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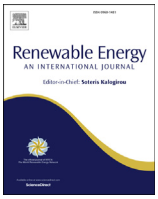

A dynamic coordinated control strategy of WTG-ES combined system for short-term frequency support

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ABSTRACT

In this article, a dynamic coordinated control strategy is proposed for wind turbine generator (WTG) and energy storage (ES) combined system, which enables the combined system to participate in the short-term frequency regulation of the utility gird. The theoretical analysis of the equivalent inertia of the combined system is performed and the mechanism of the short-term frequency regulation is revealed. The coordinated control strategy is designed considering the variability of wind power and the state of charge (SoC) of ES, which ensures a good performance of the frequency support under the wind variation and the SoC changing. Case study is used to validate the proposed strategy, which indicates that, this strategy can adaptively adjust the power distribution between the WTGs and the ES units during the frequency support, keep the output power stable when the wind speed changes, and diminish the decrease of SoC of the ES units.

1. Introduction

With the increasing penetration of wind power, the problem of low inertia has risen gradually and posed a great challenge for stable operation of power grid [1]. When there exists a mismatch between the power generation and the consumption, the conventional power system utilizes the inertia of synchronous generators (SGs) to provide a short-term frequency support, thus the deterioration of system frequency can be relieved. However, the rotor speed of wind turbine generator (WTG), which corresponds to the WTG's inertia, is decoupled from the frequency of utility grid, which means higher risk of frequency collapse for the wind power integrated system [2]. Therefore, it is essential to exploit the frequency-supporting capability of WTGs.

The strategies on frequency support of WTG in power system have been studied in the previous works, which are classified into two scenarios: long-term frequency support (LTFS) [3,4] and short-term frequency support (STFS) [5,6]. LTFS usually depends on the de-loading (DL) operation scheme, which keeps the WTG from the maximum power point tracking (MPPT) and thus maintains a certain amount of power reserve for frequency support [7]. The DL based LTFS can provide the system with more controllable power reserve, but the loss of the wind power cannot be neglected. STFS utilizes the kinetic energy (KE, corresponding to WTG's inertia) stored in rotating masses by decreasing rotor speed, thus provides a temporary power support. Due to its avoidance of spillage of wind, KE based STFS has drawn a great attention. However, a second frequency drop (SFD) might be caused during the rotor speed restoration, and some complementary control strategy are proposed to address this problem, such as dynamic droop coefficient control [8] and wind speed adaptive control [9].

With the development of energy materials, the energy storage (ES) devices are being widely used in the power grid [10]. ES has a great contribution to enhance the stability when the high percentage renewables accessed in the power system [11]. In Ref. [12], the potential of the ES to improve the frequency performance of isolated grid is explored. In Ref. [13], a coordinated H_∞ control strategy is proposed for ES and generator to enhance the frequency stability of power system. In Ref. [14], the ES units are used for wind farm to suppress the power fluctuation due to the variation of wind speed, which is formed as WTG-ES combined system. However, in practice, the applications of large-scale ES are limited due to the

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Nomenclature

WTG	wind turbine generator
ES	energy storage
STFS	short-term frequency support
DL	de-loading
MPPT	maximum power point tracking
SoC	state of charge
KE	kinetic energy
SFD	second frequency drop
DFIG	double fed inductive generator
RSC	rotor-side converter
GSC	grid-side converter
β	pitch angle
v_{Wind}	wind speed
ω_r	rotor speed
P_m	mechanical power extracted from wind
P_e	electrical power of DFIG
P_{WTG}	output power of WTG
P_{ES}	output power of ES unit
ρ	air density
S	rotor sweep area
λ	tip speed ratio
β	blade pitch angle
C_p	aerodynamic power efficiency
ω_{opt}	optimal mechanical rotor speed
R	rotor radius of wind turbine
H_{WTG}	inertia constant of WTG
W_{WTG}	kinetic energy of the rotor
S_{WTG}	rated power capacity of WTG
J	moment of inertia of WTG
HSTFS WTG	inertia constant of the WTG system in STFS
HSTFS WES	equivalent inertia constant of the combined system in STFS
ω_0	initial rotor speed
ΔPSTFS WTG	additional power increment of the WTG when releasing KE
ΔPSTFS WES	output power of ES units for STFS
ΔP VD	power reduction due to the speed decrease
ΔPWTG	instant total increment of WTG's active power
ΔP WTG WES	additional increasing power of WTG in combined system
P0 WTG	initial output power of WTG
ΔP_{ES}	additional increasing power of ES in combined system
P0 ES	initial output power of ES unit
VRef r	reference RSC voltage
Δt	duration time of STFS
k_{ES}	adaptive participation factor of ES
k_{WES}	primary frequency coefficient
f_{Ref}	reference frequency
Δf_0, Δf_m, Δf_s	initial, maximum and steady-state frequency deviation
t_m, t_s	frequency peak time and regulation time during STFS
V_g, V_r	speed of frequency gliding and restoration
FN	frequency nadir

high investment and the varied state of charge (SoC) during operation [15,16].

Recently, there are some researches on the utilization of WTG-ES coordination potential for STFS. In Ref. [17], a coordinated control strategy is proposed, which releases the KE of WTG when the frequency drops, and ES is activated when the rotor speed reaches the lower limit, thus ES serves as the auxiliary reserve to participate in the frequency support when the WTG runs out of its power reserve or in the large disturbance of power mismatch. However, this leads to the waste of ES capacity. In Ref. [18], a fuzzy-logical based control scheme is proposed, and various signals, such as frequency deviation, wind speed, and SoC, have been taken into consideration. However, the output power of The WTG-ES combined system is not determined proportionally to the frequency change, which means the combined system cannot perform like SGs in STFS when the system operators make power dispatching decision. In Ref. [19], a hybrid control strategy STFS is proposed considering the DL state of WTG and the SoC of ES. However, the frequency response power of the combined system is calculated on the premise of obtaining the load power, which is hard to acquire precisely in practice.

In this article, a coordinated control strategy is proposed for the WTG-ES combined system. The WTG and ES can take part in the STFS simultaneously. As the frequency response power is calculated using the formula analogous to the primary frequency regulation, the WTG-ES system features similar response characteristics of SGs in STFS. By considering the variation of wind power and state of charge (SoC), the stability of the combined system during frequency support can be enhanced and the frequency performance can be improved as well.

2. Operation of WTG-ES combined system

Fig. 1 shows the topology of the WTG-ES combined system, which contains a wind turbine, double fed inductive generator (DFIG), back-to-back converters, step-up transformers, inverter based ES unit, and the coordinated controller. The ES unit is installed at the grid connected point of the WTG. The coordinated controller is used to monitor and adjust the output power of both the WTG and the ES unit. When a frequency disturbance at the grid side occurs, the controller will determine the participation factors according to the variables (e.g., SoC of ES, wind speed, grid frequency and rotor speed) to adaptively adjust the output power of WTG and ES unit, which takes good advantages of the frequency-support ability of the WTG-ES combined system.

The WTG system outputs electric power by absorbing the mechanical power from the wind energy and transfers it by DFIG. The amount of output power is determined by wind speed, pitch angle, rotor speed, etc. Therefore, without additional control loop, the characteristic of WTG can be described as [20]:

$$P_m = \frac{1}{2}\rho S v_{\mathrm{Wind}}^3 C_p(\lambda, \beta) \tag{1}$$

where P_m is the mechanical power extracted from wind; ρ is the air density; S is the rotor sweep area; v_{Wind} is the wind speed; λ is the tip speed ratio; β is the blade pitch angle; and C_p is the aerodynamic power efficiency expressed by:

$$C_p = 0.73\left[\left(\frac{151}{\lambda_i}\right) - 0.58\beta - 0.002\beta^{2.14} - 13.2\right]e^{(-18.4/\lambda_i)}\lambda \tag{2}$$

where