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Fast Frequency Support at a Wind Energy System Using Time-Varying Inertia and Droop Controls based on Globally Optimal H_∞ Control Design

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Abstract—The aim of this paper is to find an efficient strategy to provide local services for wind energy systems (i.e., regulate DC line voltage, active power, reactive power), frequency stability and support in both frequency deviation (using droop control) and rate of change of frequency (RoCoF) from generating units when it is used in an interconnected power as well as isolated ones. In order to achieve the research objectives, different strategies were studied. It's about the modeling of Permanent Magnet Synchronous Generator (PMSG) based on variable speed wind system connected grid using back to back converters and systems control. 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. Sufficient conditions are derived for robust stabilization in the sense of Lyapunov stability and are formulated in Linear Matrix Inequalities (LMIs). The performances and limits of the proposed controller are evaluated by means of dedicated simulations.

Index Terms—wind generation, H-infinity control, robustness, LMI, grid frequency support.

I. INTRODUCTION

WITH the increasing level of Renewable Energy Sources (RES), frequency stability of power system has drawn considerable attentions from system operators [1]. This is due to the fact that these sources are systematically grid connected by power electronics which increases the Rate of Change of Frequency (RoCoF) and decreases the Frequency Nadir (FN) of the overall power system [2]. Moreover, the variable speed Wind Turbine Systems (WTS) are mostly operating in Maximum Power Point Tracking (MPPT) mode and thus do not regulate their active power to support the power grid when the grid frequency deviates

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from its nominal value.

Recently, there are many research works for power converter optimal control based on linear matrix inequalities (LMI), including H_2 and H_∞ for local services [3]. Also, the research works for wind turbine system control are heavily investigated, both for Doubly Fed Induction Generator (DFIG) [4] and Permanent Magnet Synchronous Generator (PMSG) [5]. However, there is no a comprehensive methodology which addresses both local services and frequency in terms of global control at the same time.

Frequency support for renewable in general, and for wind turbine in particular, is the ability of frequency regulation by adjusting the produced power from the generators [6], [7]. This is not only acting on frequency deviation using droop control [7], but also taking into account of RoCoF behavior to ensure the stability of considered system and its neighbor [8]. The frequency regulation in renewable energy is heavily investigated, both in frequency deviation using classical droop control [6], [7], [9] and in inertia control (or RoCoF regulation) using hidden inertia control [6], [10] and fast power reserve [6], [11]. This work is totally adequate in the view of frequency support, however, lack of a global control structure which should include the local services control. The control system model with frequency support for neighbor grid is introduced. To perform and evaluate the performance of the frequency support strategies, one must find a way to include the dynamic of neighbor grid frequency [6], [7] into the control system model. However, to globally achieve both objectives of frequency support and local services (i.e. regulate DC line voltage, active power, reactive power), not only the frequency dynamic is considered as in [7] but also the relationship of frequency and terminal voltage of the grid has to be taken into account. In [9], many methodologies are introduced and proven effective for the neighbor grid, but still, the lack of relationship of frequency and terminal voltage of the grid makes the mentioned strategies less practical.

The objective of this paper is to focus on the wind

generators connected to a large scale grid, a sector in which profitability is far from certain and which therefore requires a degree of optimization of energy efficiency [12]. In this context, the production of these energy sources has to be optimized, that is to say extracting a maximum power under all conditions of operation, for which we have proposed a maximum power point tracking control [6], [12]. Several combinations of controls based on pitch control, droop control [9] and frequency control (for RoCoF improvement) using H_∞ optimization. The main control strategy used to emulate an inertial behavior of generators connected to the grid by power electronics was detailed, namely hidden inertia controller [10] and fast power reserve emulation [11] to obtain a frequency support. In addition, the local services [5] (DC voltage control, generator speed control, reactive current of grid side converter) as well as grid frequency support are studied using Matlab/Simulink to illustrate the effectiveness of the proposed methods.

The paper is organized as follows. In Section II, the grid-connected PMSG dynamics are modeled and the control problem is formulated. In Section III, the proposed Globally H_∞ Controller is constructed. Simulation results that illustrate the effectiveness of the proposed strategies are presented in Section IV. Finally, the conclusions and future prospects are presented in Section V.

II. NONLINEAR MODEL OF GRID CONNECTED PMSGs

Consider the PMSG structure, with LCL filter and two converters as in the Fig. 1:

The PMSG nonlinear system in the d-q synchronous reference frame is given in [5].

Consider now 2 PMSGs connected to the grid as in Fig. 2:

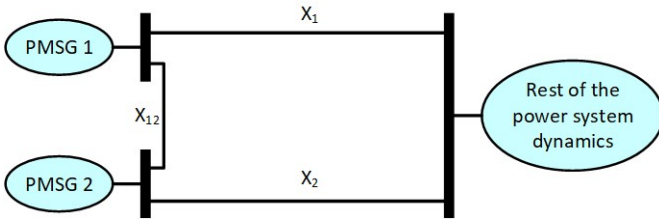


Fig. 2. The VSC-HVDC power structure

The dynamics of pitch angles are totally decoupled from the other PMSGs dynamics [13]:

$$\begin{cases} \frac{d\beta_{PMSG1}}{dt} = -\frac{1}{\tau_{C1}}\beta_{PMSG1} + \frac{1}{\tau_{C1}}\beta_{PMSG1ref} \\ \frac{d\beta_{PMSG2}}{dt} = -\frac{1}{\tau_{C2}}\beta_{PMSG2} + \frac{1}{\tau_{C2}}\beta_{PMSG2ref} \end{cases} \quad (1)$$

where

$$\begin{cases} \beta_{\min} \leq \beta_{PMSG1}, \beta_{PMSG2} \leq \beta_{\max} \\ \left(\frac{d\beta}{dt}\right)_{\min} \leq \frac{d\beta_{PMSG1}}{dt}, \frac{d\beta_{PMSG2}}{dt} \leq \left(\frac{d\beta}{dt}\right)_{\max} \end{cases}$$

Typically, as in [13], these limitations come from the servo motor:

$$\begin{cases} \tau_{C1} = 0.2 (s); \tau_{C2} = 0.2 (s) \\ \beta_{\min} = 0 (\text{deg}); \beta_{\max} = 20 (\text{deg}) \\ \left(\frac{d\beta}{dt}\right)_{\min} = -10 (\text{deg}); \left(\frac{d\beta}{dt}\right)_{\max} = 10 (\text{deg}) \end{cases}$$

As a consequence, the pitch angle will be controlled separately from the other PMSGs dynamics.

A. Droop control with deloading methods

From the deloading lookup values in Fig. 3, for frequency support, the wind generator has to run at deloading point (10%) rather than MPPT to reserve an amount of power. For example, consider the wind turbine is running at 17 (m/s) wind speed in Fig. 4 [6], the wind turbine will produce power at 10% deloading point A to reserve 10% of its power capacity. To utilize this reserved power for frequency support, a droop relationship is established [7]:

$$\Delta P_{ref} = -\frac{1}{R}\Delta f, \quad (2)$$

where ΔP_{ref} is the required amount of change in power when there is a change in frequency Δf .

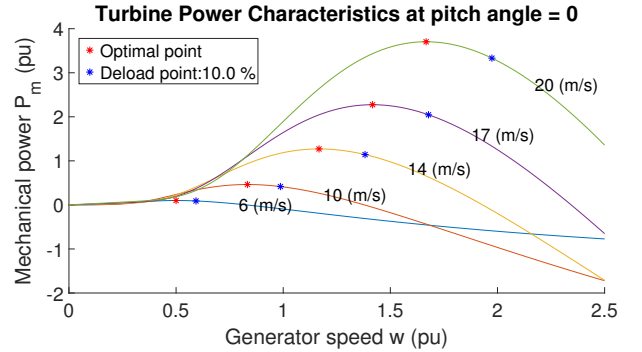


Fig. 3. The output power with different wind speeds at MPPT and at 10% deload

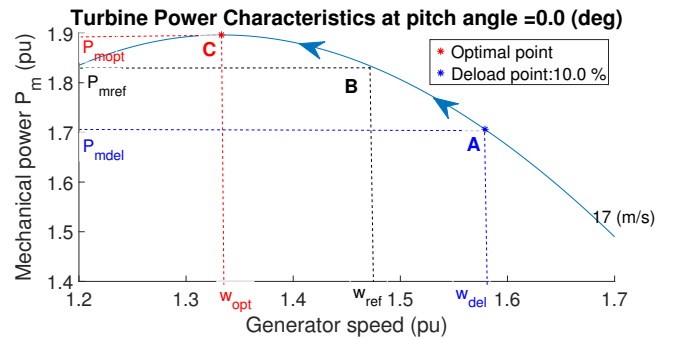


Fig. 4. The strategy for generator speed deloading

An increase in grid load or shortage in power generation will generate a droop in the frequency of grid [7]. To compensate

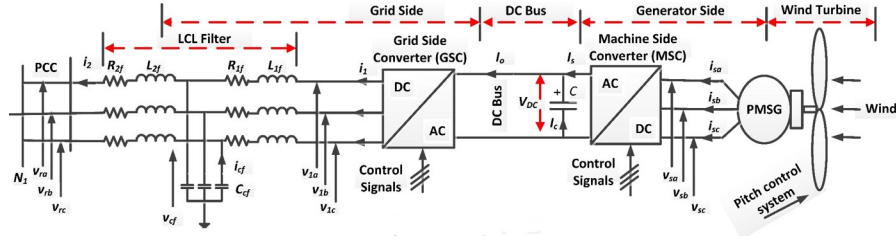


Fig. 1. The VSC-HVDC power structure

this frequency droop, there is a need to increase power production using the reserved power. As a consequence, following (2), the operating point of wind generator moves from A to B to increase the mechanical power. Following Fig. 4, this will result in increasing of the produced power. Thus, P_{mref} will be used to determine the desired generator speed w_{ref} as follows [6]:

$$P_{mref} = P_{mdel} + \Delta P_{ref} \quad (3)$$

and

$$P_{mref} = P_{mdel} + (P_{mopt} - P_{mdel}) \frac{w_{del} - w_{ref}}{w_{del} - w_{opt}} \quad (4)$$

From equation (4), the value of w_{ref} will be calculated as:

$$w_{ref} = w_{del} - (w_{del} - w_{opt}) \left(-\frac{1}{R} \frac{\Delta f}{P_{mopt} - P_{mdel}} \right) \quad (5)$$

The relationship between desired produced power P_{mref} and desired pitch angle β_{ref} is:

$$P_{mref} = P_{mdel} + (P_{mopt} - P_{mdel}) \frac{\beta_{del} - \beta_{ref}}{\beta_{del} - \beta_{opt}} \quad (6)$$

Thus, from droop control relationship (3) and (6), the desired pitch angle β_{ref} is

$$\beta_{ref} = \beta_{del} - (\beta_{del} - \beta_{opt}) \left(-\frac{1}{R} \frac{\Delta f}{P_{mopt} - P_{mdel}} \right) \quad (7)$$

B. Wind generator inertia control

The emulated inertia control methodology is given in Fig. 5 [6]. From the RoCoF feedback, the converter controller is able to produce immediate active power according to the status of RoCoF.

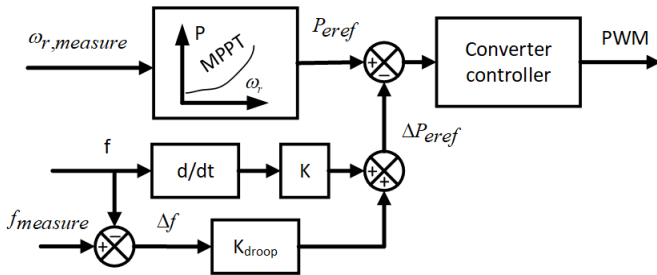


Fig. 5. The hidden inertia control structure [6]

The gain K is chosen based on the fact that the change of the power of the grid with respect to the variation of the grid frequency is

$$\Delta P_L = 2H \frac{df}{dt}, \quad (8)$$

where H is the global inertia of the AC grid, f is grid frequency and ΔP_L is the total power change. The principle of inertia control is to immediately generate the same amount of total power change to keep the RoCoF as small as possible. Thus, the required power to be supplementary produced in order to compensate the fall in RoCoF is

$$\Delta P_{eref} = K \frac{df}{dt} \quad (9)$$

$$\Delta P_{eref} = -\Delta P_L = -2H \frac{df}{dt}. \quad (10)$$

The generator speed is controlled by a reference generated from a predefined active power amount [6]

$$\omega_{r,ref} = \sqrt{\omega_{r0}^2 - 2 \frac{P_{const}}{J} t}, \quad (11)$$

where J is the inertia of the wind turbine, P_{const} is the predefined active power. The produced power is controlled by the scheme in Fig. 6 [6].

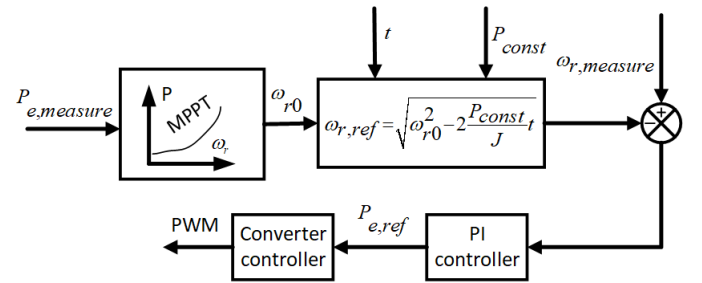


Fig. 6. The fast power reserve control structure [6]

C. Global structure for PMSGs control with frequency support

All of the aforementioned levels, including rapid response (RoCoF), slow response (droop control), and local requirements, should all be ensured in frequency support. As a result, the suggested control (which is a novel H_∞ control detailed in the following section) includes a mix of deloading methods,

inertia control, droop control, and converters control for local services, as described in Fig. 7 [14]:

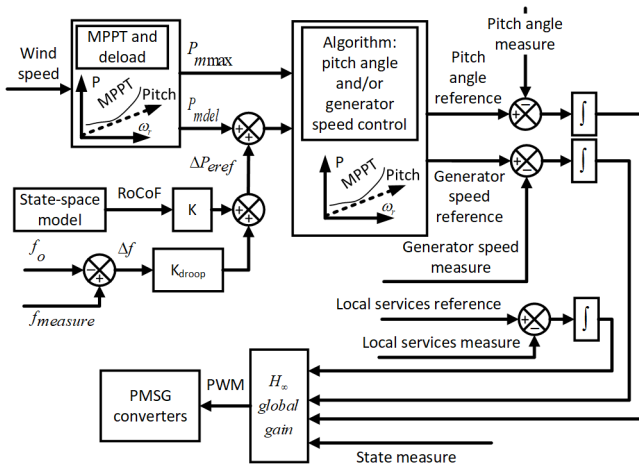


Fig. 7. The global control for PMSG with local services and frequency support

The deloading techniques (3) for droop control and the emulated inertia control (10), the desired power which meets the need of droop control and RoCoF (very fast frequency control) support is:

$$\begin{aligned} P_{mref} &= P_{mdel} + \Delta P_{refdroop} + \Delta P_{refinertia} \\ &= P_{mdel} + \left(-\frac{1}{R}\right) \Delta f + (-2H) \frac{df}{dt} \end{aligned} \quad (12)$$

From the desired power (12), K_{droop} and K in fig. 7 are

$$\begin{cases} K = -2H \\ K_{droop} = -\frac{1}{R} \end{cases} \quad (13)$$

The steps for switching generator speed control and/or pitch angle control in the algorithm in Fig. 7 are

- (i) Regulate and stabilize the PMSG with produced power at deloaded point P_{mdel} .
- (ii) Continuously calculate the desired produced power based on equation (12) from frequency and RoCoF status using state-space model.
- (iii) If $P_{mref} \leq P_{opt}$: maintain the same pitch angle, determine the equivalent generator speed w_{ref} from the desired generated power P_{mref} using (4).
- (iv) If $P_{mref} > P_{opt}$: at this stage, the generator speed control alone cannot generate enough power for frequency regulation. Hence, set $w_{ref} = w_{opt}$ and determine the desired pitch angle β_{ref} from the desired produced power P_{mref} using (6).
- (v) The equivalent generator speed w_{ref} and pitch angle β_{ref} become the input of the global control along with local services to globally fulfill both goals of local control and frequency supports.

D. Augmented system for local services

After linearization using first order approximation of the nonlinear PMSGs and grid system of the Fig. 1, one obtains the state-space form with disturbance

$$\begin{cases} \dot{X} = AX + B_1U + B_2W \\ Y = CX \end{cases} \quad (14)$$

Consider the *extended state* \bar{X} and *output* \bar{Y} for the purpose of step reference tracking along with output error e :

$$\bar{X} = \begin{bmatrix} \dot{X} \\ e \end{bmatrix}; \bar{Y} = e; e = -CX + Y_{ref}. \quad (15)$$

The *extended system* which corresponds to this extended state and output is:

$$\begin{cases} \dot{\bar{X}} = \bar{A}\bar{X} + \bar{B}_1\bar{U} + \bar{B}_2\bar{W} \\ Y = \bar{C}\bar{X} \end{cases} \quad (16)$$

where:

$$\begin{aligned} \bar{A} &= \begin{bmatrix} A & 0 \\ -C & 0 \end{bmatrix}; \bar{B}_1 = \begin{bmatrix} B_1 \\ 0 \end{bmatrix} \\ \bar{B}_2 &= \begin{bmatrix} B_2 \\ 0 \end{bmatrix}; \bar{C} = [0 \quad I] \end{aligned}$$

System (16) can be stabilized by the state-feedback control which, in original variables, results into a multivariable PI controller

$$\dot{U} = \bar{K}\bar{X} \Rightarrow U = \bar{K} \left[\int X \, edt \right] \quad (17)$$

III. SYNTHESIS OF THE PROPOSED GLOBALLY H_∞ CONTROLLER

Consider the linear state-space system:

$$\begin{cases} \dot{X} = AX + B_1U + B_2W \\ Y = CX + D_1U + D_2W \\ U = KX \end{cases} \quad (18)$$

The transfer function from disturbance W to the output Y is

$$\begin{cases} Y(s) = G(s)W(s) \\ G(s) = (C + D_1K)(sI - (A + B_1K))^{-1}B_2 + D_2 \end{cases} \quad (19)$$

It is obvious that:

$$\|Y\|_2 \leq \|G\|_\infty \|W\|_2. \quad (20)$$

Problem 1:

For the above system, the H_∞ problem is to design a static state feedback control law such that:

$$\|G\|_\infty < \gamma \quad (21)$$

Hold for a given positive scalar γ .

Theorem 1:

The H_∞ problem 1 has solution if and only if there exist a symmetric positive definite matrix $X_p \geq 0$ and a matrix W_p , such that

$$\begin{bmatrix} \Psi & B_2 & (CX_p + D_1W_p)^T \\ B_2^T & -\gamma I & D_2^T \\ CX_p + D_1W_p & D_2 & -\gamma I \end{bmatrix} < 0 \quad (22)$$

where

$$\Psi = (AX_p + B_1W_p)^T + AX_p + B_1W_p. \quad (23)$$

The solution of the problem can be given as

$$K = W_p X_p^{-1}. \quad (24)$$

Proof 1:

It is well-known that with linear system:

$$\begin{cases} \dot{X} = AX + BU \\ Y = CX + DU \end{cases} \quad (25)$$

The H_∞ problem with this system:

$$\begin{cases} Y = G(s)U \\ G(s) = C(sI - A)^{-1}B + D \end{cases} \quad (26)$$

Is solved by [5], [15]- [18] if and only if there exist a symmetric positive definite matrix X_p , such that:

$$\begin{bmatrix} X_p A^T + AX_p & B & X_p C^T \\ B^T & -\gamma I & D^T \\ CX_p & D & -\gamma I \end{bmatrix} < 0 \quad (27)$$

Apply this for the linear system with disturbance (equation (18)), where $G(s)$ is in the form of equation (19), the problem 1 is solved if and only if:

$$\begin{cases} \begin{bmatrix} \Psi & \bar{B}_2 & (\bar{C}X_p + \bar{D}_1\bar{K}X_p)^T \\ \bar{C}X_p + \bar{D}_1\bar{K}X_p & \bar{D}_2 & -\gamma I \\ \Psi & (\bar{A}X_p + \bar{B}_1\bar{K}X_p)^T & (\bar{A}X_p + \bar{B}_1\bar{K}X_p) \end{bmatrix} < 0 \\ \Psi = (\bar{A}X_p + \bar{B}_1\bar{K}X_p)^T + (\bar{A}X_p + \bar{B}_1\bar{K}X_p) \end{cases} \quad (28)$$

and by defining $W_p = \bar{K}X_p$, the inequality turns into theorem 1.

IV. SIMULATION AND RESULTS

The proposed control methodologies are applied to the 2 PMSGs in Fig. 2. Several combinations of controls were considered: all controls simultaneously applied or only pitch and drop control without fast frequency control (for RoCoF improvement) or other combinations. In all situations, H_∞ control was used. The latter control was synthesized in a coordinated manner for the 2 PMSGs. The local services (DC voltage control, generator speed control (or, equivalently, produced power control), reactive current of grid side converter (or, equivalently, reactive power)) as well as grid frequency support are checked by the following simulations.

Consider the scenario of load change of the overall power system in Fig. 8. Fig. 9 and Fig. 10 show that pitch control and

generator speed control provide a significant amount of power, which play an important role in frequency deviation regulation. At the same time, fast regulation (inertia control) provides a rapid impact on produced power, which has a positive impact on RoCoF (Fig. 11 and 12). Due to the strong relationship between generator speed and produced power (which is shown in MPPT relationship), the H_∞ optimization on frequency w_f provide no increase of power supply, which means that there will be no effect on frequency behavior.

From the comparison given in Fig. 11, one can also conclude that the RoCoF is greatly improved by using fast frequency control (inertia control in our case). The pitch angle control and generator speed control also help to improve RoCoF but with less impact.

Frequency deviation shown in Fig. 12 is less severe when speed and pitch angle controls are used.

From results in Fig. 9 and Fig. 10 one can also deduce that generator speed control alone also increases power supply, which in turn diminishes frequency deviation.

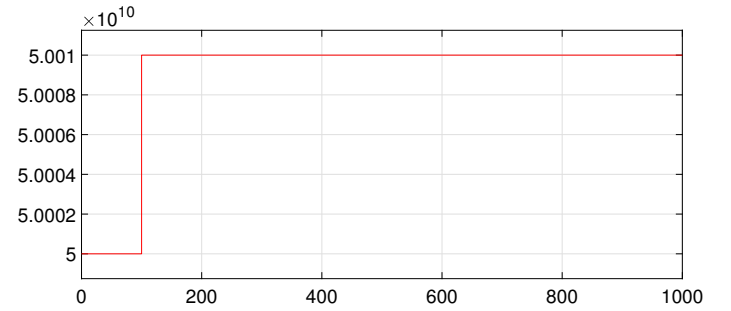


Fig. 8. The change on load (in [W]) of the grid

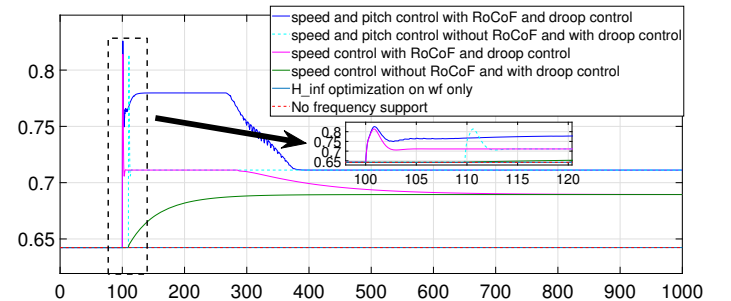


Fig. 9. Produced power (in [pu]) of PMSG 1 in different control strategies

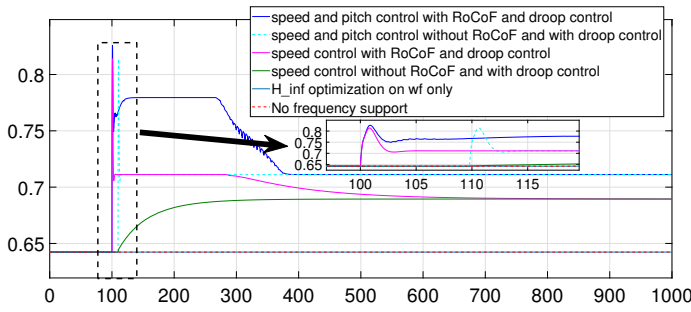


Fig. 10. Produced power (in [pu]) of PMSG 2 in different control strategies

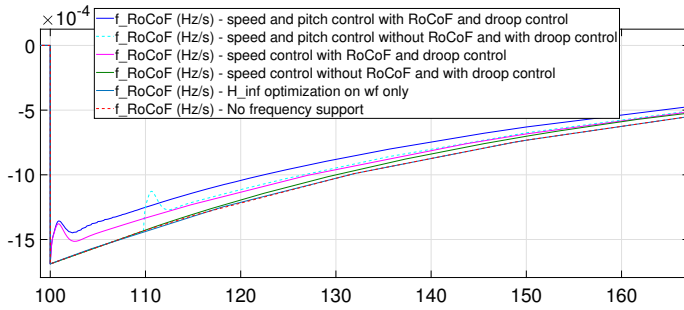


Fig. 11. RoCoF behavior (Hz/s) of the grid in different control strategies

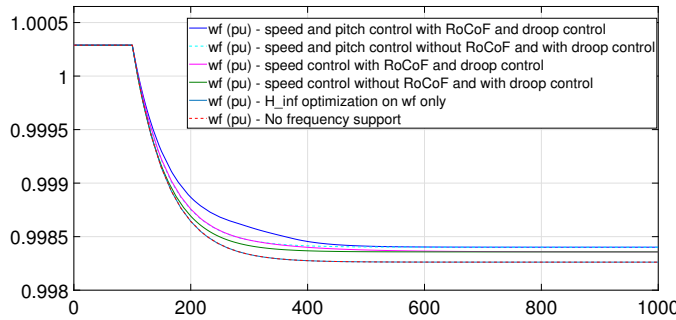


Fig. 12. Frequency behavior (pu) of the grid in different control strategies

V. CONCLUSION

This paper presents a control method applied to wind turbines mainly fall under primary frequency control. In order to find an efficient strategy to provide local services for wind energy systems (i.e., regulate DC line voltage, active power, reactive power), frequency stability and support in both frequency deviation (using droop control) and RoCoF from generating units when it is used in an interconnected power as well as isolated ones. Therefore, different control strategies were studied. It's about the modeling of two PMSGs based on variable speed wind system connected grid using dual converters and systems control. The proposed control methodologies are validated using this model. Several combinations of controls based on pitch control, drop control and frequency

control (for RoCoF improvement) using H_∞ optimization. The effectiveness of the proposed methodologies are finally demonstrated through a wind energy system with two PMSGs to illustrate the effectiveness of the proposed methods. The local services (DC voltage control, generator speed control (or, equivalently, produced power control), reactive current of grid side converter (or, equivalently, reactive power)) as well as grid frequency support are studied using Matlab/Simulink. In future work, the performance of the proposed methods will be implemented and tested through Experimental Setup.

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