Integrated Inertial and Droop Frequency Controller for Variable Speed Wind Generators

A. BONFIGLIO[1], F. GONZALEZ-LONGATT[2] AND R. PROCOPIO[1]

[1]The Wolfson School: Electronic, Electrical and Systems Engineering
Loughborough University
Loughborough, UNITED KINGDOM

[2]Department of Electrical, Electronic, Telecommunications Eng. and Naval Arch.
University of Genoa
Genoa, ITALY

a.bonfiglio@unige.it

Abstract: - One of the major and more challenging problem that is going to affect the future electricity system is the one relate to the frequency stability and support from generating units. In traditional power networks frequency support were transiently provided by the rotating mass of the generator (directly connected to the grid) while the steady state contribution to frequency is provided by a droop control primary regulation. With the massive diffusion of under-converter generation the system is facing and increasing of the overall installed capacity, and a reduction of the percentage of "inertial responding" generators and of generator actively participating in frequency regulation. This situation negatively affects the system frequency response and may increase the risk of generation outages and blackouts. The aim of the present paper is that of analysing the possible contribution of variable speed wind generating units in frequency support, by means of the definition of dedicated control strategies to be implemented at power electronic level. Then, the paper also proposes the integration of inertial and droop frequency controller in order to define a control strategy capable of emulating the frequency response behaviour of a traditional generating unit. The performances and limits of the proposed controller is evaluated by means of dedicated simulations.

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.

From this point of view, the increasing penetration of renewable generation sources have introduces new problems and issue in guaranteeing specific power quality issues [2]-.[3], but also some improvements from a flexibility point of view, thanks to the employment of power electronic devices [4].

Among these, the 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 [5]. However, future power systems will increase the installed power capacity (MVA) but the effective system inertial response will stay the same nowadays [5, 6]. 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 [7] and simulation [8] of the inertial response of *wind turbine generators* (WTGs) and some of them provide general ideas about possible impacts on power systems and their effects on transient under-frequency response [9]-[10].

This situation negatively affects the system frequency response. The aim of this paper is to evaluate the integration of inertial and droop frequency control 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* (SFR) 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; (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 and (iii) to evaluate the possible integration of the hidden inertia and droop controller in order to obtain an effective frequency support in all the phases of the perturbation. Finally, Section VI provides some conclusive remarks and proposes some future improvements for the topic.

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):

$$\frac{2H_i}{f_0}\frac{df_i}{dt} = p_{mech,i} - p_{elec,i} = \Delta p_i \qquad (1)$$

where $p_{mech,i}$ is the p.u mechanical power of prime mover, $p_{elec,i}$ the p.u electrical power, Δp_i is the load/generation imbalance, in p.u , 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:

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

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:

$$H_T = \left(\sum_{i=1}^{N} S_{N,i}\right)^{-1} \sum_{i=1}^{N} H_i S_{N,i} \qquad (3)$$

$$f_{COI} = \left(\sum_{i=1}^{N} H_i\right)^{-1} \sum_{i=1}^{N} H_i f_i \qquad (4)$$

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, WTGs 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 moment of inertia is up to 500 kilogram-square metres (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 [11]: (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, 13].

The WT industry has created several controllers for modern WTG's in order to provide an *inertial response* (and governor response in some cases) for large frequency deviation for, short-duration, *releasing hidden inertia*.

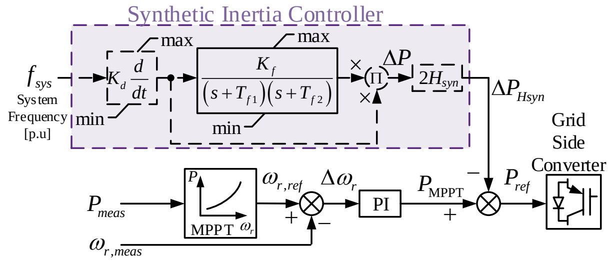

Fig. 1. Representative block diagram of *Maximum Power Point Tracking* (MPPT) controller and releasing hidden inertia controller [1].

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 [14]: General Electric WindINERTIA™ [15], ENERCON® Inertia Emulation [16]. The objective of the synthetic inertia control is "*to extract the stored inertial energy from the moving part on WTGs*" [17].

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. *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 [8], [18]. This control loop increases the electric power output of the WTG during the initial stages of a significant downward frequency event (see Fig. 1). The active power, sometimes called *inertial power* (ΔP_{Hsyn}) of the controller, is achieved by the use of the following mathematical formulation:

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

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], [19], [20]. 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 ($\omega_{r,\mathrm{ref}}$) 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 Fig. 2. The fast power reserve provides FR for a short period and saves time for other slower generators to participate in the frequency control.

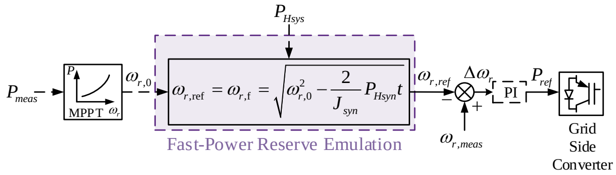

Fig. 2. A representative block diagram of Maximum Power Point Tracking controller and fast power reserve emulation [1].

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.

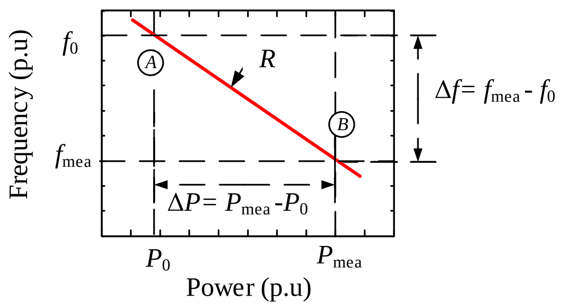

Fig. 3. Frequency droop characteristic.

Frequency droop controller 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 [21]-[23].

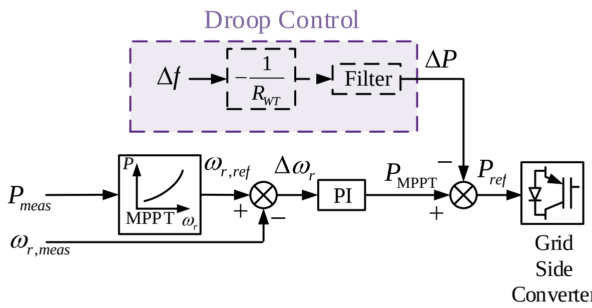

Fig. 4. A representative block diagram of a Frequency Droop Control for full converter rated VSWT [5].

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.

3.4. Integration of releasing "hidden inertia and droop controller

This sections briefly shows the proposed integrated hidden inertia and droop controller for VSWT. The idea behind this controller is to mimic the frequency response provided by a classical synchronous generator. An integrated frequency support strategy should provide support during the first moments after the system frequency disturbance, as for the classical synchronous machines, to kick-in and obtain a frequency stability condition. Moreover, an effective integrated controller should also include a steady-state frequency support (this requirement for renewable generating units is up to now included in almost every grid code requirement [24]-[26]).

Following these guidelines, the proposed integrated frequency controller is intended to provide two contributions on the frequency support: inertial response and steady-state frequency support integrating the hidden inertia and droop controller described in the previous sections. This procedure implies two main criticalities to be considered: (i) the operational time frame of the two frequency controllers have to be decoupled, in order to avoid dangerous and undesired interaction between the transient and steady state frequency regulation; (ii) if the inertial controller provides a transient contribution exploiting the stored kinetic energy of the rotating masses in the VSWT, the droop one has an impact of the steady-state operation of the turbine, and so, it has to be properly integrated with the MPPT controllers of the plant.

In order to meet the requirements of decoupling the two controllers effects, the insertion of suitable dead bands is proposed for the activation of the droop controller. In accordance to [24], the droop controller is activated if the frequency falls over or below a range of 0.5 Hz, and it is deactivated when the frequency came back to a band of semi-amplitude equal to 0.1 Hz. In this way, it is possible supposing that when the droop controller kicks-in the frequency transient partially done and the contribution of the hidden inertia controller will be almost extinguished. The activation of the hidden inertia controller will also be provided with a dead band on the time derivative of frequency in order to avoid its continuous action during normal operation slow frequency transients.

It is clear that in the case of under frequency dynamics, the steady state contribution of the droop part of the controller is not possible if a proper active power reserve is not previously created. In this case, the droop characteristic of the controller should be asymmetric and should consider the only over frequency part of the plane.

On the contrary, it is possible to define a complementary logic to the MPPT one, in order to create an active power reserve to be used in case of under-frequency transients. This aspect can be found in some grid code requirements [26].

In the following section, some simulation will be performed to evaluate the performances of the proposed integrated control in both under and over frequency test cases. In the under frequency one, active power reserve is created acting directly on the power regulator reference, bypassing the MPPT, since the definition of the active power reserve controller is out of the scopes of the present paper and would require a proper discussion and description.

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.

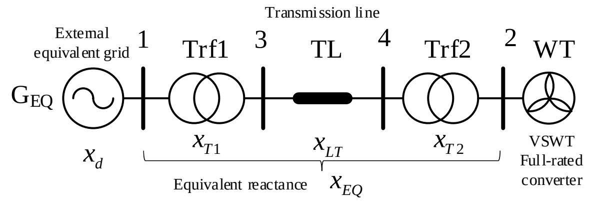

Fig. 5. Test system: Representative transmission system including an equivalent WTG.

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 a full-rated converter and their details are taken from [11, 13, 27]. Models parameters used are escalated to simulate an equivalent 5 MW wind turbine.

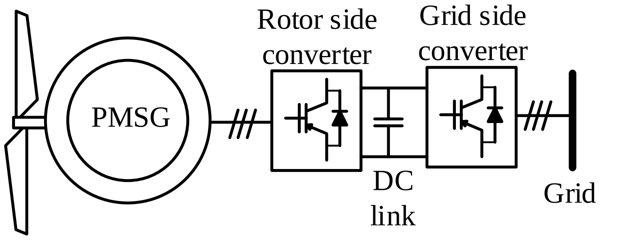

Fig. 6. The general structure of a VSWT with a direct-drive synchronous generator and a full-rated power converter.

Fig. 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.

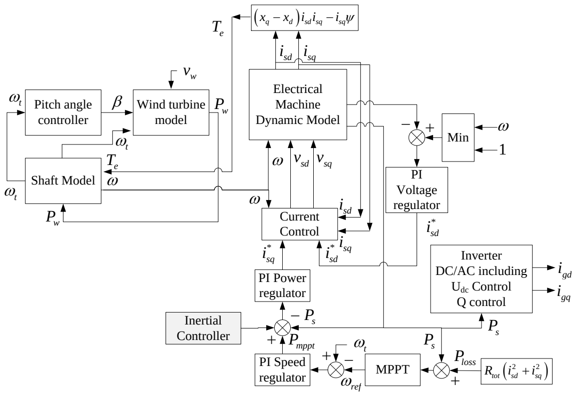

Fig. 7. A representative block diagram of main elements, controller, and signals using the model of VSWT with a DD synchronous generator with a FRPC.

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 [28], [29].

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.

5.1. Sensitivity analysis on the hidden inertia controller

In the first case, the synthetic inertial (H_{syn}) 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.

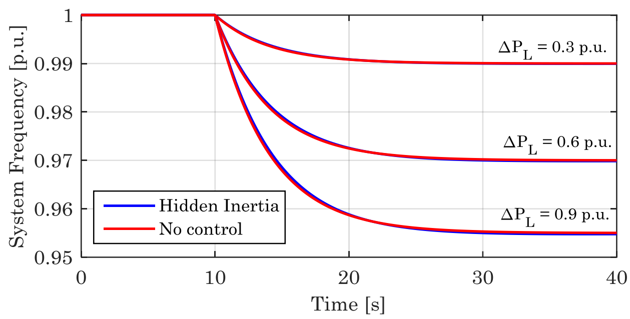

Fig. 8. System frequency dynamic response during system frequency disturbance considering three different power imbalances (ΔP_L), H_{syn} = 0.25H_{WTG}.

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.

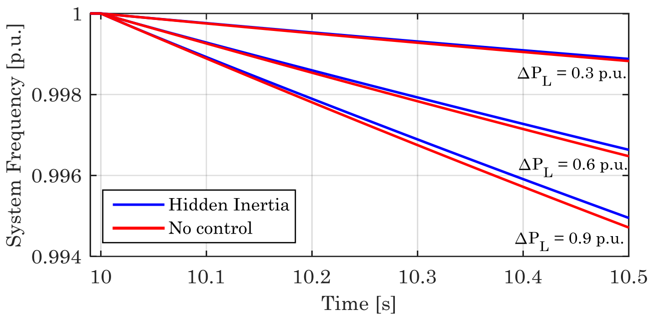

Fig. 9. Details at the very beginning (0.50 sec) of the system frequency response.

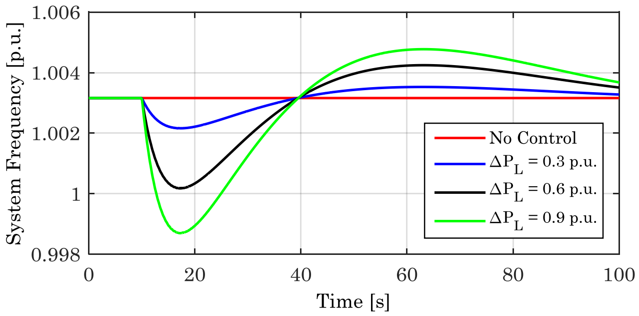

Fig. 10. Rotor speed response during system frequency disturbance. Inertia controller gain adjusted at H_{syn} = 28.0 sec.

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

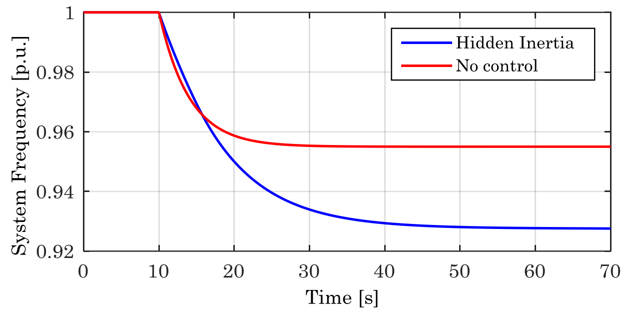

Fig. 11. System frequency response: System frequency disturbance ΔP_L = 0.90 p.u and inertia controller gain H_{syn} = $3H_{WTG}$.

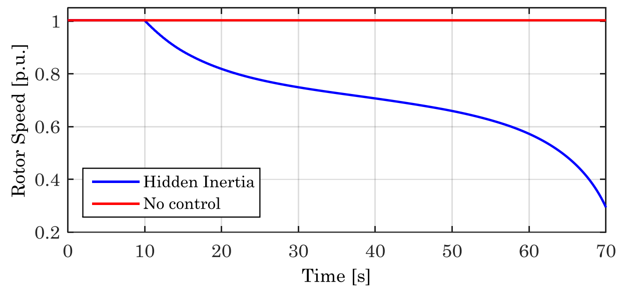

Fig. 12. Rotor speed response: ΔP_L = 0.90 p.u and inertia controller gain H_{syn} = $3H_{WTG}$.

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 suggests 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 **(p.u)**	**Synthetic inertia limit** $H_{syn,max}$ **(sec)**
0.30	$5H_{WTG}$
0.60	$3H_{WTG}$
0.90	$2H_{WTG}$

5.2. Application of the integrated hidden inertial and droop control strategies.

This subsection presents simulation results of the three test cases, the objective of those tests is to illustrate and verify the behaviour of the proposed integrated frequency support controller considering: under, over frequency disturbances and an over-frequency with restoration. The gain value of the synthetic inertia controller is chosen equal to overall WTG inertia ($H_{synt} = H_{WTG}$) while the gain of droop is set to R = 0.08 p.u./p.u..

5.2.1. Over-frequency transient

Over-frequency is a rare event in electrical power system. However, there is a possibility that it happens and the VSWT must be able to cooperate on frequency support during that kind of disturbances. Fig. 13 shows a typical system over-frequency, starting from steady-state, a disturbed base on a load rejection is imposed at t = 10.0 s. The steady-state frequency is equal to 50.65 Hz, which is a higher value than the 50.5 Hz, the dead band provided for the droop controller (Fig. 13).

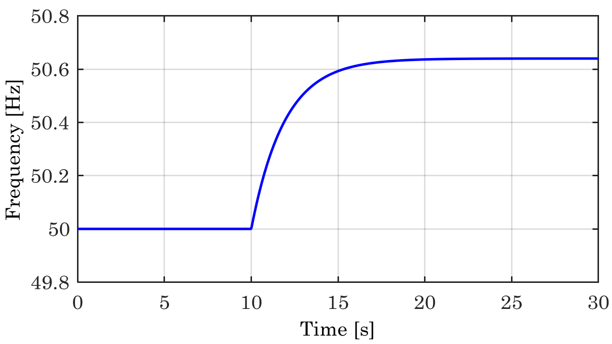

Fig. 13. Over-frequency transient caused by load rejection at t = 10.0 s.

The active power response of the VSWT is provided in Fig. 14. It must be highlighted that the WTG generator initially decreases its active power production storing energy into its rotating masses thank to the hidden inertial controller; a few seconds later, when system frequency goes above 50.5 Hz, the droop controller starts its active power contribution. Fig. 15 point out the details of the active power contribution provided by the proposed controller, indicating both actions. As one can see, the hidden inertia contribution is quick and transient while the droop one is activated later and last until the system steady-state.

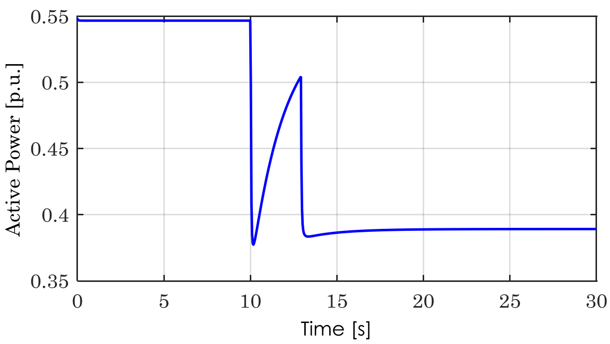

Fig. 14. Active power production of VSWT considering the proposed controller as the response of an over-frequency (Fig 13).

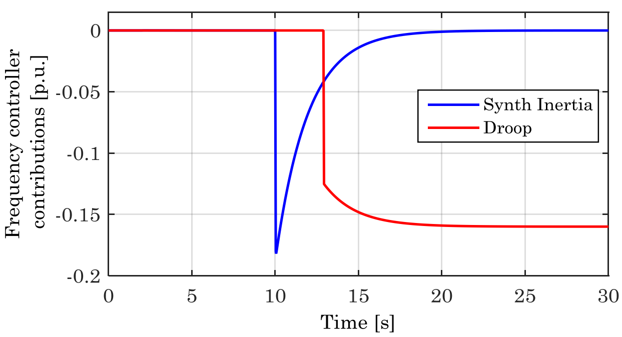

Fig. 15. Active power contribution of proposed controller showing individual contributions considering an over-frequency (Fig 13).

5.2.2. Under-frequency transient

Fig. 16 shows an under-frequency caused by a sudden load increase at t = 10.0 s. As one can see from Fig. 16, the load event provides a frequency transient that falls below the activation limit of the droop controller (set to 49.5 Hz). In case of under frequency, the generator is required to increase its active power production, in order to try reducing the power unbalance. As detailed earlier, to do se, the system need to previously create an active power reserve by means of the dedicated active power reserve control logic (not detailed in the present article for the sake of brevity). For simulative purposes, the active power reference of the WTG is manually decreased after 2.0 s, in order to create a 0.25 p.u power reserve to be used during the under frequency transient. As a result, (see Fig. 17) after the frequency disturbance the VSWT initially responds using its stored kinetic energy, while after a few seconds it provides a steady-state contribution (this is due to the fact that the system frequency does not come back inside the admissible range).

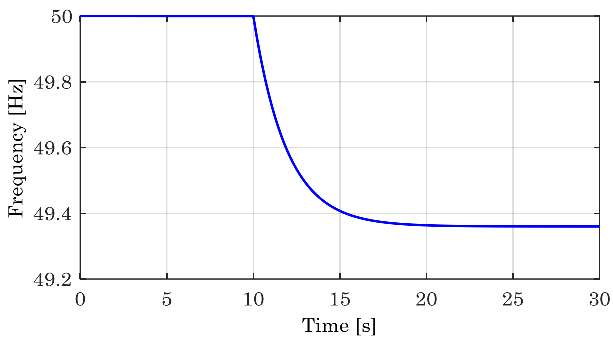

Fig. 16. Under-frequency transient caused by sudden load increase at t = 10.0 s.

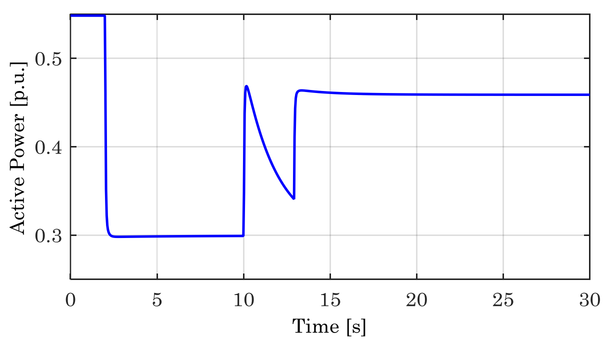

Fig. 17. Active power production of VSWT considering the proposed controller as the response of an under-frequency (Fig 16).

Fig 18 shows the individual contributions of the frequency support controller integrated into the proposed controller, one acting immediately after the disturbance (red one –inertial response) while the other is delayed and provide a continuous contribution (blue one –droop controller).

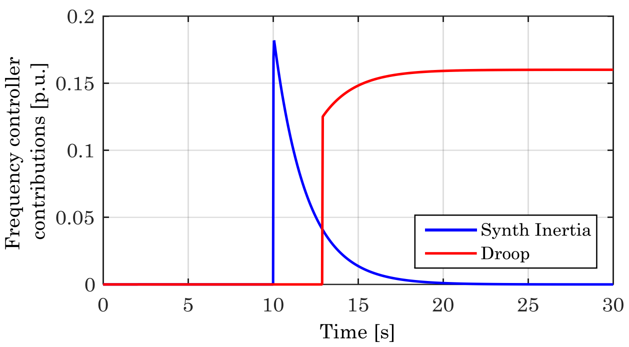

Fig. 18. Active power contribution of proposed controller showing individual contributions considering an under-frequency (Fig 16).

5.2.3. Over-frequency transient and frequency restoration

In this final test-case, a time series of frequency events are proposed in order to assess the performance of the proposed controller (considering an initial over-frequency and subsequent frequency recovery). The over-frequency starts at t = 10.0 s and then the system frequency is restored at t = 40.0 s as depicted in Fig. 19.

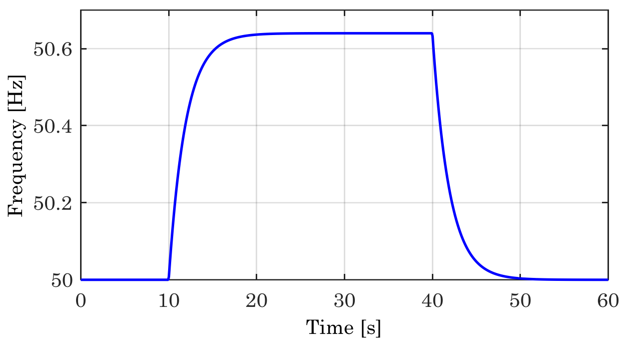

Fig. 19. Synthetic frequency considering over-frequency and frequency recovery.

After the frequency control activation, the proposed integrated frequency control senses the frequency transient providing an inertial contribution together with the active power reduction of the droop control, see Fig. 20. The droop control effect is switched off when the frequency comes back under 50.1 Hz, at almost 44 s.

Fig. 21 shows how the deactivation of the droop control brings the system back to the initial operating point, provided by the MPPT control.

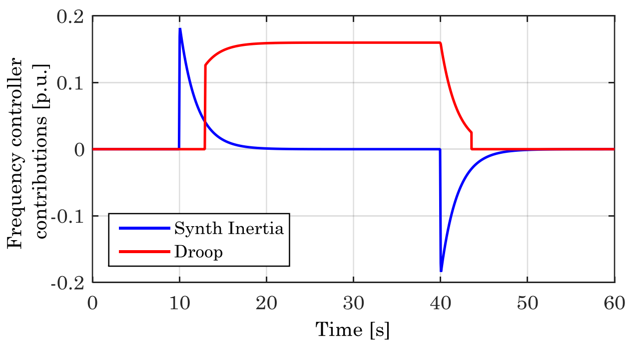

Fig. 20. Active power production of VSWT considering the proposed controller considering the system frequency is shown in Fig 19.

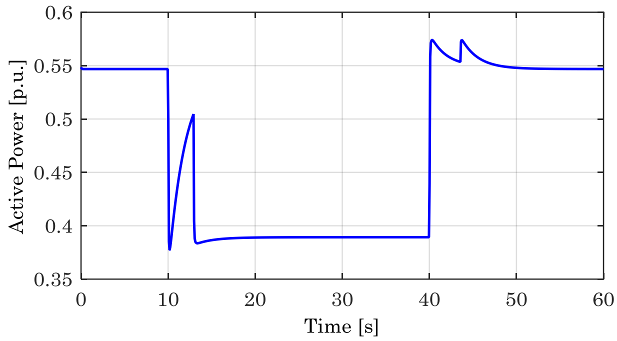

Fig. 21. Active power contribution of proposed controller showing individual contributions considering the system frequency shown in Fig 19.

6 Conclusion

The aim of this paper is that of describing the possible impact of variable speed wind generating unit on frequency support. As well known, under converter generation contribution in frequency support is null, due to the frequency decoupling between the generator and the grid. For this reason it is necessary to design and implement some frequency support control logic to be integrated with the conventional power converter unit control system of the wind generator. With this purpose, the main control strategy used to emulate an inertial behaviour of under converter generators where detailed, namely hidden inertia controller a fast power reserve emulation. These two strategies allows a fast active power contribution, and the fast power reserve emulation controller provides a smoother response depending on the slope included in the controller (P_{syn}/H_{syn}). The last proposed control strategy for frequency support is the droop control concept. This provides a contribution in a longer time frame similar to those provided by frequency control system for traditional power plants. After an overall and general description of the three control strategies it is proposed and integrated approach of the hidden inertia and droop controller, in order to obtain a frequency support control scheme that is capable of managing both the transient and the steady state of the frequency evolution.

The effect of this family of control system has been evaluated on a simplified wind turbine and network model implemented in Matlab/Simulink. Simulation initially aimed at pointing out the positive effects of the hidden inertia controller in the support of the first frequency transient and possible drawbacks of its application from a system stability point of view.

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. Then, simulation considered the integrated hidden inertial and droop controller considering three specific frequency disturbances: (i) over-frequency, (ii) under-frequency and (iii) over-frequency with frequency restoration. Proposed simulations pointed out the good performances of the frequency controller avoiding interaction between the two strategies and providing a frequency support contribution in all the periods of the transient.

Future works will concern the possibility to study the nature of the unstable behaviour of the hidden inertia Controller, pointing out its possible dependency on the other WTG control systems, in order to provide some criteria for the optimal and secure design of hidden inertia controller. Moreover, the integrated control strategy will require, to operate properly in under frequency condition, the design of a proper active power reserve control, in order to achieve the generation of a dedicated amount of active power to be delivered in case of under frequency events.

References:

[1] F. Gonzalez-Longatt, "Frequency Control and Inertial Response Schemes for the Future Power Networks," in *Large Scale Renewable Power Generation*, J. Hossain and A. Mahmud, Eds., ed: Springer Singapore, 2014, pp. 193-231.

[2] B. Delfino, F. Fornari, R. Procopio, “An effective SSC control scheme for voltage sag compensation”, IEEE Trans. On Power Delivery, vol.20, n.3, July 2005, pp. 2100-2107.

[3] F. Fornari, R. Procopio, M.H.J. Bollen, “SSC Compensation Capability of Unbalanced Voltage Sags” IEEE Trans. On Power Delivery, vol.20, n.3, July 2005, pp.2030-2037.

[4] F. Delfino, G. B. Denegri, M. Invernizzi, R. Procopio, G. Ronda, “A P-Q capability chart approach to characterise grid connected PV-units”, CIGRÉ International Symposium: Integration of Wide-Scale Renewable Resources into the Power Delivery System, Calgary, Canada, 29 – 31 luglio 2009

[5] F. Gonzalez-Longatt, "Impact of emulated inertia from wind power on under-frequency protection schemes of future power systems," Journal of Modern Power Systems and Clean Energy, pp. 1-8, 2015/08/12 2015.

[6] F. Gonzalez-Longatt, E. Chikuni, W. Stemmet, and K. Folly, "Effects of the synthetic inertia from wind power on the total system inertia after a frequency disturbance," in Power Engineering Society Conference and Exposition in Africa (PowerAfrica), 2012 IEEE, 2012, pp. 1-7.

[7] S. Yuan-Zhang, Z. Zhao-Sui, L. Guo-jie, and L. Jin, "Review on frequency control of power systems with wind power penetration," in Power System Technology (POWERCON), 2010 International Conference on, 2010, pp. 1-8.

[8] J. Ekanayake and N. Jenkins, "Comparison of the response of doubly fed and fixed-speed induction generator wind turbines to changes in network frequency," Energy Conversion, IEEE Transactions on, vol. 19, pp. 800-802, 2004.

[9] R. Doherty, A. Mullane, G. Nolan, D. J. Burke, A. Bryson, and M. O'Malley, "An Assessment of the Impact of Wind Generation on System Frequency Control," Power Systems, IEEE Transactions on, vol. 25, pp. 452-460, 2010.

[10] I. Erlich, W. Winter, and A. Dittrich, "Advanced grid requirements for the integration of wind turbines into the German transmission system," in Power Engineering Society General Meeting, 2006. IEEE, 2006, p. 7 pp.

[11] F. Delfino, R. Procopio, M. Rossi, “Evaluation of forces in magnetic materials by means of energy and co-energy methods”, The European Physical Journal B, 25, n. 1 (2002), pp. 31-38, doi: 10.1140/e10051-002-0005-y.

[12] F. M. Gonzalez-Longatt, "Impact of emulated inertia from wind power on under-frequency protection schemes of future power systems," Journal of Modern Power Systems and Clean Energy, pp. 1-8, 2015/08/12 2015.

[13] G. Lalor, A. Mullane, and M. O'Malley, "Frequency control and wind turbine technologies," Power Systems, IEEE Transactions on, vol. 20, pp. 1905-1913, 2005.

[14] F. M. Gonzalez-Longatt, "Activation schemes of synthetic inertia controller for full converter wind turbine generators," in PowerTech, 2015 IEEE Eindhoven, 2015, pp. 1-5.

[15] N. Miller, K. Clark, and R. Walling, "WindINERTIA: Controlled Inertial Response from GE Wind Turbine Generators," presented at the 45th Annual Minnesota Power Systems Conference, Minneapolis, Minnesota, 2009.

[16] S. Wachtel and A. Beekmann, "Contribution of Wind Energy Converters with Inertia Emulation to Frequency Control and Frequency Stability in Power Systems," presented at the 8th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Farms, Bremen, Germany, 2009.

[17] F. Gonzalez-Longatt and J. M. Roldan, "Effects of dc voltage control strategies of voltage response on

multi-terminal HVDC following a disturbance," in Universities Power Engineering Conference (UPEC), 2012 47th International, 2012, pp. 1-6.

[18]J. Morren, S. W. H. De Haan, W. L. Kling, and J. A. Ferreira, "Wind turbines emulating inertia and supporting primary frequency control," Power Systems, IEEE Transactions on, vol. 21, pp. 433-434, 2006.

[19]K. Ping-Kwan, L. Pei, H. Banakar, and B. T. Ooi, "Kinetic Energy of Wind-Turbine Generators for System Frequency Support," Power Systems, IEEE Transactions on, vol. 24, pp. 279-287, 2009.

[20]A. Teninge, C. Jecu, D. Roye, S. Bacha, J. Duval, and R. Belhomme, "Contribution to frequency control through wind turbine inertial energy storage," Renewable Power Generation, IET, vol. 3, pp. 358-370, 2009.

[21]N. R. Ullah, T. Thiringer, and D. Karlsson, "Temporary Primary Frequency Control Support by Variable Speed Wind Turbines— Potential and Applications," Power Systems, IEEE Transactions on, vol. 23, pp. 601-612, 2008.

[22]Y. Jeong and C. S. o. M. D. o. Engineering, Comparison and Testing of Active Power Control Strategies for Grid-connected Wind Turbines: Colorado School of Mines, 2011.

[23]J. Duval and B. Meyer, "Frequency behavior of grid with high penetration rate of wind generation," in PowerTech, 2009 IEEE Bucharest, 2009, pp. 1-6.

[24]CEI 0-16 2012-12 - Reference technical rules for the connection of active and passive consumers to the HV and MV electrical networks of distribution Company Issue, Italian Technical Guidelines.

[25]IESO Power to Ontario on Demand Market Rules – Chapter 4 Grid Connection Requirements Issue Data: June 5, 2013 Canadian Technical Guidelines.

[26]ENTSO-E Network. "Requirements for Grid Connection Applicable to all Generators." *European Network of Transmission System Operators for Electricity, ENTSO-E (2013 March)* (2013).

[27]F. M. Gonzalez-Longatt, "Activation schemes of synthetic inertia controller on full converter wind turbine (type 4)," in Power & Energy Society General Meeting, 2015 IEEE, 2015, pp. 1-5.

[28]O. Anaya-Lara, Wind energy generation : modelling and control. Oxford: Wiley, 2009.

[29]T. Ackermann, Wind power in power systems. Chichester: John Wiley & Sons, 2005.