High Wind Power Penetration in Isolated Power Systems—Assessment of Wind Inertial and Primary Frequency Responses

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***Abstract*—Grid operational challenges are significant to increase securely the wind penetration level. New embedded control functions are therefore required in order to make participate wind generators in power system management. In this paper the implementation of inertial response and primary frequency control in a wind turbine controller are investigated. Main factors affecting the performances of the frequency regulation are identified and characterized. The influence of control parameters and the turbine operating point on the inertial response are analyzed through obtained performances in an islanded power system. The combined control scheme using both controllers is also developed and the potential of the obtained grid service at partial load is discussed.**

***Index Terms*—Droop controller, frequency response, inertial response, isolated power systems, primary frequency control, rate of change of power.**

I. INTRODUCTION

IN areas where the wind penetration is relatively significant, system operators begin to encounter serious frequency control concerns [1]. The situation is worse in isolated island systems that already have a small kinetic energy from their base-load generators [2]. Especially when wind power production is relatively large during off-peak hours, conventional synchronous generators may be switched off to balance generation and demand. This results in less system inertia and frequency response reserve in the system. Therefore, some utilities have already updated their grid codes to ensure power system security and reliability so that wind generators are now expected to provide frequency response. For example, Eirgrid, as other Nordic grid operators, requires that wind farms provide an automatic control of their active power as a function of the system frequency [3], [4]. Thus, many research works have been oriented to the design of frequency controllers for wind plants in recent years [5], [6]. Two solutions are particularly interesting for frequency regulation with variable speed wind turbines (VSWT): respectively the inertial control and the primary speed-droop control.

The design of the inertial control was initially proposed in [7] and [8] and then further studied in [9]–[11]. A "virtual" wind inertia is created to respond to frequency drops by using the kinetic energy stored in rotating masses of the wind turbine (WT). The paper [12] discusses factors affecting the provision of inertial response, such as the converter maximum currents and controller parameters. Furthermore, [13] shows that the WT inertial response capability can be higher than that of a synchronous machine for the same inertia value, since greater speed variations are acceptable for VSWT and so more kinetic energy can be converted into electrical energy.

The capability of providing long-term primary frequency regulation for doubly fed induction wind generators and full-converter wind turbines have been respectively studied in [14] and [15]. As for conventional power plants, the proposed control strategy requires WTs to preserve a power margin. The primary droop controller adjusts wind active power according to the frequency variation (Δf) through the pitch regulation. In [16], both frequency control schemes, described before, are exploited for further grid frequency improvements.

The implementation of a frequency control response into VSWT has been investigated and proven by many papers. However, some important points still require further studies. First, only the rated operating point of Wind Farms (WF) has been simulated and analysed in a lot of published works, such as in [12], [14], [16], and [17]. This is obviously not sufficient, since the full load operation period represents only a small part of the total operating time for most WFs. For example, WFs connected to the Portuguese power network can produce more than half of the rated power during only 10% of the overall operating time according to [18]. General conclusions should thus not be drawn from those papers, as the full-load operation is not representative enough. In the present paper, the performances of inertial response for full load and one partial load operating points are assessed.

Secondly, the limitation on the rate of change of WT electrical power (dP/dt) has hardly been considered in previous studies. References [19] and [20] showed that (dP/dt) should

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be limited by a maximum value to avoid fast variations of the turbine power output and reduce mechanical stresses. On the other hand, to enhance the WT frequency response, a minimum response rate of each online WT should be required by system operators [4]. Therefore, impacts of the (dP/dt) value on the WT frequency response as well as on the turbine behavior are characterized in this paper.

Section II details and illustrates key parameters that can affect the performance of inertial response. In Section III the principle and the contribution of the primary frequency control are presented. Section IV compares the WT inertial response and the primary governor response and investigates the potential of a combined scheme of both control functions. Full-load and partial-load operating points are considered and studied in this paper. Performances of the system frequency response are assessed through dynamic simulations by considering a French isolated power system as it may be affected by large amounts of wind generation. Section V presents main conclusions and future works.

II. Synthetic Inertia of Wind Turbines

A. Inertial Control Principles

1) Inertial Control Implementation: The control strategy of a wind generator is a combination of the pitch-control and the static power electronic converter control [25]. The inertial controller consists in adjusting the torque reference as a function of the derivative of the grid frequency (Fig. 1). When the grid frequency falls, the electromagnetic power setpoint increases, leading to a deceleration of the rotor speed and thus an extraction of the kinetic energy stored in rotating masses. The required power can therefore be released to the grid for dynamic frequency control support. The frequency has to be estimated by using a phase locked loop (PLL) synchronization. In order to minimize noise impacts, a low-pass filter is introduced in the control loop [21], with a T_f time constant (about 100 ms according to the performance of the equipments). The controller gain K_{ic} determines the quantity of additional injected wind power in case of a grid fault. To reduce mechanical stresses, wind turbines must not generate abrupt variations in power output. Consequently, the rate of change of power (ROCOP) injection is limited by the parameter $(dP/dt)_{\max}$ in order to reduce mechanical stresses on the drive train. According to manufacturer's data, the value of $(dP/dt)_{\max}$ should not exceed 0.45 p.u./s [19].

2) Wind Turbine Response at Different Operating Points: The dynamic behavior of a wind turbine providing inertial response is sensitive to initial operating conditions.

If the wind speed is above rated, the turbine is initially operating at full load and the pitch actuator is activated to maintain the rotor speed at its maximum value.

In the case of an under-frequency event (at $t = 10$ s), additional power is demanded [Fig. 2(a)], which results in a turbine speed drop [Fig. 2(c)]. Then the pitch angle is reduced to raise the rotor speed to its reference value [Fig. 2(b)]. After the power surge, the inertial control adjusts progressively the total wind power to the pre-disturbance level [Fig. 2(a)]. As the electrical power exceeds during a small time the steady-state rating of the turbine, the magnitude of the incremental power will depend on the power electronic sizing.

For moderate or low wind speeds, the pitch angle is maintained at zero to maximize wind production [Fig. 2(e)]. When

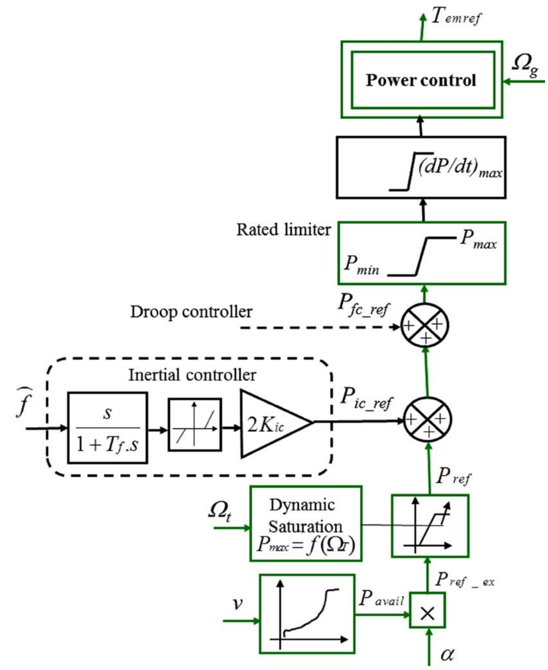

Fig. 1. Integration of the inertial controller in the control system.

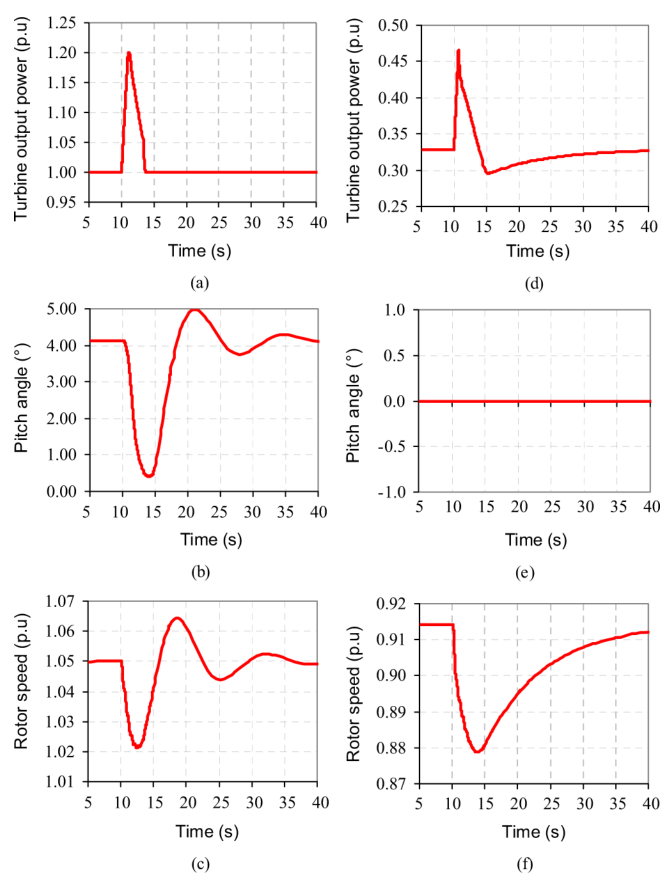

Fig. 2. Wind turbine inertial response at different operating points [(a), (b), (c) at full load and (d), (e), (f) at partial load].

the inertial controller is activated, additional power is first injected to the grid as at full load [Fig. 2(d)], leading to a decrease in the rotor speed. Then the turbine can no longer operate at the optimum speed issued from the "MPPT (Maximum Power Point Tracking)" control [Fig. 2(f)]. Therefore, compared to the initial production, less power will be delivered to the grid after the power surge until the turbine speed returns to its initial optimum value [Fig. 2(d)]. The duration of the speed recovery period depends on the turbine mechanical dynamics and lasts generally several tens of seconds.

Similarly to the inertial behaviour of synchronous machines, the WT inertial response at partial load is essentially energy neutral, meaning that the period of increased power is followed by a period of decreased power, during which the released kinetic energy is recovered by "withdrawing" power from the grid. However, the inertial response at full load is fundamentally different. From an energy point of view, the incremental electric power is supplied by the power available from the wind and the turbine speed is recovered via pitch control. Therefore, there is not any decrease of the wind output power after the disturbance.

B. Inertial Response Performance Characterization

1) Theoretical Comparison With a Synchronous Generator: In the first seconds following a fault, the electrical power from a grid-connected synchronous generator varies naturally in order to counteract frequency deviations. This natural inertial reaction of a synchronous machine can be characterized by the following equation:

$$P_e(S) = -2H.\widehat{f}(s).s. \tag{1}$$

where H is the synchronous machine inertia constant, s is the Laplace variable and $\widehat{f}$ is the measured per-unit frequency. Typical values of H lie between 2 to 6 MWs/MVA according to the type of generating unit [24]. The power response is therefore instantaneous and does not depend on the dynamics of speed control loops.

The WT inertial response is dominated by the additional control function presented in Fig. 1 and so does not have the same recovery phase as conventional machines. The power set-point variation in the first seconds after a fault is therefore characterized by the following formula:

$$P_{ic\_ref}(S) = -2K_{ic}\frac{S}{1+T_{f.S}}\cdot\widehat{f}(S) \quad \text{if} \quad \frac{dP_{ic\_ref}}{df} \leq \left(\frac{dP}{dt}\right)_{\max}. \tag{2}$$

Because of the measurement and filter delays, the frequency responses are different from those obtained using synchronous generators. Besides, protections may saturate the WT inertial response. In this case, the derivative of the power is forced to be a constant as shown in (3), and then the inertial contribution is limited:

$$P_{ic_ref}(t) = \left(\frac{dP}{dt}\right)_{\max}\cdot t \quad \text{if} \quad \frac{dP_{ic\_ref}}{dt} > \left(\frac{dP}{dt}\right)_{\max}. \tag{3}$$

A dead band is used to restrict the WT inertial control to large events (Fig. 1). The continuous small perturbations in frequency that characterize normal grid operation are not passed through to this controller. Theoretical analysis state that the performances of the inertial response are mainly affected by the value of the K_{ic} controller gain and the $(dP/dt)_{\max}$ ROCOP limitation parameter, but not by the turbine inertia constant.

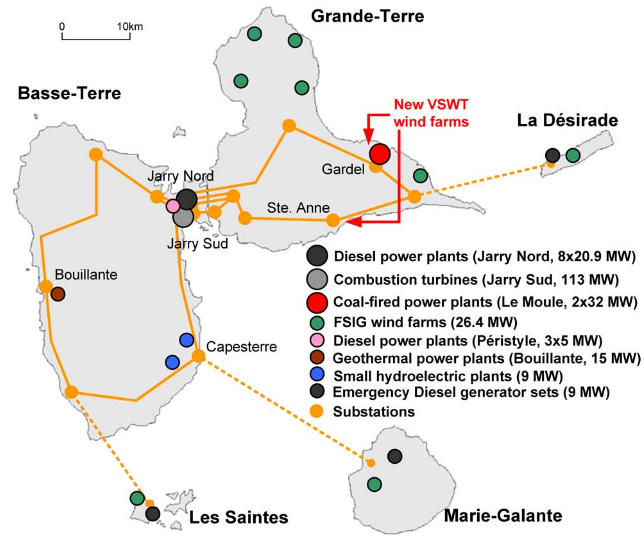

Fig. 3. HV grid, main generation plants, and DG locations in Guadeloupe.

2) Presentation of the Guadeloupe Power System: Impact on the power reserve has been studied and validated for a real isolated power system. Located in the eastern Caribbean Sea, the Guadeloupe archipelago is composed of five main (interconnected) islands. It covers 1600 km^2 and its population is about 404 000 inhabitants. The peak demand reached 260 MW in 2010. Fig. 3 presents the structure of the HV grid as well as the main generation sites. The transmission system is operated at 63 kV and includes 13 substations, each consisting of 2 step-down 63/21 kV transformers (10, 20 or 36 MVA) equipped with on-load tap changers. The model of the Guadeloupe power system including HV lines, transformers and power plants has been previously simulated with the Eurostag software package [26] and validated, since obtained results are very closed to sensed system responses [27], [28] .

Currently, according to the French feed-in tariff and purchase obligation scheme, renewable energy sources (RES) have the highest priority level in the dispatch order and do not participate in frequency control [29]. The primary reserve is mainly provided by Diesel engines, bagasse/coal-fired units and combustion turbines during peak demand times.

3) Simulated Scenarios: As shown in Table I, the 24.7 MW coal-fired plant at "Le Moule" does not provide governor frequency response but contributes inherently to system inertia. The power response of this plant after a grid disturbance will only be determined by its inertial nature, and thus, can be compared with the WT inertial response. The considered fault was based on the tripping of another "Le Moule" power plant producing 21.3 MW before the disturbance. This scenario with only 11% wind penetration is considered as the reference scenario.

In a second scenario with VSWT the "Le Moule" power plant that does not participate in primary frequency control is replaced by VSWT generation with the same power output, leading to a

TABLE I
SET-POINTS FOR THE REFERENCE SCENARIO WITH 11% WIND POWER

Power station	Units online	Power set-point	Reserve
Jarry Nord	4	55.8 MW	27.8 MW
Le Moule	*1*	*21.3 MW*	*Disconnected*
	1	***24.7 MW***	*0 MW*
Péristyle	2	9.4 MW	0.8 MW
VSWT	0	***0 MW***	*0 MW*
Other renewables	Various	27.3 MW	0 MW
Total		**138.5 MW**	**28.6 MW**

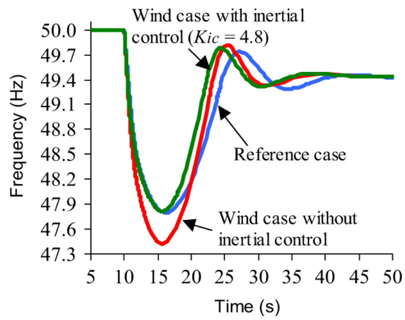

Fig. 4. Frequency response.

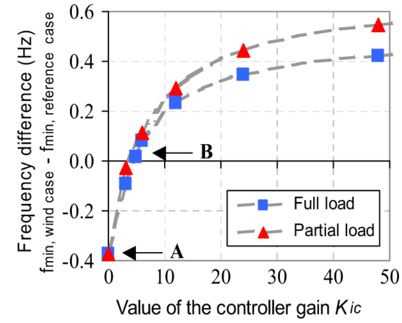

Fig. 5. Frequency nadir difference.

29.5% wind penetration. Power set-points of other generators remain unchanged. Hence, more than a quarter of the total rotating masses of the grid is lost, since the steam turbines provide a significant part of kinetic energy.

Three different scenarios will be studied and compared: the reference case, the wind case without inertial control and with inertial control. Since the focus of the simulations is the study of short-term dynamic performances, no long-term models (e.g., automatic generation control [24]) have been included. All automatic load shedding (ALS) relays were also removed to provide a clear comparison between various cases.

4) Impacts of the Controller Gain: Each manufacturer has his own maximum ROCOP parameter $(dP/dt)_{\max}$. For the presented simulations the 0.2 p.u./s minimum $(dP/dt)_{\max}$ value has been used in order to get a general model adequate with possible larger $(dP/dt)_{\max}$ values. Moreover, further exposed results (in Fig. 9) will prove that larger values for the $(dP/dt)_{\max}$ parameter does not improve the inertial response performance. As the dynamic behavior of a WT providing inertial response changes according to initial wind conditions, both full-load and partial-load operating points have been studied.

At high wind speeds, all VSWT are supposed to operate at full load because of the small size of the Guadeloupe Island. In Fig. 4, the dynamic behaviors of the frequency for the reference case and the wind cases are shown. In the absence of inertial control, the frequency nadir of the wind case is deeper than that of the reference case due to the reduction in system inertia. However, when the inertial control is enabled, the minimum frequency can be maintained at the same level as for the reference case with a pertinent controller gain.

Different values of the controller gain were implemented and tested. The minimum grid frequency is used as the key performance metric in this analysis, since it can be correlated to tripping thresholds in ALS schemes. The curve with squares in Fig. 5 describes the difference of frequency nadirs between wind cases and the reference case as a function of the controller gain for the full load operating range. With wind inertial response, the grid minimum frequency is reduced while the controller gain is increased.

Two interesting operating points can be identified. Point A corresponds to the case without inertial control $(K_{ic} = 0)$. A very important 400 mHz deviation from the reference case was observed, hence, the reduction in system inertia can change significantly the system frequency response. Therefore, the possibility of providing an inertial response seems to be essential for wind integration, as it would help to avoid load-shedding in some high-wind cases. At point B, WTs have an "equivalent" contribution to system inertia as the replaced conventional plant. With higher controller gain, the WT inertial response could even have better performances.

The same studies were also performed for the partial-load operating range (with 0.33 p.u. initial production of WFs) in the same condition. Hence, more wind turbines are used to produce the same total wind power.

According to Fig. 5, with a given controller gain, the minimum frequency in the partial-load case is closed to that in the full-load case, especially in case of low gain values. Since three times more turbines are connected to the grid at partial load, it seems that the inertial response of a single WT is less efficient in this case. In fact, at full load, additional power can be extracted from the wind via pitch regulation to provide inertial response [Fig. 2(b)], therefore, with the same controller gain, more power is injected by a single turbine to the grid in the first seconds for frequency support compared with the partial-load case [Fig. 2(a) and (d)]. Moreover, a WT operating at partial load requires recovering its optimum speed after discharging kinetic energy. Hence, the inertial response is always followed by a negative power spike [Fig. 2(d)], which offsets the contribution of the power surge.

Fig. 6 shows the inherent inertial response of the coal-fired generator (reference case) and the controlled inertial responses of WTs for different controller gains at partial loads. As demonstrated by theoretical analysis, the synchronous generator reacts almost instantaneously after the disturbance, while the WT inertial response is delayed and limited by the admissible rate of change of electrical power. More power is injected to the grid by WFs after the grid fault, as the wind nominal power in the

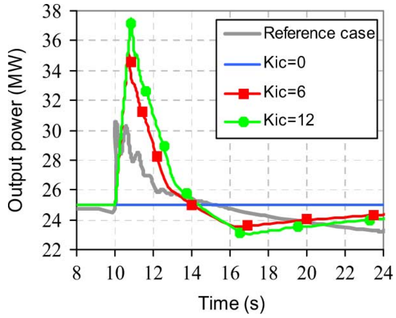

Fig. 6. Inertial response at partial load.

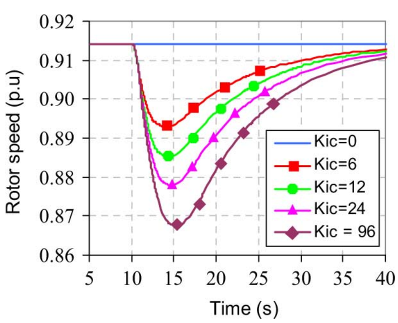

Fig. 7. Rotor speed.

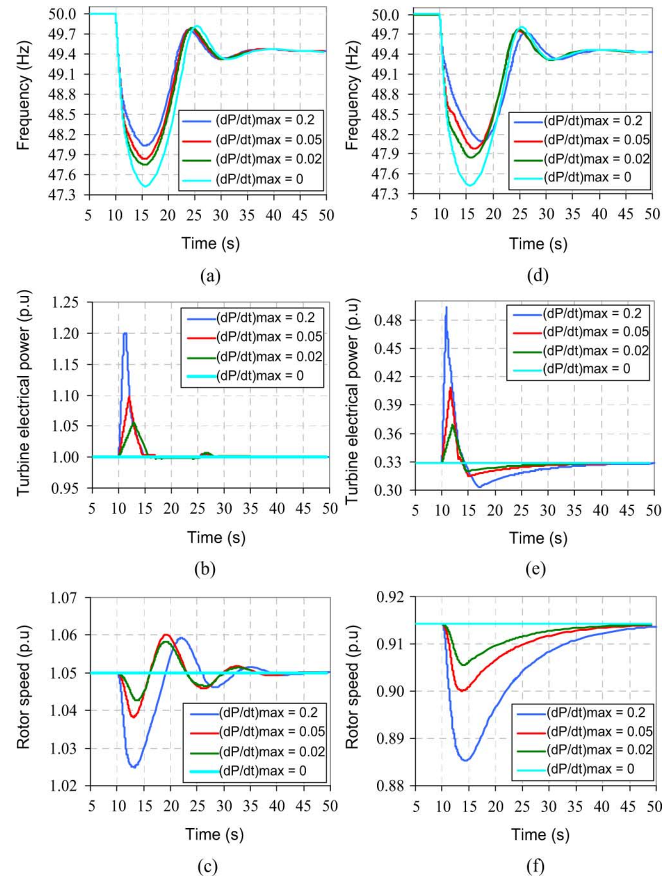

Fig. 8. Influences of the limit of the ROCOP. (a) Frequency response (full load). (b) Inertial responses (full load). (c) Rotor speed (full load). (d) Frequency response (partial load). (e) Inertial responses (partial load). (f) Rotor speed (partial load).

partial-load case is much higher than that of the replaced conventional power plant (75 MW v.s. 32 MW).

Since large values of K_{ic} leads to a faster drop of the turbine speed, this latter one should be supervised while WTs provide inertial response to make sure that the implementation of large gains is feasible. Generally, the rotor speed of VSWT should not fall below 0.7–0.8 p.u. in order not to disrupt its normal operation. According to our tests, even with very high controller gain values, the minimum turbine speeds remain far above 0.8 p.u (Fig. 7). Thus, the WTs still have the potential to extract more kinetic energy for inertial response.

However, as shown in Fig. 5, the benefit of increasing the controller gain is not proportional to its value, as the WT inertial response is saturated for high values of K_{ic}. Thus, it is not effective to set high controller gains, which could induce more wear and tear on wind turbines without significant increase in performances.

5) Influence of the ROCOP Limit: In order to reduce mechanical stresses of drive trains and so increase the WT lifetime, it might be desirable to set small values of $(dP/dt)_{\max}$ inferior to 0.2 p.u./s. The "wind case" scenario has been simulated. The controller gain was kept constant $(K_{ic} = 12)$ whereas the value of $(dP/dt)_{\max}$ has been progressively decreased, from 0.2 p.u./s to 0 p.u./s (which means that all power variations are eliminated i.e., the inertial control is not enabled).

Both full-load and partial-load cases were tested. As shown in Fig. 8(a)–(d), the frequency nadirs become deeper while the $(dP/dt)_{\max}$ value is reduced. This can be explained by the fact that the inertial response of wind farms is limited with low values of $(dP/dt)_{\max}$ [Fig. 8(b)–(e)].

If $(dP/dt)_{\max}$ is decreased, less incremental power will be injected to the grid via inertial control, i.e., less kinetic energy will be extracted from rotating masses. This results in a slower drop in the rotor speed [Fig. 8(c)–(f)]. In consequence, the fatigue of mechanical parts will be moderated.

Fig. 9 shows the maximum frequency deviation from the normal value after the fault as a function of the ROCOP limit. Even with a very low slope of the power variation (0.02 p.u./s), the inertial response still has remarkable effect compared to the case without any inertial control ($(dP/dt)_{\max} = 0$ p.u./s), since a reduction of about 400 mHz in frequency nadir can be obtained. However, the benefit is not linear. It was observed that above a certain limit (0.12 p.u./s), the increase in $(dP/dt)_{\max}$ has very slight contributions to improve the performance of the inertial response. It is therefore not necessary to set very high $((dP/dt)_{\max}$ values.

III. Primary Frequency Response

A. Principles of the Primary Frequency Control

The WT inertial control can only be used as a short-term dynamic frequency support. For effective long-term primary frequency regulations, an additional frequency droop control, which takes into account quasi-steady-state frequency deviations, must be integrated into the active power control loop of VSWT [14], [22] . The implemented droop control is similar to

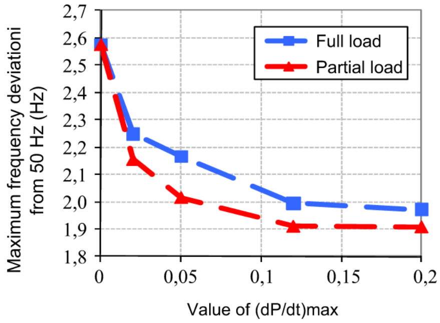

Fig. 9. Influence of the limit of the ROCOP on frequency response.

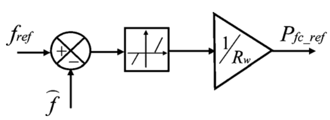

Fig. 10. Block diagram of the droop control for primary frequency response.

the one usually in use in synchronous generator (Fig. 10) and generates a power reference that is added into the WT power control system (Fig. 1). When frequency deviations exceed a specified deadband, the active power increment is proportional to the grid frequency variation and is defined as

$$P_{fc\_ref} = \frac{1}{R_w}(f_{ref} - \widehat{f}). \tag{4}$$

The droop parameter R_w is expressed in % of the wind turbine rating. In order to enable an increase of the wind plant active power output in response to an under-frequency condition, some active power production must be kept in reserve, i.e., the plant must be operated below the available power.

At deloaded operating points, the WT rotor speed is accelerated until its maximum value is reached. For further power curtailment, the pitch control is activated to reduce mechanical power extracted from wind [25].

B. Application on the Guadeloupe Power System

The wind primary frequency control has been applied in the scenarios corresponding respectively to 20.2% and 29.2% wind penetration rates, as load-shedding was observed after the grid fault (loss of the largest online generator) in the absence of wind participation in frequency regulation. The 29.2% wind penetration case with a high wind speed is taken as an example in this paragraph to illustrate dynamic behaviors of the frequency and WT responses. The power set-points of Diesel and wind power plants as well as the power reserve distribution are shown in Table II. Without a primary frequency control, all VSWT produce the maximum available power (25 MW) and the online Diesel plants provide 25.2 MW primary reserve. In the second case, 10% of the available wind power is kept in reserve and the VSWT production is deloaded (22.5 MW), which induces an increase of the conventional production, thus a decrease in conventional power reserve (22.7 MW).

As the fixed speed induction generator (FSIG) wind farms are not able to participate in primary frequency control, their production remains unchanged (16 MW). This transfer of power

TABLE II
POWER RESERVE DISTRIBUTION FOR THE 29.2% WIND CASE

	Without primary frequency response	With primary frequency response
Power set-point of Diesel power plants	*37.5* MW	*40* MW
Reserve provided by Diesel power plants	***25.2 MW***	***22.7 MW***
Power set-point of wind farms	25 MW (VSWT) + 16 MW (FSIG)	22.5 MW (VSWT) + 16 MW (FSIG)
Reserve provided by wind farms	***0 MW*** *(VSWT) + 0 MW (FSIG)*	***2.5 MW*** *(VSWT) + 0 MW (FSIG)*

reserve from Diesel plants to VSWT induces a slight reduction in wind penetration (from 29.2% to 27.5%). A 4% droop setting is used in our studies. This value should be carefully chosen, as a very low droop setting may induce unstable operating conditions of WTs and an unsuccessful frequency support [15], [23] .

Although the total power reserve remains constant in both cases, the minimum frequency is reduced by 250 mHz with a WT primary frequency response [Fig. 11(a)]. Then load-shedding previously observed can therefore be avoided (the first stage of ALS scheme in the Guadeloupe power system is triggered when the frequency decreases below 48.5 Hz). As it can be seen in Fig. 11(b), the total wind power reserve (0.1 p.u. $=$ 10%. 25 MW wind power) can be released into the grid in 0.5 second thanks to the fast response of power electronic converters and following the 0.2 p.u./s ROCOP setting.

Thus, the active power from WTs can be controlled almost instantaneously when compared with Diesel plants. As the dynamics of the WT mechanical part is much slower than that of converters [Fig. 11(d)], the mechanical torque stays lower than the electromagnetic torque during the first seconds after the grid fault. In consequence, a transient drop appears in the rotor speed [Fig. 11(c)]. In steady state, the turbine speed stabilizes to its rated value while the pitch is kept lower than the initial angle [Fig. 11(d)].

IV. RESULTS WITH BOTH CONTROLLERS

The WT primary frequency control can be applied, together with the inertial control, to further improve grid frequency responses [16]. Fig. 12 shows the maximum transient frequency deviation from the rated value for different wind penetration rates. The simulated scenario is based on the outage of the largest generation infeed during off-peak hours and with a high wind speed. In Guadeloupe, load shedding starts when the system frequency drops to 48.5 Hz, which is the under-frequency protection relay setting.

Fig. 12 shows that the inertial control and the primary droop control have "equivalent" contributions for the system, as grid frequency nadirs are almost identical with only one controller enabled. One level of load-shedding in the defense plan could be avoided with either inertial or primary frequency response. So fewer consumers would experience the outage when WTs participate in frequency control. If both controllers are simultaneously activated, transient frequency excursions will be further reduced (e.g., two stages of ALS are avoided at 20.2% wind penetration).

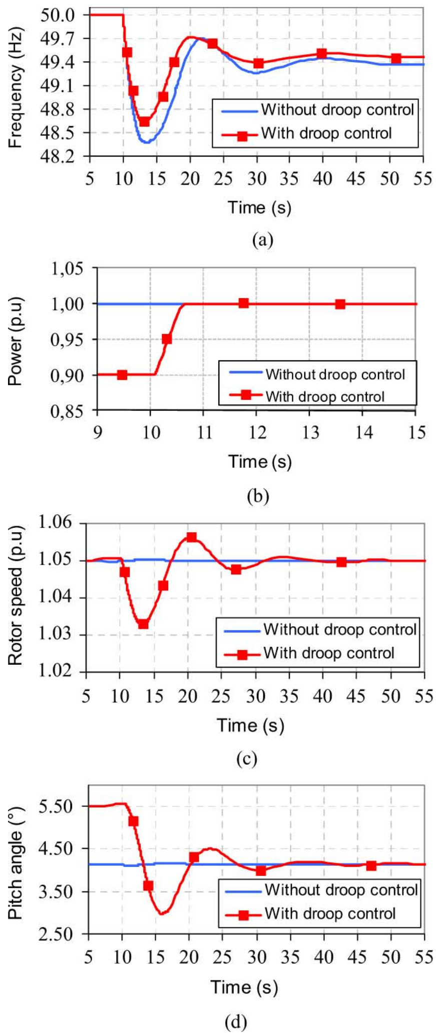

Fig. 11. Grid frequency and wind turbine dynamic behavior.

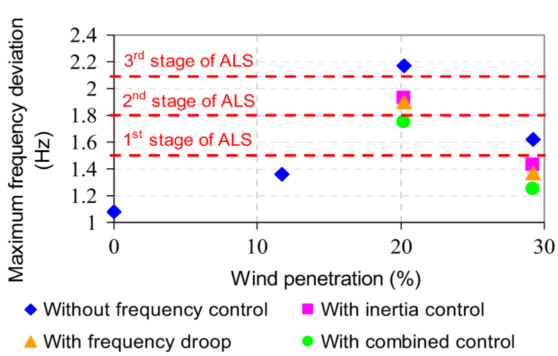

Fig. 12. Contribution of wind turbine frequency control (full-load case).

The same studies have also been performed for medium wind speeds, which are more realistic in practice. In order not to change the grid operating point in this case, the wind power is held constant, and thus, more turbines are connected to produce the same power. As shown in Fig. 13, when the inertial control and the primary frequency control are both enabled, the improvement in frequency response is strongly better compared with the full-load case. At 29.2% wind penetration rate,

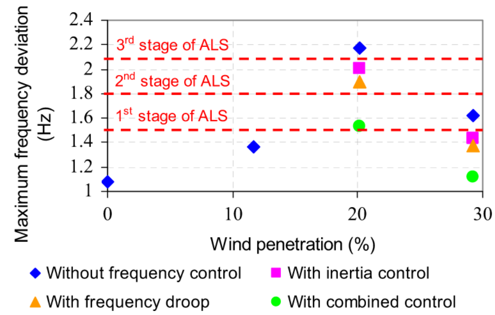

Fig. 13. Contribution of wind turbine frequency control (partial-load case).

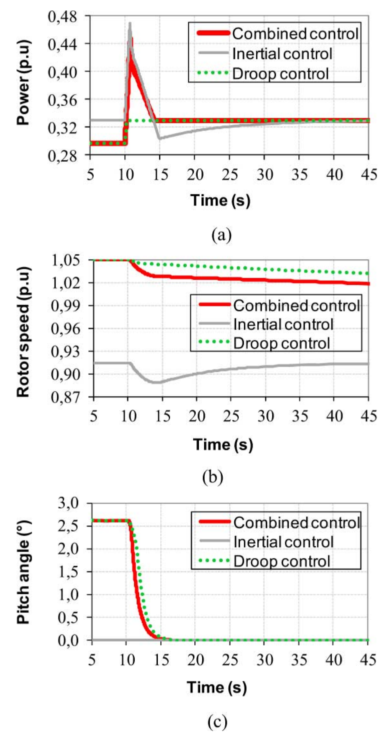

Fig. 14. Wind turbine dynamic behavior with various control schemes.

the wind combined-control service can help to bring the minimum frequency (after the disturbance) up to about the level of the no-wind case (0% wind penetration, i.e., maximum system inertia).

At partial load and with an inertial response, the turbine speed would need to come back to its optimum value after the extraction of kinetic energy [Fig. 2(d)–(f)]. This reduces the output power of the wind turbine as the rotor accelerates. The performance of the inertial response could be modified by this speed-recovery phase, since other generators must compensate for this temporary—but necessary—reduction in wind active power output. However, the combination with the primary frequency control could solve this problem. The combined-control response of the WT with both frequency control functions is presented in Fig. 14.

In fact, when wind power is deloaded, the turbine is forced to operate away from the maximum power extraction curve. Unlike the case in which only the inertial controller is enabled, the initial turbine speed under combined control is higher than the optimum speed [Fig. 14(b)].

During the grid fault, the rotor speed decreases, as a part of kinetic energy is released for frequency support. Then the WT operating point will move towards the optimal point with the decrease of the rotor speed [Fig. 14(b)]. Consequently, there is no need to recover the rotor speed and the wind power will not be reduced after the inertial response [Fig. 14(a)]. From an energy point of view, at partial-load operating points, as the stored kinetic energy is increased when the WT is deloaded, the inertial response is much improved, which leads to a better performance of the combined control scheme compared with the full-load case.

V. Conclusions and Discussions

Although natural delays appear for the deployment of the synthetic inertial response of VSWT in comparison with the inherent response of classical direct-connected synchronous generators, studies presented in this paper have shown satisfying performances and even better contribution to frequency stabilization after the loss of a major generation infeed than with synchronous machines. The performance of the WT inertial response can be improved by either increasing the auxiliary controller gain or relaxing the limit on the rate of change of wind electrical power. However, the benefit is not linear and the WT will suffer more wear and tear in these cases; the economic consequences are still to be assessed. Therefore, a good compromise should be made for appropriate controller parameter settings, which allow WTs to satisfy the grid code but do not impact seriously their own stability and lifetime. Moreover, the capability of WTs to stand repetitive mechanical stresses resulted from inertial contribution should be carefully examined by analysis over a long period before industrial applications.

The initial operating point of the WT also influences the inertial response performance. Future works should consider more operating points to better investigate the limitation of inertial response at partial load and quantify performances of inertial response.

The WT primary droop control could also help to increase system robustness by reducing frequency excursions following grid disturbances. The total wind power reserve can be released into the system in less than one second thanks to the fast response of power electronic converters. The combined control with both inertial and primary frequency controllers improves the frequency behavior and mainly when the WT is operating at partial load. In this case, the deloading of the turbine leads to an increase in rotor speed. Thus, more kinetic energy will be stored in rotating masses and the contribution of the inertial response can be much improved.

However, dynamic simulations performed over a time horizon of about one minute applied in this work are not sufficient to characterize the reliability of wind primary reserve. Indeed, as wind power generation is of variable nature and hard to forecast, the power reserve provided by WTs would logically not be as reliable as that procured from conventional generators. Future works should therefore take into consideration the wind variability and the prediction errors when assessing the potential and the performance of the WT participation in primary frequency control.

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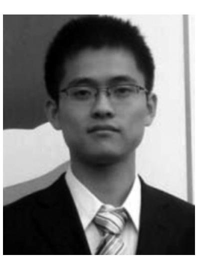

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