The renewable power plant is controlled to provide such services similar to the leader synchronous generator, but scaled down/up to match the rating of the renewable power plant by integrating supplementary controllers that are associated with the synchronous generator response. Two approaches are proposed to provide voltage support, besides a supplementary frequency support controller. These RAS-based voltage and frequency support methods are compared to other methods proposed in the literature. Results show the positive impact of RAS concept on the provision of active power and reactive compensation to tackle frequency and voltage events respectively, following the response of the leader synchronous generator. DIgSILENT PowerFactory is the applied simulation environment.

1. Introduction

The foreseen high penetration of Renewable energy sources (RES), mainly wind energy into power systems imposes strong challenges regarding the provision of ancillary services (AS) [1,2]. The key challenge of RES, except hydro, is their connection method to the grid as they are decoupled through power electronics converters (PEC), which act as an interface between the energy harvesting systems (e.g. solar panels, wind turbine generators; WTGs), and the AC grid [3]. Hence, the PEC screen the variations and events on the grid side, and handle it rapidly without being observed by the WTGs. Consequently, the WTGs do not naturally provide conventional frequency and voltage support similar to synchronous generators (SGs). Conversely, a conventional SG is directly connected to the AC grid, which enables it to respond to all changes in voltage and frequency in the grid using its exciter and governor systems. The main differences between the two generation technologies are summarized in Table 1.

Frequency response is executed by synchronous power plants through a natural response, i.e. rotating parts inertia, and primary response provided by the governor, i.e. droop setting [4]. Frequency measurement is not required to drive both types of response, where the governor receives the deviation in generator speed compared to its

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Nomenclature

AS	ancillary services
D_F	de-loading factor
f_{low}	frequency deadband in conventional support method
f_d^m	frequency deviation to release full support
HVDC	high voltage direct current link
k_1, k_2	coefficients of RAS-based frequency support method
PCC	point of common coupling
PEC	power electronic converters
PMU	phasor measurement unit
P_{ref}^o	wind turbine optimal active power reference
P_{ref}	wind turbine actual reference active power
P_{SG}, Q_{SG}	active and reactive power at the leader generator bus respectively
pu	per unit
Q_{ref}^o	default reference reactive power
Q_{ref}	actual reference reactive power
RAS	renewables association with synchronous generators
REC	receiving end converter
RES	renewable energy sources
$RoCoF_m$	maximum rate of change or frequency
SG	synchronous generator
V_{PCC}	voltage at PCC (suffix *o* stands for nominal value)
V_{RAS}	voltage limit to initiate RAS voltage support
v_{SG}	voltage at leader generator bus
WTG	wind turbine generator

Table 1
Differences between SGs and RES in provision of AS (PCC: point of common coupling).

Point of comparison	Conventional generation	Renewable generation
Energy source	Dispatchable fossil fuel	Predictable and intermittent
Connection to AC grid	Direct connection	Decoupled by power electronics
Grid frequency sensing	Direct through generator speed	Measured at a certain point of the grid
Response to frequency events	Inertia (natural), primary and secondary	Integrative inertia and primary response using special controls
Grid voltage sensing	Direct at connection point	Measured at PCC
Response to voltage events	Reactive compensation using exciter	Low voltage ride-through using special controls in WTG and/or receiving converter station

synchronous speed, which is the nominal frequency of the grid, and regulates the input mechanical power (e.g. valve opening in case of steam turbines) to maintain the nominal speed. The literature proposed a wide range of control methods to enable WTGs to provide frequency support, namely synthetic inertia and primary response [5,6]. The provision of frequency support by wind power, includes three technical obstacles, intermittent wind speed that makes the provided supportive active power highly uncertain, the applied method to secure active power reserve during normal operation, and frequency measurements. There are two main concepts to secure power reserve by wind power, kinetic energy (KE) extraction and droop de-loading. The KE extraction method does not deviate the WTG from the traditional Maximum Power Tracking (MPT) operation, where during frequency drops the rotor speed decelerates, and the extractable KE is converted into electrical energy to deliver power support retaining the balance between generation and demand [7,8]. The de-loading concept relies on continuous de-rating of the WTG output to secure a certain margin between the available optimum output and the actual de-loaded output. This margin can be a constant value or a ratio of the available production, these two approaches are known as Balance and Delta de-loading respectively [9]. With the previous methods rely on frequency measurements, where the frequency deviation is the main input to the integrated supplementary controllers, and it is communicated to WTG or wind farm (WF) controls to determine the required power support. The provided support does not follow a certain predetermined pattern, but it depends on the incident wind speed, applied support method and event severity. There is also a more generic concept of Virtual Synchronous Machine (VSM) where the power electr0nics coupled system is controlled to provide responses acting as a virtual SG. This concept has been applied to WFs [10] and electric vehicles as well to provide frequency support [11]. There is also a strong research and industry trend to curtail this challenge by enabling the demand side response, including electric vehicles, where certain uncritical loads can be curtailed to mitigate frequency drops and provide artificial and passive frequency support on behalf of RES [12,13].

The WTGs/WFs are required to ride through system faults and provide reactive compensation contributing to voltage recovery during and shortly after voltage events [14,15], where this type of AS is always prioritized over frequency support [16]. This splits into two tasks, the WTGs/WF must keep connected to the grid and does not trip, within the early stage of the fault without causing any damage to the WTG [17]. Afterwards, it has to inject reactive power/current to mitigate the voltage drop and recover the nominal voltage. This process is executed in SG by the field winding exciter, which increases the field current when the voltage across the machine terminals drops [4]. However, supplementary controllers are integrated to regulate the *d* and *q* components of the current (i_d and i_q) to inject a certain level of reactive current by WTG grid-side converter or the onshore converter stations that deliver WF power, without violating their ratings and controllers' limitations [18–20].

In the context of the previous discussion, this paper presents the novel RES association with synchronous generators concept (RAS) to enhance the provision of frequency support and reactive compensation by wind energy. The offshore WF, integrated into the investigated test system, is connected to an AC grid through a high voltage direct current link (HVDC). A supplementary controller is proposed and integrated into the generic double-fed induction generator (DFIG) WTG model to associate the provided frequency support by each WTG in the WF with a leader SG located near PCC of the onshore converter station. Two control approaches are proposed and integrated into the Receiving End Converter (REC) controller to mimic the response of the leader SG during voltage dips. Thus, the application of RAS is examined on two fronts, WTGs and the onshore converter station. The proposed controllers are compact and avoid complicated methods as they rely on one or two inputs received from simple measurements at the leader SG bus. These measurements are utilised to manipulate the set-points of active power and reactive power of WTG and REC controllers during frequency and voltage events respectively. The application of this concept is expected to avoid the dependence on frequency measurements and make the provision of AS more predictable, as it follows the conventional patterns of SGs responses during critical events. Both voltage and frequency controls are integrated and operational simultaneously, which is an additional aspect of novelty because most of the research studies, oriented to the provision of ancillary services, focused on one AS only ignoring the possible mutual interactions if more than one support method is integrated. Moreover, the proposed concept is valid