Analysis of Grid-Forming Wind Turbine Frequency Response

Johan Boukhenfouf[1], Xavier Guillaud[1]

[1] Univ. Lille, Arts et Métiers Institute of Technology, Centrale Lille, Junia, ULR 2697 - L2EP - Laboratoire d'Électrotechnique et d'Électronique de Puissance, F-59000 Lille, France

ABSTRACT – As the share of renewable energies increases, it is essential to study its impact on the power systems. A major concern is the frequency dynamics after an event due to the loss of inertia in the system. To support the frequency with converter based generation, the grid-forming control has been proposed. This paper focuses on the application of such control on wind turbines. Thanks to simplified models, the inertial response of grid-forming wind turbine is analyzed. It is concluded that the MPPT control of the wind turbine reduces the inertial effect of the converter. Delaying the MPPT action with a filter can improve the inertial effect. Finally, if the wind turbine operates in the speed limitation region, interactions with synchronous machines may emerge.

Key-words – Frequency Dynamics, Wind Turbine, Grid-Forming Converter

1. INTRODUCTION

In power systems, the grid frequency is kept thanks to the balance between generation and load. In case of major event, for example a system split, [1, 2, 3], the system reacts as follows. First, the natural inertial effect of synchronous generators limits its decline (first seconds). Then, the First Frequency Reserve (**FFR**) reacts to contain it (15-30s). Finally, the Frequency Restoration reserve restore (**FRR**) it to its original value (15-30 minutes). However, this response is challenged by the increasing share of renewable energy . Indeed, the traditional grid-following control does not provide inertial effect. So, during the first step mentioned above, the frequency may drop to forbidden level.

Various solutions to support the frequency of the grid has been developed for grid-following wind turbine (**WT**) [4]. To support both frequency and voltage, grid-forming converters (**GFM**), also called virtual synchronous machine (**VSM**), has been developed. Its inertial effect is studied in [5]. In [5], it is demonstrated that a grid-forming converter provides as much inertia as a synchronous generator. Moreover, if equipped with a frequency droop (i.e participate to the First Frequency Reserve), it reduces significantly the frequency nadir because its response is faster than the turbine of the synchronous machine. However, these conclusions were drawn with a GFM with constant DC bus. The latter is equivalent to an extremely fast infinite source of energy, so a more realistic primary source is needed to confirm the results.

In [6, 7, 8], the impact of GFM type-4 wind turbine the frequency dynamics is analyzed. (wind turbine with synchronous generator and back-to-back converter). [6], the linear model of the grid-forming wind turbine is derived in order to analyze the influence of various parameters on the inertial effect of the device. It shows that wind turbine can effectively provide inertial effect but the latter depends on the operating point and the speed controller parameters. In [7], a similar analysis is conducted but with a power balance approach. In this study, the wind turbine is operated in de-loaded mode, so it can provide FFR and FRR. Then, it operated perfectly in accordance with [5]. In [8], a field test of grid-forming control on wind turbine is presented. The results are reassuring.

Similarly to [6], this paper proposes a theoretical analysis of the inertial effect of GFM wind turbine. However, it studies another implementation of the MPPT algorithm, that does not use a speed controller. It proposes a solution to enhance inertial effect for such type of wind turbine that does not operate in de-loaded mode. Moreover, operation in the speed limitation zone is also examined.

In section 2, the model used for the analyses are introduced. Then, 3 studies the inertial effect of the wind turbine. 4 provide solutions to enhance it. Finally, part 5 gives the final remarks.

2. METHODOLOGY AND MODELING

To study system frequency response, simplified models of power systems have been proposed in the literature. For example, [9] introduced an aggregated single mass model whose input power is driven by the governors of the power plants. Such model were applied to wind turbines in [10]. In this paper, another approach is used : the classical second-order model of generator [11] is adopted. The power of the swing equation is fed by the prime mover. Generators are connected to each other through the synchronizing torque of the grid. This methodology, used in [6, 5], is simple enough for an in-depth analysis and require less simplification than the single-mass-model. The validity of these simplified models is confirmed by EMT simulations. This section presents the modeling of the power system elements.

2.1. *The synchronous machine*

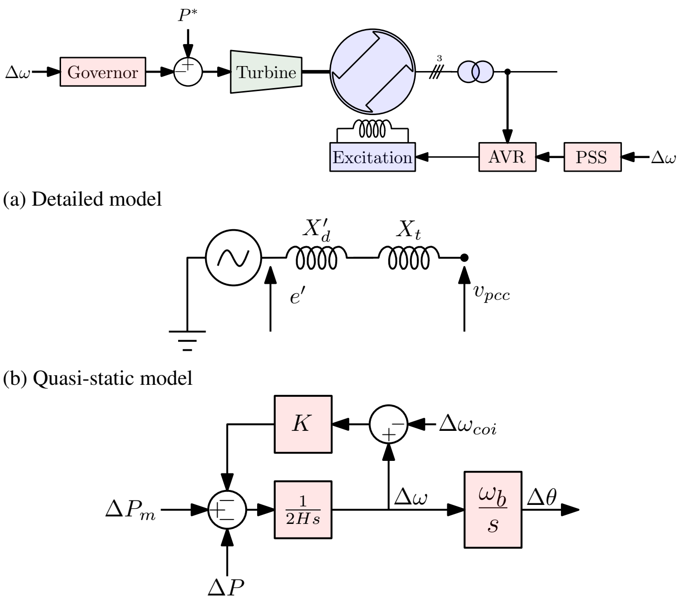
As a referenced model, the detailed eighth order model of a 900 MW round rotor synchronous machine is used. It is equipped with transformer, static excitation system ST1C, PSS1A [12], and governor IEESGO [13] as showed in figure 1a. Equations, models and parameters for these systems are available in [5] or [11]. However, in this work, the nominal frequency is 50 Hz.

The classical model, employed in this work, is a constant voltage source behind impedance (figure 1b) whose angle is driven by the swing equation (figure 1c). The main issue with this model is the determination of the damping constant K. However, this is not a concern as it hardly affects the system frequency response. Still, in this work, K is estimated in order to fit the EMT simulation results as much as possible.

2.2. *The Grid-Forming Converter*

The referenced model of the converter is depicted in figure 2a. For the equations, the VSC is represented by an average model. The power control is realized through the angle as represented in figure 2c. Reference voltage amplitudes v_d^*, v_q^* are respectively 1, 0 and are adapted by the transient virtual resistance [14]. The parameters of the converter are given in table 1.

The classical model of the generator is established under strong hypothesis that includes the quasi-static model of the grid and the disregard of fast dynamics. By applying these to the grid-forming, the same type of simplified model can be deter-



(a) Detailed model

(b) Quasi-static model

(c) Simplified model

FIG. 1. Synchronous generator models

mined : a constant voltage source behind an impedance (figure 1b) whose angle is driven by the power control (figure 1c). The derivation of this model is realized in [5].

TABLE 1. GFM Parameters

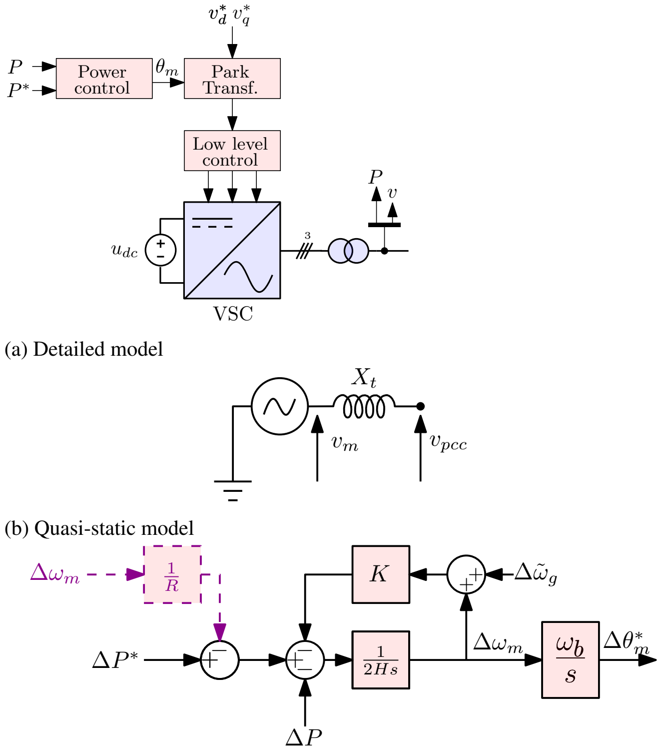
Parameter	Value	
Nominal frequency (f_n)	50	Hz
Nominal power (P_n)	900	MW
Connection voltage (U_n)	230	kV
Converter voltage (U_{vsc})	20	kV
Transformer resistance (R_t)	0.005	p.u
Transformer reactance (X_t)	0.15	p.u
Inertia (H)	6.5	s
Damping coefficient (K)	333	p.u
Transient virtual resistance (R_v)	0.09	p.u
Transient virtual resistance bandwidth (ω_v)	60	rad/s
PLL integral constant (K_i)	0.61	
PLL proportional constant (K_p)	29.34	
DC Capacitor (H_c)	40	ms

2.3. *The wind-turbine and power conversion model*

Fig. 3 presents the type-4 wind turbine model and its connection to the converter as introduced in [15] and [16]. The dynamics of the synchronous generator and machine size converter are neglected. The electrical power from the wind turbine is assumed equal to its reference.

Moreover, the pitch control is not considered in this study. Indeed, it is supposed that the converter is not over-sized and therefore, it cannot provide inertial effect when operating at nominal power.

As for the turbine, a one-mass rotor is considered as modeled by (1). The mechanical power captured by the wind is given in (2). c_p is the power coefficient and depends on the wind turbine design. λ is the tip speed ratio as defined by 4. The turbine



(a) Detailed model

(b) Quasi-static model

(c) Power control

FIG. 2. Grid-forming converter models

parameters are given in table 2.

$$\frac{d\omega_T}{dt} = \frac{1}{2H_t}(T_m - T_e) \quad (1)$$

$$T_m = \frac{1}{\omega_T} * \frac{1}{2}\pi R_t^2 c_p(\lambda, \beta) V_w^3 \quad (2)$$

$$T_e = \frac{P_{dc}}{\omega_T} \quad (3)$$

$$\lambda = \frac{\omega_t}{v_w R_t} \quad (4)$$

$$c_p = 0.73(\frac{151}{\lambda_i} - 0.58 * \beta - 0.002\beta^2.14 - 13.2)e^{-\frac{18.4}{\lambda_i}} \quad (5)$$

$$\text{where}\lambda_i = \frac{1}{\lambda - 0.1\beta} - \frac{0.003}{\beta^3 + 1}$$

TABLE 2. Wind turbine Parameters

Parameter	Value	
Farm Nominal Power (P_{nom})	900	MW
Number of turbines (N_t)	180	
Turbine Nominal Power ($P_{t_{nom}}$)	5	MW
Nominal wind speed ($v_{w_{nom}}$)	11.487	m/s
Nominal rotor speed ($w_{t_{nom}}$)	1.1664	rad/s
Rotor radius (R_t)	63	m
Turbine total inertia (H_t)	2.3162	s

The reference power of the converter is driven by the MPPT algorithm implemented in the indirect way, that is to say,

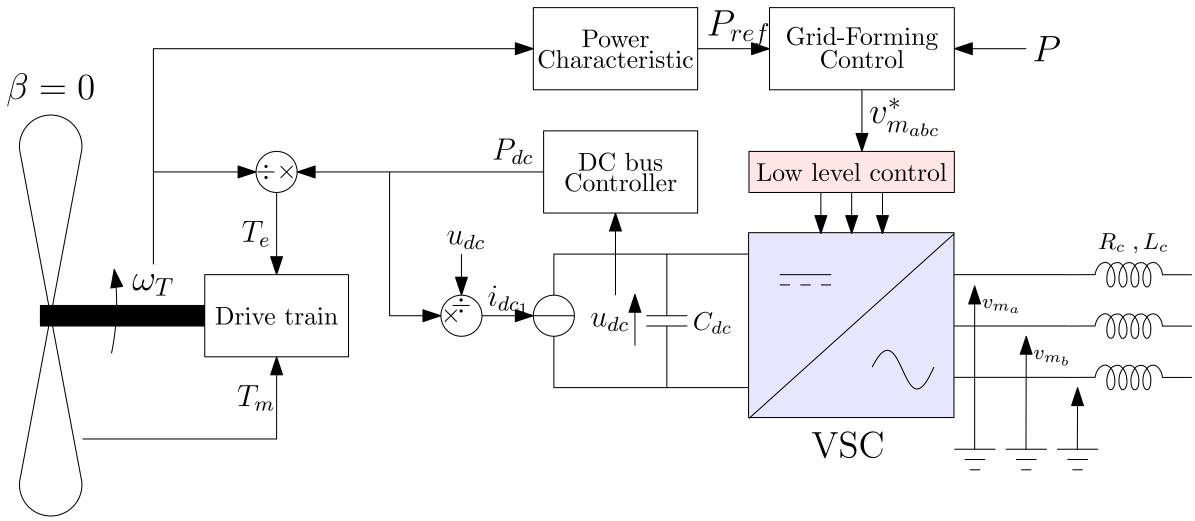


FIG. 3. Detailed model of grid-forming wind turbine

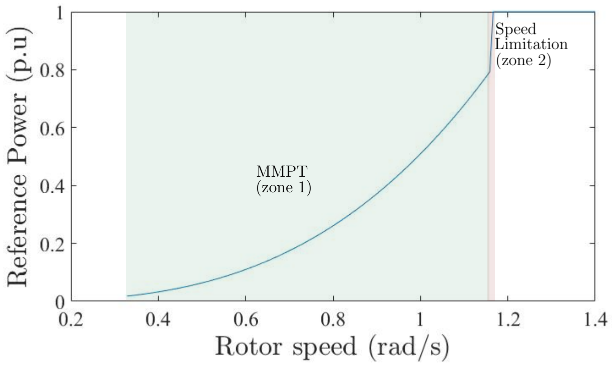


FIG. 4. Power characteristic of the turbine

through the feedback of the rotor speed considering the optimal tip speed ratio 6. Doing so, as the wind speed grows, the nominal speed is reached before the nominal power, therefore there is a region in which the speed is limited by the control. The power characteristic is depicted in fig. 4.

(2).

$$P_{mppt} = \frac{1}{2}\rho\pi R_t^2 * c_{p,opt} * \left(\frac{\omega_t R_t}{\lambda_o pt}\right)^3 \tag{6}$$

For the simplified model, the linearized wind turbine is associated with its power conversion, the converter is still represented by the power control. However the power reference is now driven by the wind turbine as shown in fig.5.

2.4. *The grid*

The reference model of the grid corresponds to Kirchhof's laws in the dq-frame. The simplified model need to comply with the input/output of the sources which are the power and the angle. Therefore, the convenient representation of the grid corresponds to the synchronizing torque matrix. Its calculation is explained in appendix D of [5] or chapter two of [17].

In this section, both reference and simplified models of the elements have been introduced. Next section will analyze the impact of wind-turbine on the inertial effect of the GFM.

3. INERTIAL EFFECT OF GRID-FORMING WIND TURBINE

The two-generator bed-test of fig.6 is employed in this work. It is reminded that the generators are considered with their transformers. They are connected to through a line of of 100 km whose parameters are displayed in table 3. The original operating point is given in table 4.

TABLE 3. Line Parameters

Parameter	Value	
Nominal frequency (f_n)	50	Hz
Base power (P_n)	100	MW
Nominal Voltage (U_n)	230	kV
Resistance(r_d)	0.0001	p.u/fm
Inductance (x_d)	0.001	p.u/km
Susceptance (b_d)	0.00175	p.u/km

TABLE 4. Operating point (S_{base} = 100 MW, U_{base} = 230 kV)

Device	Type	P (p.u)	Q (p.u)	V (p.u)	δ (°)
LOAD	PQ	9	0.5	1	0
GEN1	PV	5.4	0.63	1	32.0
GEN2	Swing	3.9	2.18	1	0

3.1. *Impact of the wind turbine on the inertial effect of the converter*

To analyze the inertial effect, the load is increased by 100 MW at 2s. for seek of comparison, three configurations are tested :

- SM-SM : both generators are synchronous machines.
- GFM-SM : GEN1 is a GFM with constant DC bus.
- WT-SM : GEN1 is a GFM with wind turbine.

The simulation results, obtained with Matlab Simulink, are displayed in figure 7.

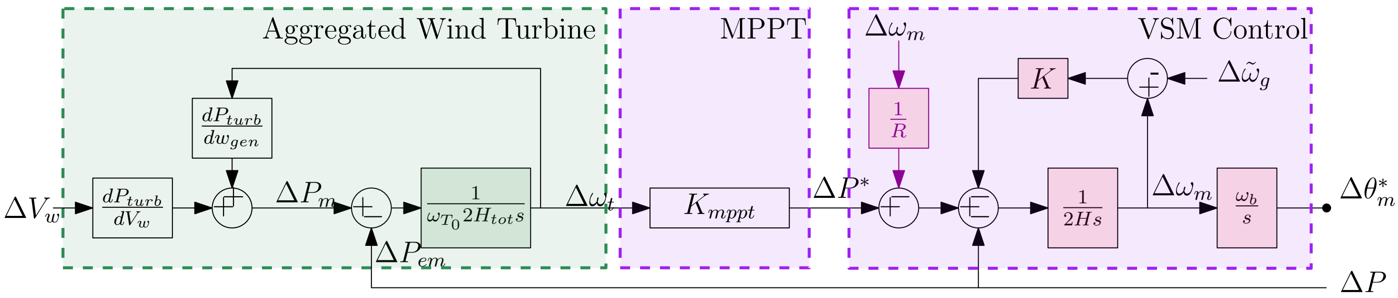


FIG. 5. Simplified linearized model of grid-forming wind turbine

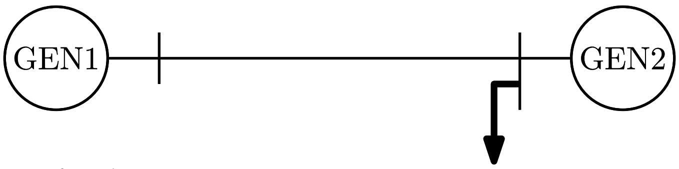
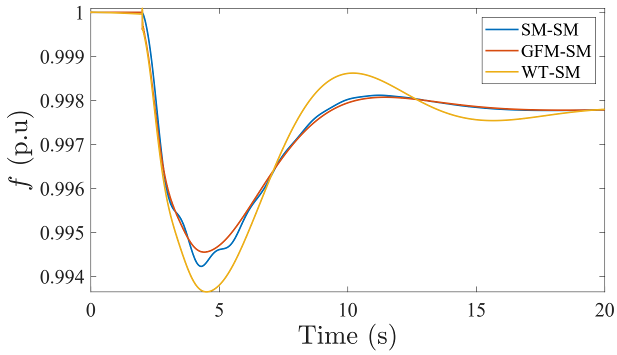
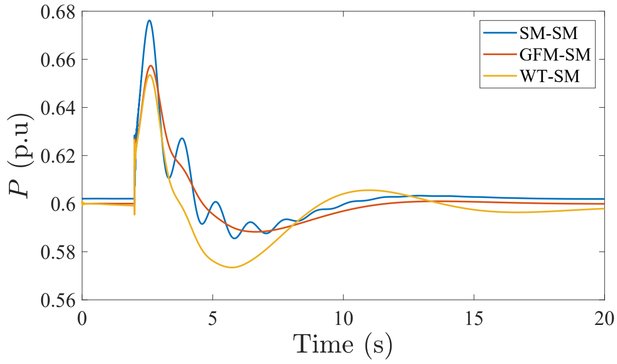


FIG. 6. Bed-test power system



(a) Frequency of the converter



(b) Power delivered by the converter

FIG. 7. Response of WT after applying a load step of 100 MW

First, notice that the inertial effect of the GFM with constant dc bus is similar to the synchronous generator. The difference between both response is the oscillatory behavior. As for the wind turbine, it can be seen that the inertial effect of the converter decreased when its dynamics are considered.

Fig.5 clarifies this phenomena. Indeed, it can be seen, that the addition of the wind turbine on the converter creates a second path for the inertial effect that counters the increase of power of the converter. In fact, the following series of event happens.

1. The load step occurs.
2. The inertial effect of the GFM delivers more power.
3. The unbalance between GFM power delivery and wind generation slows down the turbine .
4. The MPPT algorithm reduces the reference of power.

3.2. *Influence of the operating point*

The MPPT is non-linear gain that increases with the rotor speed (see (6) and fig.4). When the turbine spins fast, the MMPT gain is large,thus the counter-effect is high. Ironically, it is when the turbine stores the most kinetic energy that it releases the least on the network in case of disturbance.

To illustrate this idea, several operating conditions of the wind turbine were tested while maintaining the load at 900 MW : the power of the synchronous machine is adapted. Results are displayed in fig. 8. On one hand, the results corroborate the previous analysis, the power deliver and the minimum frequency decrease with the increase of the operating point. On the other hand, at $P = 0.9$ p.u, a growing oscillation is created.

At $P = 0.9$ p.u, the wind turbine is in the speed limitation zone (fig. 4), so the gain between ω_t and P_{ref} is extremely high gain. The loop is now faster and participates to the inter-machine mode (judging by the frequency of the oscillation). To verify this hypothesis, a small-signal stability study was carried out on the detailed model and the results are presented in fig.9. The accurate identification of the poles were verified using participation factors.

To sum up, the addition of wind turbine as primary source of the grid-forming converter decreases the inertial effect of the latter due to the MPPT loop. This counter-effect depends on the operating point of the turbine. Moreover, in the speed limitation zone, it may creates instability by exciting inter-machine modes. In the next part, a solution is proposed to enhance these responses.

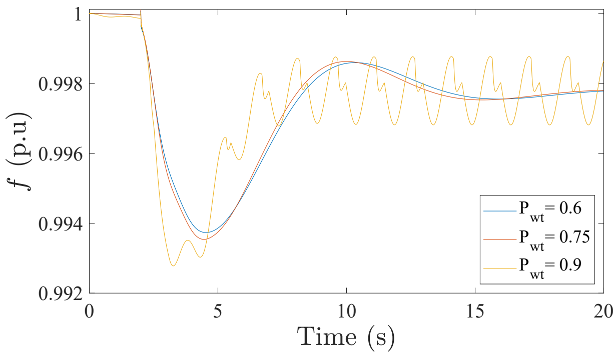
4. ENHANCEMENT OF INERTIAL EFFECT

4.1. *Design of the filter*

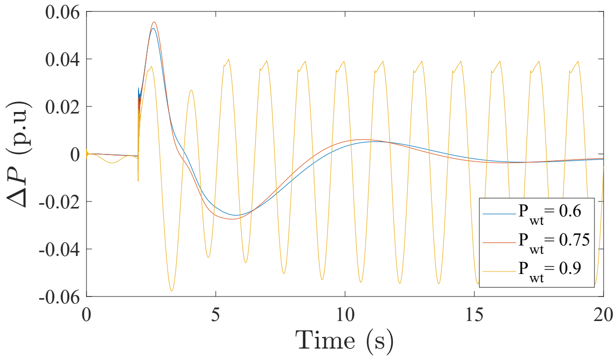
The inertial effect is decreased by the action of the MPPT,so the first idea to counter this phenomena is by delaying it with a filter (7) to extract more kinetic energy from the turbine. The slowest the filter, the more inertial effect. However, the energy taken from the turbine has to be recovered after. It means that it will produce less and thus, more FFR is needed. So, the design of the filter is a trade-off between inertial effect and FFR.

$$H_f(s) = \frac{\omega_f}{\omega_f + s} \tag{7}$$

But, as observed in the previous section, in the speed area limitation, the grid-forming wind turbine may cause unstable inter-machine oscillations. Hence, an other criteria of design could be to chose the filter that damp this mode. It is this one that is used in this work. To do so, a parametric variation of the filter frequency was executed for an operating point of 0.9 p.u. The results are displayed in fig. 10 and the value chosen for is $\omega_f = 3$.



(a) Frequency of the converter



(b) Power delivered by the converter

FIG. 8. Response of WT after applying a load step of 100 MW

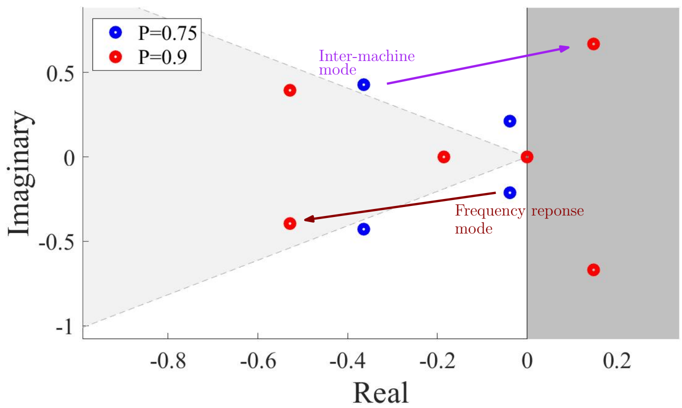


FIG. 9. Small-signal stability analysis for various operating point.

4.2. *Validation of the concept*

Simulation results for an operating point of 0.75 p.u (i.e zone 1) are presented in fig. 11. It is clear that the filter with $\omega_f = 3$ rad/s is not effective. The response is still too fast and the frequency is barely affected. This is why, to prove the efficiency of delayed MMPT, $\omega_f = 0.1$ rad/s was tested. In this case, the frequency nadir is better but its oscillatory behavior is intensified.

For the operation in the speed limitation, simulation results for an operating point of 0.9 p.u are displayed in fig. 12. As predicted by the small signal stability analysis, the system is stable only with $\omega_f = 3$. However, the damping of the oscillation remains low and again, the frequency dynamics are not enhanced.

In conclusion, in theory, delaying the MPPT action with a filter allows a better inertial effect of the grid-forming wind. This idea was validated in the MPPT range of operation. However, the behavior in the speed limitation region makes the design of the filter challenging.

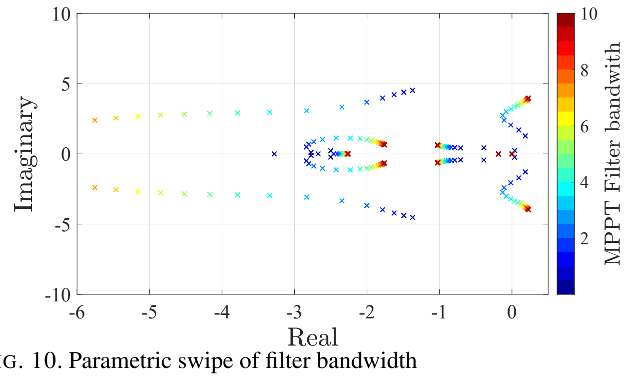


FIG. 10. Parametric swipe of filter bandwidth

5. CONCLUSIONS

This paper presents an analysis of the inertial effect of the wind turbine connected to a grid thanks to simplified models. It revealed the negative influence of MPPT implementation on the inertial effect of the GFM converter. Furthermore, this impact depends on the operating point of the wind turbine.

In the MPPT operation zone, the previous analysis applies perfectly. Moreover, it is possible to enhance the inertial effect by implementing a filter to delay the MPPT action in the first instants. It should be notice that, by doing so, more kinetic energy is taken from turbine and a longer recovery time will be needed.

The issue comes from the speed limitation zone. In this study case, unstable inter-machines oscillations emerged in this range of operation. These can be damped with a proper tuning of the aforementioned filter but then, it does not enhance the frequency dynamics anymore.

The results presented must be consolidated in future works. Operation of wind turbine in the speed limitation zone must be analyzed thoroughly, as it seems to be problematic. For the filter, a simple first order was used in this work but it does not act satisfactorily. More complicated structure have to be investigated, such as lead-lag for example.

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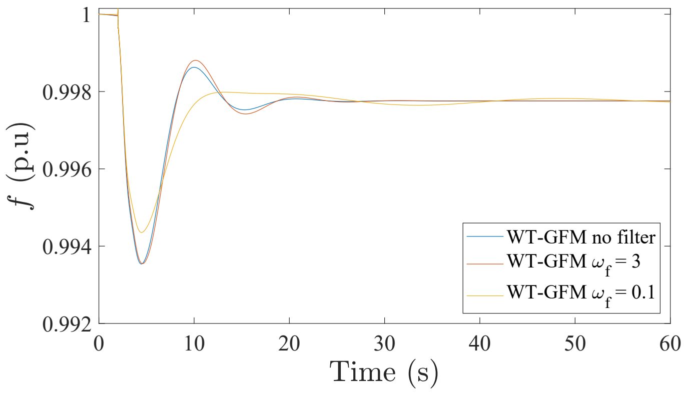
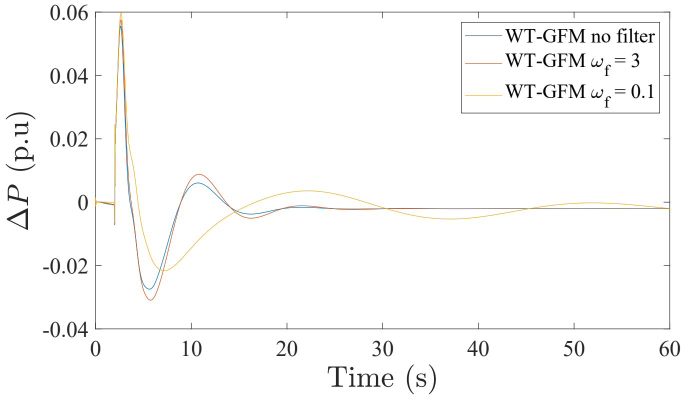
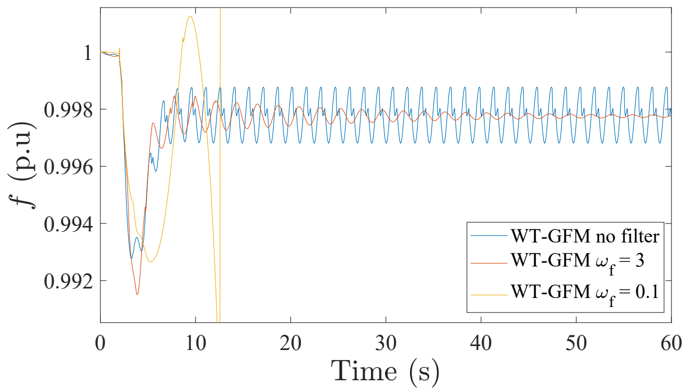


(a) Frequency of the converter

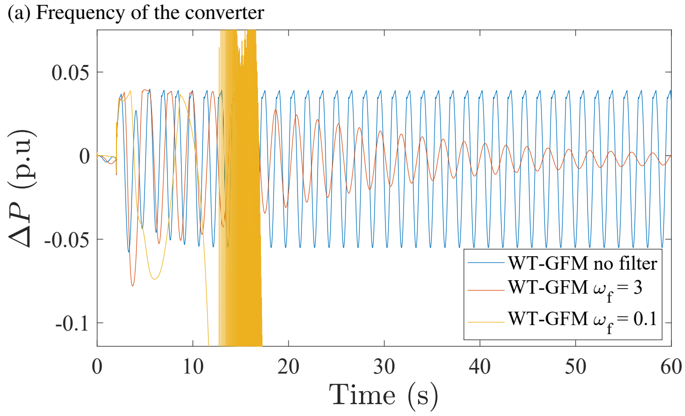


(b) Power delivered by the converter

FIG. 11. Response of WT with filter after applying a load step of 100 MW ($P = 0.75$ p.u)



(a) Frequency of the converter



(b) Power delivered by the converter

FIG. 12. Response of WT with filter after applying a load step of 100 MW ($P = 0.90$ p.u)

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