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Penetration impact of wind farms equipped with frequency variations ride through algorithm on power system frequency response

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ABSTRACT

Focus of power system engineers is currently directed to the impact of wind power on system frequency. Research efforts concentrate on the ability of wind farms to contribute in the frequency droop events by injecting active power to the grid. This paper presents a detailed analysis for the effect of wind farm connection to a certain power system on the system frequency response. Most of wind farm parameters were considered, namely, the actual wind speeds, wake effects inside the wind farm, the different arrangements of wind turbines inside the wind farm and pitch control mechanism. Moreover, the major data of a h power system were included; different conventional generation technologies and their suitable speed governors. In addition, instant dynamic load variations were implemented. Five case studies were conducted through this system to test the system frequency attitude during normal operation and in case of sudden and large load changes. Three basic values are used to estimate the mentioned impact; the time needed to reach the safe margin after a certain droop, the RMS value of frequency deviation after the fault initiation by a given fixed time span and the maximum frequency drop for each event. All the previously stated studies are performed using MATLAB and Simulink simulations depending on real wind speeds data.

1. Introduction

Energy market is directed strongly towards renewable energies. The facts of running out of conventional fuels like coal and oil beside the high rates of CO_2 emissions have forced many countries to concentrate their research and future power generation planes in the field of clean renewable energies. Companies and governments are always seeking for the renewable energies of the cheapest and easiest installations and operation methods, namely, wind energy. It is expected that by the end of this decade wind energy generation will form about 20–25% of the generation capacity in several developed countries [1] (e.g. USA, Germany and Netherlands).

Through the last two decades research efforts focused on finding feasible solutions for the variable nature of the wind speed which in turn affect the output power of WFs. This creates a great challenge for power system engineers to estimate the share of WFs in supplying the normal demand. Moreover, setting an optimum scenario for the WFs to support the power system during frequency drop events is a top priority. Frequency support is mainly based on the amount of the stored KE in the rotating masses of the connected machines in the system and the time required by these machines to release a certain amount of this energy avoiding any possibilities of losing synchronization and protecting the system stability [2,3]. Research work in [4] offered a criterion which estimates the available stored KE in each WT based on the instantaneous wind speed. Obtaining a considerable stored KE capacity was based on de-rating the WT operating speed by a certain factor so that it runs at a given value of C_p which is less than the optimum value of C_p. Effect of replacing conventional generators by WFs was studied in [5]. It concluded that penetration of DFIGs in power system does not affect its total inertia if it doesn't replace a conventional power generator. This returns to the independency of the converter-coupled generator frequency from the grid frequency. Anyhow, it tried to evaluate the inertia constant of a DFIG if it supplies its rated electrical torque at the frequency drop instant within a given acceleration time using an auxiliary controller. Reference [6] presented a strategy which controls the active output power of a WF at various categories of wind speeds. Pitch angle control was mainly used in case of high wind speeds to keep the output latched to a predetermined reference output power. In addition; it estimates the power margin of each WT as the difference between the available wind power and the scheduled output power. Almost a similar work was proposed in [7]; it focused on modeling the WT and DFIG in steady state and dynamic conditions. Wide spectrum of literature tried to link between simplified and complicated models of wind speeds variations and the dynamic modeling of the output power of WF [8]. Three different types of control techniques were studied along with their effect on improving the WF performance during frequency drops.

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Nomenclature

WT	wind turbine
WF	wind farm
KE	kinetic energy
C_p	wind turbine coefficient of performance
DFIG	double fed induction generator
AGC	automatic generation control
pu	per unit value for any given parameter
β	AGC biasing frequency droop coefficient (MW/Hz)
C_{pAGC}	AGC proportional constant
K	AGC frequency deviation gain factor (MW/Hz)
T_n	AGC delay time constant
R	generator frequency droop (pu power/pu frequency)
n	number of power plants
H	system inertia (s)
S_b	overall power system generation base value MVA
S_i	MVA base value for power plant number (i)
f_o	nominal system frequency
D	damping coefficient for the frequency dependent loads (Hz/MW)
W_o	damping coefficient of frequency disturbances for rotating mass loads (MW/Hz)
$\Delta P_{\mathrm{AGC}}(s)$	transfer function of the implemented AGC
$\Delta P^{i}_{\mathrm{AGC(pu)}}$	the instantaneous per unit mechanical power signal from AGC to generation plant (i)
ω_A, ω_B, ω_C, ω_D	angular speed of the WT at points A, B, C and D respectively in per unit values
P_A, P_B, P_C, P_D	output power of the WT at points A, B, C and D respectively in per unit values
P_{ref}	reference WT output power for the pitch controller
K_i, K_p	integral and proportional gains for the pitch angle PI controller
$K_{actuator}$	gain of the servomotor controller adjusting the pitch angle
$T_{actuator}$	time delay of the servomotor controller adjusting the pitch angle

This paper merges some of the basic algorithms highlighted above. The main target is to propose a well managed forecasting theory for the power system frequency stability performance at different cases of study considering wind power penetration. Moreover, it offers a simplified method to simulate WFs reaction in case of loss of load or generation events in the power system. Variation of wind speeds and the wake effect are considered in evaluating wind speeds at each WT inside the WF for each time step as described in [9]. The paper is arranged as follows; the second section describes the proposed algorithm for the WF simulation during normal and fault conditions. Sections 3 and 4 summarize comprehensive data about the power system, wind streams and WFs implemented in this research work. Section 5 is a detailed explanation for all the simulated case studies. Finally, Section 6 displays the main results plus a short discussion while Section 7 highlights the most important conclusions and outcomes beside the expected future work.

2. Proposed approach

Some research works dealt with WFs as sources with no spinning reserve so they do not play any role during frequency droops [10]. On the other hand, the most applicable method was to force the WT to feed a certain amount of electrical power counting on the stored amount of KE at the instant of fault [11,12]. This certain fixed electrical power is fed to the power system as long as the angular speed of the WT is more than 70% of its nominal rated value. This fixed active power value is pre-determined by the operator. In this paper it is assumed to be 80% of the WT full rating (1.2 MW). At 70% of the nominal speed the machine has already extracted 51% of the KE stored in its rotating parts. Therefore, beyond this limit the machine is in the risk of complete stopping.

This paper explains a methodology to manage the injected active power by the WF to the power systems at different operating conditions. The offered approach manages the output power of each WT inside the WF through the following three modes.

2.1. Normal operation mode

This mode describes the operation of the WT if the system frequency deviation is kept within predefined acceptable limits. During this mode WT feeds the available power based on the instantaneous value of the wind speed. The borders of this region are defined by two points; the maximum accepted drop and the maximum limit for the frequency positive deviation. In this research work these values are −0.08% and 0.1% of the system frequency respectively. The output of the WT is divided accordingly to five sub-modes:

2.1.1. Low wind speeds

Relation between rotational speed and mechanical output power are considered to be linear as in Fig. B.1. It is presented by the following equation [13]:

$$\omega_{\mathrm{pu}} = \left(\frac{\omega_B - \omega_A}{P_B - P_A}\right)(P_{\mathrm{m\_pu}} - P_A) + \omega_A \tag{2.1}$$

2.1.2. Medium wind speeds

Default curve through the majority of literature which depends on calculation the optimum value for C_p to extract the maximum available power in the wind.

2.1.3. Relatively high wind speeds

Linear relation from points C to D describes the variation of output mechanical power based on WT rotational speed. This curve [13] is applied to increase the accuracy of estimating the available mechanical power instead of using the standard power curve. The applied function is as follows:

$$\omega_{\mathrm{pu}} = \left(\frac{\omega_D - \omega_C}{P_D - P_C}\right)(P_{\mathrm{m\_pu}} - P_C) + \omega_C \tag{2.2}$$

2.1.4. Wind speeds lower than wind speed A

Wind speed A is the cut-in velocity. In this case the output mechanical power is zero.

2.1.5. Wind speeds between point D and the cut-out velocity

Pitch angle control mode is activated to limit the output mechanical power of the turbine to match the ratings of the generator. The pitch angle controller is shown in Fig. B.2.

In most of literatures it is assumed that the WT is following only one curve through the whole spectrum of WS starting from (cut in till rated speed). In this paper, the curve is split into three regions according to the wind speed. Afterwards, pitch control is activated