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Evaluation of Inertial Frequency Support Provided by Variable Speed Wind Generators

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Abstract: - The massive integration of wind power using power converters imposed several challenges to the future power system. One of them is related to the decoupling effect of new power sources from the AC power grid, incapacitating a natural frequency response. This situation negatively affects the system frequency response. The aim of this paper is to evaluate the inertial frequency support provided by variable speed wind generators. Time domain simulations of a test system are used for an evaluation of the inertial response provided by the wind turbines. Two major contributions of this paper are: (i) to highlight the positive effect of the inertial response on the system frequency response considering different load variation conditions; and (ii) to practically identify a limit of the synthetic inertia parameter, beyond that the wind turbine stalls negatively affecting the power system.

Key-Words: - Frequency controller, frequency stability, power system, protection scheme, wind turbine generator

1 Introduction

The frequency control is being traditionally performed by conventional synchronous generators in almost all power systems [1]. Traditionally, wind farms have not contributed to system frequency support. However, as the global penetration of wind power into the power system increases, the grid code requirements are gradually becoming more demanding. Apart from the well-known *fault-ride through* capability for wind farms the frequency stability support is also becoming an important aspect of grid codes around the world. Massive integration of wind power is expected to be part of the power system and therefore some countries have started to establish new grid codes relevant to wind farms. Several transmission system operators have discussed the inclusion of frequency response in grid code. During a *system frequency disturbance* (SFD) the generation/demand power balance is lost, the system frequency will change at a rate initially determined by the total system inertia [2]. However, future power systems will increase the installed power capacity (MVA) but the effective system inertial response will stay the same nowadays [2, 3]. The result is deeper frequency excursions of system disturbances.

Many modern *wind turbines* (WT) have the ability to control active power output in response to grid frequency in ways that are important to overall grid performance and security. Several publications relate the main aspects and considerations about modelling [4] and simulation [5] of the inertial response of wind turbine generators (WTG) and some of them provide general ideas about possible impacts on power systems and their effects on transient under-frequency response [6]-[7].

This aim of this paper is to evaluate the inertial frequency support provided by variable speed wind generators. The paper is organized as follows. Section II introduces the main concepts related to power-system frequency-response, Section III the main controllers used for frequency support in wind turbines. Section IV presents the main description of the system modelling used in this paper. Section V presents the simulation and results. In this paper, time domain simulations are used to evaluate the system frequency response SRF provided by evaluating the inertial frequency support provided by a variable speed wind generator. The main contributions of this paper are: (i) to highlight the positive contribution of hidden inertia controller under different load variation conditions; and (ii) to practically identify there is a possible point out that high values of the synthetic inertia parameter, may stall the wind turbine negatively affecting the power system. Finally, Section VI concludes.

2 Power system frequency response

The system frequency (f) is related to the rotational speed of the rotor of all synchronous machines directly connected to the grid. Any variation of the electric demand or power generation will produce changes in the system frequency. For this reason, the frequency is an electrical variable that must be controlled second by second by second using controllers to preserve the instantaneous balance between system demand and total generation.

An active power change (ΔP), at any point of the network, is propagated throughout the whole power system by a change in the electric frequency (Δf). Consequently, the system frequency is the useful index to detect system generation and load unbalance.

For a better understand of the described frequency phenomena, let us consider an electric power system accounting for N synchronous generators. For the generic i^{th} synchronous machine, it is possible defining the following relation between the individual incremental mismatch power (Δp_i) and individual the frequency (f_i):

$$\frac{2H_i}{f_0}\frac{df_i}{dt} = P_{mech,i} - P_{elec,i} = \Delta P_i \quad (1)$$

where $P_{mech,i}$ is the pu mechanical power of prime mover, $P_{elec,i}$ the pu electrical power, ΔP_i is the load/generation imbalance, in pu , H_i is the inertia constant in seconds, f_i is the frequency in Hz and f_0 is the rated frequency.

Assuming a strong coupling between the generation units, it is possible obtaining a relation similar to (1) but extended for the entire power system:

$$\frac{2H_T}{f_0}\frac{df_{COI}}{dt} = p_{mech,T} - p_{elec,T} = \Delta p_T \quad (2)$$

where $P_{mech,T}$, $P_{eelec,T}$, and S_T are respectively the algebraic sum of the individual synchronous machine electric power, mechanical power and rating capacity, while the total system frequency inertia (H_T) and the frequency of the centre of inertia (f_{COI}) can be written as:

$$H_T = \frac{1}{\sum_{i=1}^{N} S_{N,i}} \sum_{i=1}^{N} H_i S_{N,i} \quad (3)$$

$$f_{COI} = \frac{1}{\sum_{i=1}^{N} H_i} \sum_{i=1}^{N} H_i f_i \quad (4)$$

Examining (2) and (3), it is clear that the system frequency dynamic strongly depends on the overall value of the system inertia (H_T). Increasing the number of generators connected to the grid using power converter increases the total installed capacity (S_T) but the inertial contribution of those generators is zero because the power converter interface hides the inertial contribution of its generation. Enabling the inertial response of power converter-based generators requires proper controllers for that purpose. Therefore, installing fully rated power converter generation units produces a reduction of the total system inertia that can lead to a quick and dangerous drop of system frequency adversely affecting the frequency stability of the electric power system. On this aspect, wind turbine generators (WTG) can play an important role providing the support of *frequency response* (FR). A WTG has the inertia of their rotating parts such as blades, gearbox, generator, etc. The overall value of wind turbine inertia is up to 500 kg/m^2 and it represents a relevant amount of kinetic energy stored in rotating components of the WTG. Using appropriate control strategies at converter level, it is possible to extract the kinetic energy of the WTG and uses it to support the FR of the power system.

3 Frequency control in wind turbines

Frequency control in power systems is mainly provided by the primary and secondary control. Power system requires the active participation of all generation unit, including WTG. Although generators electronically interfaced to the grid do not provide a contribution to the FR, this capability can be obtained by the additional control to the power converters [1]. Various control schemes can be drawn to enable the WTG to provide active power contribution to FR, it can be divided into three-level hierarchy [1]: (i) *wind turbine (WT) controller* –local control, (ii) *wind farm (WF) controller*, (iii) *power system level controller*.

Local control at WT level is used to provide primary frequency control and other additional auxiliary services then WF level controller allows coordination between the central and local control in order to achieve the desired generation for the system. Power system level controllers are used for secondary frequency control; it provides better system frequency behaviour by the coordination between the AGC and the WFs. The *WT level controllers* are local controllers added to the *variable speed wind turbines* (VSWT) subsystems in order to enable frequency support. The WT controller can enable the primary frequency control by two important parts of the FR [8]: (i) Inertial response by the use of the *inertial controller* and (ii) governor response, a slow response by using the *governor controller*. In this paper, the main concern is related to the dynamic behaviour of the inertia controller on system frequency support. The inertial controller can be implemented using several approaches, however, there are two basic concepts: (i) *Releasing "Hidden Inertia*" and (ii) *Fast Power*

Reserve Emulation. Those controllers are described in details in the next sub-sections.

3.1 Releasing "hidden inertia" control

Modern WTGs use power electronics converters to enable variable speed operation in order to capture wind energy over a wide range of speeds. However, the power converter isolates the rotational speed from the system frequency as a consequence the WTGs based on back-to-back AC/DC/AC converters offer no *natural* response to system frequency [9], [4].

The WT industry has created several controllers for modern WTG's in order to provide *inertial response* (and governor response in some cases) for large frequency deviation for, short-duration, *releasing hidden inertia*. There are several names for this sort of controllers: *Artificial*, *Emulated*, *Simulated*, or *Synthetic Inertial*. Examples of synthetic inertia controlled commercially available for WTG are [10]: General Electric WindINERTIA™ [11], ENERCON® Inertia Emulation [12]. The objective of the synthetic inertia control is "*to extract the stored inertial energy from the moving part on WTGs*" [13]. There are several versions of synthetic inertia controllers; however, they can be classified into two main approaches: (a) *Releasing "hidden" inertia* and (b) *Reserve capacity in pitch*. In this paper, the hidden inertia approach is considered and it is named *synthetic inertia* from here on.

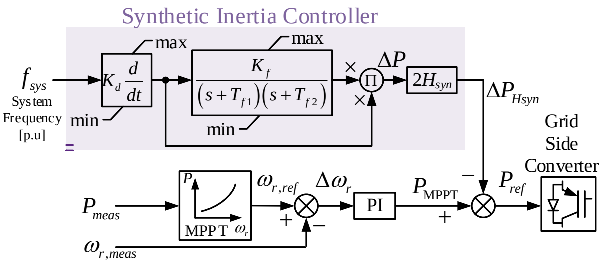

Fig. 1. Representative block diagram of *Maximum Power Point Tracking* (MPPT) controller and releasing hidden inertia controller.

Synthetic inertia concept is based on a controller which allows taking the kinetic energy from a WT rotating mass. This controller has been comprehensively explained in several scientific publications [5], [14]. This control loop increases the electric power output of the WTG during the initial stages of a significant downward frequency event. The active power, sometimes called inertial power, ΔP, of the controller is achieved by the use of the following mathematical formulation:

$$\Delta P = 2H_{syn} f_{sys} \frac{df_{sys}}{dt} \tag{5}$$

where H_{syn} express the synthetic inertia (sec) and f_{sys} system frequency (p.u). Implementation of synthetic inertia controller in a VSWT is depicted in Fig. 1.

3.2 Fast Power reserve emulation control

The *fast-power reserve emulation* controller is designed to provide a short-term constant power, this power provides FR for a short period of time [15], [16], [17]. The *fast-power reserve* (P_{Hsyn}) is derived from a simple integration of kinetic energy stored in the wind turbine rotor:

$$P_{Hsyn} t = \frac{1}{2} J_{syn} \left(\omega_{r,0}^2 - \omega_{r,\mathrm{f}}^2 \right) \tag{6}$$

where t ($t<t_{max}$) is the lasting time of the fast-power reserve since the beginning of the frequency disturbance, $\omega_{r,0}$ is the initial rotational speed and $\omega_{r,\mathrm{f}}$ is the rotor rotational speed corresponding to t.

This controller acts on the reference rotational speed ($\omega_{r,ref}$) creating an artificial change in the rotational speed to allow release kinetic energy from the wind turbine rotor. The change in the rotational speed ($\omega_{r,\mathrm{ref}}$) is obtained as:

$$\omega_{r,\mathrm{ref}} = \omega_{r,\mathrm{f}} = \sqrt{\omega_{r,0}^2 - \frac{2}{J_{syn}} P_{Hsyn} t} \tag{7}$$

A general scheme for the fast-power reserve emulation controller is depicted in Figure 2. The fast power reserve provides FR for a short period and saves time for other slower generators to participate in the frequency control.

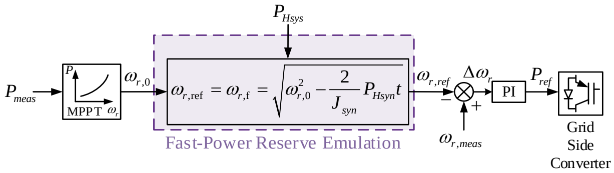

Fig. 2. A representative block diagram of Maximum Power Point Tracking controller and fast power reserve emulation.

3.3 Droop control strategy

If the two previously described control strategies aim at supporting the initial frequency response of the system, the droop control strategy is designed with the aim of providing support to the frequency in a longer time. This is in accordance to the to the classical control strategy of the conventional power plant where the droop approach allows sharing the load variation among the generators to achieve and acceptable steady state frequency until secondary control will not act.

The governor control refers to control actions that are done locally (at the power plant level) based on the set-points for frequency and power.

The steady-state properties of the governor controller are defined by the *permanent droop* (ρ), which is defined as the change in frequency (Δf), normalised to the nominal frequency (f_0), divided by the change in power output (ΔP), normalised to a given power base, (P_{base}).

$$\rho = \frac{\Delta f\,[p.u]}{\Delta P\,[p.u]} \tag{8}$$

The inverse of the droop is R and it is referred to as *the stiffness of the generation unit* (ρ).

$$R = \frac{1}{\rho} = \frac{\Delta P\,[p.u]}{\Delta f\,[p.u]} \tag{9}$$

The *droop controller* is described by a steady-state frequency characteristic as shown in Fig. 3. It produces an active power change that is proportional to the frequency deviation.

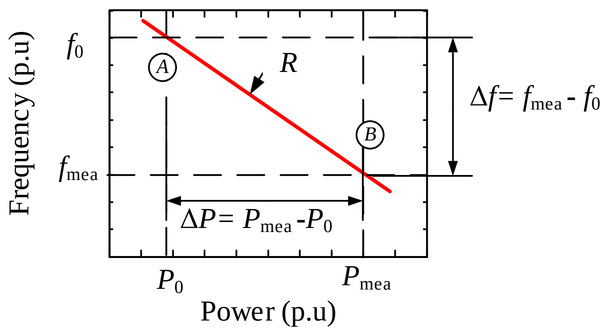

Fig. 3. Frequency droop characteristic.

Frequency droop control can be included in a control loop in modern WTs based on generators electronically controller and/or electronically connected to the power system. Fig. 4 shows an implementation of the frequency droop control for a converter based VSWT [14], [18], [19].

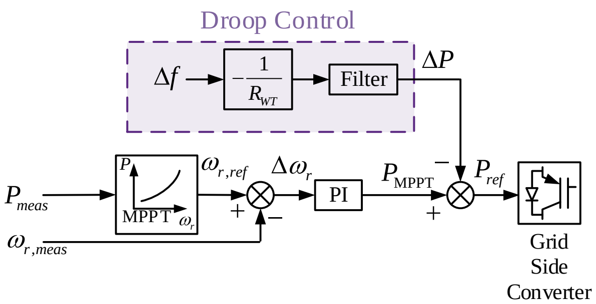

Fig. 4. A representative block diagram of a Frequency Droop Control for full converter rated VSWT.

The droop control in WTG emulates the similar frequency droop characteristic to the synchronous generators. However, the power increase (ΔP) during a sudden drop in system frequency must be obtained from the kinetic energy of the rotation parts of WTG, it causes a decrease in rotational speed due to the *Maximum Power Point Tracking* (MPPT) operation. The support of steady-state frequency requires extra-steady-state power to reduce the frequency deviation; this extra-power is provided in the long term from the prime-mover in classical generation units.

Droop controller has not high impact on the initial ROCOF after frequency disturbance but it largely influences the frequency in the most critical condition of the transient. However, a decrease in rotational speed on wind turbines equipped with droop controllers may be not avoided because extra wind speed cannot be obtained, for this reason, droop controller requires the support of other wind turbine components to avoid turbine stall by rotational speed falling too low. This issue can be solved using two approaches: stopping frequency droop contribution or de-loading the wind turbine.

Frequency droop controller can be equipped with a triggering system to allow finishing the action control in time to avoid a potential stall condition on the wind turbine. This triggering off system is similar to one use in fast power reserve emulation. This solution is easily implemented, however, its real benefit is in doubt because power contribution will be interrupted creating a potential risk of frequency disturbance.

4 Wind turbine generator model

This section presents the system modelling used in this paper. A very simple test system is considered, as shown in Fig, 5.

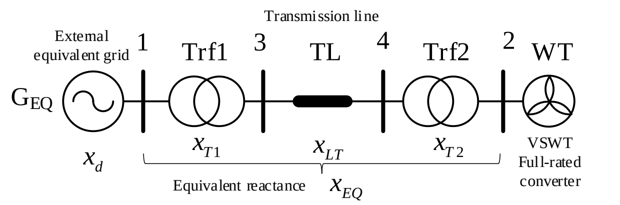

Fig. 5. Test system: Representative transmission system including an equivalent WTG.

It consists of a large equivalent external grid (G_{EQ}) connected to a WT using a multi-voltage level transmission system. For simplicity, this is a lossless transmission system and reactances of transformer and transmission system can be combined together (bus 3 and 4 disappear) and an equivalent reactance (x_{EQ}) used instead. The next subsections present details of the modelling of the different aspects relevant for SFR. The main grid is assumed to be characterized by a total inertia (H_{net}) equal to 40.0 s (on machine power base) and a 5% equivalent droop. Fig. 5 depicts the general structure of a *variable-speed wind turbine* (VSWT) with a *direct-*

drive (DD) *permanent magnet synchronous generator* (PMSG). This wind turbine uses a full-rated power converter in the form of back-to-back topology. The models used full-rated converter and their details are taken from [8, 10, 20]. Models parameters used are escalated to simulate an equivalent 5 MW wind turbine.

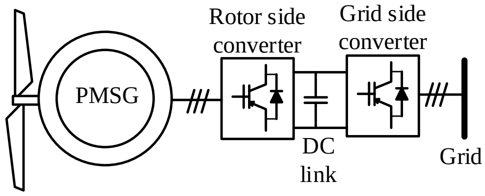

Fig. 6. The general structure of a VSWT with a direct-drive synchronous generator and a full-rated power converter.

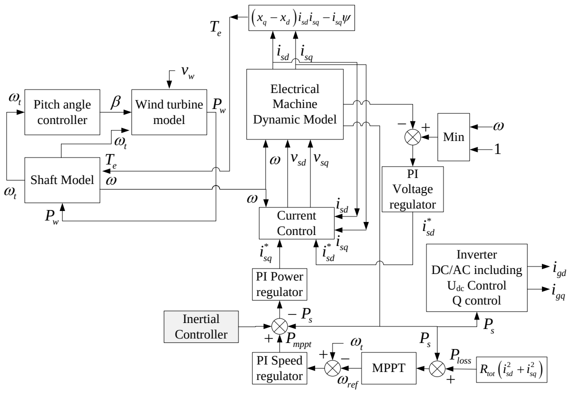

Fig. 7. A representative block diagram of main elements, controller and signals using on the model of VSWT with a DD synchronous generator with a FRPC.

Fig. 5 shows a block diagram of the main components and controller considering on the modelling of VSWT with a DD synchronous generator with a FRPC as an interface to the grid. A time series can be used as input to wind turbine rotor model, for simplicity in this paper *constant* speed is assumed during the simulation time. The variable speed wind turbine rotor model consists of the classical polynomic relationship between wind speed and mechanical power. The model for the mechanical shaft consists of a simple a classical two mass representation. Maximum power point tracking controller is included in order to provide the speed control of the wind turbine and it is aimed to maximize its power production. Pitch angle controller is included in the model aiming to reduce the power extracted from the wind at very high wind speed. As far as the generator side converter is concerned, two main control loops are present, namely: the active power/speed control loop and the voltage control loop. Such loops will provide the reference signals for the two inner current control loops. The grid side converter is composed of basically two outer control loops, regulating the voltage (U_{dc}) on the DC link and the reactive power (Q_{net}) delivered to the network. Again, such loops will provide the reference signals for the two inner current control loops. Details of control modelling are beyond the scope of this paper, however, further details can be found on [21], [22].

5 Simulations and results

Using the network structure described in Section 4, a set of simulations is presented in this section. Simulations are used to show the active power contribution provided by the Releasing "Hidden Inertia" strategy on the SFR, and it is compared with the classical behaviour of fully rated converter wind turbines without controller enabling the frequency support.

An equivalent synchronous generator and a load are used as a representative equivalent model of a traditional power system and, an equivalent transmission system is included between generation and demand considering two voltage levels. Power system model and wind turbine controllers are implemented using Matlab®/Simulink™. In this paper, system frequency disturbance consists of generator outage, which is simulated by a sudden increase in active power demand (ΔP_L). The system frequency disturbance is inserted at t_0 = 10.0 s. In the first case, the synthetic inertial (H_{synt}) is assumed equal to the 25% of the overall inertia of the WTG (H_{WTG}) and the system performance is evaluated in three different conditions of power imbalance (ΔP_L = 0.30, 0.60 and 0.90 pu considering the WTG power as a base).

As one can see from Fig. 8 and Fig. 9 the initial transient of the frequency is supported by the contribution of the inertia controller become less and less impacting while the frequency transient tent to extinguish. Moreover, the inertial control action and the frequency support contribution are higher for bigger power imbalance, associated with a wider decreasing rate of frequency. The dynamic performance of generator rotor speed is shown in Fig. 10; the action of the inertial controller initially provides a deceleration of the generator that after a swing come back to the optimal speed defined by the MPPT of the turbine.

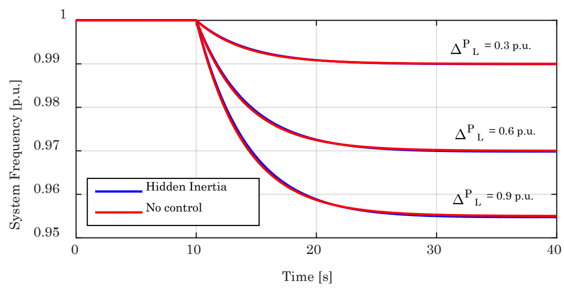

Fig. 8. System frequency dynamic response during system frequency disturbance considering three different power imbalances (ΔP_L), $H_{syn} = 0.25H_{WTG}$.

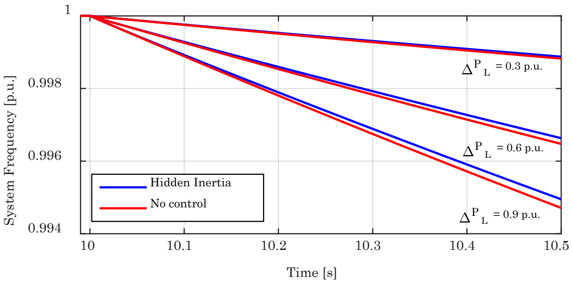

Fig. 9. Details at the very beginning (0.50 sec) of the system frequency response.

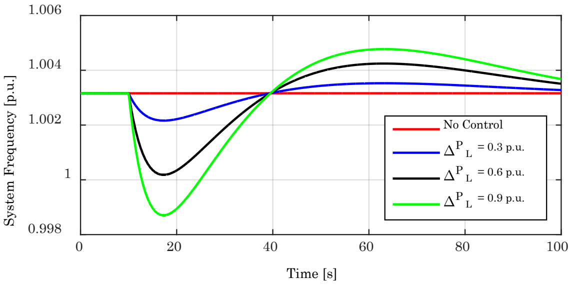

Fig. 10. Rotor speed response during system frequency disturbance. Inertia controller gain adjusted at H_{syn} = 28.0 sec.

It should be noticed, the implementation of this kind of frequency support strategy has to be properly designed since as high value of the synthetic inertia may lead to a problem in the wind turbine dynamic. In Fig. 10 and 11 show the system frequency response and generator rotor speed in case of inertial controller gain adjusted to three times the wind generator inertia ($H_{syn} = 3H_{WTG}$) and system frequency disturbance of 0.90 pu

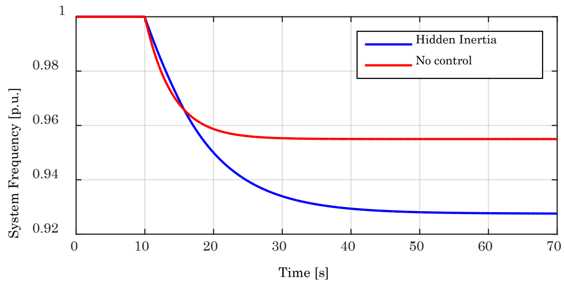

Fig. 11. System frequency response: System frequency disturbance ΔP_L = 0.90 pu and inertia controller gain $H_{syn} = 3H_{WTG}$.

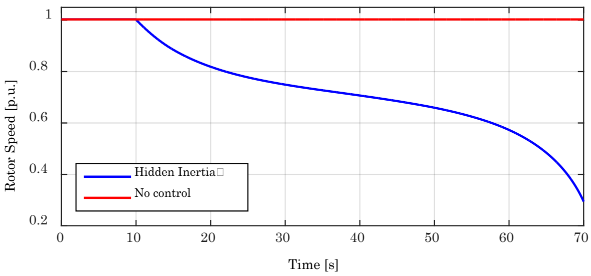

Fig. 12. Rotor speed response: ΔP_L = 0.90 pu and inertia controller gain $H_{syn} = 3H_{WTG}$.

Fig. 12 shows a clear condition where the wind turbine generator stalls by means of a drift of the rotor speed and the consequent shut down of the WTG. This is a very critical condition for frequency stability since it produces a further system frequency disturbance by losing wind turbine generation and decreasing in frequency. Analysing the mathematical rule of the synthetic inertia controller (5), it is possible to notice that its contribution does not provide a change in the possible steady-state equilibrium point of the power system, since the additional term is proportional to the time derivative of frequency. This suggest that the frequency instability problem is not related to the feasibility of the system equilibrium point but is probably related to the interaction between the WTG controller and the synthetic inertia one.

The limit value of the synthetic inertia controller gains for the stable operation of the system vary in accordance with the amplitude of the frequency disturbance. In this paper, the limit values of stable conditions are obtained by means of dedicated simulations, Table 1 shows the results for the three-power imbalance conditions used in the previous simulations.

Table 1: Hidden Inertia limits for stable operation.

Load variation ΔP_L (pu)	**Synthetic inertia limit $H_{syn,max}$ (sec)**
0.30	$5H_{WTG}$
0.60	$3H_{WTG}$
0.90	$2H_{WTG}$

6 Conclusion

The aim of the present paper is to evaluate the inertial frequency support provided by variable speed wind generators. With this purpose, the main control strategy used to emulate an inertial behaviour of under converter generators where detailed, namely hidden inertia controller. It allows a fast active power contribution, fast power reserve emulation controller, that provides a smoother response depending on the slope included in the controller (P_{syn}/H_{syn}) and finally the droop control concept, that provides a contribution in a longer time frame similar to those provided by frequency control system for traditional power plants. The effect of this family of the control system has been evaluated considering the hidden inertia controller in a simplified wind turbine and network model implemented in Matlab/Simulink. The simulation highlighted the positive impact of the proposed controller on the system frequency in different load conditions highlighting the positive contribution of Hidden Inertia Controller under different load variation conditions. In this sensitivity analysis, it was also possible to point out that high values of the synthetic inertia parameter, may destabilize the power system causing the stall of the WTG. Future works will concern the possibility to study the nature of this unstable behaviour of the Hidden Inertia controller in order to provide some criteria for the optimal and secure design of this controller. Moreover, it will be necessary to evaluate the possible integration of the synthetic inertial controller and the droop ones in order to achieve a more effective effect of a wind generator in the support of frequency beyond the first instants of the transient.

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